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**An M dwarf planet search programme using the photometric transit method:
implementation of a new ground-based survey**

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Declaration of Authorship

I, Mario DAMASSO, declare that this thesis titled, 'An M dwarf planet search programme using the photometric transit method: implementation of a new ground-based survey' and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

Date:

Things happen, in Saint-Barthèlemy...

There's a starman waiting in the sky... [David Bowie, Starman (1972)]

Bisogna provare...provare...provare, provare, provare...

[from the movie 'Non ci resta che piangere' (1984)]

Abstract

In questo lavoro sono descritti i passi più importanti che hanno portato allo sviluppo e alla messa in funzione della survey APACHE (A PATHway toward the Characterization of Habitable Earths), e vengono presentati alcuni dei principali risultati ottenuti dopo la prima stagione osservativa. APACHE è la prima campagna osservativa di lunga durata con base in Europa finalizzata alla ricerca di pianeti in orbita attorno a stelle nane rosse nelle vicinanze del Sole accuratamente selezionate, utilizzando il metodo fotometrico del transito. Il progetto è stato concepito alla fine del 2008 e la schiera di cinque telescopi automatici di 40 cm di diametro utilizzati per le ricerche sono entrati in funzione tra luglio 2012 e marzo 2013. L'introduzione presenta alcuni aspetti chiave che negli ultimi anni hanno portato le nane rosse al centro degli interessi dei cacciatori di mondi alieni, determinando la crescita del numero di campagne osservative dedicate al monitoraggio delle stelle più fredde, sia fotometricamente che tramite spettroscopia ad alta risoluzione. Vengono poi ripercorse le tappe fondamentali che sono servite per preparare e definire il design iniziale della survey APACHE (studio di fattibilità e studio pilota, discussi nei Capitoli 1 e 2), mentre il Capitolo 3 si concentra sulla descrizione delle caratteristiche più rilevanti dell'impianto della campagna osservativa, come la definizione del catalogo con i potenziali target osservativi (APACHE Input Catalogue) e della strategia osservativa, e la costruzione del software utilizzato per ottenere e analizzare le curve di luce. Nel Capitolo 4 sono presentati i risultati preliminari ottenuti dopo il primo anno di osservazioni a regime, e l'analisi si concentra soprattutto sullo studio della variabilità fotometrica di oltre 130 nane rosse. Tre target hanno mostrato evidenza di brillamenti stellari, e sono stati misurati periodi di rotazione attorno al proprio asse di cinque stelle attraverso l'analisi dei periodogrammi relativi alle loro curve di luce. Alle serie temporali fotometriche di queste stelle è stato applicato un semplice modello a singola macchia per descrivere la modulazione quasi-sinusoidale osservata in termini di macchie stellari/regioni attive, ottenendo in particolare una stima dell'angolo di inclinazione dell'asse di rotazione rispetto alla linea di vista. Il Capitolo si conclude con la presentazione di più di 90 nuove stelle variabili scoperte da APACHE nel corso del primo anno. Il lavoro si chiude con il Capitolo 5, dove viene descritta la strategica sinergia instaurata tra il progetto APACHE e l'esteso programma osservativo nazionale GAPS (Global Architecture of Planetary Systems) che fa uso dello spettrografo ad alta risoluzione HARPS-N montato al Telescopio Nazionale Galileo (Isola di La Palma, arcipelago delle Canarie) per ricerche nell'ambito dei pianeti extrasolari. Tra gli obiettivi di GAPS c'è quello di scoprire pianeti in orbita attorno a nane rosse attraverso l'analisi delle variazioni temporali

delle velocità radiali stellari, e il Capitolo 5 presenta i risultati preliminari ottenuti per i target in comune con il progetto APACHE. In particolare, viene sottolineata l'importanza delle serie temporali fotometriche come aiuto per una corretta interpretazione di segnali periodici trovati nelle serie temporali di velocità radiali che potrebbero essere dovuti agli effetti gravitazionali indotti sulla stella da un compagno di massa planetaria. I risultati discussi in questa Tesi dovrebbero dimostrare l'importante contributo che un ricco archivio di dati come quello prodotto dalla survey APACHE potrà assicurare sia alla scienza dei pianeti extrasolari che allo studio delle nane rosse.

This work describes the most relevant steps undertaken for the development and installation of the survey APACHE (A Pathway toward the Characterization of Habitable Earths), and some of the main results obtained after the first observing season are presented. APACHE is the first long-term observing campaign based in Europe which is devised expressly for detecting extrasolar planets orbiting well selected, nearby M dwarfs by using the photometric transit method. The project was conceived at the end of 2008 and the survey makes use of an array of five automated 40 cm telescopes which started routine observations between July 2012 and March 2013. In the Thesis introduction some key issues are discussed which in the last years have placed the cool stars at the centre of the planet hunters' interests, producing an increase in the number of photometric and high resolution spectroscopic surveys targeted on red dwarfs. In Chapters 1 and 2 the milestones which led to the preparation and initial design of APACHE are presented (the feasibility and pilot study), while Chapter 3 is focused on the description of the most relevant characteristics of the survey structure, as the accurate definition of the catalogue of eligible targets (the APACHE Input Catalogue) and observing strategy, and the implementation of the software package used for obtaining and analyzing the light curves. In Chapter 4 the preliminary results obtained after the first observing season at regime are presented and discussed, with the analysis mainly focused on the study of the photometric variability of more than 130 M dwarfs. Three targets showed evidence of stellar flares, and rotation periods have been measured for five stars through the analysis of their light curve periodograms. A simple single-spot model has been applied to the time series of these stars to describe the observed sinusoidal-like modulation in terms of stellar spots/active regions, obtaining in particular an estimate of the spin-axis inclination angle relative to the line of sight. The Chapter ends with a presentation of more than 90 new variable stars discovered in the stellar fields observed by the APACHE telescopes during the first year. The Thesis concludes with Chapter 5, where the strategic synergy established between APACHE and the large National observing programme GAPS (Global Architecture of Planetary Systems)

is described. GAPS observations are carried out with the high resolution spectrograph HARPS-N at the Telescopio Nazionale Galileo (TNG, @ La Palma island in the Canary archipelago) for an extensive study in the field of extrasolar planets. Among the goals of GAPS, of particular relevance is the detection of planets orbiting M dwarfs by analyzing the time variations of the stellar radial velocities, and in Chapter 5 preliminary results are presented for a sample of targets in common with the APACHE project. In particular, it is highlighted the importance of having photometric light curves as a support for a correct interpretation of periodical signals found in the radial velocity time series which could be due to the gravitational effects induced on the star by a planetary mass companion. The results discussed in this Thesis should demonstrate how effectively a large photometric database such that of APACHE is expected to contribute to both the exoplanet science and the physics of the cool stars.

Acknowledgements

The subject of this Thesis is the history of the APACHE survey and its first results. APACHE is the outcome of a hard preparatory work lasted almost four years and carried out by a small group of adventure companions, characterized by a strong perseverance and a deep passion for the sky above us. Thanks to them, I have learned very much since the day of my arrival at the Astronomical Observatory of the Autonomous Region of Aosta Valley (OAVdA), at the end of 2008. I am grateful to the Director of the Observatory, prof. Enzo Bertolini, who provided the initial opportunity for me to join the team at OAVdA, and for his strong belief in the Project, that he has constantly supported day by day. Warm thanks go to my colleagues of the OAVdA, we have grown up together with an important sense of sacrifice. They shared with me not only countless nights of work, but more in general all my life in the last 5 years: Andrea Bernagozzi, Paolo Calcidese, dr. Albino Carbognani, dr. Davide Cenadelli, Jean Marc Christille, Paolo Giacobbe, and the other friends and former colleagues dr. Giorgio Toso and Matteo Perdoncin, for their valuable contribution at some point along the APACHE pathway. We did it, guys! Me and all the Apaches are grateful to "those of the first floor", Erika Bancod, Christine Grange, Liliana Laval, Paolo Recaldini and Matteo Soldi, and to "Mr. Planetarium" Paolo Pellissier, because, among thousands of other different duties, APACHE is anyway part of their life too.

APACHE was conceived in 2008 by colleagues from the INAF-Astrophysical Observatory of Torino, as an innovative and original project in the context of the international research for extrasolar planets, in particular within the National borders, where the astronomers working on exoplanets were still few in number at that time. Without their ideas, enthusiasm, and constant support my work would not have been possible. I am particularly grateful to dr. Alessandro Sozzetti, the Chief of the Italian APACHEs. He has been the essential scientific reference point who guided my work, and he has firmly contributed to settle in me a golden rule for a good scientist: always be open minded...especially when dealing with extrasolar planets! I warmly thank prof. Mario G. Lattanzi, one of the fathers of APACHE, for having always 'fed' the project, and dr. Ricky Smart, for his advices which helped the survey to become more robust.

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Abbreviations

AIC	Apache Input Catalogue
APACHE	A PA tway toward the C haracterization of H abitable E arths
CCF	Cross-correlation F unction
FoV	Field of V iew
GAPS	G lobal A rchitecture of P lanetary S ystems
HZ	H abitable Z one
L-S	Lomb-Scargle
OAVdA	O sservatorio A stronomico della Regione Autonoma Valle d' A osta
RV	R adial V elocity
SDE	Signal D etection E fficiency
TEEPEE	Transiting E xoplan E ts P ip E lin E
TSE	Transit S entinel

*To all the planet hunters in the Universe, who have spent part
of their life to discover that they are not alone*

Introduction

When I was a child, I do not remember that I have ever dreamed to be an astronaut, and I never played with a telescope. Nonetheless, in my life I have always had the instinct of raising my eyes to the sky, spurred by those questions that everyone asks oneself at least once in a lifetime: are we the only observers in the Universe? Do planets orbiting other stars exist? If they exist, how many could host life? Are the Earth and the Solar System somewhat peculiar in the general context of the Universe? These questions, and many others, have somehow guided important decisions in my life, and I have been very lucky to be born in a revolutionary epoch during which, in less than 20 years, for some of them we finally came to an answer or at least we could start building one. We can now answer quantitatively to questions like: How common are planets in our Galaxy? How they distribute according to their radius and distance from their parent star? How many potentially habitable planets exist? How common are in the Galaxy planetary systems with an architecture similar to our Solar System? The fact of living in an epoch when some classical subjects of science fiction have become real science is the reason why I have chosen to become a *planet hunter*. A wonderful opportunity was offered to me at the end of 2008 by a small Astronomical Observatory, built in 2003 in the Western Italian Alps. When I was contacted to join the staff of young astronomers at the Astronomical Observatory of the Aosta Valley (OAVdA. See Appendix A), who had just moved there from their hometowns to live at walking distance from the Observatory, a scientific collaboration had just been established between the OAVdA and astronomers from the Astrophysical Observatory of Torino (National Institute for Astrophysics). The possibility of implementing a survey aimed at detecting planets around early-to-mid M dwarfs by using the photometric transit method [Haswell, 2010] was then investigated. The survey was named APACHE (A PATHway toward the Characterization of Habitable Earths), and at that time it was cast the first stone without knowing exactly where that pathway would have conducted us. As for me, I decided to face this challenge with great enthusiasm, building on APACHE

my PhD. All the rest is already history, and the topics discussed in this Thesis represent a great part of the history of the APACHE Project, which has now become reality and will sail across the sky for five years.

Transiting planets and the M dwarf opportunity

Planets transiting their parent stars make up a precious treasure in the sky. Among the hundreds of planets already detected outside our Solar System, the ones that transit the disk of their host stars are very important for the study of exoplanets, because they can be studied in the greatest detail. Indeed, their orbital parameters, mass and radius can be precisely measured, and their atmosphere can be probed during and outside eclipses, imposing strong constraints on their actual nature [Winn, 2011]. While the most ambitious goal remains the detection of an Earth-like planet orbiting a Sun-like star, which can be discovered in transit only with observations from space due to the very feeble signal in the light curve, a very promising target to be considered for discovering potentially habitable transiting planets is represented by M dwarf stars. M dwarfs, with masses $M \leq 0.6 M_{Sun}$ make up the vast majority of the reservoir of nearby stars within $\sim 25 \div 30$ pc. These stars have not traditionally been included in large numbers in the target lists of radial velocity (RV) searches for planets for two main reasons: 1) their intrinsic faintness, which prevented Doppler surveys in the optical from achieving very high radial-velocity precision ($5 \div 10 \text{ ms}^{-1}$) for large samples of M dwarfs (e.g. Eggenberger and Udry [2010] and references therein), and 2) the fact of being considered as providers of very inhospitable environments for potentially habitable planets [Huang, 1959, Dole, 1964]. These two paradigms are now shifting (e.g. Heath et al. [1999], Segura et al. [2005], Tarter et al. [2007], Scalo et al. [2007], Segura et al. [2010], Zendejas et al. [2010] and references therein) and there are several important reasons for such a change in perspective, which can be grouped according to two main themes. First, the observational evidence gathered by ultra-high-precision space-borne photometric surveys (e.g. *Kepler*) indicates that the frequency of low-mass planets, i.e. Neptunes and super-Earths, is an increasing function of decreasing stellar mass [Howard et al., 2012, Dressing and Charbonneau, 2013]. This result has recently been strengthened by the findings of ground-based RV programs carried out with state-of-the-art facilities (e.g., HARPS): super-Earths with $M_p \leq 10 M_{Earth}$ within the Habitable Zone (HZ) of low-mass stars appear ubiquitous [Bonfils et al., 2013]. It is thus clear why low-mass M dwarfs, reckoned for long to be providers of inhospitable environments for life, are now being moved at the center of the stage in the extrasolar planets arena. The astronomical community is convinced that

probably the first habitable rocky planet will be discovered around a red dwarf in the backyard of the Solar System. Secondly, the sample of the nearest ($d < 25 \div 30$ pc), relatively bright ($J < 9 \div 10$) M dwarfs is amenable to combined studies with an extensive array of observational techniques, which can be exploited at the best of their potential providing the opportunity to characterize the architecture of planetary systems across orders of magnitude in mass and orbital separations in a way that is not readily achievable for solar analogs. For example, the possibility to reach detection of short-period transiting rocky planets from the ground with modest-size telescopes (30-50 cm class) is guaranteed by the small radii of M dwarfs [Billings, 2011], leading to deep transits ($\Delta \text{mag} \sim 0.005$ mag) for the case of planets with $R_p \leq 4 R_{Earth}$ [Charbonneau et al., 2009]. In addition, the favourable mass ratios allow the detection of rocky, potentially habitable planets with the RV technique, thanks to the moderately large amplitudes of the RV signals (a few m s^{-1}). Similarly, at intermediate separations ($\sim 1 \div 4$ AU) high-precision astrometry becomes sensitive to planets in the mass range between Neptune and Jupiter [Casertano et al., 2008]. Systematic studies of planetary systems orbiting low-mass stars can thus crucially provide information about planet formation and evolution, as well as structural and atmospheric models, particularly when seen in connection with the properties of the host stars (Seager and Deming [2010], and references therein). The opportunity for seriously considering the search for possibly habitable planets around M dwarfs, and investigating how these stars could support habitable worlds, has also been reinforced by studies carried out during the second half of 1990s about the stellar evolution of red dwarfs. The research about this topic has languished in the backwaters of stellar astrophysics for decades, until in 1997 a paper appeared examining in detail the fate of low mass stars [Laughlin et al., 1997], laying the foundation for subsequent researches into the habitability of planets orbiting them. In parallel, original researches about the physical properties of the red dwarfs were carried out [Baraffe et al., 1998], focusing on the determination on how their chemistry, luminosity and size vary with mass. The unconventional fates of the low mass stars and their peculiar chemistry entail that red dwarfs have an influence on their planets which is as unique as their lives. In particular, the dominant emission of infra-red radiation, and a lifetime orders of magnitudes greater than a Sun-like star, mean that the influence upon the habitability of their planets is unlike that of any other, more massive star. The issue of the evolution of red dwarfs has been then undertaken again in mid 2000s [Adams et al., 2004], with some of the same authors addressing also the problem of planet formation and evolution around M dwarfs. They predicted the existence of few Jovian-like planets around them [Laughlin et al., 2004, Adams et al., 2005]. This is one relevant issue which could be confirmed through

the observation of a large sample of red dwarfs, and thus represents a key point for which APACHE could provide a valuable contribution.

M dwarfs and extrasolar planets: increasing interest and observational efforts

When APACHE was conceived at the end of 2008, the only existing survey expressly targeted on searching for transiting planets around M dwarfs was the MEarth project [Nutzman and Charbonneau, 2008], based in Mt. Hopkins (Arizona, USA), and the first, long-term radial velocity surveys focused on low mass stars had started just a few years before, with the bulk of the results still to come [Endl et al., 2006, Zechmeister et al., 2009, Bonfils et al., 2013]. In 2012, the topic of the search and characterization of extrasolar planets around M dwarfs was already so much considered that the brief Workshop *Transiting planets in the House of the Sun*¹, held on June on the Maui island (Hawai'i, US), was totally dedicated to a discussion about planets around low mass stars. Besides enjoying the second transit of Venus across the Sun of my life from the top of the mount Haleakala, during the meeting I had the important chance to give a talk about APACHE. One member of the LOC, prof. E. Gaidos (University of Hawai'i), is particularly active in the field and is one of the authors of the catalogue of M dwarfs that we have used to build the APACHE Input Catalogue [Lépine and Gaidos, 2011]. It was during that Workshop that another catalogue of bright M dwarfs was presented, which has to be considered the most complete collection of $K_s < 9$ M dwarfs currently available and specifically conceived as a foundation for future exoplanet transit studies [Frith et al., 2013]. Still, it was in that occasion that I learnt about the first results coming from the WFCAM survey, which is a large field, near-infrared photometric campaign running at the United Kingdom infrared Telescope (UKIRT) and designed to discover planets around M dwarfs [Birkby et al., 2011, Kovács et al., 2013]. Other techniques for detecting extrasolar planets began to be employed for monitoring M dwarfs, as in the case of the Planets Around Low-Mass Stars (PALMS) survey, which is a high-contrast adaptive optics imaging search for giant planets around nearby, young M dwarfs using the Keck-II and Subaru telescopes [Bowler et al., 2012]. In the very near future, several very interesting new observational projects, both ground- and space-based, will focus on low mass stars to search for planets, and others, for which M dwarfs are not the primary targets, will anyway dedicate some efforts to observing them. Here I want to mention the Next Generation Transit Survey (NGTS), a ground-based sky survey designed to find transiting Neptunes and super-Earths by covering at

¹<http://www.soest.hawaii.edu/GG/FACULTY/GAIDOS/haleakala.html>

least sixteen times the sky area of *Kepler* with an array of 20 cm telescopes, under the sky of the ESO Paranal Observatory [Wheatley et al., 2013]. Another interesting, forefront survey is ExTrA (Exoplanets in Transit and their Atmospheres), a newly founded European project that, like APACHE and MEarth, will also use small automated telescopes to search for planets transiting M dwarfs by performing differential spectro-photometry with a low-resolution near-infrared multi-object spectrograph (Xavier Bonfils, private communication). ExTrA proposes a novel method to overcome the systematics of ground-based observations and should be sensitive to smaller/cooler planets than other competitive surveys. In 2016 should see the first light the telescopes of the SPECULOOS project (Search for habitable Planets Eclipsing ULtra-coOL Stars), a survey based on the ESO Paranal site and optimized for detecting planets of Earth-size and below transiting the nearest Southern ultra-cool stars [Gillon et al., 2013a,b]. Also the MEarth group has upcoming news. The US project, which has inspired APACHE, will double, by building a duplicate array of telescopes in the southern hemisphere at the Cerro Tololo Inter-American Observatory (CTIO) in Chile; this MEarth-South observatory should be on sky soon [Berta, 2013]. All these efforts demonstrate that M dwarfs will be for several years to come among the preferred targets for hunting exoplanets from ground that could support life [Reich, 2013]. In this context, the APACHE project will still remain a unique survey for its characteristics in the Northern hemisphere. Of course, after the breakthrough represented by the amazing results of the *Kepler* satellite, a lot of expectations for planet hunters are put in the upcoming space missions. The NASA's next big mission dedicated to transiting exoplanets is TESS (Transiting Exoplanet Survey Satellite), a space telescope that will spend two years identifying planets around the 500,000 brightest stars as seen from Earth. TESS, which will be launched in 2017, will observe many types of stars, including some 10,000 M dwarfs. If selected by ESA, the PLATO 2.0 space telescope (now a mission candidate for M3 launch opportunity in 2022/24, Rauer et al. [2013]) should detect several hundreds of terrestrial planets in the HZ of bright solar-like stars, including the brightest M dwarfs, pushing much further the results already obtained by *Kepler*. While writing, the ESA cornerstone Gaia satellite has successfully reached its destination at the L2 point, 1,500,000 km from the Earth. The Gaia mission should dramatically improve our knowledge of the Galaxy structure and evolution, and its lift-off is accompanied by a lot of promises for the astronomers. Among these, Gaia is expected to provide a great contribution in the search for extrasolar planets by using the astrometric technique [Sozzetti et al., 2001, Sozzetti, 2013]. In particular, in a very recent paper [Sozzetti et al., 2014] the potential of Gaia to detect and characterize astrometrically giant planetary companions to low-mass M dwarfs within ~ 30 pc from the Sun has been investigated, shedding light on some

of the potentially relevant synergies between Gaia astrometry and other ongoing and planned planet detection and characterization programs, both from the ground and in space. Looking towards the future, observational and theoretical challenges about the search for exoplanets around M dwarfs and the characterization of the host stars are discussed in [Rojas-Ayala et al. \[2013\]](#). The authors review the current knowledge on M dwarf stars and exoplanets in order to prepare for current and future exoplanet searches focusing on low mass stars, underlining the importance of an accurate determination of their fundamental parameters for the proper characterization of their exoplanets and better understanding of the planet formation mechanisms. Moreover, while the scientific community is working very actively in the field of detection and characterization of potentially habitable planets orbiting M dwarfs, examples which demonstrate the great interest recently reached by cool stars can also be found in (high-level) popular literature [[Stevenson, 2013](#)], showing that, indeed, cool stars are cool.

Since 2009: the story told by the *Kepler* mission about planets transiting M dwarfs.

As mentioned, results from ultra-high precision space-borne photometric surveys, mainly those from *Kepler*, although still a matter of debate [[Fressin et al., 2013](#)], indicate that the frequency of close-in ($P < 50$ days) low mass planets is an increasing function of decreasing stellar mass [[Howard et al., 2012](#)]. This result has recently been strengthened by the findings of ground-based RV programs carried out with state-of-the-art facilities (e.g. HARPS): super-Earths with $M_p = 6 \div 10 M_{Earth}$ within the HZ of low mass stars are abundant [[Bonfils et al., 2013](#)]. Very recent analyses of *Kepler* data have only further corroborated this evidence [[Dressing and Charbonneau, 2013](#), [Kopparapu, 2013](#)]. In particular, [Kopparapu \[2013\]](#) revised the definition of planetary Habitable Zone (which is a fundamental step for any reliable statistical analysis) and applied it to the sample of M dwarfs observed by *Kepler*, deriving for η_{earth} -the fraction of stars that have at least one rocky planet within their HZ- the value of $0.48^{+0.12}_{-0.24}$ for planets up to $1.4 R_{Earth}$, rising to $0.51^{+0.1}_{-0.2}$ when including planets up to $2 R_{Earth}$. This highly encouraging result becomes still more meaningful when assuming the more optimistic HZ limits available from recent calculations, pushing η_{earth} up to the value $0.61^{+0.07}_{-0.15}$. Another result particularly meaningful for the main purposes of the APACHE survey has been presented recently by [Morton and Swift \[2013\]](#). They analyzed 113 planet candidates with orbital periods < 90 days around the smallest and coolest stars in the *Kepler* Object of Interest sample (KOI), and derived an empirical distribution for planetary radii

(Fig. 4 in their manuscript). According to their results, there should be approximately 1.5 planets per M dwarf with radius $<4 R_{Earth}$ and orbital period less than 90 days, with $\sim 1 R_{Earth}$ as the most common planet size to survive at length in short orbits around cool stars. A relevant finding is that the distribution indicates that planets larger than $\sim 3 R_{Earth}$ should be very rare around cool stars, thus Gliese 1214b, the only $2.7 R_{Earth}$ transiting planet discovered up to now by the MEarth survey [Charbonneau et al., 2009], appears as an exception. The results of Morton and Swift [2013] demand a theoretical explanation in terms of planetary system formation and evolution around M dwarfs, and while they will be improved by new *Kepler* data and represent an incentive for the future of ground-based surveys as they will become more sensitive to smaller planets, they are of primary importance for APACHE. Being especially sensitive to signals produced by transiting mini-Neptune-to-Neptune sized planets, which then seem to be quite rare around cool stars, APACHE could effectively test the results of Morton and Swift [2013], and a null detection at the end of the survey would represent a point in their favour. When generalizing the findings of Morton and Swift [2013] to 12,000 *Kepler* stars with the lowest photometric noise and considering planets with sizes $0.5 \div 8.0$ times that of the Earth and orbital periods between 5 and 50 days [Petigura et al., 2013], one finds that the distribution of planet sizes displays a power law rise in occurrence from $5.7 R_{Earth}$ down to $2 R_{Earth}$, with that rise ending at $2 R_{Earth}$. The occurrence of planets is consistent with constant from $2 R_{Earth}$ toward $1 R_{Earth}$, suggesting a distinct planet formation processes for planets above and below $2 R_{Earth}$.

As final words it must be said that, while on the one hand these conclusions are indeed interesting, they are drawn from results coming from the photometric transit technique only and could be somewhat biased. In fact, in addition to the case of Gliese 1214b, it is noteworthy to recall here those of GJ 436b and GJ 3470b, two Neptune-size planets ($R \sim 4 R_{Earth}$) transiting their parent red dwarf that were first discovered by RV surveys [Butler et al., 2004, Bonfils et al., 2012]. Velocimetry surveys usually observe only few hundreds of targets (i.e. a sample not so large) and are not constrained by the geometry of planetary systems, then the fact that two planets have been discovered with a radius falling in the apparently "forbidden" zone should make one think about the actual scarcity of M dwarf planets with size greater than $2 R_{Earth}$: they could be more abundant than estimated.

The atmospheres of the exoplanets: the opportunity offered by planets transiting M dwarfs

Transiting planets offer the opportunity to probe the chemical and physical composition of the planet atmospheres. During the transit, if the planet has an atmosphere, it does not behave as an opaque disk with a sharp edge but the opacity will gradually diminish with height as the atmosphere becomes thinner. The stellar light that passes through the atmosphere is selectively absorbed by atoms and molecules, or Rayleigh scattered, resulting in an increase of the observed planetary radius at wavelengths having a high opacity compared to that at a low opacity. As a consequence, any observed wavelength dependence of the transit depth versus the central wavelength can be used to probe the planet atmospheric composition. Planets transiting bright M dwarfs are among the favourite targets for exo-atmosphere studies. The super-Earth orbiting the M4.5V star GJ 1214b has been the subject of an intense series of observations aimed at measuring its atmosphere from the optical (e.g. [Bean et al. \[2011\]](#), [Murgas et al. \[2012\]](#), [de Mooij et al. \[2013\]](#), [Teske et al. \[2013\]](#)), to the infrared (e.g. [\[Bean et al., 2011\]](#), [Croll et al., 2011](#), [Désert et al., 2011](#), [Berta et al., 2012](#), [Fraïne et al., 2013\]](#)). Recently, a search for methane in the atmosphere of the planet has been performed at the Gran Telescopio Canarias with narrow-band observations, ruling out its presence [\[Wilson et al., 2013\]](#). Still more recently, new measurements of the transmission spectrum of GJ1214b at near-infrared wavelengths, obtained with the Hubble Space Telescope, show what can be considered a definitive evidence of high clouds blanketing the planet and hiding information about the composition and behavior of the lower atmosphere and surface [\[Kreidberg et al., 2014\]](#). The new Hubble spectra also revealed no chemical fingerprints in GJ 1214b's atmosphere, but the data are so precise that cloud-free compositions of water vapor, methane, nitrogen, carbon monoxide, or carbon dioxide should be ruled out. The wealth of available data made GJ 1214b an emblematic case for modelling its physical, bulk structure, resulting in an interesting degeneracy: allowed scenarios include a “mini-Jupiter” with a small solid core and large envelopes of primordial H/He; a Neptune-like planet with an atmosphere made of sublimated ices; a “water world” or a rocky super-Earth with an outgassed atmosphere [\[Rogers and Seager, 2010\]](#). Studying the atmosphere composition of favourable planets like GJ 1214b to characterize the bulk properties is then very important to understand the planetary formation processes, either finding evidence for validating an *in situ* formation scenario or preferring the hypothesis of inward migration of the planet which actually formed further out its present location. Another interesting case is that of the transiting planet GJ 3470b, one of the last discovered orbiting an M dwarf [\[Bonfils et al., 2012\]](#). It has been considered right after its first detection as a favourable

target for transit spectroscopy and photometry follow-up aimed at characterizing the atmosphere of a low-mass planet. It is a rather inflated, low-density planet classified as 'hot Uranus', having a mass of $13.9 M_{Earth}$ and a radius of $0.41 R_{Jupiter}$ (as measured from *Spitzer* photometry) [Demory et al., 2012], and an orbital period $P = 3.336649 \pm 0.000002$ days. Crossfield et al. [2013] carried out in-transit spectroscopic measurements in K-band (by using the Keck/MOSFIRE spectrograph) and in the band $0.73 \div 1.02 \mu m$ (by using the Gemini-North/GMOS spectrograph) to determine the atmospheric transmission of the planet. Fukui et al. [2013] carried out optical (g' , R_c , and I_c bands) to near-infra-red (J band) simultaneous photometric observations during a transit of GJ 3470b, by using the 50 cm MITSuME telescope and the 188 cm telescope, both at the Okayama Astrophysical Observatory. Particularly noteworthy in the context of the Italian contribution to the exoplanet science is the work of Nascimbeni et al. [2013]. They present very accurate ground-based light curves of GJ 3470b gathered by the LBC camera at the Large Binocular Telescope (LBT). Through simultaneous narrow-band photometry in the ultraviolet ($\lambda_c = 357.5$ nm) and optical infra-red ($\lambda_c = 963.5$ nm) they detected a significant change of the effective radius of GJ 3470b as a function of wavelength (the planet radius increases with decreasing wavelength), which they interpreted as a signature of scattering processes occurring in a cloud-free and low mean molecular weight planetary atmosphere, consistent with that of a H/He-dominated atmosphere with sub-solar chemical abundances. Moreover, they demonstrate that with LBT photometric transits of Earth-sized planets around M dwarfs could be detected, pushing to the limits the photometric accuracy presently achievable from ground-based telescopes. The results of the mentioned works do not yet point to a clear picture for the planet atmosphere structure and composition, and present GJ 3470b as an intriguing case study. Especially the work of Nascimbeni et al. [2013] represents an important achievement from the point of view of the APACHE Project, because any planet discovered by the Apaches around a bright star will become a primary target for studying its atmosphere using the LBT, of which Italy has 25% of the total observing time. When looking at the future of exo-atmosphere observations, many expectations are placed in the EChO space mission, which has been selected by ESA for an Assessment Study in the context of the Medium-size (M3) mission opportunity call. EChO is a $1.2 \div 1.5$ m space telescope with spectrometers operating from visible to medium infra-red bands, expected to characterize the atmospheres of giant and terrestrial exoplanets [Tinetti et al., 2012]. EChO will characterize planets in the habitable zone of late type stars. APACHE can strongly contribute to the EChO mission at least in two ways. First, obviously, bright stars with transiting planets discovered by APACHE will be immediately proposed as targets for EChO. Secondly, the combination of the data from the APACHE survey with those

from HARPS-N (collected for the GAPS programme, as I will discuss later) will improve the knowledge of the intrinsic activity of the M dwarfs, which is a crucial information for an optimal selection of the targets for EChO. Considering ground-based facilities, high-dispersion spectroscopy with large-size telescopes will provide a strong alternative for finding biomarkers in the atmospheres of habitable planets around M dwarfs. Strong oxygen absorption features can be found using the next generation of Extremely Large Telescopes [Pallé et al., 2011, Snellen et al., 2013]. This result has been reinforced very recently by Rodler and López-Morales [2013], who stated that the detection of molecular Oxygen in the atmosphere of an Earth twin will be only feasible with the Extreme Large Telescopes if the planet is orbiting a bright close-by ($d \leq 8$ pc) M dwarf with a spectral type later than M3. Finally, M dwarfs are optimal targets for the detection of hydrogen coronae and energetic neutral atoms (ENA) around terrestrial exoplanets with a mass as low as one Earth mass [Lammer et al., 2011]. These features can be produced via charge exchange as the result of the interaction between the host star plasma environment and the planets' upper atmosphere, with the effects produced by the interaction expected to be stronger for active stars [Lammer et al., 2012]. Because most of M dwarfs are longer active in X-ray, SXR and EUV as compared to Sun-like G stars and the corresponding habitable zones (HZs) are closer to the stars, the plasma environment around the HZs should resembles that of the young Sun during the first $100 \div 500$ Myr after its arrival at the Zero Age Main Sequence (ZAMS). For these reasons, transit follow-up observations in the UV-range of terrestrial exoplanets around M-type stars with space observatories such as the World Space Observatory-UV (WSO-UV) would provide a unique opportunity to test the theories about the origin and the early evolution of the atmospheres of Earth-like planets, including those of our own Solar System [Lammer et al., 2011, Lammer, 2013]. In view of a possible discovery by APACHE, which will be a target with high priority for studying its atmosphere, the characterization of the target variability levels through the collection of many photometric data could be of great help for the studies focused on the planet atmosphere composition. In fact, since high stellar magnetic activity is colour dependent it may significantly influence the characterization of planetary atmospheres, other than the derivation of the planetary and stellar parameters [Ballerini et al., 2012]. By using broad-band photometry to monitor the stellar variability levels, the effects due to the stellar magnetic activity could be constrained and removed.

A step forward in studying M dwarfs and their planets: the Near Infra-Red spectroscopy

At the forefront of the observational studies about M dwarfs is the use of Near Infra-Red (NIR) spectroscopy to search for planets via the radial velocity method and for the determination of the fundamental physical parameters of the M dwarfs, which presently are still poor known. Present visible wavelength range RV surveys cover preferentially dM stars of spectral type earlier than M2 or M3, with the faintness of the targets in the wavelength range and the intrinsic stellar jitter having up to now limited the investigation of stars with even lower masses. The effects of the stellar activity in M dwarfs are significantly diminished in the near-IR, as also demonstrated by the photometric variability study in J-band conducted by the WFCAM survey [Goulding et al., 2012]. NIR spectrographs can then be used in principle to observe especially active late-type stars to search for small planets, and they represent an innovative approach, with new instruments almost ready to be used for this scope. These include the CARMENES (Calar Alto high-Resolution search for M dwarfs with Exo-earths with near-infrared and optical Echelle Spectrographs) next-generation instrument for the 3.5 m telescope at the Calar Alto Observatory, that will be used for conducting a five-year exoplanet survey targeting ~ 300 M stars [Quirrenbach et al., 2010]; the Habitable Planet Finder Spectrograph [Mahadevan et al., 2010, 2012], a proposed instrument for the 10 m class Hobby Eberly telescope to be used for discovering low mass planets around M dwarfs, covering the wavelength range $0.9\div 1.65\ \mu\text{m}$, i.e. the *Y*, *J* and *H* NIR bands; the SPIRou spectrograph (SpectroPolarimètre Infra-Rouge), a near infrared spectropolarimeter that will be mounted at the 3.6-m Canada France Hawaii Telescope (CFHT) in 2017, with a major goal of this unique spectropolarimeter to search for habitable exo-Earths orbiting low-mass and very-low mass stars using high-accuracy RV (better than $1\ \text{ms}^{-1}$) [Santerne et al., 2013]; and the Italian high-resolution NIR spectrograph GIANO [Oliva et al., 2006, 2012], which will operate at the 3.58 m TNG Italian telescope in La Palma (Canary islands) and, by providing a quasi-complete coverage of the $0.95\div 2.5\ \mu\text{m}$ wavelengths range in a single exposure, will be used to search for rocky planets with habitable conditions around low-mass stars. These same instruments will be used for deriving very accurate abundances of many atomic and molecular species in any class of cool stars. At present it is very difficult to spectroscopically determine the M dwarf metallicity with a high degree of precision, and these measurements are fundamental for a complete characterization of the exoplanet host stars and for the understanding of the planet formation scenarios. Many efforts have been done to provide empirical photometric calibrations for determining accurate M dwarfs metallicity (e.g. Neves et al. [2012] and references therein), and

some recent studies started to make use of NIR moderate resolution spectroscopy for this purpose [Rojas-Ayala et al., 2010, 2012, Terrien et al., 2012, Mann et al., 2013, Newton et al., 2013]. As a first step, the large photometric database that APACHE will collect along the five nominal years of operations could be of great help especially for selecting the most promising targets to be observed in the upcoming NIR radial velocity surveys, based on the measured activity levels in their light curves. Moreover, as the MEarth team has very recently done [Newton et al., 2013], the APACHE stars could become targets for spectroscopic determinations of their metallicities, thus improving the knowledge of one of the main stellar parameters.

Characterizing the stellar activity for ongoing spectroscopic surveys in the optical band aimed at detecting planets around M dwarfs

While the high potential of the NIR spectroscopy for detecting terrestrial planets around M dwarfs still has to be investigated, cool stars are objects of intense study for challenging, ongoing RV surveys with some optical high-resolution spectrographs, offering the best performances attainable to date, as for example HARPS-N, recently operating at the Telescopio Nazionale Galileo in the island of La Palma. As stated above, one sizeable complication for the analysis of the radial velocity variations and a correct interpretation of periodic signals is represented by the intrinsic stellar jitter due to the (usually) high level of magnetic activity in low mass stars. How the effects of the M dwarfs activity in radial velocity and photometric time-series can be actually modelled is still not clear at all. What a long-term photometric database as that of the APACHE project could tell about the variability of hundreds of M dwarfs is of invaluable importance for discriminating a spectroscopic signal due to one or more planetary companions from an effect of the stellar activity, in particular by determining the rotation period of a star with the analysis of its light curve. Actually, this is exactly the kind of support that APACHE is already providing to the challenging large programme like GAPS, a spectroscopic survey conducted with HARPS-N which is monitoring, among others, the RV variations of a large sample of M dwarfs in common with APACHE. Considering the relevance of this strategic collaboration, a Chapter of this Thesis is dedicated to discussing the potential offered by this joint spectro-photometric monitoring of several targets by presenting some preliminary results. The treasure trove represented by the APACHE database could reveal all its utility also in future, by providing a characterization of the long-term variability of M dwarfs (over a timescale of a few years) which has been investigated in spectroscopic data only recently and for a small sample of stars by, for example, da Silva et al. [2011, 2012].

Outline of the Thesis

In this work I will describe the milestones and the very preliminary results of the survey APACHE, the first Europe-based transit search for small-radius planets orbiting bright, nearby M dwarfs. It builds upon the pioneering work carried out by the MEarth project, in that it adopts a one target per field approach and the corresponding constraints on the observing strategy optimized for the array of five APACHE telescopes and the characteristics of the observing site. It extends and complements MEarth in the Northern hemisphere, in that it targets early- to mid-M dwarfs, conceding in detectable planet radius for fixed photometric precision but focusing by conception on a target sample that is in principle more favourable for atmospheric characterization work in case of positive detection. The search for new worlds around M dwarfs is the main goal of the APACHE survey, which has started the scientific observations in July 2012. Due to the intrinsic difficulty in observing multiple transits of a planet within the very first year, we expect to provide a scientifically serious discussion and to draw meaningful conclusions about this topic after at least a couple of observing seasons at regime. For my Thesis I could consider for a first analysis only data collected during the first year of routine observations, and thus I have concentrated my efforts partly in characterizing the survey performances and, to a greater extent, in characterizing the photometric variability of the targets (as well as field stars), pointing out the relevant connections with spectroscopic observations aimed at discovering planets with the RV technique. With this work, I hope to succeed in providing a thorough picture of how the APACHE large photometric database could be useful for improving our knowledge of the physics of M dwarfs. In Chapters 1 and 2 the two main preparatory steps toward the long-term survey are described, covering the period 2009-2011. In Chapter 3 I discuss the work done mainly before the Summer of 2012 in preparation to the official kick-off of the survey. This has dealt with the definition of the target input catalogue and of the observing strategy, the implementation of the data reduction and analysis pipeline, and a lot of hard, 'background' work during many nights spent on testing and fine-tuning the new instruments, and on carefully and patiently debugging the complex software for the telescope system control, in order to make APACHE a professional and competitive laboratory. Some preliminary results about the photometric variability of the targets observed during the first season are discussed in Chapter 4, while in Chapter 5 I discuss some results from the strategic synergy developed between APACHE and the GAPS large programme. Conclusions and future prospects are presented in the last Chapter.

Chapter 1

The dawn of the Apaches: the feasibility study

The first “brick in the wall” of the APACHE Project has been a characterization study aimed at demonstrating the feasibility of the APACHE Project in terms of the quality of the observing site. The result was that the OAVdA satisfied the requirements that the APACHE Team had identified as basic for investing resources in a long duration survey. This study was the necessary first step to begin a demanding fund raising campaign for purchasing all of the hardware and the refurbishment of the OAVdA infrastructure. The subject of this Chapter is the site testing study. The results appeared in 2010 in the journal PASP [[Damasso et al., 2010b](#)]. The paper is attached at the end of this Chapter, and it forms an integral part of the Thesis. I have greatly contributed to this work in several ways and, generally, I took part to each step of the study. I have been involved in the preparation and maintenance of the instrumentations and I have collected most of the data used in this work. I have collaborated in creating from scratch the first version of the customized pipeline TEEPEE for data reduction and analysis, at that time not yet available. Essentially, the site characterization study has been a fundamental, formative experience for me, because it has gotten me in front of the issues related to stellar photometry for the first time. It has been during the period of the feasibility study that I became very interested in the detection and study of new variable stars, that I have carried out also during the first season of the APACHE survey (see Chapter 4). A handful of them have been reported in [Damasso et al. \[2010b\]](#). Moreover, other new variable stars were found and published in a paper appeared on the Open European Journal on Variable Stars [[Damasso et al., 2010a](#)]. Also this article is attached at the end of this Chapter and forms an integral part of the Thesis.

Photometric Transit Search for Planets around Cool Stars from the Western Italian Alps: A Site Characterization Study¹

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ABSTRACT. We present the results of a site characterization study carried out at the Astronomical Observatory of the Autonomous Region of the Aosta Valley (OAVdA), in the western Italian Alps, aimed at establishing its potential to host a photometric transit search for small-size planets around a statistically significant sample of nearby cool M dwarfs. For the purpose of the site testing campaign, we gathered photometric and seeing measurements utilizing different instruments available at the site. As in any search for new locations for astronomical observations, we gauged site-dependent observing conditions such as night-sky brightness, photometric precision, and seeing properties. Public meteorological data were also used in order to help in the determination of the actual number of useful observing nights per year. The measured zenithal *V*-band night-sky brightness is typical of that of very good, very dark observing sites. The extinction registered at the *V*-band is not dissimilar from that of other sites. The median seeing over the period of in situ observations is found to be $\sim 1.7''$. Given the limited duration of the observations, we did not probe any possible seeing seasonal patterns or the details of its possible dependence on other meteorological parameters, such as wind speed and direction. Moreover, our data show that the seeing at the observatory was reasonably stable during most of the nights. The fraction of fully clear nights per year amounts to 39%, while the total of useful nights increases to 57%, assuming a (conservative) cloud cover of not more than 50% of the night. Based on the analysis of photometric data collected over the period of 2009 May–August for three stellar fields centered on the transiting planet hosts WASP-3, HAT-P-7, and Gliese 436, we achieve seeing-independent best-case photometric precision $\sigma_{\text{ph}} \lesssim 3$ mmag (rms) in several nights for bright stars ($R \lesssim 11$ mag). A median performance $\sigma_{\text{ph}} \sim 6$ mmag during the observing period is obtained for stars with $R \lesssim 13$ mag. A by-product of the significant amount of photometric data collected in the stellar fields of WASP-3 and HAT-P-7 was the identification of a handful of new variable stars, four of which are presented and discussed here. Our results demonstrate that the OAVdA site is well poised to conduct an upcoming long-term photometric survey for transiting low-mass, small-size planets around a well-defined sample of M dwarfs in the solar neighborhood.

Online material: color figures

1. INTRODUCTION

The discovery by Charbonneau et al. (2009) of a $\sim 6.5 M_{\oplus}$ planet (a super-Earth) with a radius of $\sim 2.7 R_{\oplus}$ in transit across the disk of the late-M dwarf GJ 1214 with a period of ~ 1.6 days has heralded the first success for a novel approach to ground-based photometric searches for transiting planets. Until recently,

two main typologies of search programs for planetary transits had been adopted: (1) deep narrow-field surveys using medium-to large-size telescopes with a narrow field of view (FOV) to monitor many faint sources and (2) shallow wide-field surveys utilizing small telescopes with a wide FOV to probe for photometric variability a large number of bright, relatively nearby solar-type stars. The former approach has so far produced the overwhelming majority of transiting planet detections and is the preferred choice for ongoing (CoRoT, Kepler) and planned (PLATO, TESS) space-borne transit searches (for a review, see Charbonneau et al. 2007).

Among the many paradigms which the fast-developing field of extrasolar planet science is continuously reformulating, a special focus has been given in recent times to the choice of the stellar type to be probed for planets. Driven by the available instrument performance for a given technique (and by a small amount of hard-to-die solar-system centrism), initial planet

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search surveys (be they spectroscopic or photometric) focused exclusively on main-sequence solar-type stars. This is changing, however, with increasing awareness of the need to extend the number of detected planets around varied star types, for a proper global understanding of the complex processes of planet formation and evolution. With the primary goal of reaching sensitivity to short-period planets with (minimum) masses lower than the mass of Neptune, a number of dedicated radial-velocity surveys have been targeting low-mass stars (e.g., Endl et al. 2006; Zechmeister et al. 2009 and references therein). High-precision Doppler data (Rivera et al. 2010; Udry et al. 2007; Forveille et al. 2009; Mayor et al. 2009) have unveiled the existence of a population of low-mass, close-in planets with $M_p \sin i \approx 2\text{--}10 M_\oplus$ around cool stars.⁶ At wider separations, super-Earths around M dwarfs have also been revealed by microlensing surveys (Beaulieu et al. 2006).

As for the transit technique, the combination of photometric data and Doppler measurements for targets at the bottom of the main sequence implies the possibility of deriving estimates of the bulk composition for super-Earth planets (with typical radii in the range $2\text{--}4R_\oplus$), with requirements on the photometric precision necessary for their detection which are readily fulfilled from the ground (for details, see Nutzman & Charbonneau, for example 2008). However, the specific choice of targets has imposed a redefinition of the observing strategies. Given the sparseness of bright M dwarfs throughout the whole sky, the wide-field approach can only be carried out effectively by utilizing 4 m class telescopes and shifting to near-infrared observing wavelengths in order to be able to probe tens of thousands of M dwarfs which would be otherwise too faint in the visible, as it is done by the WFCAM/UKIRT Transit Survey (WTS),⁷ for example. Alternatively, the narrow-field approach has been reformulated by designing transit search programs which aim at *individually* probing all the sparsely spread, bright, nearby M dwarfs in the sky, utilizing a cluster of identical telescopes at one location, such as the MEarth project (Nutzman & Charbonneau 2008). The discovery by Charbonneau et al. (2009) is the proof of the cunningness of the latter method, given that only for transiting super-Earth planets orbiting nearby small stars it is possible to carry out more in-depth characterization studies, such as spectroscopic investigations of their atmospheres.

The ground-breaking discovery of GJ 1214b has, however, also highlighted some of the present limitations in our understanding of transiting systems composed of low-mass primaries and small-size planets. The first source of uncertainty comes from the existing discrepancies between theory and observations in the determination of the sizes of (late) M dwarfs which,

as reported by Charbonneau et al. (2009 and references therein), are of the order of 10%–15%. This problem, likely stemming from the need to introduce the detailed treatment of the effects of nonzero magnetic fields on the properties of low-mass stars in stellar evolutionary models (e.g., Mullan & McDonald 2001; Ribas 2006; Torres et al. 2010 and references therein), has significant repercussions on the inferred composition of the planet. An important by-product of the long-term photometric monitoring of a large sample of low-mass M dwarfs is the discovery of new eclipsing binary systems with low-mass components (e.g., Irwin et al. 2009), leading to a sample of accurate measurements of their radii which can in turn provide a useful testing ground for improving stellar evolution models. Second, degeneracies in the models of the physical structures of super-Earths, such as objects with very different compositions having similar masses and radii, also prevent one from exactly inferring their interior composition (Seager et al. 2007; Rogers & Seager 2010. See also the discussion in Charbonneau et al. 2009) when only a mass and radius measurement are available. It is thus clear that more discoveries of transiting low-mass, small-radius planets over a range of periods around nearby relatively bright late-type stars are highly desirable. This is of particular relevance as the further spectroscopic characterization studies of the atmospheres possible for these planets are one of the most effective ways to mitigate the degeneracies of exoplanet interior composition models (see, for example, Miller-Ricci et al. 2009).

If the wild diversity of transiting giant planets properties is a proxy for what to expect from transiting Neptune and super-Earths, and if the predictions from recent population synthesis models of planetary systems formation are on target, which envision increasing planet frequencies with decreasing planet mass, one then realizes how the effort being invested in present and planned transit search programs is well justified, both from the ground and in space. One lesson learned from the experience of wide-field ground-based transit surveys for giant planets around bright solar-type stars is that in order to optimize the phase coverage and thus maximize the chances of success, a distributed network of telescopes should be built. Multisite campaigns carried out by the HAT-Net and super-WASP networks have contributed the large majority of the transiting planet discoveries to date (the HAT-South network is now coming online, see Bakos et al. 2009). With this in mind, our group has started investigating the prospects for a Europe-based photometric transit search for small-size planets orbiting low-mass stars using a network of small telescopes. As a first step toward this goal, we have attempted to gauge the potential of the recently inaugurated (2003) Astronomical Observatory of the Autonomous Region of the Aosta Valley (OAVdA)⁸ to become the primary node of such a network. Due to its short history, OAVdA is significantly involved in teaching and public outreach activities,

⁶ Evidence for their presence around solar-type stars has been presented by Bouchy et al. 2009 and Fischer et al. 2008 and more recently by Howard et al. 2009, Vogt et al. 2010, and Rivera et al. 2010.

⁷ See <http://star.herts.ac.uk/RoPACS/>.

⁸ See <http://www.oavda.it>.

but it also has an early record of collaborative efforts in a variety of scientific programs (e.g., monitoring of near-Earth objects and blazar events). The primary reasons for an in-depth characterization of the potential of the site for the purpose of a transit search program are as follows. First, the observatory is located in the northwest of the Italian Alps (45.7895° north, 7.47833° east), at 1675 m above sea level; thus, its high-altitude location and remoteness provide almost light-pollution-free night-sky conditions. Second, clear-sky observing conditions are realized at OAVdA on $\sim 57\%$ of the total nights in a year, which is a conservative estimate based on 4 year statistics collected at the site (see § 4.2). Third, the OAVdA site has two platforms with electronically controlled track-mounted ceilings that can be completely opened to the sky. One of these can host a variable number of telescopes, depending on system specifications and usable area on the platform. The availability of a single movable enclosure (the site is essentially unique in Europe) and of much of the associated support infrastructure at OAVdA will allow, in perspective, very substantial cost savings for the project.

The generic design requirements for a ground-based photometric transit search for small-size planet around M dwarfs which uses a network of small identical robotic telescopes (optimal bandpass and field of view, telescope aperture, telescope time allocation, and observing strategy) have been laid out by Nutzman & Charbonneau (2008). That study assumes that the well-characterized Mount Hopkins site in Arizona chosen for the survey guarantees that (1) the limiting system performance (photometric precision) for transit detection is achieved, and (2) the requested number of useful observing nights per year is reached. This work presents the details of a characterization study carried out at OAVdA, which aims at demonstrating that the main site-specific requirements (night-sky brightness, number of useful nights, seeing, and photometric stability) are satisfied, and OAVdA is therefore an optimal choice for hosting a precision photometric search for low-mass, small-size planets around a well-defined sample of M dwarfs in the solar neighborhood which utilizes an array of small telescopes.

The paper is organized as follows. In § 2 we describe the instrumentation presently available at OAVdA, which was utilized for the purpose of the feasibility study, and we outline in § 3 the various steps involved in the dedicated pipeline for the data processing and analysis of the photometric data under development. We present in § 4 the observing strategy adopted and the main results of the feasibility study in terms of overall site characterization (i.e., the achievable photometric precision as a function of atmospheric conditions). We conclude in § 5 by discussing the preparatory steps for a long-term photometric monitoring program to characterize the microvariability characteristics of and search for transiting small-size planetary companions to a well-defined sample of low-mass stars, to be carried at the OAVdA site in the near future.

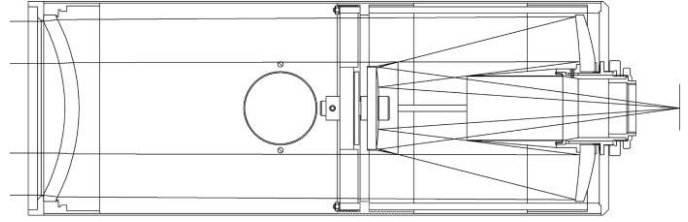


FIG. 1.—Optical scheme of the Maksutov reflector telescope (aperture 250 mm) used for the characterization study.

2. SYSTEM DESCRIPTION

2.1. Hardware

For the purpose of the feasibility study we adopted existing instrumentation available at the OAVdA site. Most of the observations were carried out with a 250 mm Maksutov telescope (the optical scheme⁹ is shown in Fig. 1), with a focal length of 950 mm ($f/3.8$), on a German equatorial mount, and no auto-guiding (while not common practice, this does not constitute a serious issue for the purpose of our study). The instrument is equipped with a front-illuminated Charged Coupled Device charge-coupled-device (CCD) camera (Moravian G2-3200ME, with sensor KAF 3200ME, area 2184×1472 pixel², and pixel area $6.8 \times 6.8 \mu\text{m}^2$), and a nonstandard Astronomik R filter (see Fig. 2). As shown in Figure 3, the sensor reaches a quantum efficiency $QE \sim 87\%$ at this wavelength. The CCD camera was operated with a nominal gain of $1 e^-/\text{ADU}$ (in 1×1 binning mode), with nominal read noise $N_r = 10 e^- \text{pixel}^{-1}$ (rms), dark current $N_D = 0.1 e^- \text{pixel}^{-1} \text{s}^{-1}$ at a temperature of -40°C and a full frame download time of ~ 8.4 s through a USB 2.0 port. The CCD chip is cooled thermoelectrically by a two-stage system of Peltier modules, which allows us to reach a maximum temperature gradient $\Delta T \approx 50 \pm 0.1^\circ\text{C}$ with respect to the ambient temperature. The chip temperature, recorded in the FITS (Flexible Image Transport System) file headers, is typically stable to better than 0.5°C . During the period of the characterization study (late spring/summer), the chip was cooled to temperatures of -30°C or -35°C (while the working temperature is usually set to -40°C during winter time). As shown in Figure 4, the typical values of thermal noise for our CCD camera remain well below $1 e^- \text{pixel}^{-1} \text{s}^{-1}$ as long as the cooling temperature is set to $\lesssim -25^\circ\text{C}$. The telescope-CCD configuration has a field of view (FOV) of $52.10 \times 35.11 \text{ arcmin}^2$ and a plate scale of $1.43'' \text{pixel}^{-1}$.

The OAVdA site also routinely utilizes two Ritchey-Chrétien reflector telescopes, one 400 mm ($f/7.64$) and one 810 mm ($f/7.9$), the latter being the primary scientific instrument of the observatory. Both the instruments have equatorial open fork mounts.

⁹ See <http://lnx.costruzioniottichezen.com>.

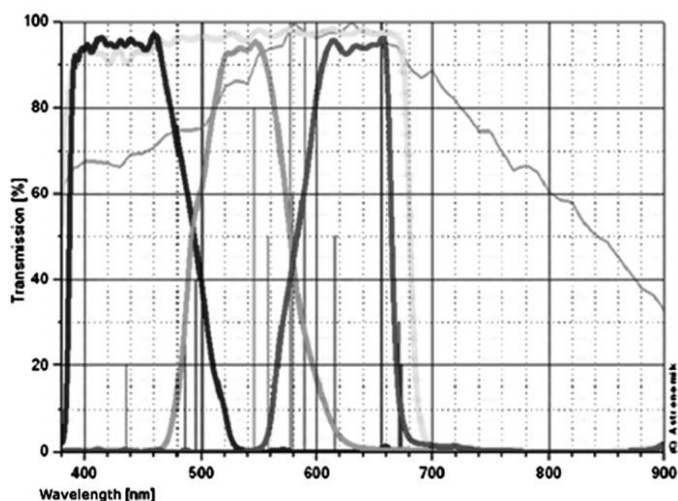


Fig. 2.—Transmission curve for the set of filters coupled to the CCD in the 250 mm telescope. For the site testing we used the *R* filter. The corresponding transmission curve is shown in dark gray, centered at approximately 630 nm. See the electronic edition of the *PASP* for a color version of this figure.

The 400 mm telescope will be used full time together with the 250 mm during the next steps following this study, as detailed in § 5. It is coupled to a front-illuminated CCD camera (Finger Lakes Instrumentation Pro Line PL1001E, with sensor KAF1001E and standard *BVRI* filters). The camera sensor area is 1024×1024 pixel² with pixel area 24×24 μm^2 . The final configuration is characterized by a FOV of 26.4×26.4 arcmin² with a plate scale of $1.55''$ pixel⁻¹. The primary telescope is coupled to a back-illuminated CCD camera (Finger Lakes Instrumentation Pro Line PL 3041-BB, with sensor Fairchild Imaging 3041 and standard *BVRI* filters). The camera sensor area is 2048×2048 pixel², with pixel area 15×15 μm^2 . The

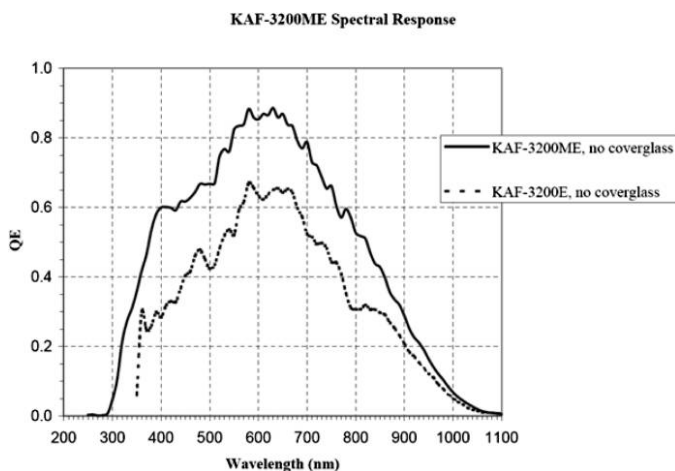


Fig. 3.—Nominal response curve of the sensor KAF-3200ME integrated in the CCD camera used in this study (solid line).

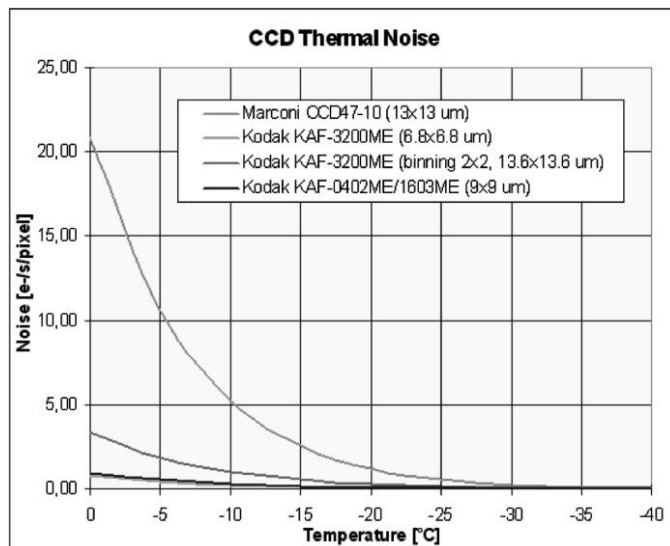


Fig. 4.—Thermal noise as a function of temperature for the sensor KAF-3200ME (pixel size 6.8×6.8 μm^2) integrated in the CCD camera used in this study (solid line). The performances of other off-the-shelf devices are shown for comparison. See the electronic edition of the *PASP* for a color version of this figure.

system has a FOV of 16.3×16.3 arcmin² with a plate scale of $0.48''$ pixel⁻¹. The detector is used routinely in binning mode 2×2 , a choice driven by the need to avoid image oversampling, considering the typical seeing conditions at our site (see § 4.4). While usually devoted to other projects, it will be used in the future to perform multiband photometric observations within the context of the necessary follow-up scheme of potentially interesting transit candidates. Each observing station is equipped with a PC which is synchronized every 15 minutes via Internet to the Network Time Protocol server of the Italian National Institute of Metrological Research. In the header of each frame, time is saved as Julian Date with six significant digits. Table 1 summarizes the specifications of each of the three telescope systems.

The 250 and 400 mm telescopes are located in one of the platforms of the observatory. Figure 5 shows a panoramic view of the telescopes location. With a theodolite, we evaluated the minimum sky altitude above the horizon, as a function of the azimuth, which can be reached with a telescope placed in the middle of the platform before encountering any obstacle limiting the observations (mountains, platform walls, or dome). The altitude-azimuth profile is shown in Figure 6. The most prominent obstacle is represented by the dome (with a 7 m diameter) hosting the primary telescope. The dome (not shown in Fig. 5) is located next to the platform. It covers ~ 20 – 24° in elevation, in the azimuth range ~ 290 – 320° . This does not represent a serious constraint, however, as per standard procedure we observe targets until they reach a minimum altitude of 30° above the horizon.

TABLE 1
SUMMARY OF THE MAIN CHARACTERISTICS OF THE TELESCOPE SYSTEMS DESCRIBED IN § 2.

Optical scheme	Telescope		CCD camera		Resulting configuration	
	Aperture (mm)	Focal ratio	Sensor area (pixel)	Pixel area (μm)	FOV (arcmin)	Plate scale (arcsec pixel ⁻¹)
Reflector Maksutov	250	$f/3.80$	2184×1472	6.8×6.8	52.10×35.11	1.43 (binning 1×1)
Reflector Ritchey-Chrétien	400	$f/7.64$	1024×1024	24×24	26.4×26.4	1.55 (binning 1×1)
Reflector Ritchey-Chrétien	810	$f/7.90$	2048×2048	15×15	16.3×16.3	0.48 (binning 1×1)

2.2. Telescope Control System

The 400 and 810 mm telescopes are managed by the control and data acquisition system CompactRIO which is based on National Instruments (NI) technology. The system is powered by a software with a graphical interface developed with the NI LabVIEW programming tools and it allows the remote control of the telescopes (the pointing is both automatic and in manual jog). The algorithms integrated in the control system were entirely developed by members of the OAVdA research staff. The system is able to dialog, through the use of the LX200 protocol, with the most popular software packages used to control astronomical instruments.

2.3. Seeing Monitoring

During the period of the characterization study, each night of observation we monitored and recorded the seeing using the differential image motion monitor (DIMM) technique (Sarazin & Roddier 1990), which minimizes the effects induced by the in-

strumentation and provides an accurate estimate of the level of the atmospheric turbulence. This technique requires the use of a two-hole mask (Shack-Hartmann mask) in front of the telescope aperture so that, slightly defocusing, two distinct and close profiles of one bright star are formed. Figure 7 shows a freeze-frame taken during a typical seeing monitoring session illustrating the DIMM procedure. A seeing estimate is then obtained measuring the relative motion of the two stellar profiles over time scales of milliseconds. To monitor the seeing we used a second 250 mm ($f/3.8$) Maksutov telescope (shown in Fig. 5) equipped with a Shack-Hartmann mask and a SBIG-STV digital integrating video camera which is able to apply the DIMM algorithm in real-time with high time sampling (typically, five measurements per second). Data are automatically saved on a PC as ASCII files. No filter was used to perform these measurements (possibly resulting in an overestimate of the seeing).

3. DATA PROCESSING AND ANALYSIS

A fundamental element of the characterization study has been the development and testing of the automatic pipeline TEEPEE (transiting exoplanets pipeline) for the reduction



FIG. 5.—The OAVdA scientific platform from which the site characterization study observations were carried out, and where an array of telescopes will be installed for a future long-term photometric survey. Numbers 1 and 3 identify the two 250 mm Maksutov telescopes used, respectively, to monitor the seeing with the DIMM technique and to acquire photometric data of fields with stars hosting transiting extrasolar planets. In the middle (number 2) is the 400 mm reflector telescope.

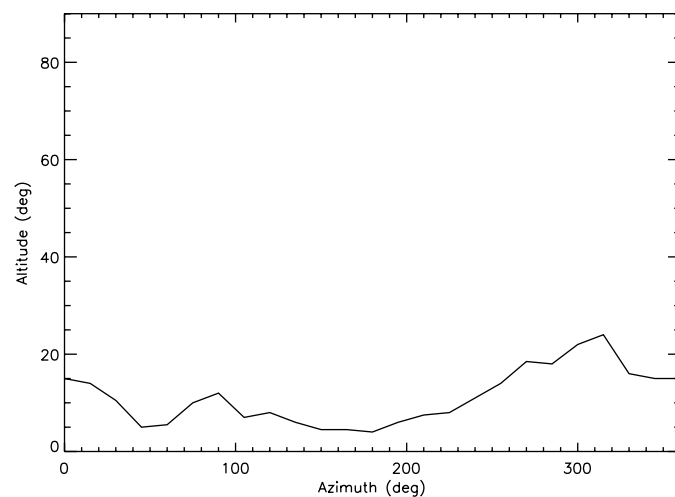


FIG. 6.—Minimum sky altitude useful for observations as a function of the azimuth, before incurring obstacles (observatory dome, platform walls, and mountains). The profile was determined with a theodolite placed in the center of the OAVdA platform which hosts the telescopes used in this study.

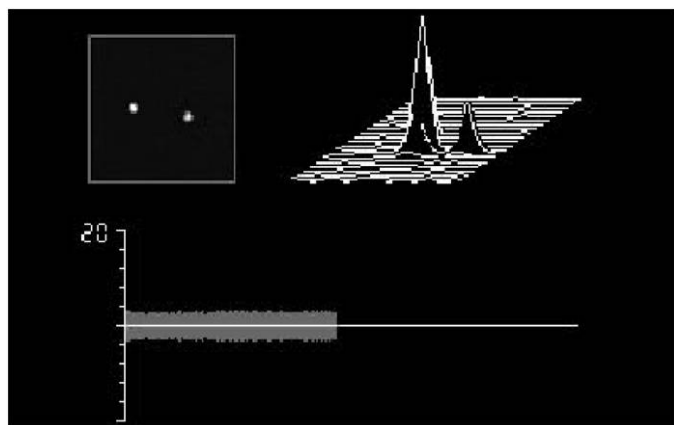


FIG. 7.—Freeze-frame from the SBIG-STV digital integrating video camera coupled to a 250 mm Maksutov telescope to monitor the seeing with the DIMM method. In the upper left corner the two images of the star used to estimate the seeing are represented, as produced by placing a two-hole Shack-Hartmann mask in front of the telescope aperture.

and processing of the photometric data. TEEPEE is a software package written in IDL,¹⁰ which utilizes publicly available software from the Astronomy Users' Library¹¹ as well as externally contributed FORTRAN routines. Two routines, *aper* and *getpsf*, are IDL versions of original IRAF routines.¹² The original portion of software is the one devoted to automatically perform ensemble differential aperture photometry on a user-specified stellar target. The various tasks performed by TEEPEE and the different routines used are summarized in the diagram shown in Figure 8. TEEPEE is organized in three main sequential blocks, whose functionalities are described next.

3.1. Image Calibration

In the routine *imgcalib*, every raw FITS image acquired by the CCD (each 6.1 MB in size) is initially dark-subtracted and flat-fielded. A master dark image is created every month from the median values of each pixel of 70 dark images having the same exposure time of the science images.¹³ The flats are prepared from the nightly averages of ~ 15 high-S/N (signal-to-noise ratio) exposures at twilight, diffused by a white opal of polystyrene.

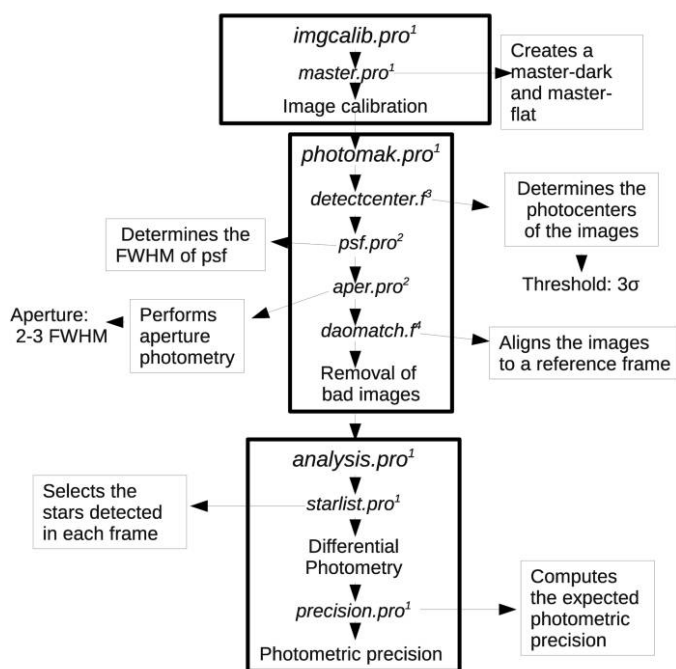
¹⁰IDL is a commercial programming language and environment by ITT Visual Information Solutions. <http://www.itvis.com/idl/>.

¹¹ See <http://idlastro.gsfc.nasa.gov/contents.html>.

¹²IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy under cooperative agreement with the National Science Foundation.

¹³The number of dark images ensures minimization of the noise for the purpose of achieving a goal of a few millimag photometric precision. We are aware of the fact that taking dark images during each observing session might improve the quality of the calibration to some degree. The protocol will be changed in the future, for example, by taking dark frames both at the beginning and at the end of the observing session

TEEPEE pipeline structure



¹ Routine developed by the authors

² IDL Astronomy user's library

³ Yu Yong

⁴ P. Steason

FIG. 8.—Flowchart summarizing the main tasks (and corresponding routines) performed by version 1.0 of TEEPEE, the pipeline for data reduction, and processing developed during the study presented in this article. More details are given in the text.

3.2. Photometric & Astrometric Processing

The first task of the pipeline routine *photomak* is the search for the photocenters in each image. This is performed automatically by the subroutine *detectcenter*, which selects each pixel with an ADU value greater than 3 times the rms of the sky background. The list of x and y coordinates of the photocenters are used as input for the subroutine *psf*, which calculates the average FWHM of the point-spread function of each detected star in every image. Then the *aper* subroutine is applied to perform single-aperture photometry on each detected object, with the radius of the user-provided circular aperture typically set to 2–3 times the average value of the FWHM. This routine counts the ADU values for each pixel in the circular aperture, while partial pixels are handled by numerical integration. Once the photometer coordinates and the instrumental magnitudes are listed, the *daomatch* subroutine aligns each image to a reference frame (usually, the first image of each series) by performing a triangulation. If in one image the stars found are less than 20% of those detected in the reference frame or the alignment procedure fails (mostly because of high variability in the sky transparency), then the image is automatically discarded.

3.3. Data Analysis

The heart of TEEPEE, for the purpose of this study, is the routine `analysis`. It performs those operations which are necessary to eliminate, when possible, all the systematics which cause the degradation of the photometric precision and outputs the photometric light curves for stars detected in every image of a field. At first, by using the subroutine `starlist`, only the stars that have been detected in every frame are selected and added to the final list. All objects that, due to telescope drifts, exited the CCD FOV or are too weak (i.e., below 3σ of the sky background level) in one or more frames are discarded. The typical drift of the 250 mm telescope is nearly 10 pixel hr^{-1} and 20 pixel hr^{-1} in the X and Y directions, respectively. Considering, for example, the fields of WASP-3 and HAT-P-7 which we monitored for this study (see § 4.3), on average $\sim 15\%$ of the stars appearing in the first frame of a series are lost because of drifts or veils, resulting in some 550–600 good stars detected on average in every frame during a night. Finally, the corrections due to atmospheric extinction are applied. The equation giving the measured magnitudes as a function of the magnitude above the atmosphere is:

$$m_I = m_o + k \times \text{AM}, \quad (1)$$

where k denotes the atmospheric extinction coefficient, m_I is the instrumental magnitude, m_o is the magnitude above the atmosphere, and AM is the air mass (AM = 1 when the object is located at the local zenith). The standard procedure requires that slope k and intercept m_o be evaluated every time from observations of photometric standard stars, such as Landolt stars. Given the purely differential approach to the photometric measurements in this study, we proceeded to calculate the extinction coefficient using all the n reference stars chosen in the field of each target. This is done by solving a global system of $n \times N_i$ linear equations of the form of equation (1) through the IDL routines `SVDC` and `SVSOL`, where N_i is the number of good frames of the series. The solution is represented by a global value for k and N_i values for m_o . As comparison stars we selected the n brightest stars detected in every frame with $m_I \leq 13$. For the purpose of this study, the R -band measurements of k are used to gauge the level of sky transparency (see § 4.1). No dedicated device (e.g., Calar Alto Extinction monitor, Sánchez et al. 2007) for the monitoring of extinction was used.

The rms of each new light curve obtained after the air-mass correction provides quick information about the stability of the atmospheric transparency during the night, but more accurate light curves are provided by the ensemble differential photometry. For each frame i , we used the average magnitude of the n reference stars as the reference magnitude m_{rif}^i :

$$m_{\text{rif}}^i = \frac{\sum_{k=0}^n m_k^i}{n}. \quad (2)$$

Then m_{rif}^i is subtracted from the magnitude of the user-defined target M_{target}^i , obtaining the difference $\Delta m^i = m_{\text{rif}}^i - m_{\text{target}}^i$. The procedure is also iteratively repeated for all the reference stars, using the remaining $n - 1$ stars as new references. We thus obtain a series of differential light curves for all the stars selected, which can be inspected for variability. The few bright variables identified with this approach (see § 4.6) are not discarded at this stage, as their impact on the photometric precision is minimized by the selection of dozens of comparison stars.

As discussed, version 1.0 of the TEEPEE pipeline can automatically perform several basic tasks. These have been tested with promising results, as described in the following sections. However, the pipeline is still far from being completed. Further refinements will guarantee improved functionality and a higher degree of robustness. In particular, a photometric survey finalized to the detection of planetary transits must take into account the effects of red noise, which can strongly affect the sensitivity thresholds (Pont et al. 2006). This feature will be included in future upgrades of the software package in preparation of the official start of the photometric survey in the near future. The pipeline will grow further to implement algorithms for the reduction of the noise and systematic variations in the light curves (detrending), such as the trend filtering algorithm (Kovács et al. 2005) or SysRem (Tamuz et al. 2005), as well as algorithms for the detection of periodic transitlike signals, such as the widely used box-fitting least-squares method (Kovács et al. 2002).

4. SITE CHARACTERIZATION STUDY: RESULTS

The main OAVdA site characterization campaign was carried out during the period of 2009 May–August. As in any search for adequate sites for new observatories, we focused on the determination of observing conditions such as night-sky brightness, number of useful nights, photometric precision, and seeing.

4.1. Night-Sky Brightness and Transparency

We have utilized measurements of the zenithal night-sky brightness collected between 2007 May and 2007 July during seven moonless nights in collaboration with the Italian Agency for Environmental Protection (ARPA), as part of an extended monitoring program of the light pollution in the Aosta Valley. The data were obtained using the 400 mm reflector telescope and a CCD camera equipped with a V -band filter. All measurements were calibrated using standard reference stars. The V -band night-sky brightness ranged between 21.12 and 21.61 mag arcsec $^{-2}$, with a mean and standard deviation of $21.29 \pm 0.16 \text{ mag arcsec}^{-2}$. These numbers are typical of those of very good, very dark observing sites (e.g., see Table 4 in Moles et al. 2009). During the same period, the V -band extinction coefficient ranged from 0.116 mag to 0.420 mag, with a mean and standard deviation of $0.26 \pm 0.13 \text{ mag}$. This value compares reasonably well with the V -band k estimates during

summer that are available in the literature for other sites (e.g., Sánchez et al. 2007 and references therein). The mean and standard deviation of our own R -band k value derived within the context of the site characterization campaign are 0.165 ± 0.090 mag. They are in good agreement with the analytical estimate, 0.146 mag, from the extinction curve formula in Sánchez et al. (2007) based on the V -band value of k reported previously. The typical conditions of sky transparency are thus in line with what to expect from a good site, although the spread around the mean conditions is relatively large. Given the limited time span of the observations, we cannot comment on seasonal variations of the extinction at the OAVdA site, nor are we in a position to investigate in detail the relative role of various contributors (e.g., dust and other aerosol particles and ozone).

4.2. Fraction of Useful Nights

In order to estimate the number of useful nights per year, we relied upon on a 3 yr baseline of data (from 2006 to 2008) collected by a weather station located next to the observatory, while for the year 2009 we also used our own internal logs. Over this time span, fully clear nights conditions are statistically realized 142 nights yr^{-1} (39%), while an additional 67 nights yr^{-1} (18%) can still be considered useful, assuming a typical cloud cover of $<50\%$ of the useful observing time (conservative upper limit). As for the year 2009, during which we carried out the feasibility study, we registered similar conditions: uninterrupted observations could be carried out 39.5% of the time, while for an additional 22% of the nights the cloud cover did not exceed 50% of the useful observing time. These figures compare reasonably well with other observatory sites in Europe.

4.3. Photometric Performance

In order to estimate the achievable photometric precision at the OAVdA site, given the aforementioned instrumental setup, the centerpiece of the site characterization study consisted of the monitoring of three stellar fields centered on the transiting planet hosts Gliese 436 (Butler et al. 2004), WASP-3 (Pollacco et al. 2007), and HAT-P-7 (Pál et al. 2008). The targets were observed during both in- and out-of-transit phases during the period 2009 May–August. All observations were performed with the CCD set up in 1×1 binning mode and at the focus of the telescope, and the exposure times were chosen at the beginning of each session (without being subsequently modified) in order to guarantee an optimum S/N for the target, while avoiding saturation. Typical exposure times were 22 s for Gliese 436 ($V = 10.68$ mag), the brightest target at the R -band, and ranged between 35 and 60 s for both WASP-3 ($V = 10.48$ mag) and HAT-P-7 ($V = 10.46$ mag), given variable conditions of air mass and sky transparency. Figure 9 shows an example of the quality of the images we collected. The whole database for this characterization study comprises $\sim 10,300$ good images, corresponding to ~ 63 GB of data.

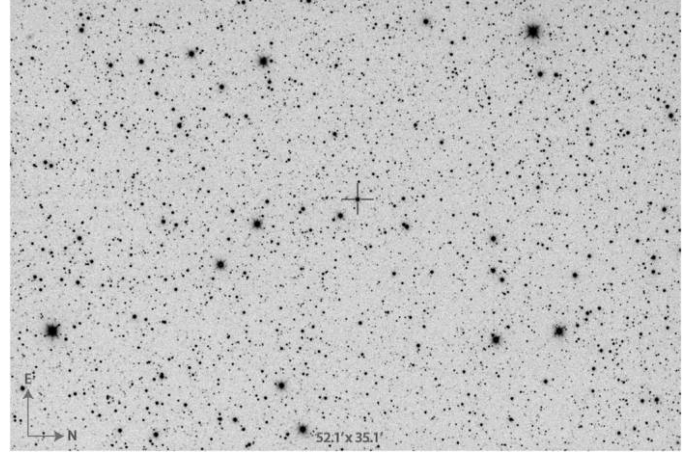


FIG. 9.—A typical FITS image obtained with the 250 mm telescope. In this example the field of the star HAT-P-7 is shown, indicated with a cross (exposure time: 60 s).

We show in Figure 10 the scatter in our differential photometry as a function of apparent magnitude in the field of the star WASP-3, for a night representative of the typical performance achieved. The results are compared to a theoretical noise estimate (Nutzman & Charbonneau, 2008) which includes contributions from the object (Poisson noise), sky, readout noise, and scintillation:

$$\sigma_{\text{ph}} = \frac{\sqrt{N_{\star} + \sigma_{\text{scint}}^2 + n_{\text{pix}} \times (N_S + N_D + N_R^2)}}{N_{\star}}. \quad (3)$$

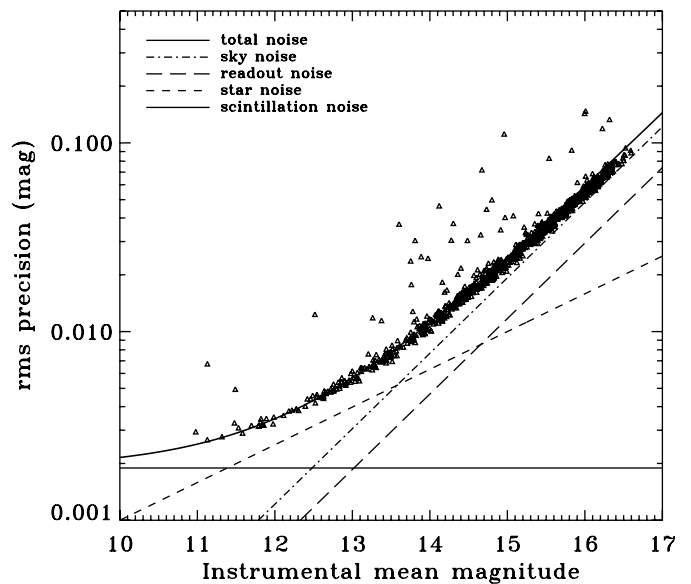


FIG. 10.—Photometric errors (rms) vs. instrumental mean magnitude in the field of the planet-hosting star WASP-3 during a good observing night (and for an exposure time of 35 s). The various contributions to the expected photometric noise, according to equation (3), are also shown.

In equation (3), N_* is the number of received photons from the star during the exposure, n_{pix} is the number of pixels in the photometric aperture, N_S is the average number of photons per pixel of the sky background (we used a number typical of the average sky conditions registered over the duration of our campaign), N_D is the dark current contribution in $e^- \text{ pixel}^{-1}$ (from § 2.1), N_R is the rms of the CCD read noise in $e^- \text{ pixel}^{-1}$ (also from § 2.1), and σ_{scint} is the noise term for the atmospheric scintillation. The expression used for σ_{scint} is (Dravins et al. 1998):

$$\frac{\sigma_{\text{scint}}}{N_*} = 0.09 \frac{AM^{3/2}}{D^{2/3} \sqrt{2t}} \exp\left(-\frac{h}{8}\right), \quad (4)$$

where AM is the air mass (we adopted a mean value of 1.5), D is the telescope aperture in centimeters, t is the exposure time in seconds, and h is the height in kilometers of the observing site above sea level.

For bright stars, the dominant sources of error are the scintillation and shot (Poisson) noise from the target star itself. Note the excellent agreement with the expected scatter values for magnitudes $R \lesssim 13$ mag. Among the most likely sources of additional scatter in the observations with respect to the theoretical predictions we list guiding errors and possible contributions from centering errors during aperture photometry. For the brightest objects we achieve a nightly rms precision of ~ 0.003 mag (during some nights the recorded scatter for these stars was even lower). For fainter stars, sky photon noise is the dominant source of scatter. Some outliers can be seen in the data set. One of them corresponds to a newly discovered variable (probable δ Scuti-type) star (Damasso et al. 2010b).

To evaluate the photometric precision of each night of observation we adopted the mean rms calculated for stars with magnitudes $R \lesssim 13$ mag. In Figure 11 we show how the nightly averaged rms varied during the period of observation. Different symbols are used to distinguish the various star fields that were monitored, as described in the figure caption. The median rms over the whole duration of the characterization study is 0.006 mag for magnitudes brighter than 13 mag. The results shown in Figure 10 can then be considered representative of a typical night at our site. Equally important is the fact that the night-to-night variations are ~ 0.002 mag (disregarding the few nights with large, >0.01 mag, scatter due to poor weather conditions). These results demonstrate that it is possible to achieve competitive precision at the OAVdA site over an extended period of time, which is a particularly encouraging result given the still nonoptimized hardware system used during this study.

4.4. Seeing Measurements

As described in § 2.3, seeing monitoring has been carried out in conjunction with the photometric measurements over the whole duration period of the site characterization study. For the purpose of this work, its role has been quantified in terms

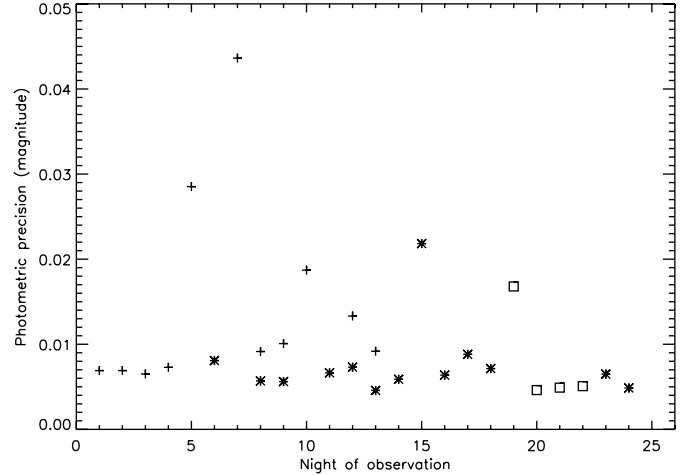


FIG. 11.—The nightly averaged photometric precision, calculated for stars with magnitudes <13 mag, is plotted for each night of observations. Different symbols are used to distinguish the three stellar fields monitored during the characterization study: a plus denotes the field of the star Gliese 436, an asterisk is used for WASP-3, while squares correspond to HAT-P-7.

of its median value over the time span of the measurements, its typical stability during a night, and its correlation with the photometric performance achieved. We note that given the limited time duration of the measurements, we cannot comment in a statistically significant fashion on possible seasonal seeing variations or in detail on its possible dependence on other meteorological parameters, such as wind speed and direction.

Figure 12 shows the distribution of seeing values as a function of the night of observation. The median seeing turns out to

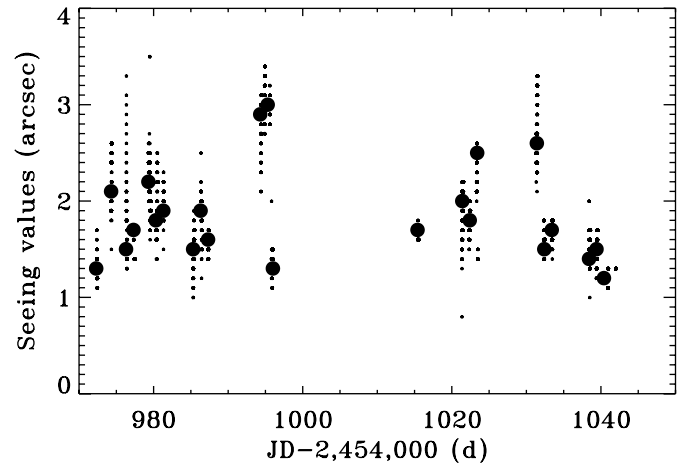


FIG. 12.—The distribution of seeing measurements over the whole period of observation. The small black stars show 7864 individual data points (many of them overlapping due to the seeing values having been approximated to the first significant digit), each corresponding to an average seeing value over a 1 min interval, rounded to 0.1". The large filled circles indicate the median seeing value for each night.

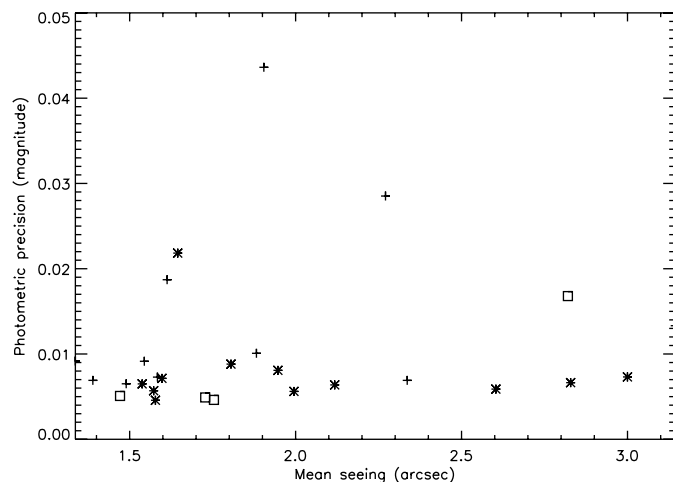


FIG. 13.—The comparison of the nightly averaged photometric precision to the corresponding mean seeing does not reveal an evident correlation between these two variables for FWHM values $\leq 3''$, given our instrumental setup. Symbols are as in Figure 11.

be $\sim 1.7''$ over the whole period. In most nights, the seeing appeared rather stable, typically remaining within 20% or so of the reference median value.

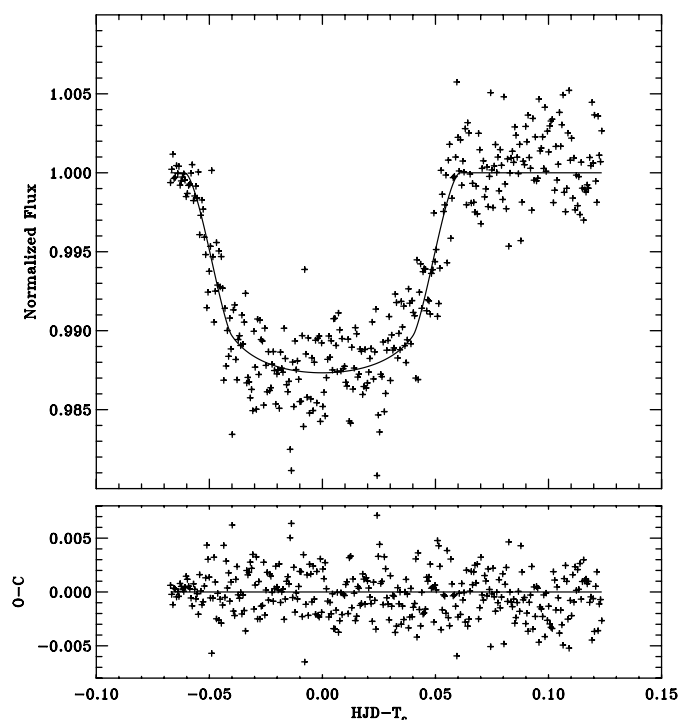


FIG. 14.—Top: transit light curve of WASP-3b during the night of UT 2009 July 28. The time of transit center occurred at $T_C = 2,455,041.411$ HJD. The 358 35 s exposures were collected over 4.6 hr. The best-fit curve is superposed. Bottom: the postfit residuals exhibit an rms of 0.0021 mag.

Indeed, the overall result is that the OAVdA site does not appear competitive with respect to other observing sites in the world (see, e.g., Table 5 in Moles et al. 2009). However, as illustrated in Figure 13 the photometric precision is essentially seeing-independent for values up to $3''$. On the basis of this result we can conclude that the typical seeing measured at the OAVdA site does not represent a limiting factor for the precision of the stellar differential photometry (with the instrumental setup we utilized), for magnitudes $R \lesssim 13$ mag. This is in accordance with the promising results found by applying the telescope defocusing technique for high-precision photometry of transiting extrasolar planets (i.e., Southworth et al. 2009a, 2009b, 2009c), which can be carried out for the brightest stars, even with small-size telescopes.

4.5. Sample Light Curves of Known Transiting Systems

As examples of the quality of the photometric data achieved with the present instrumental setup, we present two light curves showing the transits of the extrasolar planets WASP-3b (Fig. 14) and HAT-P-7b (Fig. 15). As for Gliese 436b (whose data are not shown here), unfavorable weather conditions prevented us from observing a full transit during the time span of the characterization study.

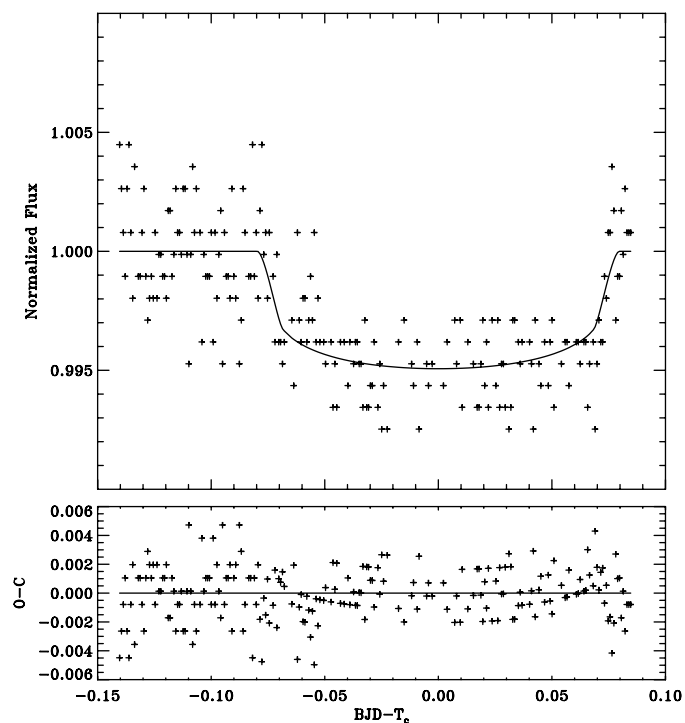


FIG. 15.—Normalized light curve of HAT-P-7 showing the shallow transit of its Jupiter-mass companion HAT-P-7b (UT 2009 July 18, 260 60 s exposures collected in 4.6 hr). The time of transit center occurred at $T_C = 2,455,031.5222$ BJD (Barycentric Julian Date). The best-fit curve is superposed. Bottom: the postfit residuals exhibit an rms of 0.0018 mag.

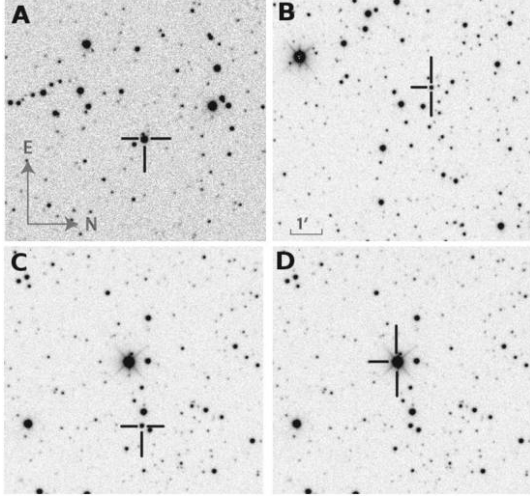


FIG. 16.—The new variable stars discovered at OAVdA and presented in this work. (A) GSC2.3 N208000215, (B) GSC2.3 N2JH035417, (C) GSC2.3 N2JH000428, and (D) GSC2.3 N2JH066192.

WASP-3 ($M_{\star} = 1.24 M_{\odot}$ and $R_{\star} = 1.31 R_{\odot}$), which hosts an $M_p = 1.76 M_J$ and $R_p = 1.31 R_J$ planet with a period $P = 1.846834$ days, was monitored for 19 nights. The rather good phase coverage allowed us to observe four transits of WASP-3b. Figure 14 shows the full transit observed during the night of UT 2009 July 28. Superposed to the normalized flux is the best-fit curve, obtained as solution of a nonlinear least-squares problem using the Levenberg-Marquardt algorithm and a merit function based on the formalism of Mandel & Agol (2002) with adjustable quantities the inclination angle i , the ratio of radii $r = R_p/R_{\star}$, and the impact parameter $b = (a/R_{\star}) \cos i$ (where $a/R_{\star}$ is the orbital semimajor axis expressed in units of the stellar radius). We assumed a quadratic limb-darkening law with R -band coefficients $u_1 = 0.2357$ and $u_2 = 0.3779$ (Claret 2000), appropriate for the stellar parameters in Pollacco et al. (2007). The subpanel of Figure 14 shows the postfit residuals, which exhibit an rms of 0.002 mag. The relatively large transit depth (0.013 mag) allowed us to derive formally precise values for the system parameters. The best-fit values and their associated $1 - \sigma$ uncertainties derived from the covariance matrix of the solution are as follows: $b = 0.665 \pm 0.003$,

$i = 81.24 \pm 0.06^{\circ}$, and $r = 0.1091 \pm 0.0006$. There appears to be some discrepancy (a less central transit) with respect to the values reported in the discovery paper of Pollacco et al. (2007) and in the work of Gibson et al. (2008). However, the results of this exercise are shown here only for illustrative purposes. Our results are undoubtedly affected by the nonoptimal choice of the limb-darkening parameters (we recall that observations were taken with a nonstandard R filter), by the lack of a proper treatment of red noise, and by the almost complete absence of data gathered before ingress.

The star HAT-P-7 ($M_{\star} = 1.47 M_{\odot}$ and $R_{\star} = 1.84 R_{\odot}$) was selected as a challenging target for our test because its transiting planet ($M_p = 1.8 M_J$, $R_p = 1.42 R_J$, and $P = 2.2047298$ days) produces a photometric transit characterized by a shallow depth (~ 0.007 mag), which is close to the detection limit for our present instrumental and data reduction and analysis setup. HAT-P-7 is located in the field of view of the Kepler space telescope, which monitored the star for 10 days during its commissioning phase, deriving an exquisite-quality optical phase curve (Borucki et al. 2009). In Figure 15 we show the transit observed at OAVdA the night of UT 2009 July 18. We could not observe a complete transit (the planet's egress is barely visible due to the approaching sunrise, which forced us to interrupt the exposures), and during the night the sky transparency varied significantly due to the presence of veils. However, the transit was clearly detected, and by using an aggressive light-curve analysis, including iterative σ clipping for the removal of outliers, we managed to clean the data set so as to perform an analogous exercise to that carried out in the case of WASP-3. The light-curve fit, assuming a quadratic limb-darkening law with R -band coefficients $u_1 = 0.3980$ and $u_2 = 0.2071$, appropriate for the stellar parameters in Pál et al. (2008), resulted in the following solution: $b = 0.321 \pm 0.006$, $i = 85.93 \pm 0.08^{\circ}$, and $r = 0.064 \pm 0.002$. In this case, the main difference is that of a value of r which is about 15% smaller than that reported in the literature. This is due to the shallower transit depth (~ 5 mmag) recovered after we applied the procedure to remove outliers. Again, we stress the illustrative purpose of the orbital fit carried out, the main aim here being simply that of showing that the transit could clearly be detected. This represents a promising result in the perspective of our long-term photometric

TABLE 2

VARIABLE STARS DISCOVERED IN THE FIELDS OF THE EXTRASOLAR PLANET-HOSTING STARS WASP-3 AND HAT-P-7. R MAGNITUDES ARE DERIVED FROM r' MAGNITUDES OF THE CMC14 CATALOG USING THE RELATION $R = r' - 0.22$ DERIVED BY DYMOCK & MILES (2009)

Object ID	Eq. coord.	Magnitude				
(GSC2.3 catalog)	RA, DEC (J2000)	B	V	R	J	K
N208000215	18:35:23.210 +35:14:45.43	12.34 ± 0.19	12.09 ± 0.18	11.622	10.962 ± 0.02	10.662 ± 0.023
N2JH035417	19:27:49.596 +48:20:47.90	-	-	12.797	12.365 ± 0.022	12.225 ± 0.024
N2JH000428	19:29:55.081 +47:50:04.41	13.34 ± 0.30	14.10 ± 0.44	12.95	11.998 ± 0.020	11.053 ± 0.019
N2JH066192	19:30:08.505 +47:49:31.16	10.11 ± 0.04	8.92 ± 0.02	-	6.857 ± 0.018	6.205 ± 0.016

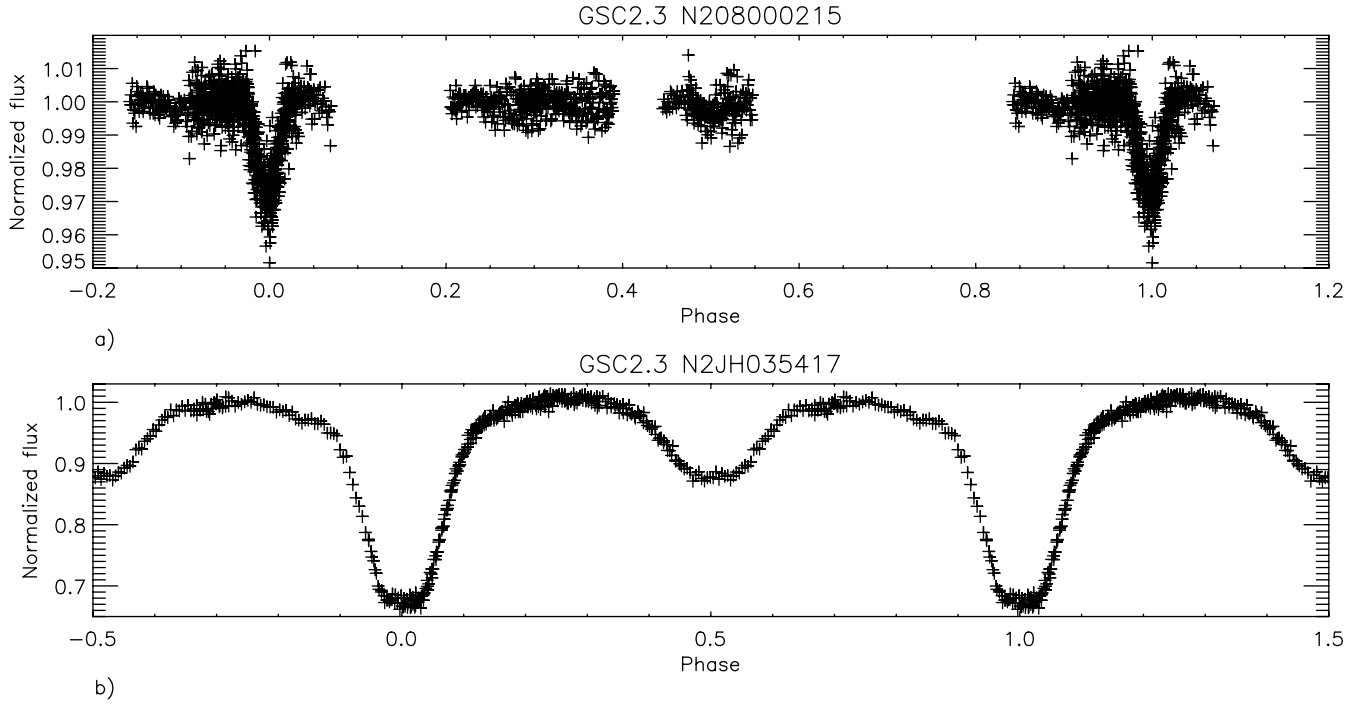


FIG. 17.—Phase-folded light curves of two eclipsing binary systems discovered during the feasibility study. Upper panel: the estimated orbital period is $P = 2.02065 \pm 0.00004$ days, and phase = 0.0 corresponds to $\text{HJD} = 2,455,041.50975 + P \times E$. Lower panel: the estimated orbital period is $P = 0.505167 \pm 0.000002$ days, and phase = 0 corresponds to $\text{HJD} = 2455031.381135 + P \times E$. In the upper and lower panels, there are 1510 and 1443 data points, respectively, taken over 11 and 6 days, respectively.

monitoring program to be started in the near future with upgraded instrumentation and an improved data reduction and analysis pipeline.

4.6. New Variable Stars

A natural by-product of high-precision, high-cadence photometry collected for hundreds of stars over a time span of several weeks, as is the case for the WASP-3 and HAT-P-7 stellar fields monitored in the context of our site characterization study, is the discovery of variable sources. A handful of previously unknown variable stars with relatively large amplitude variations ($\Delta V \gtrsim 0.05$) were uncovered during this study. Two of them are presented and discussed in Damasso et al. (2010b). Here, we report the detection of four new binary/multiple-star systems showing eclipses. The fields centered on the variables are shown in Figure 16, while the relevant data are summarized in Table 2.

We searched the literature and stellar catalogs in order to find prior variability information on the four objects. In particular, we looked at the works of Street et al. (2007) and Norton et al. (2007), and we searched the General Catalogue of Variable Stars,¹⁴ the New Catalogue of Suspected Variable Stars,¹⁵ the

International Variable Star Index¹⁶ and All Sky Automated Survey¹⁷ databases, and the VizieR database.¹⁸ We failed to identify counterparts of our objects, and so we can report them here as new discoveries.

The first two targets in Table 2 (GSC2.3 N208000215 and GSC2.3 N2JH035417) are identified as eclipsing binary systems, with orbital periods $P = 2.02065 \pm 0.00004$ days and $P = 0.505167 \pm 0.000002$ days, respectively, based on a Lomb-Scargle periodogram analysis. In the two panels of Figure 17 we show the phase-folded light curves for these two systems. For the first binary system (upper panel of Fig. 17) we derived the ephemeris of the secondary minimum, which was observed at the predicted epochs even if its depth was shallow (~ 0.005 mag) and very close to the detection limit for our instrumentation.

For the last two targets in Table 2, we observed in their light curves only one complete minimum (GSC2.3 N2JH000428) and a partial minimum (GSC2.3 N2JH066192), as shown in the upper and lower panels of Figure 18, respectively. Because we observed these minima just one time, without detecting any other evident variability in other data, we cannot estimate the

¹⁴ See <http://www.sai.msu.su/groups/cluster/gcvs/gcvs/>.

¹⁵ See <http://www.sai.msu.su/groups/cluster/gcvs/gcvs/nsv/>.

¹⁶ See <http://www.aavso.org/vsx/>.

¹⁷ See <http://www.astrouw.edu.pl/asas/?page=acvs>.

¹⁸ See <http://vizier.u-strasbg.fr/>.

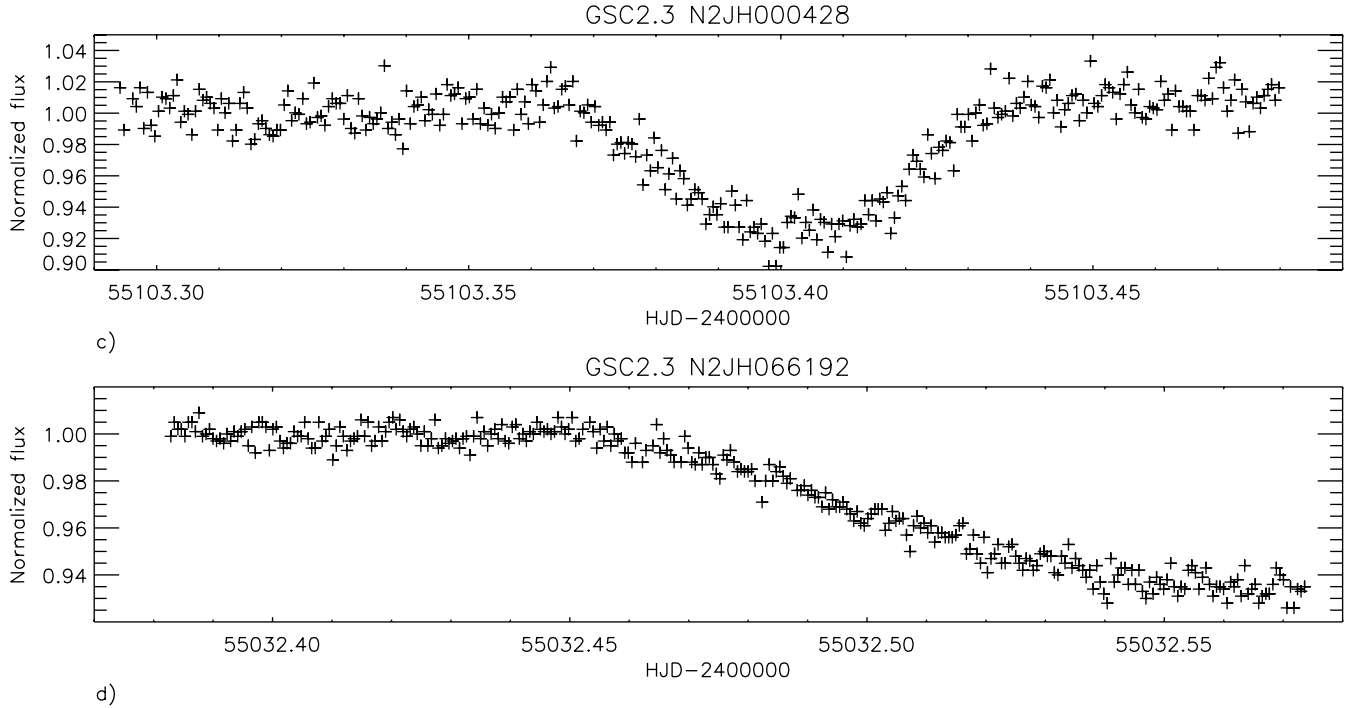


FIG. 18.—Light curves of the third and fourth objects in Table 2 (field of the star HAT-P-7) showing the occurrence of eclipses likely due (based on the observed depths) to a stellar companion. Both signals are seen only once in our data. The minimum in the upper panel was detected during an observing session aimed at gathering more data for the eclipsing binary system shown in the lower panel of Figure 17. In the upper and lower panels, there are 317 and 313 data points, respectively, taken over a single night.

orbital periods of the systems and we can only classify them generally as eclipsing binary stars.

5. CONCLUDING REMARKS

We have carried out a site characterization campaign at the Astronomical Observatory of the Autonomous Region of the Aosta Valley (OAVdA), in order to demonstrate that OAVdA can be the location for a long-term photometric survey with small telescopes aimed at detecting transiting rocky planets around nearby cool dwarf stars.

We focused the attention on those site-dependent factors that can have the largest impact on the ultimately achievable precision of the photometric measurements, such as seeing, extinction, and night-sky brightness. We then correlated them with the quality of the photometric measurements of selected target fields, monitored with 20–40 cm class telescopes available onsite, and analyzed using standard techniques of differential aperture photometry using an ad hoc developed data processing and analysis pipeline. Relevant data were collected in situ over a period of ~ 4 months and complemented by additional meteorological and photometric data sets covering a time span of > 3 years. The main findings of this study (partly presented already in Damasso et al. 2010a) can be summarized as follows:

1. The measured zenithal V -band night-sky brightness is typical of that of very good, very dark observing sites. The extinction registered at the V -band is not dissimilar from that of other sites (for the same season).

2. The median seeing over the period of in situ observations is found to be $\sim 1.7''$. Given the limited duration of the observations, we did not probe any possible seeing seasonal patterns or the details of its possible dependence on other meteorological parameters, such as wind speed and direction. Moreover, our data show that the seeing at the observatory was reasonably stable during most of the nights.

3. The fraction of fully clear nights per year amounts to 39%, while the total of useful nights increases to 57%, assuming a typical cloud cover of not more than 50% of the night. There are not yet enough statistics to determine a clear value for the fraction of photometric nights per year.

4. During 24 good observing nights over a period of over 3 months the median photometric precision was 0.006 mag for stars with magnitude $R \lesssim 13$ mag. The typical nightly photometric precision appears to be uncorrelated with the seeing, whose typical value (in principle, not competitive with other highly reputed observing sites around the world) turns out not to be a limiting factor for achievement of the photometric performance required for detection of planetary transits.

5. The observation of known transiting planets (in particular, those of WASP-3b and HAT-P-7b) allowed us to show that our differential aperture photometry approach applied to data collected with a small, 250 mm telescope achieves best-case rms precision of 0.002–0.003 mag for the brightest stars.

6. A by-product of the significant amount of photometric data collected in the stellar fields of WASP-3 and HAT-P-7 was the identification of a handful of new variable stars, four of which are presented and discussed here.

The results of the site testing campaign show conclusively that OAVdA is a suitable choice for hosting a long-term photometric survey for transiting planets around cool stars in the solar neighborhood. A preliminary step toward the definition of such a long-term photometric transit search program is the pilot study which we have begun earlier this year. We are devoting one of the 250 mm telescopes and the 400 mm instrument to the *I*-band photometric monitoring of ~ 50 M dwarfs, within ~ 25 pc from the Sun, with high-precision parallax estimates determined within the context of the Torino Parallax Program (Smart et al. 2007, 2010). This study, with a targeted duration of less than 1 yr, aims at obtaining uniform photometric monitoring of all targets (on the order of at least a few weeks of data per target), with the goal of providing benchmarks for the photometric microvariability characteristics of M dwarfs as a function of their spectral subtype (the stars in our sample span the range M0 through M9) in relation to other, primarily spectroscopic, activity indexes (e.g., based on H_{α} , Ca II lines emission). While the pilot study will likely not detect any planetary transits (given the limited number of objects in the target sample), the large photometric data set collected will help us place useful reference points for improved understanding of the impact on transiting planets' detectability of stellar activity-related phenomena (e.g., spot-induced rotational modulation) and the prospects for taking them into account via detailed modeling procedures.

In parallel to the science-driven activities of the pilot study, we are making progress in the reorganization of the scientific terrace for the purpose of hosting multiple identical 400 mm robotic telescope systems (at least five), with the start of the operations of the first pair being envisaged in connection with the end of the pilot study (fall 2010). The hardware and software requirements for the control system for data taking and storage have been clearly defined. Finally, as mentioned in § 3.3, necessary upgrades to the TEEPEE automated data reduction and analysis pipeline are being considered, in order to increase its functionality and robustness, ahead of the official start of our western Italian Alps photometric transit search for planets around M dwarfs.

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TWO NEW VARIABLE STARS OBSERVED IN THE FIELD OF THE EXTRASOLAR PLANET HOST STAR WASP-3

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Abstract: We report the discovery of two new short-period variable stars in the Lyra constellation, GSC2.3 N208000326 and GSC2.3 N20B000251, observed at the Astronomical Observatory of Autonomous Region of the Aosta Valley. Photometric measurements collected during several days are presented and discussed. One star appears to be a δ Scuti pulsating star ($P=0.07848018\pm0.00000006$ days; pulsation amplitudes $\Delta V\sim0.055$ mag and $\Delta R\sim0.045$; $(V-R)_{\text{average}}=0.378\pm0.009$, probable spectral type F2). The identity of the second star ($P=0.402714\pm0.000008$ days) resulted more difficult to be understood. We propose that this object should be classified as an eclipsing binary system where ~0.065 mag and ~0.055 are, respectively, the depths of the primary and secondary minimum in the light curve, as measured with a non standard R filter.

1 Introduction

Two new variable stars were observed at the Astronomical Observatory of the Autonomous Region of the Aosta Valley (OAVdA; 45.7895° N, 7.47833° E). The OAVdA is located at 1675 m above the sea level in the Italian Alps, close to the border with France and Switzerland. The discovery occurred during the ‘phase A’ of a photometric study aimed at establishing the potential of the OAVdA site to host a long-term photometric transit search for small-size ($R < R_{\text{Neptune}}$) extrasolar planets (Damasso et al., 2009). As a part of this feasibility study, during the period May-August 2009 and for a total of 19 nights we collected in- and out-of-transit light curves of the star WASP-3 in the Lyra constellation, known to host an extrasolar planet (Pollacco et al. 2007). These new variable stars represent an interesting by-product of our observations of the WASP-3 field.

2 Instrumentation and methodology

All observations were carried out with a 250 mm f/3.8 Maksutov reflector telescope mounting a CCD camera Moravian G2-3200ME with a camera sensor area of 2184×1472 square pixels (pixel linear dimension $6.8 \mu\text{m}$) and a quantum efficiency of $\sim 87\%$ at wavelength of 610 nm. This configuration results in a field of view of $52.10' \times 35.11'$ and a plate scale of 1.43 arcsec/pixel. All data were taken with an R filter (Astronomik) centered at the wavelength of 610 nm.

In order to collect standard photometric data for the two new variable stars, follow-up observations were conducted using:

- the OAVdA largest optical telescope, an 810 mm f/7.9 Ritchey-Chrétien reflector equipped with a Finger Lakes Instrumentation Pro Line PL 3041-BB back illuminated CCD camera with standard BVRI filters. The camera sensor area is 2048×2048 square pixels (pixel linear dimension $15 \mu\text{m}$), resulting in a field of view of $16.3' \times 16.3'$, with a plate scale of 1 arcsec/pixel in binning 2×2 .
- a 400 mm f/7.64 Ritchey-Chrétien reflector telescope, mounting a front illuminated CCD camera Finger Lakes Instrumentation Pro Line PL1001E with sensor KAF1001E and standard BVRI filters. The camera sensor area is 1024×1024 square

pixels (pixel linear dimension 24 μ m). The field of view is 26.4' x 26.4' with a plate scale of 1.55 arcsec/pixel.

To calibrate the V and R magnitudes we used the method described by **Dymock and Miles, 2009** and magnitudes reported in the CMC14 (r' magnitude) and 2MASS catalogues (J and K magnitudes).

The data were reduced and elaborated with the automatic pipeline TEEPEE (Transiting Exoplanet PipElinE) that we have developed and tested as a part of our photometric study focused on transiting extrasolar planets. TEEPEE performs image calibration (dark and flat-fielding corrections, rotation and translation to the same pixel grid using a reference image), airmass corrections (using an extinction coefficient averaged over typically dozens of stars) and ensemble differential aperture photometry, using typically up to 100 reference objects (depending on the target field) with apparent magnitudes close to the target magnitude.

To confirm that these variables are really a new discovery, we searched through several sources: the General Catalogue of Variable Stars (GCVS, <http://www.sai.msu.su/groups/cluster/gcvs/gcvs/>), the New Catalogue of Suspected Variable Stars (<http://www.sai.msu.su/groups/cluster/gcvs/gcvs/nsv/>) and in VizieR database (<http://vizier.u-strasbg.fr/>). Moreover, we also searched through the lists of new periodic variable stars reported by the team of the SuperWASP project (**Street et al., 2006; Norton et al., 2008**).

We adopted **Sterken and Jaschek (1996)**, **Breger (2000)** and **Percy (2007)** as the main references to suggest a classification for the new variable stars we observed.

3 Results and discussion on the individual objects

In Table 1 we summarize the positions, variability periods and amplitudes for both stars, and in Table 2 we list the CMC14 stars we used for calibrating the V and R magnitudes. The finding charts showing these stars are presented in Fig. 2 (1st variable) and Fig. 7 (2nd variable).

3.1 Star #1 - GSC2.3 N208000326

In Fig. 1 we reproduce a finding chart for this object. This star is not reported as a variable star in any of the catalogues we looked up. Figure 3 shows the phase-folded light curve for this star (normalized flux) obtained using a pulsation period of $0.07848018 \pm 0.00000006$ days, estimated with the Lomb-Scargle algorithm implemented in the Starlink-PERIOD package (**Dhillon et al., 2001**). The data presented here refer to 5 observing nights in the period second half of July to second half of September 2009 and were collected with the 250 mm telescope and R non standard filter. The error bars correspond to 1σ . In Fig. 4 the R and V calibrated light curves are showed, obtained with the 810 mm telescope during the follow-up measurements of the night 28-29 September 2009. The plots show that the pulsation amplitudes are ~ 0.055 mag in V and ~ 0.045 mag in R. Figure 5 shows the variation of the V-R index recorded during the same night, with an average value $(V-R)_{\text{average}} = 0.378 \pm 0.009$. The temporal variation appears to be in phase with V and R, strengthening the hypothesis that we are in front of a pulsating star. To correct this value for the interstellar reddening, we used the galactic dust reddening and extinction maps available on the Web at <http://irsa.ipac.caltech.edu/applications/DUST/> (the NASA/ IPAC Infrared Science Archive, or IRSA) which are derived from data and techniques described in **Schlegel, Finkbeiner & Davis (1998)**. At the star location (galactic coordinates $l=63.5919^\circ$ and $b=+18.4108^\circ$) the

V and R corrections are respectively $A_V=0.205$ and $A_R=0.174$ magnitudes (they represent integrated value along the line of sight) corresponding to a V-R color excess $E(V-R)=0.031$. This leads to the de-reddened estimate for the index color $(V-R)_{\text{average}}=0.347\pm0.009$, which is typical of a F2 type main sequence star, as reported in **Zombek (1990)**. Considering the shape of the light curve, the values found for the pulsation period, magnitude variations and V-R index, we suggest that this star can be classified as a δ Scuti variable.

We can then estimate the mean absolute visual magnitude of the star using the Period-Luminosity relation determined by **Poretti et al. (2008)**, which does not depend on the knowledge of the star metallicity:

$$M_V = -3.65(\pm0.07)\log(P) - 1.83(\pm0.08)$$

where P is given in days. We get $M_V = +2.20\pm0.11$.

The mean apparent V magnitude ($V=12.625\pm0.005$ from our measurements) can be corrected for the interstellar extinction using two different models of the galactic dust distribution, which lead to two independent estimates for the star distance. Using the analytic expression in **Arenou et al. (1992)**, we assume for the interstellar extinction $A_V = 0.111$ mag (integrated along the line of sight) as estimated for a star with galactic coordinates $l = 63.5919^\circ$ and $b = +18.4108^\circ$. The maximum distance of the star results $\sim 1153\pm26$ pc (~ 3761 l.y.).

Using the IRSA galactic dust reddening and extinction maps we found $A_V = 0.205$ mag for the integrated galactic extinction along the line of sight at the star location. This leads to a second, independent maximum star distance of $\sim 1104\pm25$ pc (~ 3600 l.y.).

Taking the average value of the two independent results, we then can assume $d=1128.5\pm36$ pc as the better estimate for the maximum distance of the star.

3.2 Star #2 - GSC2.3 N20B000251

The finding chart containing the second variable star is showed in Figure 6. We did not find in the literature any indication about the variability of this object. This target was observed on the 250 mm telescope (and the Astronomik non standard R filter) for 9 nights in the period June-July 2009. After the first inspection of the star light curve for the whole observing period, the object showed what appeared a pulsation period of ~ 0.2 days (obtained applying the Lomb-Scargle algorithm in the PERIOD package) and a magnitude amplitude of ~ 0.03 mag. These results in principle could indicate that the star is another δ Scuti. We then measured V and R magnitudes on 14th October 2009 with the 400 mm telescope obtaining an average V-R index $(V-R)_{\text{average}}=0.55\pm0.01$, corresponding to a fraction of the estimated period (~ 2 hr). The variations of the V-R index observed during that night is showed in Fig. 8. Then we corrected this value for the effects of the galactic dust using the IRSA maps (galactic coordinates of the target: $l=64.4724^\circ$ and $b=+18.5112^\circ$), and we assumed a color excess $E(V-R)=0.03\pm0.01$. If the target were an isolated main sequence star, our best estimate of the V-R index is indicative of a G-type star (**Zombek, 1990**). As δ Scuti are A-F spectral type stars, we were forced to reconsider our hypothesis on the real nature of this variable.

We reorganized the data using $P=0.402714\pm0.000008$ days as the variability period, which is double of the value we initially adopted. In Fig. 9 we show the corresponding normalized phase-folded light curve. The error bars correspond to 1σ . From the plot it results clear that, using the new period, the object shows two distinct minima which differ only for ~ 0.01 mag, while the maxima differs slightly in shape and has similar values. This clearly reveals that the object is a binary system. To note that the light curve did not show evident variations in its shape during the two-months period of our observations.

Only on the base of our photometric data some doubts necessarily remain regarding the precise identity of the system, and we considered here two plausible alternatives.

The object could be a short-period non eclipsing binary system showing the properties typical of an ellipsoidal variable (ELL variable star according the GCVS classification). In this case, the small changes in the luminosity are due to the so called gravity darkening induced by gravitational tidal distortion induced by the presence of a much less luminous compact object as companion, which does not contribute to the observed radiative flux (**e.g. Beech, 1985**). Besides, the system has a measured orbital period which falls in the range showed by cataclysmic variables, close to the upper limit (**e.g. Percy, 2007**).

The second possibility is that the object is a short-period, grazing eclipsing binary system where the primary and secondary stars could be assumed to be main sequence stars of different spectral type.

Our opinion is that the latter hypothesis is much more reliable and it is based on the following clues. In Table 3 we report the V, J, H and K magnitudes for this object as given by the GSC2.3 and 2MASS catalogues. The V-K color index for this target is higher than expected for a G-type star, while it is typical of a late K-type star (**Zombek, 1990**). If we are observing an elongated star orbiting a compact object, the information we get from the V-R and V-K color indexes, concerning the spectral type of the secondary star, is difficult to explain in terms of just a difference in temperature between the hotter emisphere that points towards the primary star (which is supposed to be colder) and the opposite. In this case, we should observe a redder object (K-type) when the secondary star shows us the colder emisphere, and it should appear as a G-type when it is in inferior conjunction. We did not find in literature examples of secondary stars in close binary systems which show ellipsoidal variations associated with their filled Roche lobe and which are characterized by an excursion in their spectral type as wide as the one observed for our target.

We believe that the simplest and probably true scenario is assuming the system composed of two normal stars, one that is cooler and brighter in red/near-infrared bands -then determining the observed high value for the V-K index- while the hotter companion is brigther at shorter wavelenghts, producing a V-R index shifted towards an upper spectral class.

As a further check to support our interpretation, we also looked up the HEASARC catalogue (<http://heasarc.gsfc.nasa.gov/>, a very extended Web-based archive for gamma-ray, X-ray, and extreme ultraviolet observations of cosmic sources) for a possible X-ray counterpart of the target, giving hints of the presence in the binary system of a compact object and of an exchange of matter with the secondary star, the donor companion. We did not find any source at the variable star location which is associated to high-energy emissions. This evidence is in favour of our proposed scenario.

Because we do not have any spectroscopic information on the object, we can not guess anything more about the real nature of the stellar members of the system. Therefore we will not go further in our discussion.

4 Conclusions

We reported the discovery of two new short-period variable stars in the Lyra constellation. They represent interesting by-products of a campaign finalized to the observation of extrasolar planets with the photometric transit method.

The objects were monitored for several days in order to better characterize them photometrically and to guess the properties of their variability. According to our results, we suggest that one star can be classified as a δ Scuti variable with asymmetric light curve (for which we estimated the maximum heliocentric distance: $d=1128.5\pm36$ pc). The second object should be classified as a detached eclipsing binary system but spectroscopic data are necessary to definitively confirm this hypothesis.

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We thank Ennio Poretti (INAF-Osservatorio Astronomico di Brera) for the help in understanding the nature of the second object discussed in this paper.

Table 1. Summary of the main data for the two new variable stars.

Star number	Catalogue IDs	Coordinates (J2000, GSC2.3 Catalogue)	Period (days)	Magnitude at max. brightness	Magnitude at min. brightness	Suggested variability type (according the GCVS)
1	GSC2.3 N208000326 (also CMC14 183429.5+350424 ; 2MASS 18342951+3504242)	(α) 18:34:29.51 (δ) +35:04:24.3	0.07848018 $\pm$ 0.00000006	12.57 $\pm$ 0.005 (Johnson-Cousins V) 12.20 $\pm$ 0.005 (Johnson-Cousins R)	12.68 $\pm$ 0.005 (Johnson-Cousins V) 12.29 $\pm$ 0.005 (Johnson-Cousins R)	DSCT with asymmetric light curve
2	GSC2.3 N20B000251 (also CMC14 183528.6+355325 ; 2MASS 18352859+3553255)	(α) 18:35:28.62 (δ) +35:53:25.3	0.402714 $\pm$ 0.000008	13.69 $\pm$ 0.01 (Johnson-Cousins V) 13.15 $\pm$ 0.01 (Johnson-Cousins R)	Not available	E

Table 2. Data of the field stars used to calibrate the V and R magnitudes of the new variable stars, according to the procedure described by *Dymock and Miles, 2009*.

Variable star number	Catalogue ID for the field star	Coordinates (J2000, CMC14 Catalogue)	r' mag (CMC14)	J-K index (CMC14)
1	CMC14 183449.4+351240	(α) 18:34:49.477 (δ) +35:12:40.75	11.69	0.631
	CMC14 183428.4+350219	(α) 18:34:28.435 (δ) +35:02:19.81	12.434	0.317
	CMC14 183402.0+350401	(α) 18:34:02.082 (δ) +35:04:01.54	12.621	0.367
	CMC14 183451.4+350941	(α) 18:34:51.494 (δ) +35:09:41.13	12.705	0.556
2	CMC14 183527.7+354601	(α) 18:35:27.794 (δ) +35:46:01.46	12.277	0.68
	CMC14 183550.1+354546	(α) 18:35:50.114 (δ) +35:45:46.56	12.704	0.331
	CMC14 183558.2+354717	(α) 18:35:58.238 (δ) +35:47:17.85	13.585	0.687
	CMC14 183532.9+354927	(α) 18:35:32.926 (δ) +35:49:27.39	13.35	0.394

Table 3. Photometric data of the second variable star as given by the GSC2.3 (V magnitude) and 2MASS (J, H, and K magnitudes) catalogues.

V ^a	J	H	K	V-K ^a
13.57±0.36	11.870±0.021	11.358±0.029	11.274±0.025	2.296±0.360

^a According our calibrated magnitudes, limited to ~2 hr of observations, we can assume $V=13.73\pm0.01$ as the better estimate for the average V magnitude. This is in accordance with the value reported in the GSC2.3 catalogue. If we assume our observed value for V and a color excess $E(V-K)=0.158$ as estimated using the IRSA galactic dust maps, the V-K color index results to be 2.298 ± 0.027 , in agreement with the value reported in this Table.

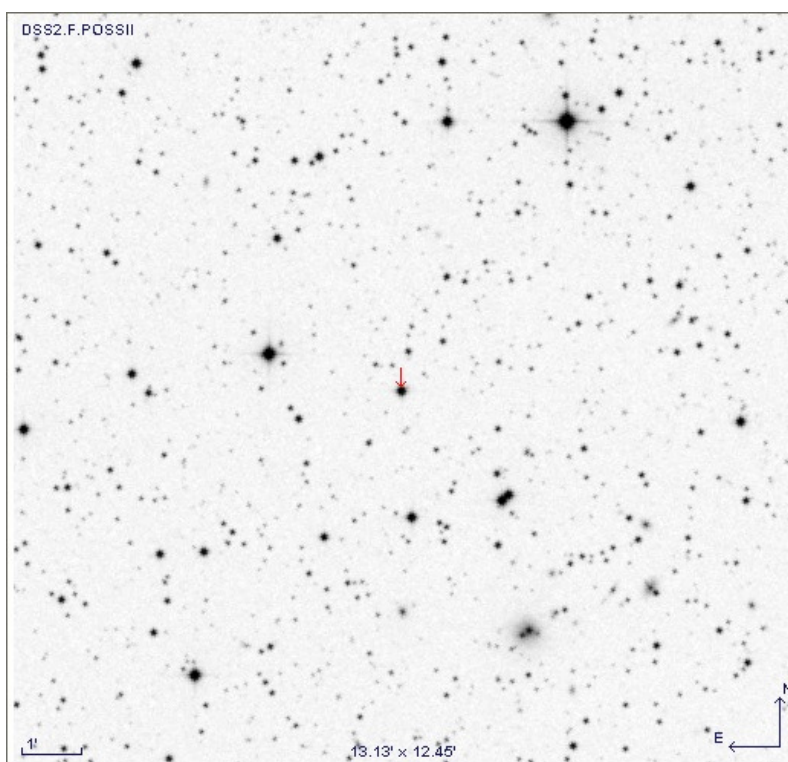


Fig. 1. Image from the ESO Digitized Sky Survey database showing the star field of the variable star GSC2.3 N208000326, which is indicated by a red arrow.

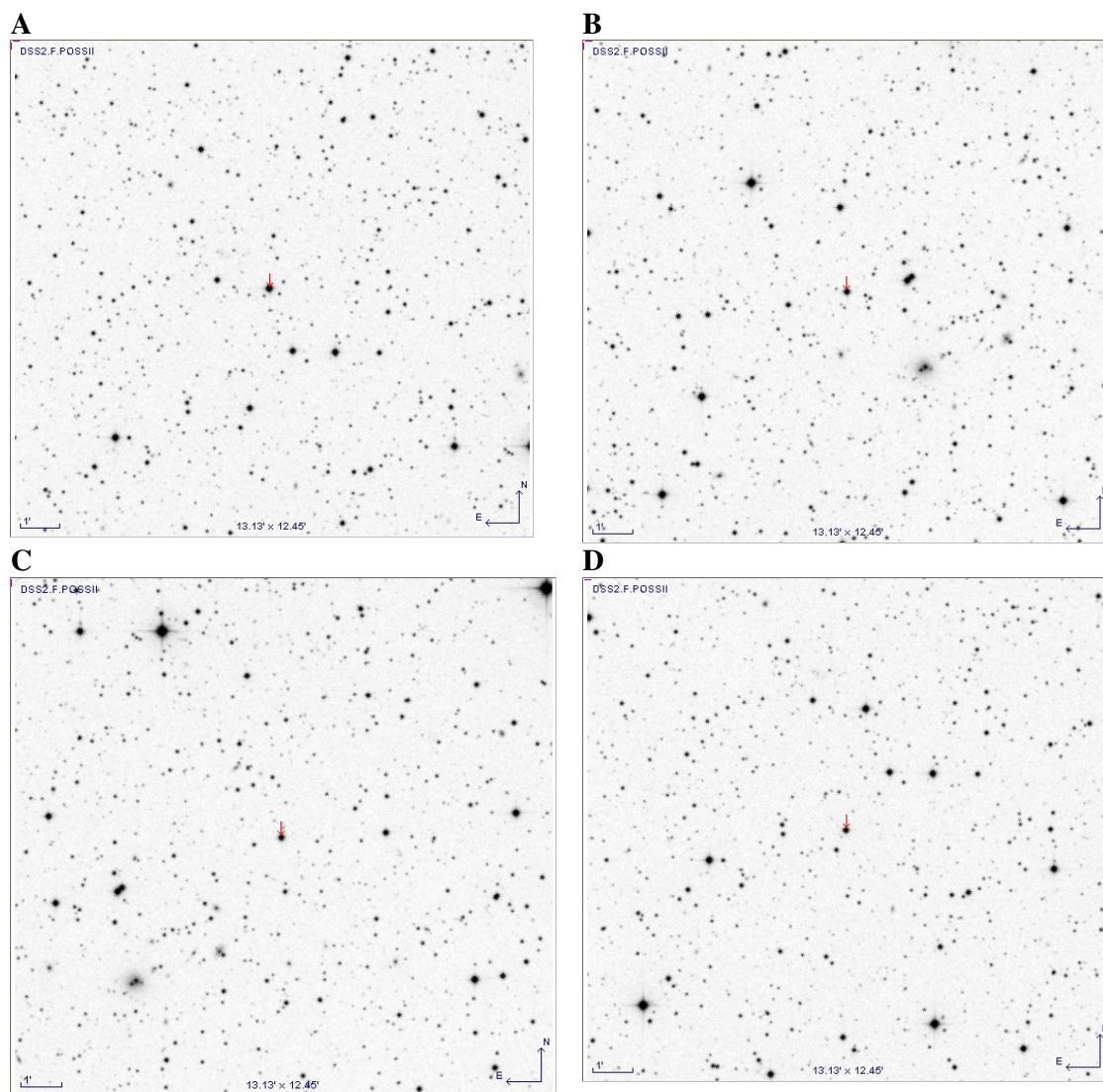


Fig. 2. Finding charts showing the field stars used to calibrate the V and R magnitudes of the first variable star (indicated by a red arrow at the center of each image), as listed in Table 2. A: CMC14 183449.4+351240; B: CMC14 183428.4+350219; C: CMC14 183402.0+350401; D: CMC14 183451.4+350941.

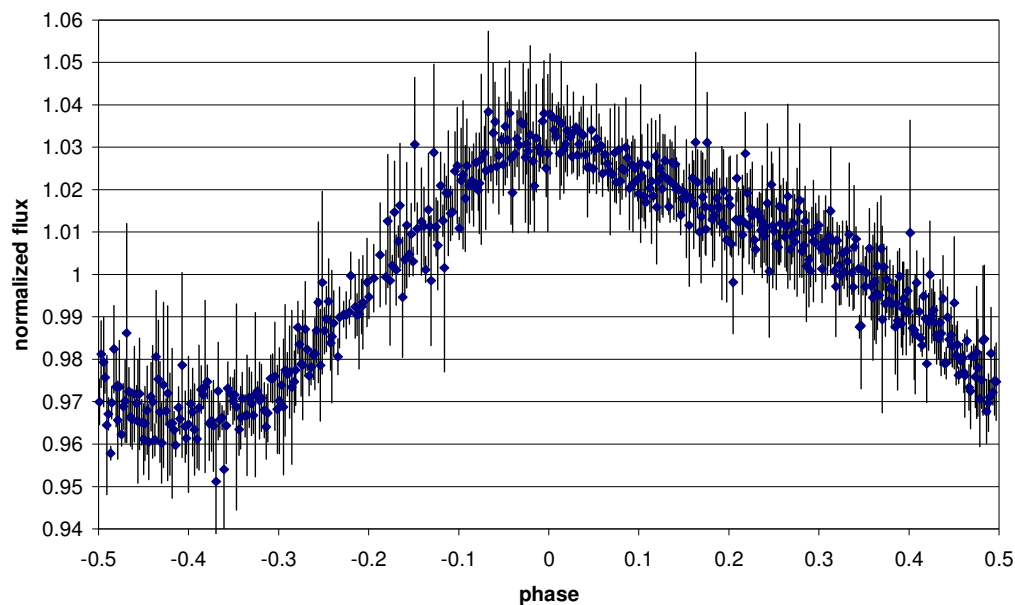


Fig. 3. Normalized phase folded light curve of the variable star GSC2.3 N208000326, obtained using $P=0.07848018 \pm 0.00000006$ days as the better estimate for the fundamental pulsation period (phase=0 corresponds to ephemeris $HJD=2455103.3939+P \cdot E$). The asymmetric shape of the light curve is clearly visible.

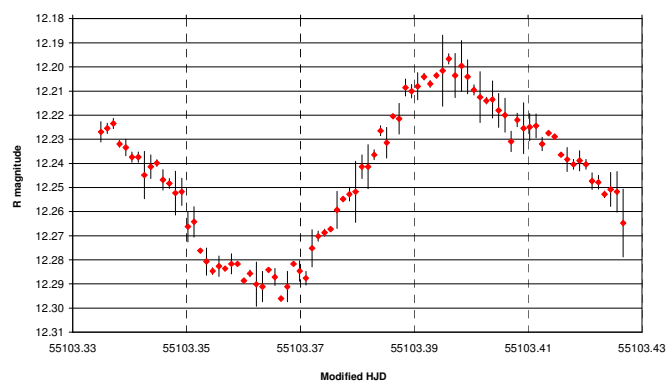
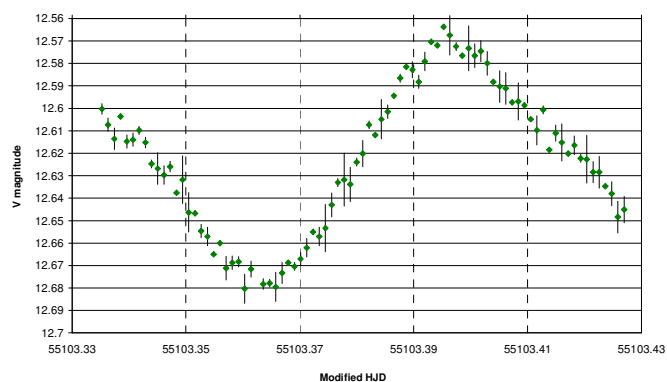


Fig. 4. V and R calibrated light curves of the pulsating star GSC2.3 N208000326 obtained during the night 28-29 September 2009, when the object was monitored with the 810 mm telescope.

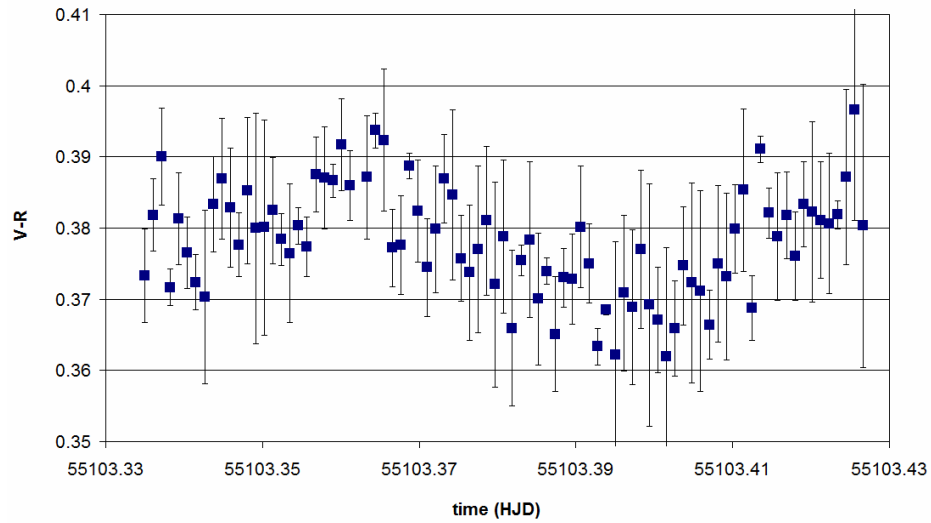


Fig. 5. Variation of the color index $V-R$ observed for the star GSC2.3 N208000326 during the night 28-29 September 2009.

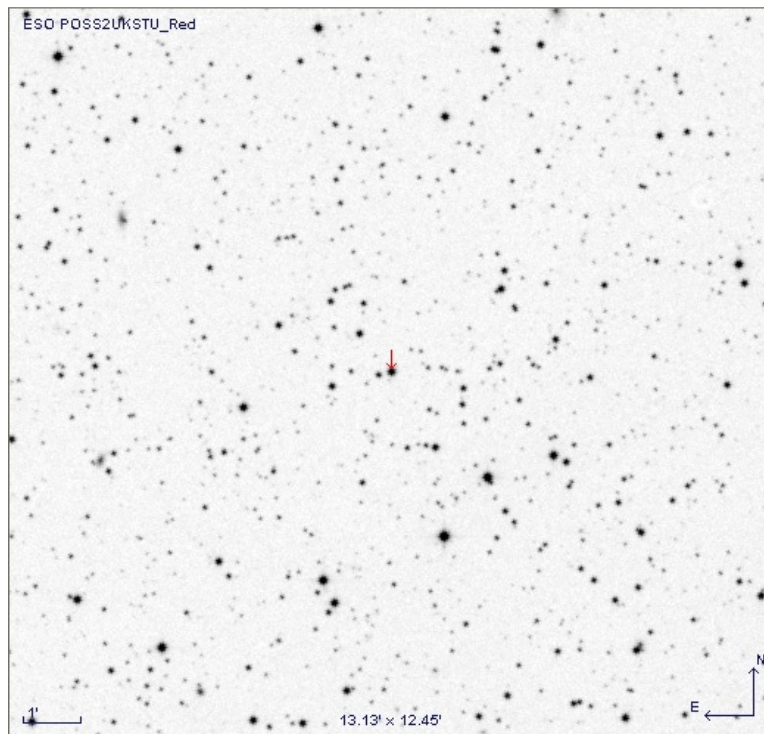


Fig. 6. Image from the ESO Digitized Sky Survey database showing the star field of the variable star GSC2.3 N20B000251, which is indicated by a red arrow.

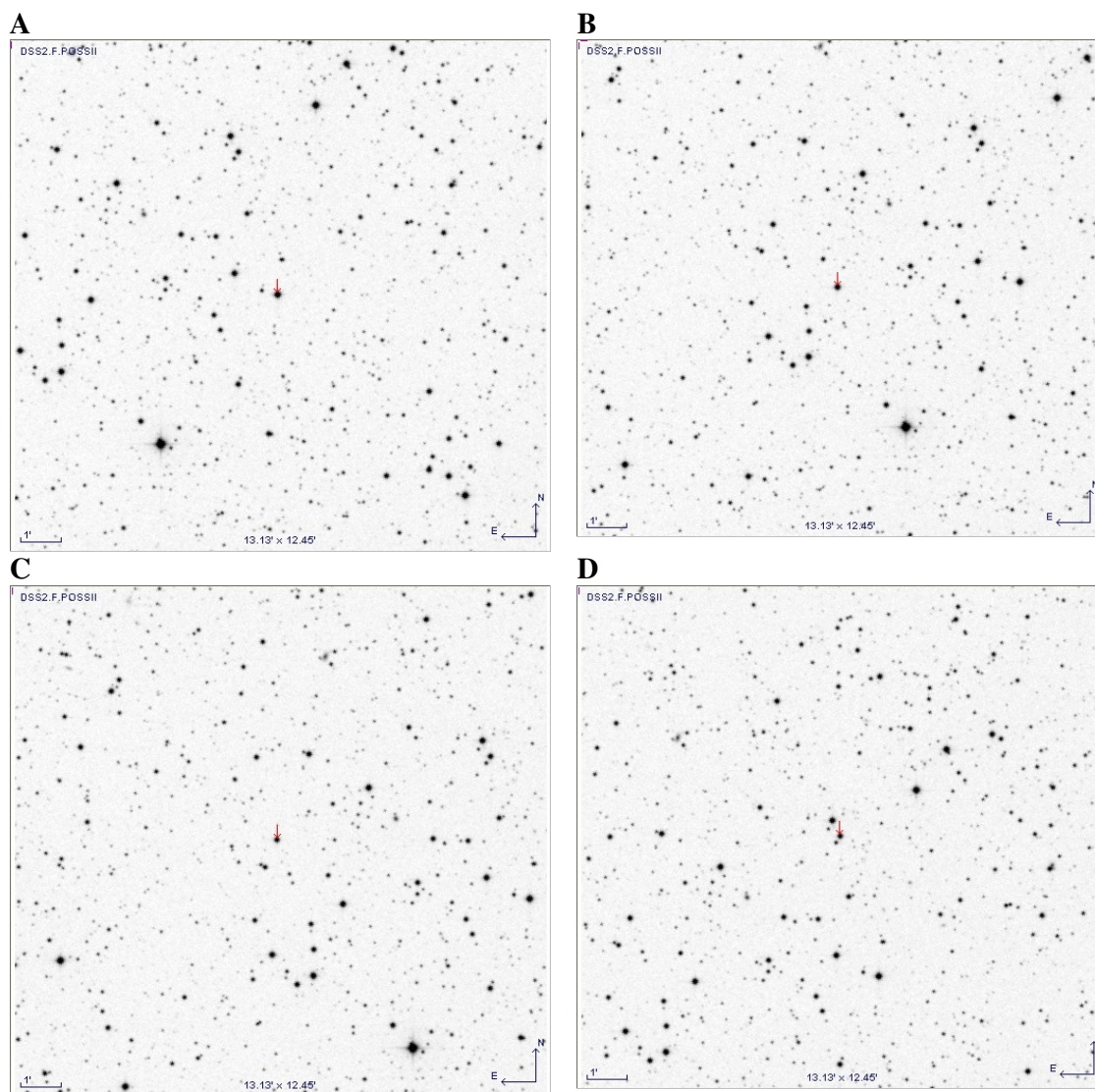


Fig. 7. Finding charts showing the field stars used to calibrate the V and R magnitudes of the second variable star (indicated by a red arrow at the center of each image), as listed in Table 2. A: CMC14 183527.7+354601; B: CMC14 183550.1+354546; C: CMC14 183558.2+354717; D: CMC14 183532.9+354927.

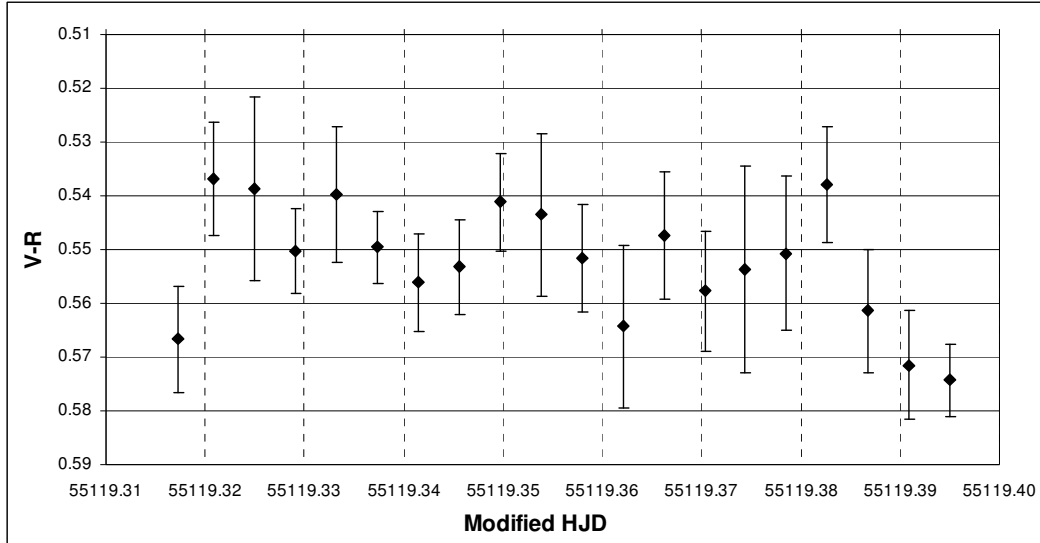


Fig. 8. Variation of the color index $V-R$ observed for the star GSC2.3 N2B000251 during the night 14-15 October 2009.

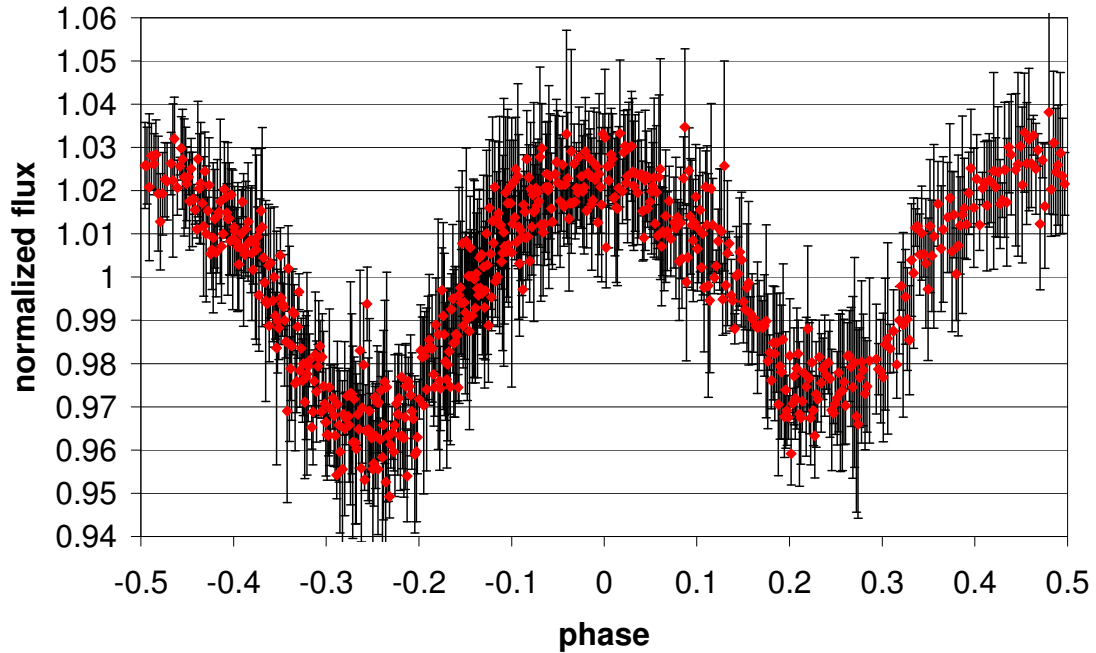


Fig. 9. Normalized phase-folded light curve of the variable star GSC2.3 N2B000251, obtained using $P = 0.402714 \pm 0.000008$ days as the better estimate for the orbital period of the target (phase=0 corresponds to ephemeris $HJD = 2454994.501335 + P \cdot E$).

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Chapter 2

A step toward the totem: the pilot study

As a fundamental step to “sharp the saw” for the upcoming longterm survey, at the end of 2009 the APACHE Team started a pilot study using the existing instrumentation in OAVdA. For more than one year, 23 M dwarfs with well determined parallaxes have been observed and their light curves have been studied for characterizing some astrophysical properties and to evaluate, via simulations, the sensitivity to the detection of transit signals of different depths and periods of up to 5 days. In particular, we wished to determine an estimate a relation between the transit detection probabilities and the phase coverage, to be used during the APACHE operations as a part of the observing strategy. Far from being a sort of short term version of the APACHE survey (different instruments were used, no automatic control system of the telescopes was still available), the pilot study indeed served as a useful training to define the main details of the survey design for the first season. In particular, an improved version of the pipeline TEEPEE for the reduction and analysis of the data was developed and represented the starting point for the more complex software tools used in the final survey. The results of the pilot study have been published [[Giacobbe et al., 2012](#)]. This paper is attached at the end of this Chapter and forms an integral part of the Thesis. As for the feasibility study, I have contributed to this work in several ways. In particular, I have been greatly involved in the setup of the instrumentation and in most of the observing nights. Concerning the software development, I have been responsible with another colleague of the improvement of the TEEPEE pipeline used for the pilot study. Finally, I focused my interest and efforts on the astrophysical characterization of the light curves of the monitored M dwarfs (rotational modulation, flares, application of a first version of

single-spot model coupled to the spectroscopic determination of the projected stellar velocities $v \sin i$). During the pilot study several new variable stars were found and published [Damasso et al., 2011]. Also this paper is attached at the end of this Chapter and forms an integral part of the Thesis. Once the pilot study was over, during the commissioning phase of the first telescope of the APACHE array we discovered an eclipsing binary with a very short period ($P \sim 0.238$ days). We considered that this system deserved a more detailed study and we followed it up using the 81 cm telescope in OAVdA. Moreover, in collaboration with colleagues of the Dept. of Physics and Astronomy of the University of Padova we took low-resolution spectra during the epoch of one of the light curve maxima using the 182 cm telescope at the Asiago Astrophysical Observatory. The results of this study have been published in 2012 [Damasso et al., 2012], and the paper is attached at the end of this Chapter.

Photometric transit search for planets around cool stars from the western Italian Alps: a pilot study

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ABSTRACT

We present the results of a year-long photometric monitoring campaign of a sample of 23 nearby ($d < 60$ pc), bright ($J < 12$) dM stars carried out at the Astronomical Observatory of the Autonomous Region of the Aosta Valley, in the western Italian Alps. This programme represents a ‘pilot study’ for a long-term photometric transit search for planets around a large sample of nearby M dwarfs, due to start with an array of identical 40-cm class telescopes by the Spring of 2012. In this study, we set out to (i) demonstrate the sensitivity to $< 4 R_{\oplus}$ transiting planets with periods of a few days around our programme stars, through a two-fold approach that combines a characterization of the statistical noise properties of our photometry with the determination of transit detection probabilities via simulations; and (ii) where possible, improve our knowledge of some astrophysical properties (e.g. activity, rotation) of our targets by combining spectroscopic information and our differential photometric measurements. We achieve a typical nightly root mean square (RMS) photometric precision of ~ 5 mmag, with little or no dependence on the instrumentation used or on the details of the adopted methods for differential photometry. The presence of correlated (red) noise in our data degrades the precision by a factor of ~ 1.3 with respect to a pure white noise regime. Based on a detailed stellar variability analysis (i) we detected no transit-like events (an expected result, given the sample size); (ii) we determined photometric rotation periods of ~ 0.47 and ~ 0.22 d for LHS 3445 and GJ 1167A, respectively; (iii) these values agree with the large projected rotational velocities (~ 25 and ~ 33 km s⁻¹, respectively) inferred for both stars based on the analysis of archival spectra; (iv) the estimated inclinations of the stellar rotation axes for LHS 3445 and GJ 1167A are consistent with those derived using a simple spot model; and (v) short-term, low-amplitude flaring events were recorded for LHS 3445 and LHS 2686. Finally, based on simulations of transit signals of given period and amplitude injected in the actual (nightly reduced) photometric data for our sample, we derive a relationship between transit detection probability and phase coverage. We find that, using the Box-fitting Least Squares search algorithm, even when the phase coverage approaches 100 per cent, there is a limit to the detection probability of ~ 90 per cent. Around programme stars with phase coverage > 50 per cent, we would have had > 80 per cent chances of detecting planets with $P < 1$ d inducing fractional transit depths > 0.5 per cent, corresponding to minimum detectable radii in the range ~ 1.0 – $2.2 R_{\oplus}$. These findings are illustrative of our high readiness level ahead of the main survey start.

Key words: techniques: photometric – stars: activity – stars: individual: GJ 1167A, LHS 2686, LHS 3445 – stars: low-mass – planetary systems – starspots.

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1 INTRODUCTION

M dwarf stars, with masses $M_* \leq 0.6 M_\odot$, make up a vast majority of the reservoir of nearby stars within $\sim 25\text{--}30$ pc. These stars have not traditionally been included in large numbers in the target lists of radial velocity (RV) searches for planets for two main reasons: (i) their intrinsic faintness, which prevented Doppler surveys in the optical from achieving very high RV precision ($< 5\text{--}10$ m s $^{-1}$) for large samples of M dwarfs (e.g. Eggenberger & Udry 2010, and references therein); and (ii) their being considered as providers of very inhospitable environments for potentially habitable planets (e.g. Scalo et al. 2007, and references therein; Tarter et al. 2007). These two paradigms are now shifting. First, the application of the transit technique to M dwarfs presents several exciting opportunities, and the advantages are especially compelling for the detection of transiting habitable, rocky planets. These include, for example, improved observing windows due to the short periods of potential planets in the stellar habitable zone (the range of distances from a given star for which water could be found in liquid form on a planetary surface, see e.g. Kasting, Whitmire & Reynolds 1993), or the possibility to reach detection of rocky planets due to the small radii of M dwarfs, leading to deep transits ($\Delta\text{mag} \sim 0.005$ mag) easily detectable from the ground with modest size telescopes (30–50 cm class), and readily confirmable with present-day precision RV measurements (owing to their moderately large RV amplitudes, of the order of $5\text{--}10$ m s $^{-1}$). Secondly, while not all concerns about their habitability have been resolved yet, there has been a recent change in view for planets orbiting low-mass M stars, now often considered as potentially hospitable worlds for life and its remote detection (e.g. Seager & Deming 2010; Barnes, Jeffers & Jones 2011, and references therein).

Advancements in our knowledge of the complex processes of planet formation and evolution cannot be achieved without a detailed understanding of the role of the central star (through its properties such as mass and metal abundance) and its environment (the circumstellar disc within which the planetary population must form). For example, the theoretical expectations (within the framework of the standard core accretion model) that giant planet frequency and upper mass limits ought to be direct functions of stellar mass M_* and metallicity [Fe/H] (e.g. Ida & Lin 2004, 2005; Laughlin, Bodenheimer & Adams 2004; Kennedy & Kenyon 2008; Mordasini et al. 2009) have so far been confirmed on relatively firm statistical grounds only for stars (mid-F through mid-K type) with masses close to that of the Sun (Santos, Israelian & Mayor 2004; Fischer & Valenti 2005; Johnson et al. 2007; Sozzetti et al. 2009), while results for stars with masses significantly different from that of the Sun still rely on small-number statistics (e.g. Endl et al. 2006; Bonfils et al. 2007; Johnson et al. 2010, 2011, 2012). Similarly, the statistical significance of the early evidence for a relatively high frequency of low-mass planets (Neptunes and super-Earths) around low-mass stars (e.g. Forveille et al. 2011, and references therein) is still hampered by the observational bias intrinsic to long-term RV surveys (only a few hundred objects monitored), and the recent, compelling evidence from *Kepler* photometry (e.g. Howard et al. 2011) of increasing occurrence rates for small-radius, short-period planets around increasingly cooler stars still suffers from small-number statistics at the latest spectral types (only a few hundred of relatively bright M0–M1 dwarfs being included in the *Kepler* catalogue). Finally, the anticipated wild diversity of the structural and atmospheric properties of super-Earths (Seager & Deming 2010, and references therein) can be most easily investigated using a sample of such planets observed as transiting

companions to nearby M dwarf primaries, given that for low-mass stars the planet-to-star flux ratio is much larger than that for the Earth–Sun system¹; thus, spectral characterization of the planet via, for example, occultation spectroscopy is much more readily attainable.

These considerations have brought about renewed efforts to monitor photometrically as well as spectroscopically large samples of nearby cool dwarfs. The first spectacular success of the dedicated MEarth transit search for rocky planets around 2000 late M dwarfs was announced by Charbonneau et al. (2009), with the detection of the low-density transiting super-Earth GJ 1214b ($M_p = 6.5 M_\oplus$, $R_p = 2.7 R_\oplus$) around a nearby M4.5 dwarf. The primary in this system is bright enough to enable detailed spectroscopic characterization of the planet’s thick atmosphere over a broad wavelength range (Bean, Miller-Ricci Kempton & Homeier 2010; Bean et al. 2011; Croll et al. 2011; Crossfield, Barman & Hansen 2011). The recent constraints on GJ 1214b’s atmospheric composition are not only essential for breaking the degeneracy between the mass, radius and composition of both the interior and a possible atmosphere in theoretical models of super-Earths (Adams, Seager & Elkins-Tanton 2008; Miller-Ricci Kempton & Fortney 2010; Rogers & Seager 2010; Désert et al. 2011; Menou 2012; Miller-Ricci Kempton, Zahnle & Fortney 2011; Nettelmann et al. 2011), but also constitute a remarkable test of planetary evolution models in a mass range (for both the primary and the planet!) not seen in our Solar system. Very recently, the M2K Doppler search for close-in planets around 1600 nearby M and K dwarfs has also started producing its first results (e.g. Apps et al. 2010). Decade-long Doppler monitoring has also allowed to detect the first Saturn-mass planet in the habitable zone of a nearby mid-M dwarf (Haghighipour et al. 2010). The early-M dwarf GJ 581, already hosting a system of four low-mass (Neptunes and super-Earths) planets, is currently the focus of a hot debate on the actual existence of a fifth planet with the mass of a super-Earth orbiting right in the middle of the habitable zone (Vogt et al. 2010; Gregory 2011; Pepe et al. 2011; Tuomi 2011). There is a growing consensus among the astronomers’ community that the first habitable rocky planet will be discovered (and might have been discovered already!) around a red M dwarf in the backyard of our Solar system.

However, not all physical properties of low-mass stars are known precisely enough for the purpose of the detection and characterization of small-radius planets. Worse still, some of the characteristics intrinsic to late-type dwarfs can constitute a significant source of confusion in the interpretation in planet detection and characterization measurements across a range of techniques. First of all, there exist discrepancies between theory and observations in the determination of the sizes of M dwarfs, typically of the order of 10–15 per cent (Ribas 2006; Beatty et al. 2007; Charbonneau et al. 2009, and references therein). It has been suggested that these problems might be stemming from the lack of a detailed treatment of the effects of non-zero magnetic fields on the properties of low-mass, fully convective stars (Ribas 2006; López-Morales 2007; Torres, Andersen & Giménez 2010, and references therein). As a result, the inferred composition of a transiting planet detected around an M dwarf might be subject to rather large uncertainties, particularly when it comes

¹ For example, in the Rayleigh–Jeans limit, this flux ratio depends on the relative surface areas and brightness temperatures of the planet and star. For a $2\text{-}M_\oplus$ super-Earth, this ratio is in the range 0.01–0.11 per cent for a mid- to late-M dwarf primary (M4V–M8V), compared to 0.00044 per cent for the Earth–Sun system.

to super-Earths, for which, as mentioned above, degeneracies in the models of their physical structure indicate a wide range of possible compositions for similar masses and radii (Seager & Deming 2010, and references therein). Indeed, for the two known transiting planets around M dwarfs, GJ 436b and GJ 1214b, uncertainties in the planetary parameters are dominated by the limits in the knowledge of the stellar parameters.

Secondly, there are at present difficulties in spectroscopically determining with a high degree of precision M dwarf metallicities² (Bean et al. 2006; Woolf & Wallerstein 2006; Woolf, Lépine & Wallerstein 2009; Rojas-Ayala et al. 2010), which are only partially mitigated by recent attempts at deriving photometric calibrations (Bonfils et al. 2005; Casagrande, Flynn & Bessell 2008; Johnson & Apps 2009; Schlafman & Laughlin 2010). In addition, studies of the rotation–activity relation³ for M dwarfs using large stellar samples are limited to young and active stellar samples (e.g. Shkolnik, Liu & Reid 2009; López-Santiago et al. 2010, and references therein), often in young open clusters (e.g. Hartman et al. 2009, and references therein; Meibom, Mathieu & Stassun 2009), while our understanding of the rotation–activity connection for M dwarfs with age greater than $t \sim 0.5$ Gyr (e.g. Pizzolato et al. 2003; Reiners 2007; Jenkins et al. 2009; West & Basri 2009) is still subject to rather large uncertainties due to the sparseness of the data. All these issues hamper at present the possibility of determining precisely the ages of (particularly mid and late) M dwarfs in the field, and this in turn has a significant impact on the calibration of the fundamental evolutionary properties of the planets they might be hosting.

Thirdly, as measurements of chromospheric activity indicators (H α line) have shown how the fraction of active M dwarfs increases as a function of spectral subtype (e.g. Bochanski et al. 2005; West et al. 2011), activity-related phenomena such as stellar spots, plagues and flares become increasingly a matter of concern for planet detection and characterization programmes targeting late-type stars. Stellar surface inhomogeneities can hamper the detection, and sometimes even mimic the signal, of exoplanets (e.g. Queloz et al. 2001), and seriously complicate the characterization of their properties. This problem has already become acute in the case of active solar analogues hosting transiting planets. An illustrative example is provided by the ongoing debate on the actual mass of CoRoT-7b, varying (including 1σ uncertainties as large as 20 per cent) between 1 and $9 M_{\oplus}$ (!), depending on how one decides to deal with the modelling of the planetary signal superposed to the much larger activity-induced stellar ‘jitter’ in both the photometric and the RV measurements (Queloz et al. 2009; Hatzes et al. 2010; Ferraz-Mello et al. 2011; Pont, Aigrain & Zucker 2011). Recently, the first serious studies attempting to gauge the limits to planet detection induced by stellar-activity-related phenomena, and

strategies aiming at minimizing such effects, have been undertaken. These have focused primarily on the impact of, and the possibility of calibrating out, activity-induced jitter in high-precision RV and astrometric measurements (Makarov et al. 2009; Lagrange, Desort & Meunier 2010; Boisse et al. 2011, and references therein; Dumusque et al. 2011; Sozzetti 2011, and references therein). Very recently, the first analyses of the impact of star spots on RV searches for Earth-mass planets in orbit about M dwarf stars have been carried out by Reiners et al. (2010) and Barnes et al. (2011), who also addressed the merit of moving from the optical to infrared wavelengths (where the star spots induced RV noise might be significantly reduced).

All the above considerations clearly underline how achieving the goal of the detection *and* characterization of low-mass, potentially habitable, rocky planets around low-mass stars requires the construction of a large (all-sky) sample of nearby, relatively bright M dwarfs with well-characterized properties. This will necessitate the combined use of time-series of spectroscopic, astrometric and photometric data of high quality. In particular, the jitter levels will have to be quantified in detail for each target individually, as the jitter properties may vary from star to star within the same spectral class, as suggested by recent findings based on high-precision *Kepler* photometry (e.g. Ciardi et al. 2011) and high-resolution, high signal-to-noise ratio (S/N) spectroscopy (e.g. Zechmeister, Kürster & Endl 2009). With the kick-off in 2009 December, we have carried out a year-long pilot study for an upcoming photometric transiting search for small-size planets around thousands of nearby M dwarfs which will utilize an array of five 40-cm telescopes at the Astronomical Observatory of the Autonomous Region of the Aosta Valley (OAVdA), in the western Italian Alps. The OAVdA site was selected on the basis of a detailed site characterization study (Damasso et al. 2010). The pilot study was focused on medium-term (typically for 2 months) photometric monitoring, using small-size instrumentation (25–80 cm class telescope systems), of a sample of 23 cool M0–M6 dwarfs with good parallaxes from the TORINO Parallax Program (TOPP; Smart et al. 2010). The primary objectives we set out to achieve in this study were (i) to demonstrate sensitivity to $<4 R_{\oplus}$ (i.e. smaller than radius of Neptune) transiting planets with periods of a few days around our sample, through a two-fold approach that combines a characterization of the statistical noise properties of our photometry with the determination of transit detection probabilities via simulations; and (ii) where possible, to better our knowledge of some astrophysical properties (e.g. activity, rotation, age) of our targets through a combination of spectroscopic and astrometric information and our differential photometric measurements.

In Section 2, we describe the OAVdA instrumentation utilized during the pilot study, and outline the dedicated pipeline for the data processing and analysis of the photometric data we have developed. We discuss in Section 3 the main characteristics of the M dwarf sample targeted by the pilot study, and present in Section 4 the main results of the study in terms of (1) achieved short-term and medium-term photometric sensitivity for our sample; (2) improved characterization of the properties of the cool M dwarfs observed, by combining the knowledge of their photometric microvariability time-scales with other available spectroscopic, photometric and astrometric observations; and (3) a careful assessment of the limits to transiting planetary companions for each star in our sample. We conclude in Section 5 by summarizing our findings and by discussing the preparatory steps for the upcoming long-term photometric monitoring programme to characterize the microvariability features of and search for transiting small-size planetary

² M-dwarf spectra are dominated by chemically complex molecular features. As a result, the identification of the continuum in an M dwarf spectrum is challenging, rendering line-based metallicity indicators unreliable. The poorly constrained molecular opacity data currently available make the determination of metallicity through spectral synthesis also difficult (e.g. Gustafsson 1989; West et al. 2011, and references therein).

³ The connection between stellar rotation and activity is usually investigated by means of (i) spectroscopic measurements of the rotational velocity $v \sin i$, usually coupled to measurements of the H α luminosity (e.g. Reiniers & Basri 2010, and references therein); (ii) spectroscopic monitoring of temporal evolution of the R'_{HK} activity index as determined from the Ca II H&K emission-line cores (e.g. Wright et al. 2004); and (iii) photometric determination of rotation periods for stars with significant spot coverage (e.g. Strassmeier et al. 2000).

companions to a well-defined sample of low-mass stars, to be carried at the OAVdA site in the near future.

2 INSTRUMENTATION AND METHODOLOGY

The instrumental setup used in this study is very similar to the one adopted for the OAVdA site characterization study described in Damasso et al. (2010). In summary, we used a small-size telescope array composed of three instruments with the diameters of 81, 40 and 25 cm. For the purpose of the pilot study described here, the 40- and 25-cm telescopes performed all the observations equipped with standard Johnson–Cousins *I* filters, while the 81-cm telescope utilized a standard Johnson–Cousins *R* filter (observations in the *I* filter with this instrument were affected by fringing). Naturally, the choice of filters was driven by red colours of the target sample. In Table 1, we summarize the main characteristics of the telescope and camera systems.

All observations were performed with the CCDs set up at the focus of the telescope, and the exposure times were chosen at the beginning of each night of observation (without being subsequently modified) in order to guarantee an optimum S/N ($\gtrsim 100$) for the target, while avoiding saturation (see Table 2 for the typical exposure times for each monitored target). The temporal sampling, including overheads, was typically of a few minutes. We chose to

observe with any given instrument one star at a time during a night, tracking it without repointing. No auto-guiding was utilized for the 25- and 40-cm telescopes (as described already in Damasso et al. 2010). For the two instruments, we recorded typical drifts of up to 100 pixels. None of the above elements of the observing strategy was optimized with the intent of reproducing the actual one to be implemented in our upcoming survey, which will employ vastly improved instrumentation and an adaptive observing strategy to be described in a future work. In this respect, the resulting photometric performances reported here can be considered as conservative.

For the pilot study, we selected 23 targets from the input target list of TOPP (see Section 3 for details). We chose an observational strategy which would allow us to monitor each target for at least 3 h per night without interruptions for a minimum of a dozen nights over a maximum period of ~ 2 months. The expected phase coverage for transiting companions within a few (1–2) days of period would exceed 70 per cent. Two stars, LHS 1976 and LHS 534, were observed for a significantly longer period of time (LHS 1976 actually over two seasons), in order to probe our sensitivity to transiting companions on periods of up to about 1 week or so. At the end of the pilot study (a little over 1 yr of observations), the whole data base comprised of 76 287 good images, corresponding to ~ 1000 GB of data. A summary of the pilot study observations is provided in Table 2.

Table 1. Summary of the main characteristics of the telescope and camera systems.

Optical scheme	Telescope		CCD camera		Resulting configuration	
	Aperture (cm)	Focal ratio	Sensor area (pixel ²)	Pixel area (μm^2)	Field of view (arcmin ²)	Plate scale (arcsec pixel ⁻¹)
Reflector Maksutov	25	f/3.80	2184×1472	6.8×6.8	52.10×35.11	1.43 (binning 1×1)
Reflector Ritchey–Chrétien	40	f/7.64	1024×1024	24×24	26.4×26.4	1.55 (binning 1×1)
Reflector Ritchey–Chrétien	81	f/7.90	2048×2048	15×15	16.3×16.3	1 (binning 2×2)

Table 2. Log of observations for the target sample.

ID	LHS	Number of frames	Number of nights	Epoch range (d)	Telescope (cm)	Typical exposure (s)
1	1104	2049	14	48	40	61
2	1475	6826	20	72	25	34
3	228	1084	18	54	40	155
4	243	774	14	44	40	137
5	1976	24761	108	482	25/81	64/7
6	6158	2804	10	40	25	28
7	269	1629	14	56	40	60
8	2220	3980	16	58	40	23
9	283	1696	12	56	25	58
10	2472	1022	8	57	25	75
11	360	46	1	1	40	120
12	–	4421	15	64	25	21
13	417	4693	34	85	25/81	10/3
14	3343	2122	17	88	25/40	60/30
15	3445	2835	19	66	25	54
16	528	1697	13	40	25	62
17	534	7346	44	122	81	8
18	1721	3028	22	61	81	6
19	370	633	9	33	81	120
20	306	75	1	1	40	75
21	–	1265	11	59	25	75
22	2686	914	10	60	40	75
23	2719	587	7	20	40	90

The data reduction procedure utilizes an upgraded version of TEEPEE (Transiting Exoplanets PipElinE), described in detail in Damasso et al. (2010). In short, TEEPEE is a software package written in IDL,⁴ which utilizes publicly available software from the Astronomy Users' Library⁵ as well as external contributed FORTRAN routines. The areas of the software written from scratch by two of us (PG and MD) are the ones devoted to automatically carry out ensemble differential aperture photometry on an user-specified target. TEEPEE is organized in three main, sequential modules:

- (i) Image calibration (including dark and bias subtraction, and flat-fielding);
- (ii) Astrometric processing (image alignment) and photometric processing (aperture photometry);
- (iii) Differential photometry of the target with respect to a chosen set of reference stars.

The heart of TEEPEE, for the purpose of this study, is the third block. It performs those operations that are necessary to correct, to a high degree of reliability, for systematic effects that cause the degradation of the precision of the photometric measurements, and it produces photometric light curves for hundreds of stars detected in the field. Our differential photometric method performs as follows. For each frame i , we use as the reference magnitude M_{rif}^i the average magnitude of n reference stars:

$$M_{\text{rif}}^i = \frac{\sum_{k=0}^n M_k^i}{n}. \quad (1)$$

The magnitude of the user-defined target M_{target}^i is then subtracted from M_{rif}^i , obtaining the difference $\Delta M^i = M_{\text{rif}}^i - M_{\text{target}}^i$. The procedure is iteratively repeated for all the reference stars, using as new references the remaining $n - 1$ stars. This procedure is also iteratively repeated for all detected field stars (based on a 3σ above background criterion), using as references the n reference stars chosen for the target.

The second and the third modules have been upgraded with respect to the previous version of the software described in Damasso et al. (2010) in order to improve the differential aperture photometric processing in an automatic way.

In the second module, we implemented a multi-aperture photometric processing. We settled on 12 apertures, typically ranging from two to four times the average full width at half-maximum (FWHM) (varying slightly depending on the telescope used).

In the third module, we first take care of picking up reference objects on a CCD subframe, avoiding the chip edges, affected by vignetting which is not fully corrected for during flat-fielding. Secondly, we use two efficient methods, based on the Burke et al. (2006) prescription, for choosing the appropriate set of references for the target. The first method (m1) selects the subset of reference stars which minimizes the RMS of the differential light curve of the target; the second method (m2) selects the subset of references which minimizes the RMS of the differential light curve of each potential reference star. Both methods are then applied to all 12 apertures in order to choose the optimal one, on the basis of a minimum-RMS prescription for the target light curve. Next, we filter out outliers using a 3σ clipping criterion, and an additional light curve correction to suppress FWHM-related effects (e.g. Irwin et al. 2007). Finally, we apply the SysRem trend filtering algorithm (Tamuz, Mazeh &

Zucker 2005), to correct for unknown systematic effects in the light curves produced with methods m1 and m2. The two resulting light curves are dubbed produced with methods m3 and m4, respectively. The whole procedure thus produces a total of four light curves for each target, for each night.

With a similar process, four additional light curves are produced for each target over the whole time-span of the observations, which we dub 'full-period' light curves. A single (the more stable) set of reference stars are chosen over the entire observation window. The only information retained from the nightly procedure is the optimal aperture for each night. In place of SysRem, a different trend filtering algorithm is utilized, Trend Filtering Algorithm (Kovács, Bakos & Noyes 2005), which after some experimenting was found to be better suited for the full-period light-curve analysis.

3 STELLAR SAMPLE

As already mentioned earlier, the M dwarfs targeted during the pilot study were selected from the TOPP input list of nearby ($d < 60$ pc) cool stars. We chose stars spanning a range of spectral subtypes, approximately M0–M6, and set an I -band magnitude limit of $I \lesssim 14$ (thus keeping exposure times typically to within a few minutes). These two criteria allowed us to probe potentially different regimes of intrinsic stellar variability (see Section 1), both in terms of amplitude and time-scales.

Most of these objects, with the exception of LHS 228, LHS 306, LHS 360 and LHS 2719, are included in the LSPM-North catalogue (Lépine & Shara 2005), with either *Hipparcos* trigonometric parallaxes or distance modulus estimates indicating they are within 33 pc from the Sun (Lépine 2005). Furthermore, for about half of the sample Smart et al. (2010) have published precision astrometric information, including direct distance estimates. For the purpose of this study, and particularly to derive the results presented in Section 4.5, it is important to provide reliable estimates of mass M_* and radius R_* for all our programme stars. For the targets presented in Smart et al. (2010), we utilized the values of M_* therein. For the other targets, we derived absolute K magnitudes from the distance estimates and we obtained M_* from the mass–luminosity calibration of Delfosse et al. (2000). For all the programme stars, the Bayless & Orosz (2006) mass–radius relation was then employed to calculate R_* . For completeness, metallicity [Fe/H] estimates are provided using the Johnson & Apps (2009) calibration in the plane $V - K - M_K$, where applicable, and only for objects with trigonometric parallaxes, along with effective temperature T_{eff} values from the Casagrande, Flynn & Bessell (2008) M dwarf $(V - K) - T_{\text{eff}}$ calibration. All the above characteristics of our sample are summarized in Table 3. For each target, the same table also reports relevant information on flaring activity (obtained from SIMBAD) and activity indicators, that is, $H\alpha$ equivalent width measurements.

4 RESULTS

4.1 Photometric precision

Accurately gauging the short- and medium-term photometric precision for our red dwarf sample, as a function of the characteristics of the instruments adopted and of the details of the methods of differential photometry utilized in the analysis, and including meaningful estimates of the degree of correlated (red) noise in the data, is of fundamental importance. The short-term precision (as defined below) is the quantity that ultimately has the most relevant impact on the probability of detecting a transit signal, and of determining its

⁴ IDL is a commercial programming language and environment by ITT Visual Information Solutions (<http://www.itvis.com/idl/>).

⁵ <http://idlastro.gsfc.nasa.gov/contents.html>

Table 3. Characteristics of the M dwarf sample.

ID	LHS	GJ	RA (hh:mm:ss)	Dec. (dd:mm:ss)	<i>d</i> (pc)	<i>V</i>	<i>J</i>	<i>K</i>	<i>M_V</i>	<i>M_K</i>	<i>M_*</i> (<i>M_☉</i>)	<i>R_*</i> (<i>R_☉</i>)	<i>T_{eff}</i> (K)	[Fe/H] (dex)	Flare star	H α equivalent width (Å)
1	1104	–	00:35:53.1	+52:41:13.7	24.7 $\pm$ 1.3 ^a	12.54 ^a	8.93	8.09	10.58	6.13	0.44	0.45	3317	0.07	n	–
2	1475	119	02:56:34.4	+55:26:14.0	16.7 $\pm$ 1.4 ^a	10.48 ^a	7.43	6.59	9.37	5.48	0.56	0.57	3620	–	n	–0.534 ^b
3	228	–	07:16:27.7	+23:42:10.4	42.4 $\pm$ 2.0 ^a	15.53 ^a	12.02	11.30	12.39	8.17	0.12	0.14	3424	–1.27	n	–
4	243	–	08:03:06.1	+34:56:54.8	24.4 $\pm$ 0.7 ^a	16.09 ^a	11.51	10.74	14.15	8.81	0.09	0.11	2986	–0.67	n	–
5	1976	–	08:03:19.5	+52:50:38.1	24.8 $\pm$ 3.1 ^a	11.38 ^a	8.06	7.24	9.407	5.26	0.58	0.58	3472	0.29	n	–
6	6158	3522	08:58:56.3	+08:28:25.9	6.8 $\pm$ 0.1 ^c	10.92 ^c	6.51	5.69	11.76	6.53	0.36	0.37	3023	0.51	y	+2.76 ^d
7	269	–	09:29:11.0	+25:58:09.3	16.7 $\pm$ 1.3 ^e	16.43 ^h	10.91	9.96	15.32	8.85	0.11	0.14	2697	–	n	–
8	2220	3585	10:06:43.8	+41:42:52.6	20.7 $\pm$ 1.2 ^f	11.31 ^g	8.21	7.40	9.73	5.82	0.49	0.50	3607	–0.21	n	–
9	283	3612	10:35:26.9	+69:26:58.8	13.2 $\pm$ 0.7 ^h	11.95 ^h	7.90	7.16	11.35	6.56	0.35	0.37	3175	0.13	n	–0.219 ^b , +0.13 ^d
10	2472	452.1	11:54:07.9	+09:48:22.8	11.3 $\pm$ 0.5 ^a	12.81 ^a	8.70	7.87	12.54	7.60	0.20	0.22	3120	–0.33	y	+1.248 ^b
11	360	–	13:46:55.5	+05:42:56.3	56.2 $\pm$ 9.5 ^a	15.22 ^a	12.39	11.66	11.47	7.87	0.28	0.29	3858	–	n	–
12	–	569B	14:54:29.2	+16:06:03.8	9.7 $\pm$ 0.2 ^f	10.38 ^g	6.63	5.77	10.45	5.84	0.48	0.49	3247	0.37	y	+0.852 ^b
13	417	623	16:24:09.3	+48:21:10.4	8.1 $\pm$ 0.08 ^f	10.27 ^g	6.64	5.91	10.73	6.37	0.38	0.40	3359	–0.14	n	–0.237 ^b
14	3343	4040	17:57:50.9	+46:35:19.1	14.6 $\pm$ 0.5 ^a	11.68 ^a	7.85	7.00	10.85	6.17	0.40	0.41	3219	0.25	n	–0.215 ^b , +0.15 ^d
15	3445	9652A	19:14:39.1	+19:19:03.7	17.9 $\pm$ 0.7 ^a	11.59 ^a	7.58	6.81	10.32	5.54	0.41	0.42	3179	0.69	y	+5.4 ^d , +5.7 ⁱ
16	528	1271	22:42:38.7	+17:40:09.2	17.4 $\pm$ 0.7 ^a	11.76 ^a	8.06	7.18	10.55	5.98	0.43	0.44	3260	0.26	n	–
17	534	4311	23:06:35.6	+71:43:25.5	17.3 $\pm$ 5.2 ^e	11.75 ^f	8.34	7.56	10.56	6.37	0.37	0.39	3445	–	n	–
18	1721	1074	04:58:46.0	+50:56:37.8	19.3 $\pm$ 0.9 ^f	11.06 ^f	7.90	7.04	9.63	5.61	0.53	0.54	3540	–0.01	n	–0.452 ^b
19	370	–	14:20:53.1	+36:57:16.8	21.7 $\pm$ 1.7 ^e	16.17 ^h	11.05	10.25	14.49	8.57	0.13	0.16	2829	–	n	–
20	306	3668	11:31:08.3	–14:57:21.1	11.8 $\pm$ 2.6 ^a	14.19 ^a	9.36	8.50	13.83	8.14	0.12	0.14	2889	–0.05	n	–
21	–	1167A	13:09:34.9	+28:59:06.6	10.8 $\pm$ 0.6 ^a	14.52 ^a	9.48	8.61	14.35	8.44	0.12	0.14	2832	–0.08	y	+4.82 ⁱ
22	2686	–	13:10:12.6	+47:45:18.4	10.3 $\pm$ 0.5 ^a	14.16 ^a	9.58	8.69	14.09	8.62	0.09	0.11	2951	–0.47	n	–
23	2719	–	13:20:27.0	–03:56:14.5	26.9 $\pm$ 2.5 ^a	15.60 ^a	11.28	10.48	13.45	8.33	0.15	0.17	3058	–0.58	n	–

^aTrigonometric parallax/*V* magnitude, after Smart et al. (2010), and references therein.^bGizis, Reid & Hawley (2002).^cTrigonometric parallax/*V* magnitude, after Henry et al. (2006).^dWalkowicz & Hawley (2009).^ePhotometric parallax/*V* magnitude, after Lépine & Shara (2005).^fTrigonometric parallax from *Hipparcos* data, after Van Leeuwen (2007).^g*V* magnitude from the ASCC-2.5 catalogue, after Kharchenko (2001).^hTrigonometric parallax/*V* magnitude, after Reid & Cruz (2002).ⁱShkolnik et al. (2009).^jTASS Mark IV photometric catalogue, version 2, after Droege, Richmond & Sallman (2006).

statistical significance. The medium-term precision is the quantity that allows one to gather insight on different time-scales of variability which are more likely to be intrinsic to the target, such as surface activity. As is usual practice, we operationally define the photometric precision of a given target monitored with one of our instruments as the RMS of a differential light curve (for one observing night or for the whole time-interval of the observations) obtained with any of the four methods (*m1*–*m4*) defined in Section 2. To first order, this corresponds to the uncertainty of each data point.

4.1.1 Global analysis

Our first goal is to determine the precision of our photometric measurements on a nightly basis (short-term precision) and over the whole temporal length of the observations (medium-term precision). For each target, we determine the short-term photometric precision of the data by computing the intra-night RMS values of eight light curves: four derived from the nightly light curves and four extracted from the full-period light curves. We determine the medium-term precision in our data set by computing the global RMS values of the four full-period light curves.

For the purpose of computing the RMS values, we utilized unbinned light curves for the 25- and 40-cm telescopes, while we utilized binned light curves (at 1.5 min) for the 81-cm telescope. The binning of the 81-cm telescope data is necessary in order to homogenize them with the typical time-sampling of the other two telescopes, and more importantly to suppress the effects of atmospheric scintillation, which usually affects to a significant degree very short (few seconds) exposures.

In the three panels of Fig. 1, we show the distributions of the mean short- and medium-term RMS values for each target, for the various methods. Visual inspection of the plots already shows qualitatively two relevant results: the apparently good agreement between different methods for differential photometry (with or without detrending), both in the short- and medium-term regimes, and the fact that the medium-term photometric precision appears degraded with respect to the short-term precision. We put the discussion on more firm statistical grounds by performing a comparison between the various RMS distributions based on the Kolmogorov–Smirnov (K–S) test, which measures the probability P_{KS} of any two distributions being statistically indistinguishable.

First, we perform the K–S test between the four distributions within each panel of Fig. 1, to gauge statistical differences in the RMS distributions between the *m1* through *m4* analysis methods, separately for the short- and medium-term regimes. The results, expressed in terms of P_{K-S} , are summarized in Table 4.

Next, the K–S test is performed to evaluate the differences between the RMS distributions in the short- and medium-term regimes. Given the results shown in Fig. 1 (i.e. methods *m1* through *m4* provide the same answers), we show here only for simplicity the comparison between the RMS distributions of method *m1* from one panel with all other distributions in the other panels. The corresponding values of P_{K-S} are summarized in Table 5.

Finally, the K–S test is performed to evaluate the differences between the RMS distributions from data obtained with different telescopes. The corresponding values of P_{K-S} are summarized in Table 6.

The results from the global short-term and medium-term photometric RMS analyses based on the K–S test highlight the following:

(1) The use of a range of instrumental setups does not impact significantly the typical performance in photometry.

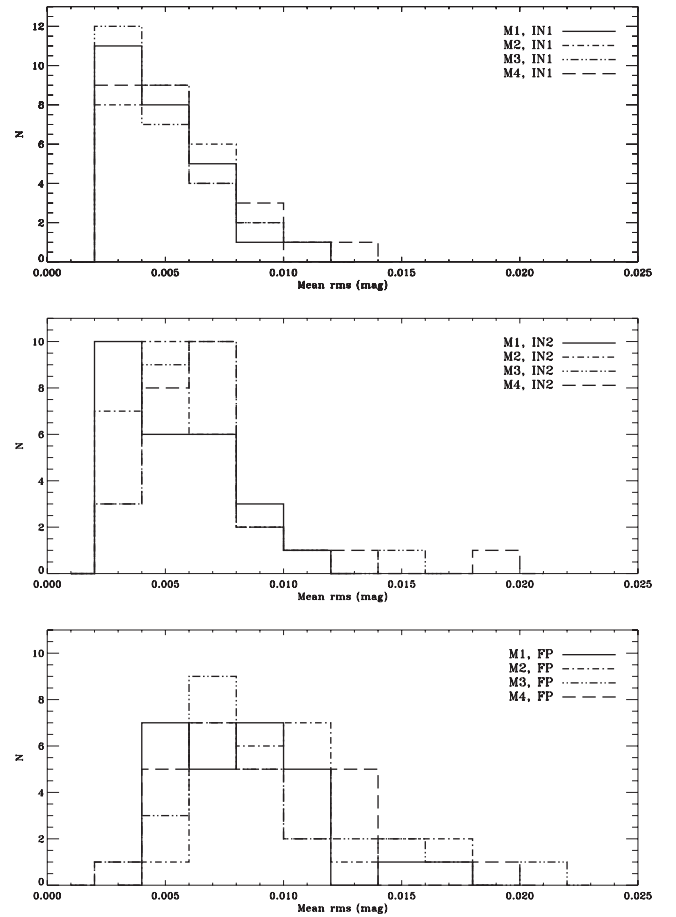


Figure 1. Distribution of the mean RMS for each target. For each of the four differential photometry methods, the panels show: the mean intra-night RMS distribution IN1 for the sample (top), the mean intra-night RMS distribution IN2 extracted from a full-period light curve for each target (middle) and the full-period RMS distribution FP for the sample (bottom).

Table 4. K–S test results (1).

m1–m2	m1–m3	m1–m4	m2–m3	m2–m4	m3–m4
0.992	0.992	Fig. 1, upper panel 0.992	0.674	0.9928	0.674
0.992	0.138	Fig. 1, middle panel 0.258	0.440	0.258	0.999
0.138	0.674	Fig. 1, lower panel 0.674	0.440	0.258	0.992

Table 5. K–S test results (2).

m1–m1	m1–m2	m1–m3	m1–m4
0.258	Upper panel (Fig. 1)–middle panel (Fig. 1) 0.138	0.012	0.031
0.001	Upper panel (Fig. 1)–lower panel (Fig. 1) 2e–8	4e–5	0.0002
0.031	Middle panel (Fig. 1)–lower panel (Fig. 1) 0.0002	0.031	0.013

Table 6. K–S test results (3).

25 cm–40 cm	25 cm–81 cm	40 cm–81 cm
0.315	0.565	0.397

(2) The differential photometry methods (without detrending) adopted within the pipeline provide consistently similar results.

(3) The similarity between the different light-curve RMS values with and without detrending indicates that our data are not particularly affected by linear systematic trends that can be easily identified and removed, such as atmospheric extinction, detector efficiency or point spread function changes over the detector, for which algorithms like SysRem are very effective.

(4) The differences between the short- and medium-term photometric precisions suggest that correlated noise (astrophysical in nature, or not) becomes important on time-scales longer than those of one observing session (one night). For example, the degradation in precision seen in the bottom panel of Fig. 1 could be ascribed in part to flat-fielding errors and/or to pointing errors and telescope drifts, the latter effectively reducing the number of reference objects used to perform differential photometry on all the nights at once (we recall that an object can be used as a comparison star only if it is detected in every frame, and the probability that a star is lost in one or more frames increases with the time-span covered by the observations).

In summary, the typical short-term photometric precision is ~ 5 mmag and the typical medium-term photometric precision is ~ 9 mmag. The former result for the M dwarf sample is in excellent agreement with the findings of Damasso et al. (2010), who had focused their analysis on a small number of stars more similar to the Sun.

4.1.2 Correlated (red) noise analysis

The RMS of the whole light curve can be assumed to be the uncertainty of each data point under a fundamental hypothesis: the photometric measurements are assumed to be uncorrelated (white noise regime). At the mmag level and in a high-cadence time-series this is generally untrue. There are many effects that can produce a correlated photometric measurement (red noise regime): changing airmass, atmospheric conditions, telescope tracking (and relative flat-field errors) and the intrinsic variability of the targets. These effects introduce some covariance between data points.

The presence of red noise can have a rather significant impact on the statistical analysis of the data. As an example, let us consider a light curve, with no evident variability, consisting of N flux measurements f_i in a fixed time-interval, with uncertainties for each data point σ_i equal to the RMS of the whole light curve σ_0 . We calculate the mean of the N flux measurements f_{mean} . The uncertainty on f_{mean} , $\sigma_{f_{\text{mean}}}$, is then the error of the mean of f_i . Using the expression for the standard deviation of the mean under the assumption of white noise (σ_w), this uncertainty is

$$\sigma_{f_{\text{mean}}} \equiv \sigma_w = \frac{\sigma_0}{\sqrt{N}}. \quad (2)$$

We note the uncertainty on f_{mean} decreases with increase in the square root of the number of points N .

The equivalent of equation (2) in the presence of red noise is

$$\sigma_{f_{\text{mean}}} \equiv \sigma_t = \sqrt{\sigma_w^2 + \sigma_r^2} = \sqrt{\frac{\sigma_0^2}{N} + \frac{1}{N^2} \sum_{i \neq j} C_{ij}}, \quad (3)$$

where C_{ij} are the covariance coefficients between the i th and j th measurements (e.g. Pont, Zucker & Queloz 2006).

Now, we can estimate σ_t from the light curves, taking into account the red noise, following the methodology described in Pont et al. (2006), and then determine the red noise component from equation (3):

$$\sigma_r = \sqrt{\frac{1}{N^2} \sum_{i \neq j} C_{ij}} = \sqrt{\sigma_t^2 - \frac{\sigma_0^2}{N}}. \quad (4)$$

For each star in our sample, we computed σ_t over an interval $\delta t = 30$ min, and repeated the calculations using the light curves from the four intra-night methods. We decided to investigate the red noise contribution to the error budget over this time-interval, as an illustrative example. Note that this interval actually corresponds to a significant fraction of the typical transit duration for few-days-period planets orbiting mid- and late-M dwarfs, and thus it is of particular interest for the purpose of this study. We show in Fig. 2 the various contributions to the photometric error budget in our data set, expressed as a function of the target J magnitude. The results shown correspond to the error analysis for the light curves obtained using method m1. The outcome of this specific study is only marginally dependent on the chosen method for differential photometry, as we discuss below. Panel (a) of Fig. 2 shows the expected trend of increasing σ_0 with magnitude in the data.

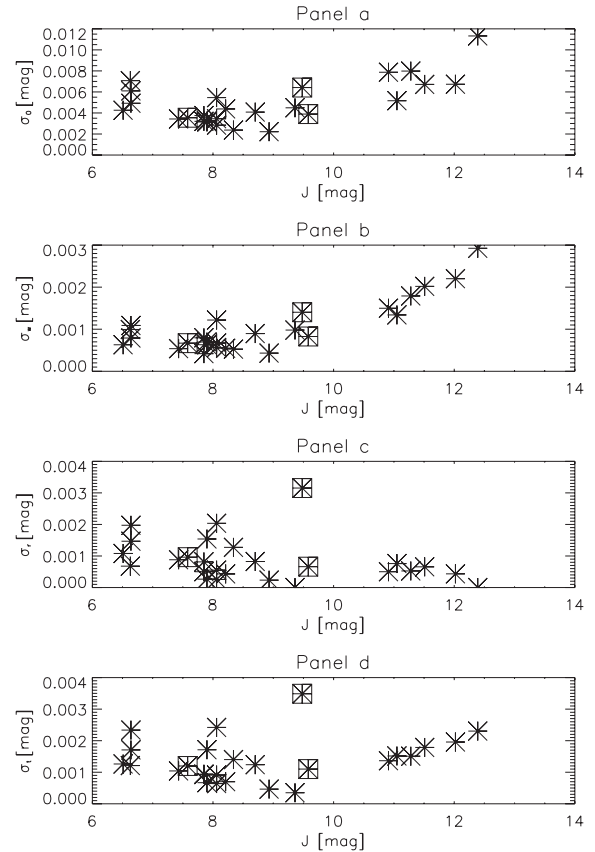


Figure 2. Panel (a): mean RMS of the unbinned light curves as a function of J magnitude. Panel (b): white noise term as a function of J magnitude. Panel (c): red noise term as a function of J magnitude. Panel (d): the total error term for the binned light curves as a function of J magnitude. The stars indicated by asterisks framed by a square are objects showing clear signs of activity (see Sections 4.3 and 4.4).

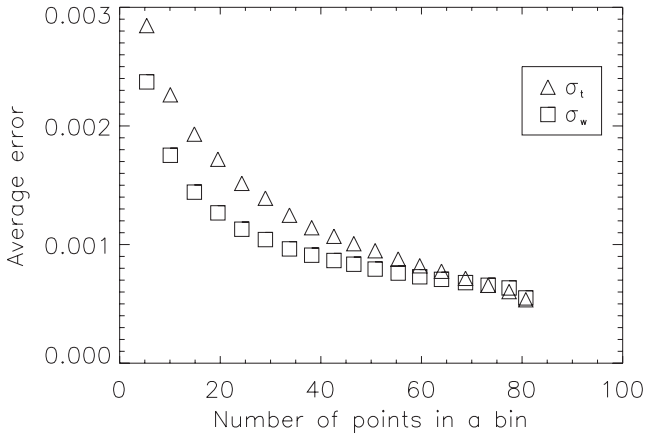


Figure 3. The behaviour of σ_t and σ_w versus number of points in time-bins.

Similarly, panel (b) emphasizes a positive correlation of σ_w with magnitude, obviously related to photon noise. This effect is also expected, as the exposure times (see Section 2) were chosen so as to guarantee a high $S/N > 100$ for each object, based on the theoretical noise estimate in equation (3) of Damasso et al. (2010). Panel (c) shows a weak inverse trend of σ_r with J magnitude, with decreasing red noise contribution for fainter objects. Again, this is expected because for faint objects σ_w dominates the total error budget, and σ_r becomes increasingly more difficult to determine at the faint end. Finally, panel (d) shows how the total photometric error σ_t in the binned data behaves as a function of J magnitude due to the combination of correlated and uncorrelated noise terms.

Fig. 3 shows, for the whole sample, the behaviour of σ_t (triangle) and σ_w (square) as a function of the number of flux points in a bin (or equivalently, time-length of the interval δt). In this case, the range of points corresponds to δt ranging from 5 to 90 min. The plot highlights that the total noise is influenced by the correlation of the data points mainly on short time-scales (small N), while the red component significantly decreases at longer time-scales. The noise σ_t , globally, follows a $1/\sqrt{N}$ relation, as it is expected in a regime where the white noise is dominant.

It is furthermore worth mentioning how the typical uncertainties over the average of the time-intervals considered here, taking into account the red noise, are 1.4, 1.6, 1.2 and 1.4 mmag for photometric methods m1, m2, m3 and m4, respectively. This corresponds to values that are 1.3, 1.5, 1.2 and 1.3 times larger than a pure white noise regime. Based on a K–S test, such differences are deemed significant with confidence levels of 94.0, 99.1, 95.4 and 99.9 per cent, respectively. As opposed to the results obtained in Section 4.1.1, where we simply used the global light-curve RMS as a comparison metric, this more in-depth analysis underlines how the detrending algorithms are actually useful for the purpose of suppressing some of the correlations present in our data.

Finally, we note how the red noise analysis can also be used in principle to investigate the intrinsic variability of a target at the mmag level. The points framed by a square in Fig. 2 are the three stars in our sample showing clear signs of activity, for which we have either observed flare events or determined their likely photometric rotation period based on the presence of surface inhomogeneities, or both (see Sections 4.3 and 4.4). In one case (GJ 1167A), the high levels of red noise could also be seen as an indication of strong activity (i.e. photometric variability) at the mmag level, and on short time-scales. Of course, in order to systematically apply this type of

analysis to describe stellar activity robust calibration procedures, a statistically significant sample of stars are necessary, together with the spectroscopic measurements. This is a challenge we plan to take up in the future, in order to better characterize the global target sample of our upcoming survey, as this might also allow us to reduce the investment in spectroscopic follow-up observations.

4.1.3 On the choice of the comparison stars

When characterizing the sources of correlated and uncorrelated noise in our photometric data, it is reasonable to expect them to at least in part be due to details in the selection of the reference objects. This is all the more so in the case of differential photometry of late-type targets observed with red filters (e.g. Bailer-Jones & Lamm 2003). To test this possibility, for each red dwarf in our sample, we calculated an ‘average’ colour index $V - K$ of the references (using the magnitudes of the NOMAD catalogue) and investigated whether the total intra-night light-curve RMS, the white noise, and the red noise contributions showed any significant dependence on colour differences between the red M dwarfs and the typically bluer sets of comparison stars. In parallel, we investigated the possible dependence of correlated and random noise on the average number of comparison stars used for each target, which could also play a role to some degree (especially if one or more of the comparison stars were to show variability).

The three left-hand panels of Fig. 4 show the average red noise (top), white noise (middle) and total RMS (bottom) for the sample as a function of the difference between the colour index of the target and the average colour index of the corresponding comparison stars ($V_r - K_r) - (V - K)$. The data are binned along the x -axis and error-bars correspond to the dispersion of the values in a bin (the rightmost bin contains only two stars). No evident trends with colour index can be found. In the three right-hand panels of Fig. 4, the same quantities are plotted as a function of the average number of comparison stars for each red dwarf in the sample. Even in this case, there is no evident correlation. On the time-scale of one observing night, the number of comparison stars or colour-dependent effects such as atmospheric extinction do not appear to impact to any significant extent our measurements. This is in line with, for example, the analysis of Bailer-Jones & Lamm (2003) and Irwin et al. (2011). The same considerations may not hold in the case of our full-period photometry, which is more prone to being affected by other sources of systematic errors, including possible dependency on colour-related effects (e.g. flat-fielding errors), as already mentioned in Section 4.1.1. An in-depth analysis to search for colour-dependent effects in the full-period light curves will be the objective of future work.

We also looked at the possibility of evaluating the impact on the noise levels by forcing the choice of red stars as comparisons. We analysed the fields of GJ 1167A and GJ 9652A, with common proper motion companions at ~ 3 arcmin and ~ 42 arcsec, respectively. Due to their faintness (at the V band they are 2–3 mag fainter than the primaries), GJ 1167B and GJ 9652B are not selected as comparison objects by any of the four intra-night differential photometry methods. By forcing their inclusion in the reference sets for both targets, no appreciable differences in either correlated or random noise levels can be observed, due to the significant number (> 10) of much brighter references selected by the pipeline in all cases.

While this preliminary analysis has not uncovered significant colour-dependent effects which could be ascribed to the choice of

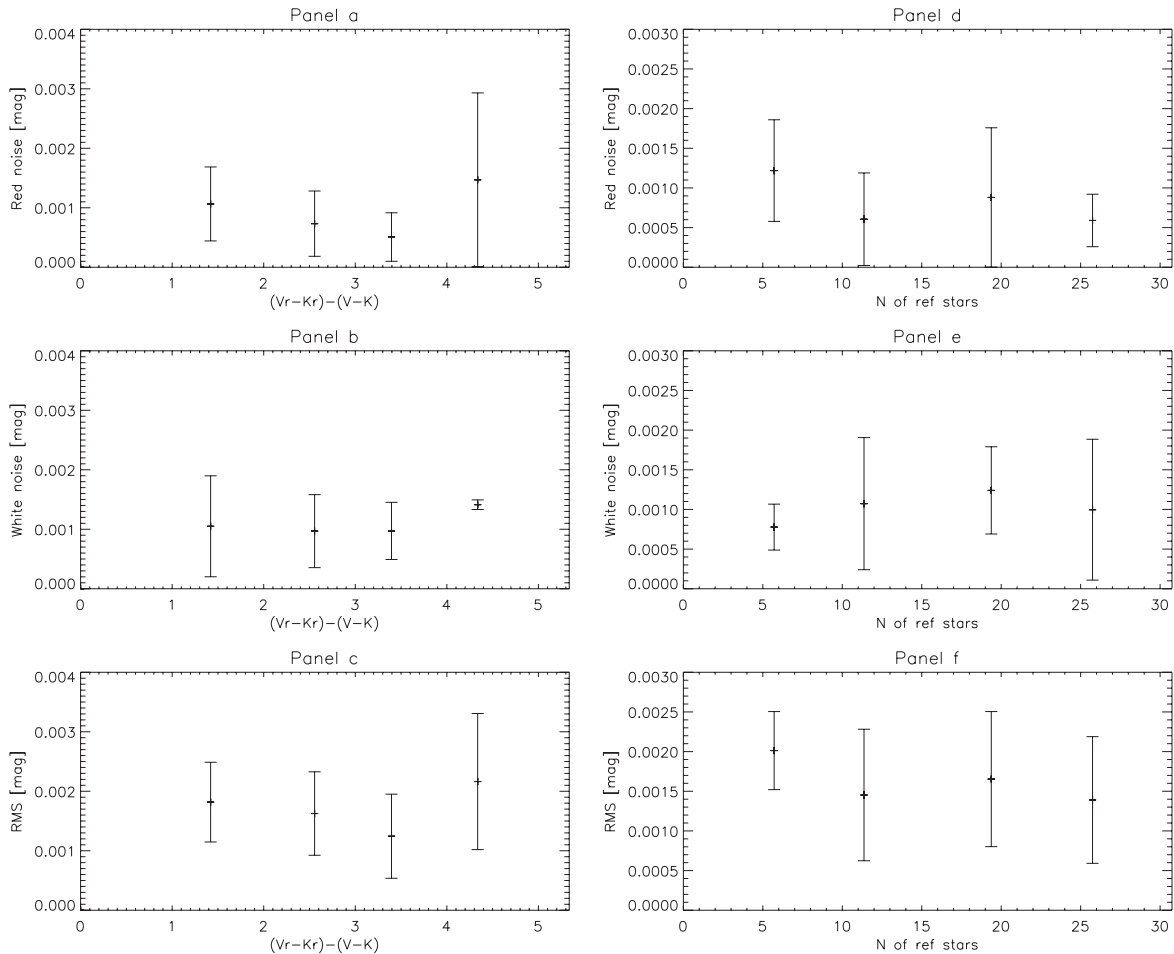


Figure 4. Left-hand column: red noise (top panel), white noise (middle panel) and total RMS (bottom panel) for the sample as a function of the difference $(Vr - Kr) - (V - K)$ between the colour index of the target and the average colour index of the corresponding comparison stars. Right-hand column: the same quantity is plotted as a function of the average number of comparison stars for each red dwarf in the sample.

references, we are aware that prescriptions within *TEEP* should still be included for handling comparison sets with average colour indexes not vastly different from that of the target, particularly when it comes to reducing data over a long period of observations. Recipes have already been identified by other programmes targeting specifically large samples of M dwarfs (e.g. Irwin et al. 2011), which are fine-tuned to the specific observing strategy, observational setup and sample size. Such a careful data treatment will be applied in the future to our survey data.

4.2 Photometric variability: periodicity analysis

After the characterization of the photometric noise properties for the M dwarfs observed during the pilot study, we describe here the key elements of the analysis segment devoted to the astrophysical characterization of the stars themselves. We look for signals in the data that are periodic in nature, and either would indicate the presence of a transiting companion or could be interpreted as intrinsic to the target (e.g. due to chromospheric activity). In separate works (Damasso et al. 2011; Giacobbe et al., in preparation), the search tools applied here to our programme stars were used to characterize the nature of tens of newly discovered variable stars in the target fields.

4.2.1 Searching for transit-like events

While showing an exact periodicity, a highly non-sinusoidal transit event cannot be modelled efficiently using standard approaches based on finite sums of sinusoidal components, such as the discrete Fourier transform method (e.g. Deeming 1975), or on period-finding techniques which minimize the scatter in smoothed light curves, such as the Phase Dispersion Minimization (PDM) algorithm (e.g. Stellingwerf 1978). As is now common practice, in order to detect periodic transit events in our data we use a method of least-squares fit of step functions to a folded signal corresponding to a grid of trial periods, as realized in the Box-fitting Least Squares (BLS) algorithm (Kovács, Zucker & Mazeh 2002).

In the analysis (performed in IDL with the exception of a C++ implementation of the BLS period search), we utilized (for each photometric reduction method) the intra-night light curves of each target without σ clipping, as (partial) transit events might in principle be recognized as clusters of outlier points and removed from the data sets. All light curves were inspected for transit-like signals using a dense grid of 10000 trial periods in the range 0.4–5.0 d. We divided the folded time-series into 300 bins and evaluated the signal residue (SR) (i.e. the BLS power spectrum) of the time-series using these binned values. We fixed the fractional transit length in the range 0.1–0.01. The study of the BLS spectra does not show any significant periodicity within the period range investigated, for

all objects in our sample. This is not unexpected, given the very small number of targets included in the pilot study, due to standard considerations of geometric transit probability.

4.2.2 Characterizing stellar rotation

For most of our programme stars, the photometric data collected during our 1-year-long observing campaign, covering a typical time-span of ~ 2 months, can be used to directly measure the stellar rotation periods if quasi-sinusoidal variations in the broad-band photometric signal are detected, under the assumption that it is produced by short- and medium-lived spots on the stellar photosphere.

In order to reveal the presence of presumably star-spot-induced rotational modulation in the full-period differential photometric data sets (extracted using methods m2 and m4) of our targets, we looked for agreement between two different periodicity search algorithms (and limiting our analysis to the determination of the most significant frequency). Both algorithms produced essentially the same results when applied on each of the two light curves, making our conclusions more robust. In the following discussion, we present the results of the period-search analysis as applied to the light curve obtained using method m4.

The first tool utilized is the `PERIOD04`⁶ software (Lenz & Breger 2005), which performs discrete Fourier transforms (DFTs) of a time-series and is used routinely in asteroseismology work (e.g. Aerts, Christensen-Dalsgaard & Kurtz 2010). The second method solves directly a linear least-squares problem: the data are folded according to a grid of different trial periods and fitted to a sine function, and at each step the reduced chi-square, χ^2 , is evaluated. While in the Fourier analysis the significant periods correspond to peaks in the amplitude spectrum, in a periodogram obtained with the second method the best-fitting period will correspond to the trial value which minimizes χ^2 . This approach has been adopted by Irwin et al. (2011) to search for rotation periods in the M dwarf sample of the MEarth survey.

We found that our programme stars can be divided into three main groups: (i) targets which do not show any significant periodicity; (ii) targets for which the power spectra show the existence of several possible periodic signals, but with low significance; and (iii) stars showing one significant frequency in the periodogram which can be reliably interpreted as the star spinning frequency (two objects in particular, ~ 10 per cent of the targets).

Here we present the results concerning the determination of the rotation periods of these two targets, LHS 3445 (a.k.a. GJ 9652A) and GJ 1167A, in order to gather independent circumstantial evidence for their periodicity being due to rotation, as observed in our photometric data. We downloaded archival high-resolution spectra of both targets obtained by Shkolnik et al. (2009) with the High Resolution Echelle Spectrometer (HIRES) on the Keck 1 telescope, and we analysed them to provide an estimate of the projected rotational velocity $v \sin i$. In short, the $v \sin i$ values for the stars are measured from the stellar linewidths via a cross-correlation technique that employs as a template a high-resolution spectrum of a slow-rotating star of similar spectral type and known projected rotational velocity (see e.g. Reid & Mahoney 2000). The width of the peak in the cross-correlation function (CCF) is dependent on the line profiles of both template and target object. We used a HIRES spectrum of the star GJ 402 (spectral type dM5) as the slowly rotating template. This spectrum is used to create artificially broadened

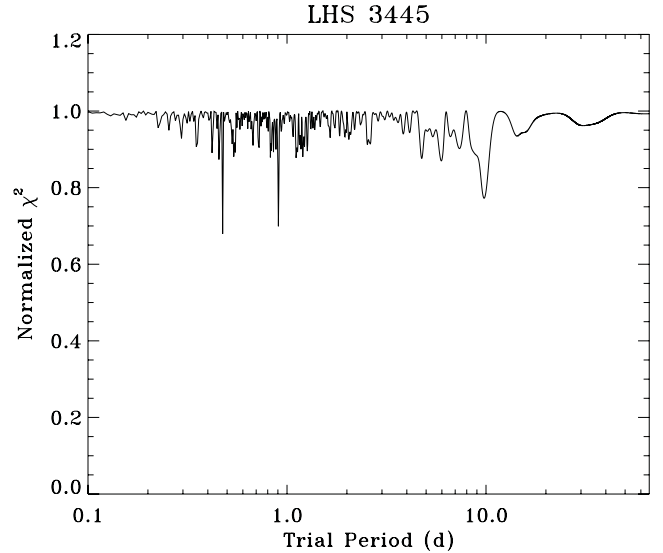


Figure 5. The search for periodicities in the full set of the photometric data for the dM star LHS 3445 revealed the existence of a signal with period $P = 0.475\,2812$ d (corresponding to the absolute minimum in this periodogram).

profiles, with an IDL code that implements the prescription of Gray (2008), and the width of the CCF peak between the unbroadened template and its broadened version is calibrated for a set of rotation speeds. The maximum in a CCF peak versus $v \sin i$ plot will correspond to the best-fitting projected rotational velocity for the target. For our analysis, we chose the echelle order covering the spectral range 7370–7490 Å, which is free of TiO bands and telluric lines which would make the analysis difficult.

The star LHS 3445 is included in the samples analysed by Shkolnik et al. (2009) and Walkowicz & Hawley (2009), and it is known to be an X-ray-active star (it has been identified in *ROSAT* data) and a flare star (see Table 3). We observed this target flaring three times, as described in Section 4.4. LHS 3445 is also considered a young star: Smart et al. (2010) indicate an estimated age in the range 30–50 Myr, while Shkolnik et al. (2009) suggest an age between 60 and 300 Myr. Fig. 5 displays the calculated periodogram for LHS 3445, showing a minimum occurring at ~ 0.47 d, and this is confirmed by the DFT analysis. This is then to be considered the most probable rotation period. A second minimum is observed very close to the period of 1 d and we discard it as an alias on the basis of the window function. Fig. 6 shows our photometric data folded according to the period $P = 0.475\,2812$ d, revealing a clear sinusoidal-like shape probably due to star-spot modulation. A single-spot model (see Section 4.3) is overplotted to highlight the consistency of this hypothesis. As shown in Fig. 7, the analysis of the Keck spectrum leads to the best estimation for the projected rotational velocity $v \sin i \sim 25$ km s^{−1}. Note in Fig. 7 that the slow-rotating star GJ 317 ($v \sin i < 2.5$ km s^{−1}; Browning et al. 2010) is used as a check for the goodness of the results for our targets (i.e. we were able to recover its low projected velocity analysing the HIRES spectrum) together with the star GJ 490 B, known to be a fast rotator ($v \sin i = 41$ km s^{−1}; Phan-Bao et al. 2009), for which we recover a high value of $v \sin i$ in agreement with the one found in the literature. Using the stellar radius indicated in Table 3 and the rotation period estimated photometrically, the mean rotational velocity of LHS 3445 results to be 44.7 km s^{−1}, which compared to the projected velocity leads

⁶ <http://www.univie.ac.at/tops/Period04/>

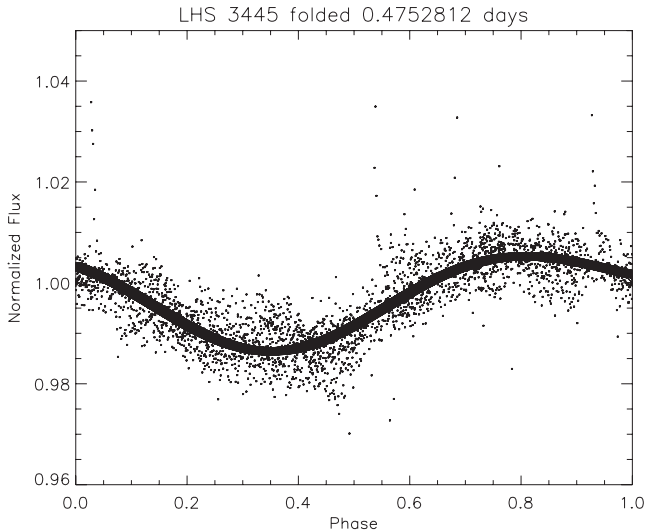


Figure 6. Photometric data for the dM star LHS 3445 folded according to its probable rotation period $P = 0.4752812$ d. Overplotted is the best-fitting single-spot model described in Section 4.3.

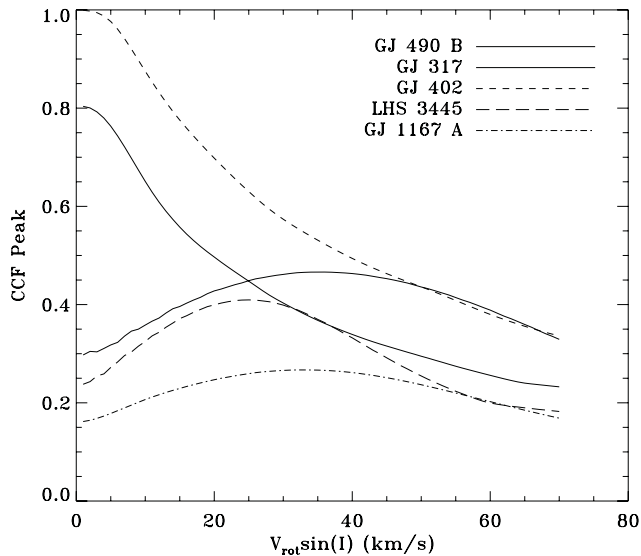


Figure 7. CCF peaks as a function of the projected rotational velocity $v \sin(i)$ for two of our dM targets, LHS 3445 and GJ 1167A, and other M dwarfs used as a template (GJ 402) and check stars used to validate the procedure. The maximum values of the CCF peak functions correspond to the projected rotation velocities measured from the spectra taken with Keck/HIRES. LHS 3445 and GJ 1167A appear to be rapid rotators.

us to conclude that the rotation axis is inclined by $\sim 34^\circ$ with respect to the line of sight.⁷

The second target that shows a clear low-amplitude sinusoidal modulation in the light curve is GJ 1167A. GJ 1167A is an active flare star (but no flares were observed over the time-span of our observations), included in the samples analysed by Shkolnik et al. (2009), who classify it as a young dM4.8 star with an age in the range 60–300 Myr. In Smart et al. (2010), GJ 1167A is reported being a dM4.0 star with a rather uncertain (0.12–10 Gyr) age. Both the DFT

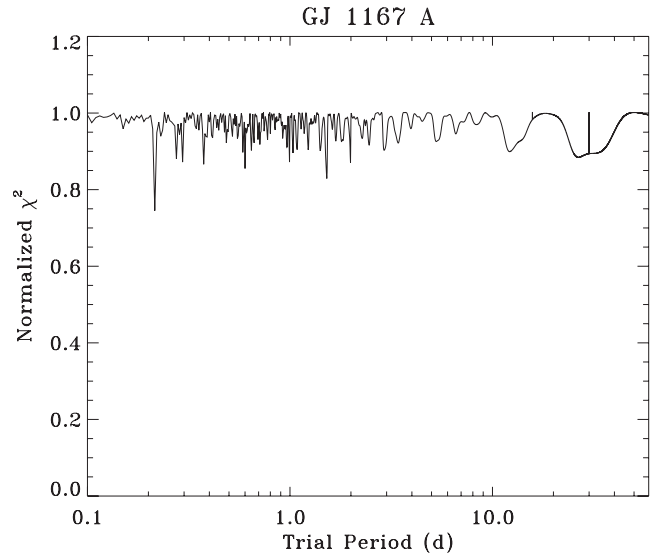


Figure 8. The search for periodicities in the full set of the photometric data for the dM star GJ 1167A revealed the existence of a signal with period $P = 0.2151997$ d (corresponding to the absolute minimum in this periodogram).

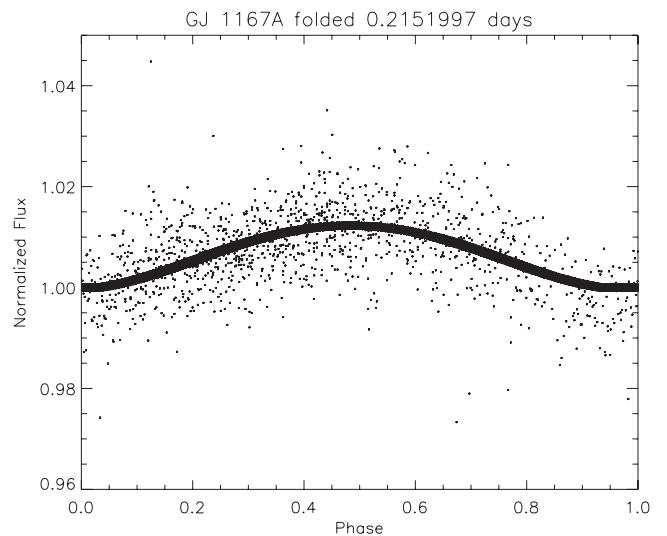


Figure 9. Photometric data for the dM star GJ 1167A folded according to its probable rotation period $P = 0.2151997$ d. Overplotted is the best-fitting single-spot model described in Section 4.3.

and PDM analyses of our photometric data reveal a clear sinusoidal periodic signal corresponding to $P \sim 0.22$ d (the PDM results are shown in Fig. 8). Fig. 9 shows the light curve folded according to this period, with superposed a single-spot model as for LHS 3445 (see Section 4.3). The fact that GJ 1167A is a very fast rotator is confirmed by the line-broadening analysis of the HIRES spectrum, as shown in Fig. 7. We estimate $v \sin i \sim 33 \text{ km s}^{-1}$. Assuming for this star a radius $R = 0.14 R_\odot$, our measured photometric rotation period implies a true rotational velocity of 32.9 km s^{-1} , which means we are looking at GJ 1167A virtually perpendicularly to its rotation axis.

Given the high rotational velocities inferred for both LHS 3445 and GJ 1167A, this possibly implies relatively young ages for these stars. Alternatively, the rapid spin period could also be due to tidal synchronization effects if these stars were to be very short period binaries. Indeed, Smart et al. (2010) hint at the possible binarity

⁷ Note that LHS 3445 has an M dwarf common proper motion companion, the star LHS 3446. We analysed its light curve, which appears to be not at all variable over the time-scale of our observations.

of LHS 3445 based on kinematics considerations. We checked the CCFs obtained from the archival high-resolution Keck/HIRES spectra, looking for evidence of double peaks, which would indicate the presence of the secondary spectrum. No such evidence is found in both cases; thus, we tentatively conclude that LHS 3445 and GJ 1167A do not harbour very short period companions of comparable mass. Naturally, a more aggressive analysis could be carried out, based, for example, on detailed modelling using improved cross-correlation techniques such as TODCOR (Zucker & Mazeh 1994), aimed at faint companions detection. We plan to pursue this issue further in future work.

4.3 Photometric variability: star-spot analysis

On the basis of the results described in the previous paragraph, we attempted at modelling the observed photometric variability of LHS 3445 and GJ 1167A assuming it is due to a rotating spot on the stellar photosphere. This work must be intended as the first step towards a more detailed model for star-spot distribution to be developed in the course of the upcoming long-term photometric monitoring programme, which will become a particularly valuable tool to evaluate the impact on the low-mass planet detection thresholds (e.g. Barnes et al. 2011).

The model we developed is based on the work of Makarov et al. (2009). This three-dimensional model describes the flux modulation due to a small circular spot rotating on the stellar surface. We modelled a single circular spot of radius r with its centre located at latitude b and longitude l in the frame of reference of the star. The star is assumed rotating around its axis with a differential angular velocity $\omega(b)$ which depends on the latitude on the stellar disc, and the spot is assumed rotating at a fixed latitude. The rotation axis is considered tilted by an angle i measured starting from the line of sight ($i = 0$ if the axis is pointing towards the observer; $i = \pi/2$ when the axis is perpendicular to the line of sight). In the model, the flux modulation can be expressed as $\frac{\Delta F}{F} = -f_s \frac{r^2 I(\theta) \cos \theta}{I_{\text{tot}}}$, where f_s is the spot contrast with respect to the local surface brightness, r is the spot size in units of the stellar radius ($r \ll 1$), I_{tot} is the integrated intensity flux from the stellar disc, $\theta = \theta(b, l(t))$ is the angle between the line of sight and the perpendicular to the star surface passing through the centre of the spot (depending upon the epoch of observation), and $I(\theta)$ is the intensity flux emitted at the spot location. Using the Stefan–Boltzmann law $I = \sigma T^4$, the contrast can be approximated by the relation $f_s = 1 - \frac{T_s^4}{T_{\text{ph}}^4}$, where T_s and T_{ph} are the mean temperatures of the spot and photosphere, respectively. Using literature prescriptions (Barnes et al. 2011), we set the contrast to vary in the range 0.2–0.8.

The parameters kept fixed in the simulation are the I -band limb-darkening coefficients (a quadratic limb-darkening law from Claret (2000) appropriate for M dwarf stars is used to describe the intensity flux distribution on the stellar photosphere) and the orbital period. The free parameters are the inclination angle of the rotation axis, spot latitude and initial longitude, and scalar $f_s r^2$ which, combining the spot contrast with its surface area, quantifies the dimming in the light intensity due to the transit of the star spot in front of the observer.

When applied to the dM stars LHS 3445 and GJ 1167A, the model reproduces well in both cases the inclination of the rotation axis, as found from spectrophotometric data: $i_* = 26.7$ for LHS 3445, and $i_* = 89.9$ for GJ 1167A. The post-fitting residuals, having RMS of 4.2 and 6.4 mmag for LHS 3445 and GJ 1167A, respectively, are comparable to the typical RMS precision achieved for the sample

Table 7. Results of the star-spot model applied to the fast rotators LHS 3445 and GJ 1167A.

Star	i_* (°)	b (°)	$f_s r^2$
LHS 3445	26.7	20.3	0.000 27
GJ 1167A	89.9	42.1	0.000 007

(see Section 4.1.1), and do not show any additional significant evidence for periodic signals. All best-fitting spot model parameters for the two stars are summarized in Table 7, and the corresponding flux modulations are overplotted to the phased photometric data for the two stars in Figs 6 and 9, respectively.

We note that our choice to fit for the scalar $f_s r^2$ rather than the individual values for the brightness contrast f_s and the spot radius r is due to the fact that in the Makarov et al. (2009) model these two parameters appear strongly correlated, and attempting to fit for them separately results in very loose constraints on their actual values, and poor overall convergence of the spot model. This effect can be easily understood, as in the disc-integrated stellar flux data the effect of a cold, small spot is difficult to distinguish from the signal produced by one which is warmer and larger. The price to pay in this case, in that we do not directly estimate the spot size and temperature, is minimal, as this exercise, for the purpose of this study, must be intended solely as a consistency check of the interpretation of the rotational modulation for the two stars based on the photometric and spectroscopic data presented above. Possible future developments include the implementation of more sophisticated (single and multiple) spot models, and the detailed assessment of their uncertainties through, for example, Bayesian statistics.

4.4 Photometric variability: flare analysis

Flaring events, a powerful indicator of the presence of strong stellar magnetic fields, are known to be relatively common among late-type stars, typically lasting between a few minutes up to several hours, and producing increases in the observed flux of up to several magnitudes. While ground-based as well as space-borne long-time-series photometric studies of open clusters and in the field over a range of wavelengths (Moffett 1974; Lacy, Moffett & Evans 1976; Audard et al. 2000; Güdel et al. 2003) have begun unveiling some important correlations between flare occurrence rates and stellar characteristics such as mass, age and activity levels (e.g. Ambartsumyan et al. 1970; Mirzoyan et al. 1989; Kowalski et al. 2009), the physics of flares is still far from being fully understood. Several open questions still need to be properly addressed, which include the details of the energy release, the mechanisms for producing the atmospheric emission, and the understanding of flares on a global scale – how do flare properties (occurrence rates, emission strength, time-scales, frequency) correlate with stellar characteristics (mass, age, activity levels)?

Upcoming ground-based photometric surveys such as Pan-STARRS (Kaiser 2004), PTF (Law et al. 2009) and LSST (Abell et al. 2009) will certainly provide the opportunity to gather flare data for large numbers ($> 10^6$) of stars, sampling wide ranges of flare amplitudes and time-scales. However, a potentially important niche for ‘classical’ flare studies (i.e. those based on the continuous monitoring of single objects) will come as a by-product of those photometric programmes, such as MEarth (Nutzman & Charbonneau 2008) or

the upcoming survey at OAVdA, targeting large numbers of relatively bright late-K and M dwarfs in search of transiting planets. For example, the detailed characterization of the flaring behaviour for K and M dwarfs, objectives of targeted searches for transiting planets, is an important ingredient towards the thorough understanding of the impact a star and its environment might have through time on the habitability of any planet it may harbour which could sustain the presence of liquid water on its surface (e.g. Kasting et al. 1993; Lammer et al. 2007; Guinan et al. 2009).

Two of the stars included in our pilot study, LHS 3445 and LHS 2686, showed flaring events in the photometry gathered over a period of 66 and 60 d, respectively. LHS 3445 is classified as UV Ceti type flare star (Gershberg et al. 1999), while no information on flaring is available in the literature for LHS 2686. Given the sampling rate of the two light curves (54 and 75 s, respectively), we were sensitive to flares with decay times larger than ~ 1 min. Visual inspection of the light curves allowed us to infer decay times of a few minutes ('impulsive' flares, see e.g. Krautter 1996). As an illustrative exercise of the type of studies that will be possible once observations are gathered in survey mode, we characterized the events following the approach of Hartman et al. (2011), that is, by solving a non-linear least-squares problem with a set of consecutive photometric measurements starting from the time of recorded maximum brightness t_0 and an exponential model function of the type:

$$m_d(t) = A \times \exp(-(t - t_0)/\tau) + m_{d,0}, \quad (5)$$

with adjustable parameters A , the peak magnitude of the flare relative to the non-flaring magnitude, τ , the decay time-scale, and $m_{d,0}$, the differential normalized magnitude (see Section 2 for its definition) of the star before the flare. The least-squares solution was obtained with an IDL implementation of the Levenberg–Marquardt method (Levenberg 1944; Marquardt 1963), MPFIT by Craig Markwardt⁸ (Markwardt 2009), and starting guesses for the model parameters A equal to the peak magnitude, $\tau = 0.001$ d, and $m_{d,0}$ equal to the average differential magnitude of each time-series. The results are shown in Fig. 10. For LHS 3445, two of the three recorded flares occurred within a time-span of 1.2 h during the same night, possibly a case of homologous flares (e.g. Martres et al. 1984; Doyle et al. 1990; Rann et al. 2000).

4.5 Limits to transiting companions

While no transit event has been recorded in our data set, as reported in Section 4.2.1, the photometric measurements obtained for our sample can be utilized to carry out simulations aimed at determining what sensitivity to transiting companions (of given radius and period) we achieved on a star-by-star basis, expressed in terms of easy-to-interpret comparison metrics, such as detection probabilities and phase coverage. These simulation tools, whose application to the data collected during the pilot study we illustrate here, will be of great use in the careful prioritization and for the optimization of the scheduling of the targets during survey operations.

In order to evaluate the sensitivity of each of the M dwarfs in our sample to transiting companions of given period and given radius, provided the primary size from Table 3 (or equivalently inducing a transit signal of given depth), a large-scale simulation was performed by injecting synthetic transit signals into the differential

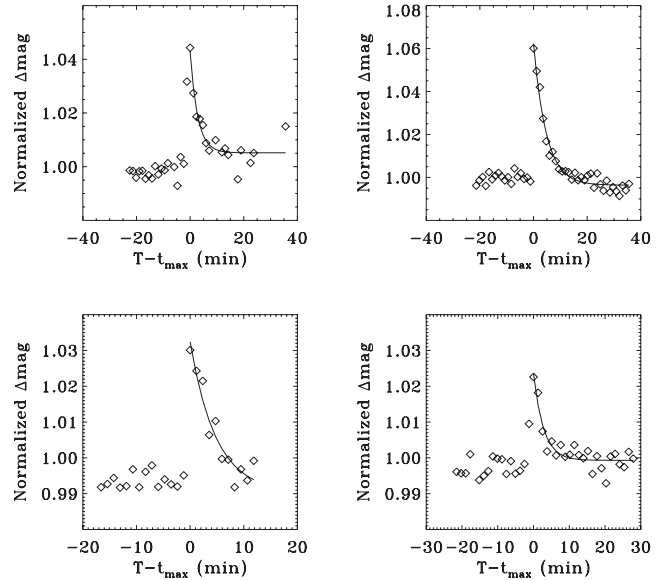


Figure 10. Four flares seen in the LHS 3445 (upper and lower left-hand panels) and LHS 2686 (lower right-hand panel) light curves. In each case, the solid line shows the fit of equation (5) to the light curve. For LHS 3445, two almost consecutive flares were recorded, with approximately equal decay times of ~ 4.5 min.

light curves (both intra-night and full period) of our targets (without σ clipping as in Section 4.2.1). We utilized these data under the hypothesis that the procedure adopted to extract it from the raw images does not affect the signal. This simplification is often adopted when dealing with such issues (e.g. Irwin et al. 2011). Furthermore, transit signal injection was performed on all light curves obtained with the four methods for differential photometry described in Section 2. We are aware that the specific choices for these elements of the simulation setup can in principle impact our findings to some extent. For example, we are not in a position to estimate quantitatively the effects on our capability to recover transit signals due to the application of trend-filtering algorithms during the production of the differential photometric data in pipeline mode. However, the goal of the present analysis is simply to gauge our ability to detect transit events as a function of the system parameters, given an observed distribution of RMS values for our stellar sample. The present simulation setup is thus appropriate for this purpose, and any in-depth evaluation of, for example, the quality of the calibration procedures against transit signal detection thresholds goes beyond the scope of this paper. We plan to relax the above assumptions and caveats in a future work in which we will carry out new studies based on a fully consistent end-to-end analysis (including extraction and differential photometry) of modified images in which synthetic transit signals will have been injected already at the pixel level.

The input parameters (and their ranges) to the simulation, which was entirely carried out in IDL, were determined based on considerations taking into account the temporal sampling, total time-span and typical photometric precision of our data. We generated

- (i) 1000 random, uniformly distributed periods in the range 0.5–5 d;
- (ii) 100 random, uniformly distributed phases for each period;
- (iii) four amplitudes of the transit signal depth t_d (in flux units: 0.02, 0.015, 0.01, 0.005) for each period and phase. The four values of transit depth simulated correspond to companion radii in the

⁸ Available at <http://purl.com/net/mpfit>. MPFIT is a port of MINIPACK-1 from FORTRAN, and is also available in C and PYTHON.

ranges 1.5–9.1, 1.3–7.9, 1.1–6.4 and 0.8–4.5 $R_{\oplus}$, respectively, given the sizes of the primaries from Table 3;

(iv) a fixed orbital inclination $i = 90^\circ$, and perfectly circular orbits ($e = 0.0$).

Consequently, the orbital radius parameter was derived from M_* (see Section 3) and from Kepler’s third law under the assumption $M_p \ll M_*$ (Seager & Mallen-Ornelas 2003). We recognize that allowing the inclination to float might change to some extent the details of the detection probability results. A detailed study of the sensitivity to non-central (eventually in the limit of quasi-grazing) transits is left for the future.

With the above simulation setup, 400 000 synthetic transit light curves were generated for each target using the Mandel & Agol (2002) algorithm. For the purpose of this analysis limb-darkening effects are essentially irrelevant and in order to speed up execution they were turned off. For each target, the synthetic transit signals were then injected on both nightly and full-period light curves. The choice of running the simulation for the whole suite of differential photometry methods was driven by the findings of Sections 4.1.1 and 4.1.2, thus allowing us to gauge the sensitivity of the transit detection probability to variable photometric precision. This was done in practice by comparing the results obtained by running the BLS algorithm on the synthetic, ‘noise-free’ data sets as well as on the combined light curves, with the prescription of discarding data sets in which a transit would have occurred only once.

Fig. 11 summarizes the process of injection of a transit signal in a differential light curve. The top panel shows the synthetic folded light curve, without limb darkening, produced by the Mandel & Agol (2002) formalism for a transit with a fractional depth of 2 per cent and a period of 1.846 8372 d. The middle panel shows the actual phased light curve of LHS 1976, while the bottom panel shows the combined light curve in phase. The data sets shown in the upper and lower panels are both fed to BLS.

In the analysis with the transit search algorithm of a given light curve, BLS was run using 500 period steps in the range 0.5–5 d, the folded time-series was divided into 100 bins, and the SR of the time-series (see Kovács et al. 2002) was determined using these binned values. We fixed the fractional transit length to lie in the range 0.1–0.01.

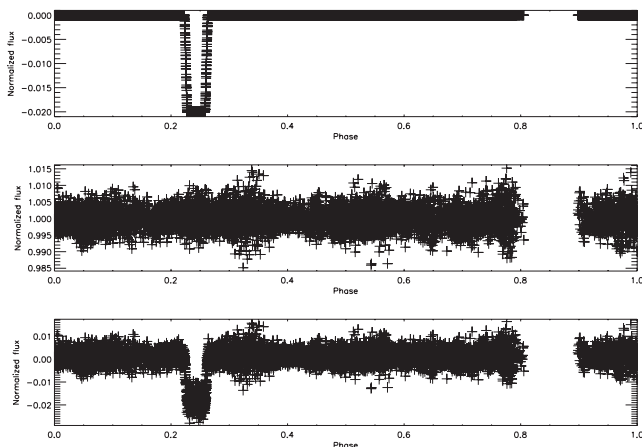


Figure 11. Top panel: synthetic folded light curve with $t_d = 2$ per cent and a period of 1.846 8372 d. The times of observation are those of LHS 1976. Middle panel: the actual phased light curve of LHS 1976. Bottom panel: the combined light curve for LHS 1976.

As mentioned above, the main results of the simulation are expressed in terms of two simple comparison metrics, which we identified to be the phase coverage and the transit detection probability.

Here we calculate the phase coverage, in a period range of 0.5–5 d, for 10 000 trial periods. We divide the phased light curve in bins corresponding to 20 min in length (obviously the number of bins changes with the trial period). A single bin is flagged as ‘filled’ (i.e. containing a satisfying number of data points) if at least five points coming from three different nights fall within. The phase coverage (expressed as percentile) represents the relative number of bins that satisfy this condition with respect to the total number of bins.

We define the detection probability as the relative number of periods that are detected by BLS with respect to the total number of injected periods. We considered as detections all those signals for which BLS returned a period T' such that $|T' - T_{in}|/T_{in} < 0.01$, where T_{in} was either the actual period of the injected signal, or half that period, or twice that period. We are aware of the fact that this requirement might be somewhat stringent: in practice, we do not consider as detections transits identified with the correct depth, but with an incorrect period due to, for example, the sampling properties of the light curve. We adopted this more conservative approach to the definition of detection probabilities as a way to partly compensate for the caveats and assumptions of the simulation scenario listed at the beginning of this section.

Fig. 12 shows the phase coverage as a function of injected period for a signal with $t_d = 0.02$ for three representative objects in our sample, LHS 1976, LHS 417 and LHS 3343, with very different (from poor to excellent) levels of phase coverage.

For the same three stars, and in the case of differential light curves obtained with method m3, Figs 13, 14 and 15, respectively, give an overview of all the fundamental ingredients provided in output from the simulation. In every figure, the first set of panels (a) show, for each of the values of t_d simulated, the original distribution of injected transit signals (solid line) and that of those signals whose corresponding light curves (synthetic as well as combined) are subsequently fed to BLS (dashed line), both expressed as a function of period. The second set of panels (b) show the fraction of BLS-detected signals in the synthetic data sets (solid line) and in the combined light curves (dashed line). The third set of panels (c) show

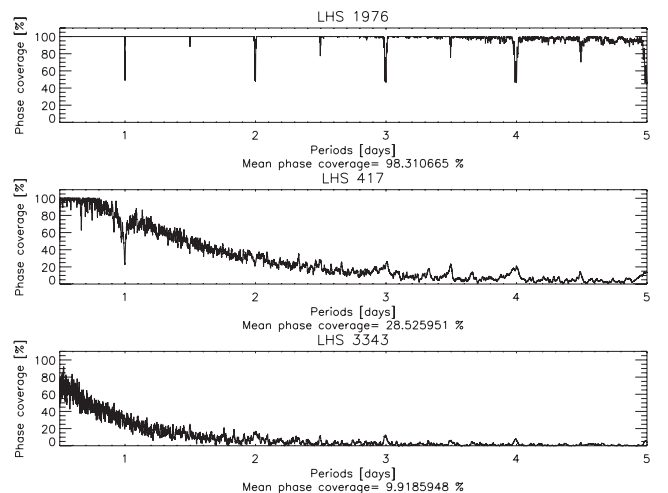


Figure 12. Phase coverage as a function of period of the injected transit signal ($t_d = 2$ per cent). Top panel: LHS 1976. Middle panel: LHS 417. Bottom panel: LHS 3343.

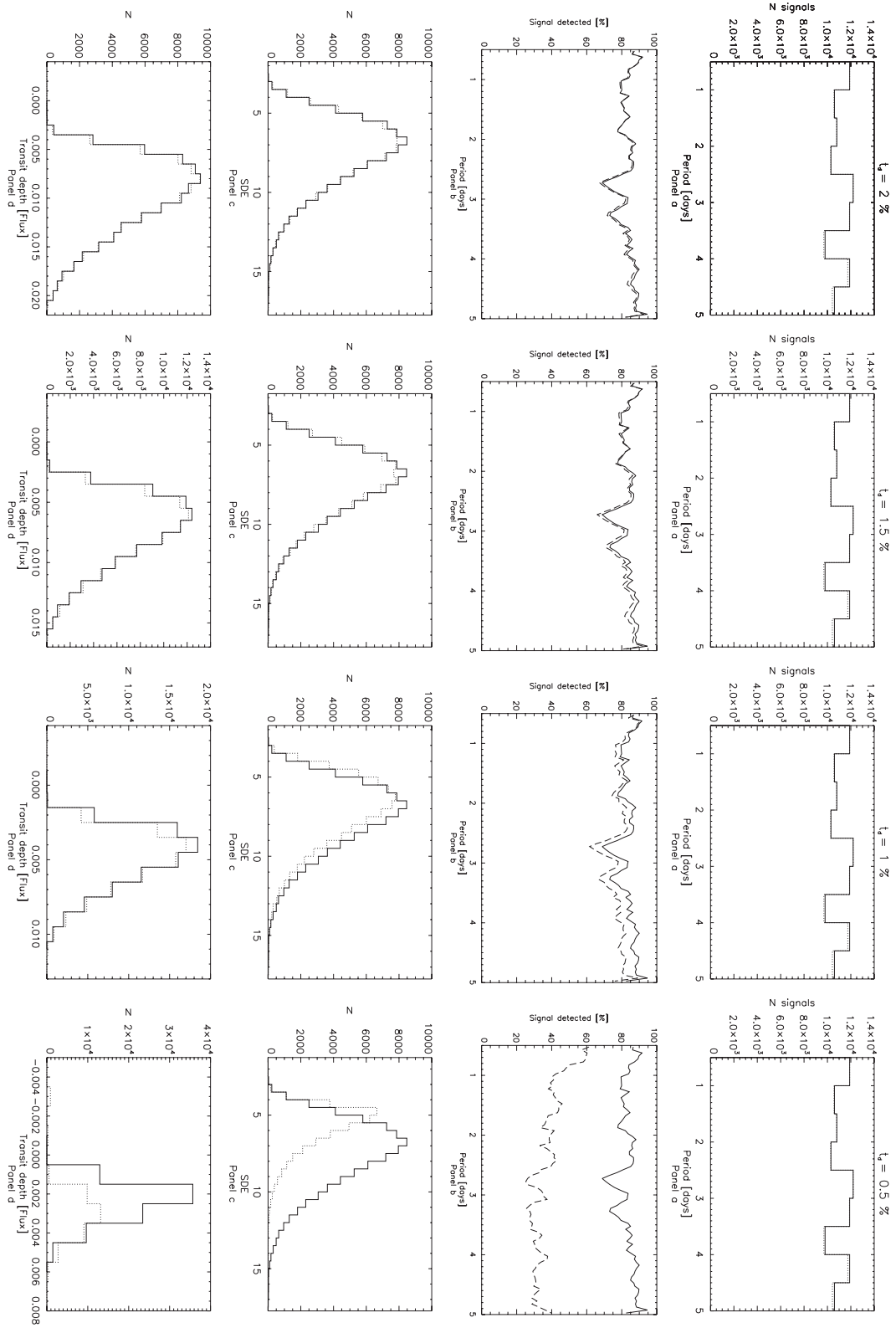


Figure 13. Summary of simulation output for LHS 176 (see the text for details). Panels (a): number of signals versus period; panels (b): detection probability versus period; panels (c): SDE distributions; panels (d): distributions of transit depths of the detected signals.

the distribution of the signal detection efficiency (SDE) parameter both for synthetic light curves (solid line) and for the combined light curves (dashed line). We remind the reader that a value for SDE, which quantifies the statistical robustness of a detected transit-like

periodic signal in the language of BLS, is computed as

$$\text{SDE} = \frac{\text{SR}_{\text{peak}} - \langle \text{SR} \rangle}{\text{sd}(\text{SR})}, \quad (6)$$

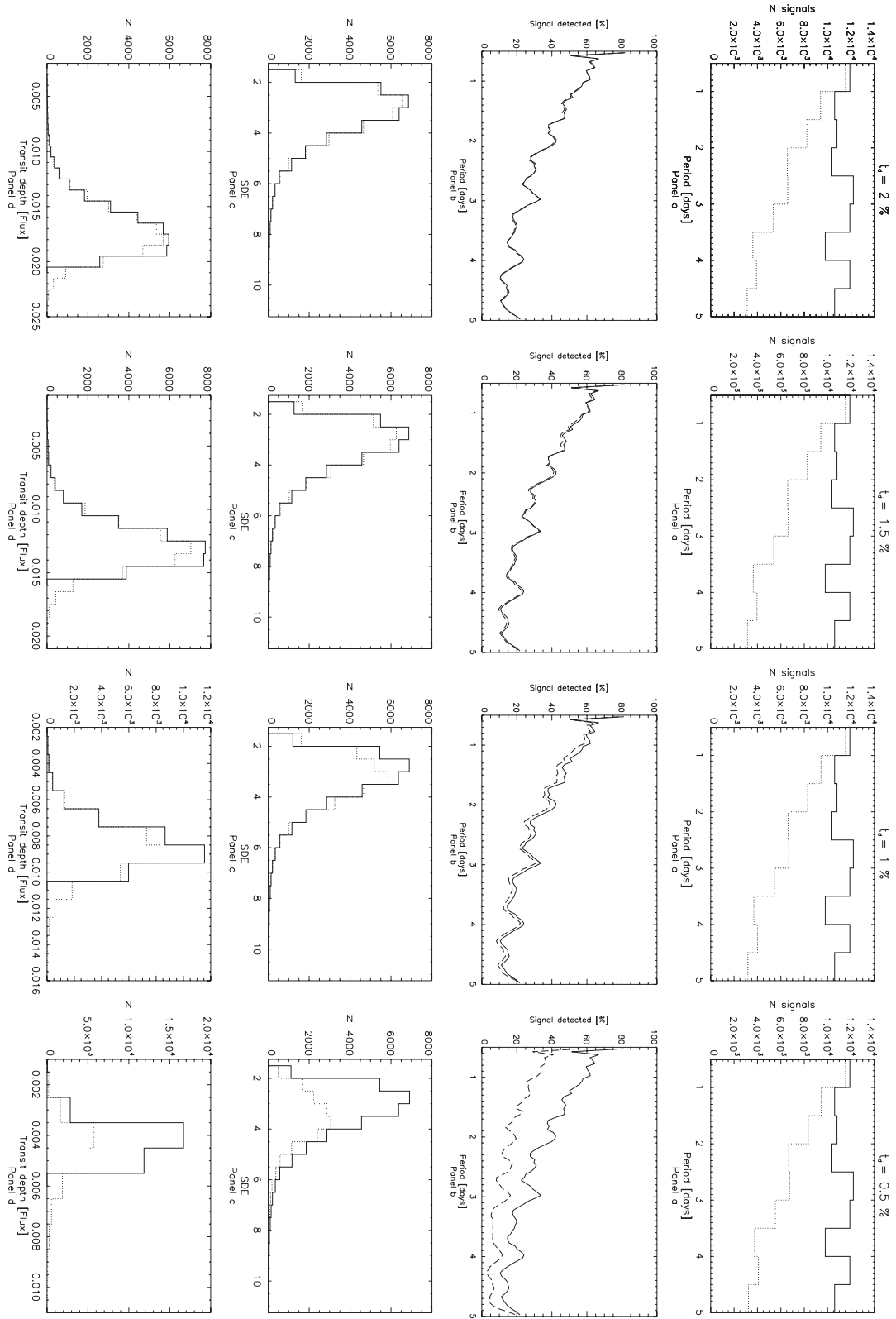


Figure 14. Summary of simulation output for LHS 417 (see the text for details). Panels (a): number of signals versus period; panels (b): detection probability versus period; panels (c): SDE distributions; panels (d): distributions of transit depths of the detected signals.

where SR_{peak} is the value of the peak in the SR distribution, while $\langle SR \rangle$ and $sd(SR)$ are, respectively, the mean and standard deviations of SR over the frequency band tested (see Kovács et al. 2002 for details). Finally, the last set of pan-

els (d) show the distribution of the transit depths of the detected signals as evaluated by BLS from the synthetic light curves (solid line) and from the combined light curves (dashed line).

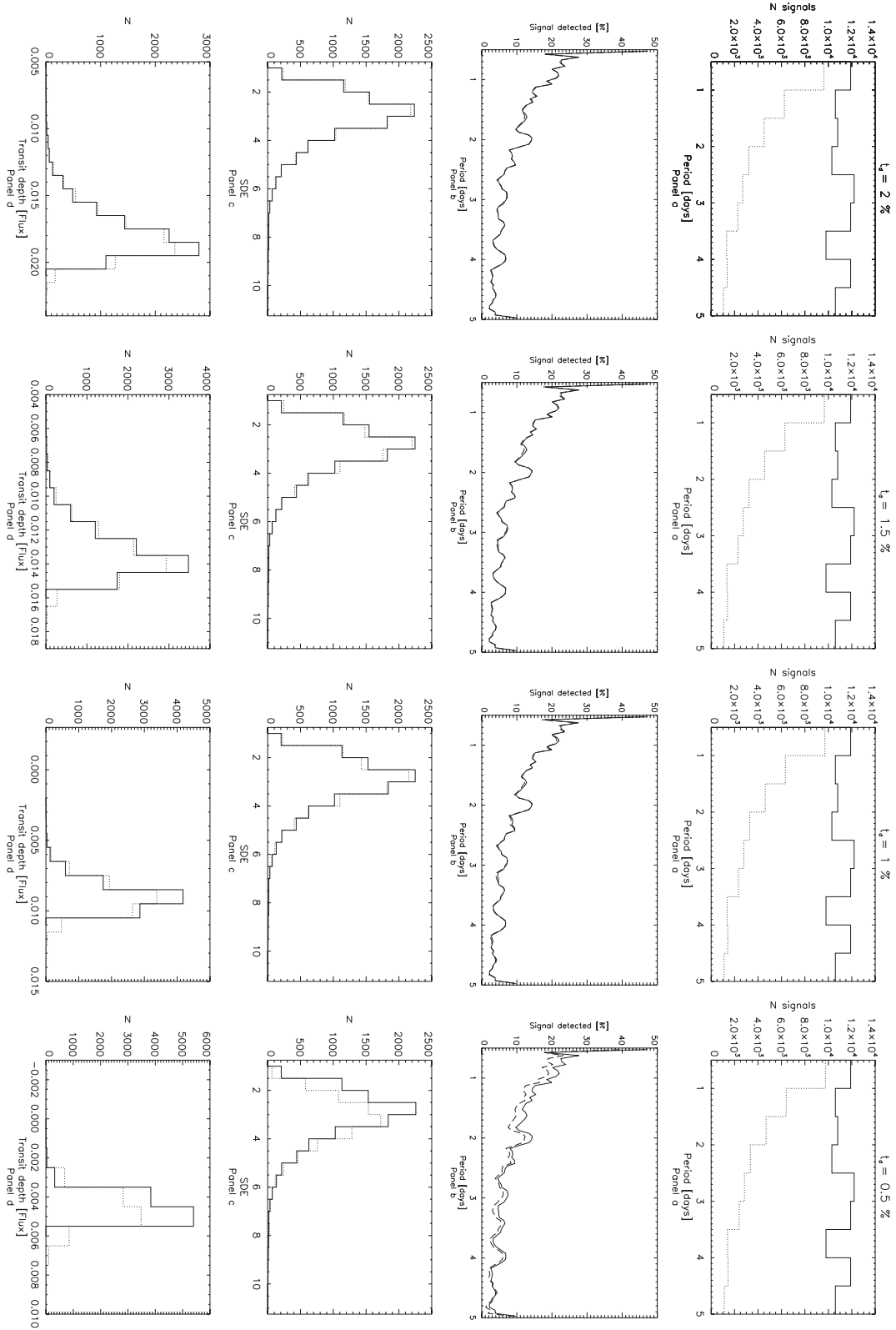


Figure 15. Summary of simulation output for LHS 3343 (see the text for details). Panels (a): number of signals versus period; panels (b): detection probability versus period; panels (c): SDE distributions; panels (d): distributions of transit depths of the detected signals.

For all three figures, panels (a) and (b) clearly illustrate the dependence of transit detection probability on period. As expected, this behaviour is very similar to the trend of phase coverage with period (see Fig. 12). Panels (b) also quantify the

amount of degradation in detection probability, with respect to the ‘noise-free’ case, when the transit depth approaches the typical photometric precision, even when the phase coverage is very good.

The three sets of panels (c) illustrate how the statistical significance of a detection, as measured by the SDE values, changes with phase coverage and signal depth. The values of SDE can also be used to quantify the probability of a detection being a false positive. The actual behaviour of SDE depends on many factors, some intrinsic to the algorithm (e.g. number of bins, number of trial periods) and others depending on the quality of the data and of the signal (e.g. S/N); however, the statistical studies (e.g. Kovács et al. 2002) indicate a value of SDE ~ 5 above which the false positive probability is low (< 10 per cent). Above such value, SDE does not depend on the input parameters of BLS (fig. 5 of Kovács et al. 2002). The plots in Fig. 13 show how the typical value of SDE decreases with the amplitude of the signal and with the phase coverage. In Figs 14 and 15 this trend is less evident. This is due to the SDE values fluctuating within a regime where the false positive probability is very high. The fact that many signals are detected with a low SDE highlights the robustness of the BLS algorithm, which is capable of uncovering weak and noisy signals albeit with low statistical confidence.

The analysis of the transit depth distribution, as shown in panels (d), is a further test of the BLS reliability. Generally, BLS provides a good estimate of the signal amplitude, but looking at the three figures an underestimation of the signal amplitude can be noticed. This is due to the initial parameters (number of bins, number of trial periods) of BLS that, in this case (in order to reduce the CPU time calculation), are insufficient to define precisely the ‘border’ of the signal. This effect appears to increase with phase coverage. This should be explained taking into account that the number of ‘spurious’ points increases with such phase coverage. To verify that this underestimate depends on the input parameters of BLS, we ran the algorithm on our archive data for the transiting planet WASP-3b (Damasso et al. 2010) increasing the number of trial periods to 10 000 (in the same range of the simulation) and the number of bins to 300, and we recovered a transit depth in good agreement with the published one (nearly 2 per cent).

The previous considerations allow us to relate directly the two comparison metrics whose properties we have analysed here, that is, transit detection probability and phase coverage. We show in Fig. 16, for the full stellar sample under investigation and using the simulation results based on light curves obtained with method

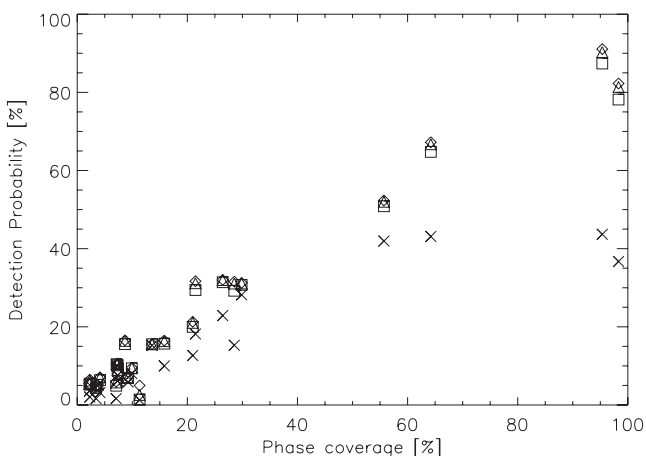


Figure 16. Average detection probability as a function of average phase coverage over the period range 0.5–5.0 d. Different symbols are used to show the trend of detection probability for the four regimes of transit depth simulated ($t_d = 2.0$ per cent: diamonds; $t_d = 1.5$ per cent: triangles; $t_d = 1.0$ per cent: squares; $t_d = 0.5$ per cent: crosses).

m3, detection probability as a function of phase coverage, both averaged over the whole period range 0.5–5.0 d. Different symbols are used to show the trend of detection probability for the four regimes of transit depth simulated. For the definitions of transit detection probability and phase coverage provided above, the plot suggests a limit to the probability of detecting a transit, at least utilizing a real-life detection algorithm such as BLS, even when the phase coverage is almost 100 per cent, a limit which becomes severe when the magnitude of the signal approaches the typical precision of the photometry. We believe that this effect is due to several factors, which include (but are not limited to): (i) the way we actually define a detection: as discussed above, we adopt here a conservative definition, likely contributing to missing some of the correctly identified transit depths simply because the period did not fall within the stringent agreement constraints required; (ii) the fact that detection probabilities are averaged over period ranges which include values (close to integer and half-integer days) not optimally sampled in a ground-based, single-site campaign (see Fig. 12); and (iii) the way we actually define the phase coverage: the choice of bin size and the prescription for the number of points in a bin required to define a specific phase covered can also impact the likelihood that the transit will be detected at that specific phase.

Similarly, Fig. 17 shows the trend of detection probability as a function of phase coverage when limiting ourselves to the period range 0.5–1.0 d. Overall, for objects with good (> 50 per cent) phase coverage, we would have had > 80 per cent chances of detecting transiting companions with transit depths in the range $0.5 < t_d \leq 2$ per cent. Given the estimated stellar radii for these stars, this translates into a sensitivity to companions with minimum radii in the range ~ 1.0 – $2.2 R_\oplus$. Fig. 17 also shows how, when enough transits (> 3) are observed, even signals of magnitude comparable to the photometric precision can be reliably retrieved in our data.

As mentioned earlier, the results shown here cover the analysis of the simulation based on light curves derived with the m3 photometric analysis method. The results based on the other three intra-night methods (not shown here) are very similar while they worsen significantly when the full-period light curves are considered. This is an expected result because those methods produce more noisy light curves (see Section 4.1). However, such an effect is a cause of no significant worries, as operationally transit like events, whose duration for objects in short periods does not exceed the typical length of observations during one single night, are to be searched for in nightly reduced differential photometric data sets.

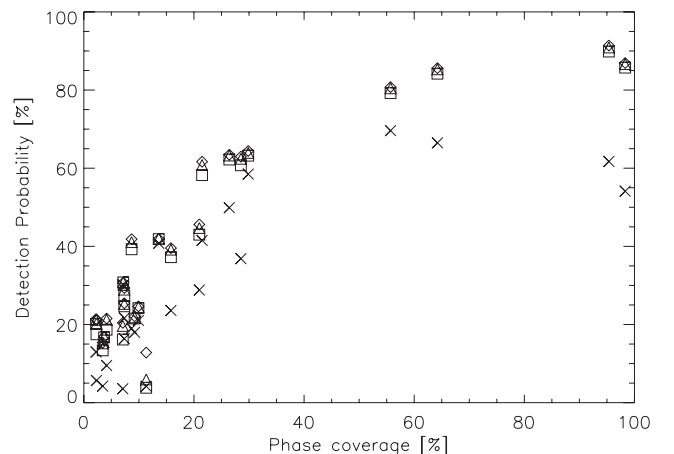


Figure 17. Average detection probability as a function of average phase coverage for $P < 1.0$ d. All symbols are as described in Fig. 16.

To conclude, two points are worth mentioning further here. First, in a large-scale survey of thousands of M dwarfs, while some degree of prioritization of the targets based on their measured and/or inferred variability properties (e.g. activity indicators and rotation information) will be possible, for many stars disregarding variability will simply not be an option. As for the two stars for which we successfully determined rotation periods, the probability of detection of a transit is not affected by the presence of the rotational modulation effect, as in both cases the time-scales of central transit events probed in our simulations (between 0.8 and 1.8 h for LHS 3445 and between 0.4 and 0.9 h for GJ 1167A) are significantly shorter than the observed rotational periods. Certainly, for much longer transit durations, or much shorter rotational periods, variability can instead become a matter of concern as it would directly interfere with a transit search. Rotational modulation on time-scales of 0.1 d is indeed observed (e.g. Irwin et al. 2011), and such an issue will be addressed and dealt with in detail in the future. Secondly, variable degrees of correlated noise, either instrumental (tracking, flat-fielding), environmental (airmass, absorption, seeing) or astrophysical (colour, variability) in nature, can also affect our capability to detect transits. As shown by Pont et al. (2006), red noise primarily impacts the significance thresholds with which a transit event can be recovered from the data in a survey. As discussed in Section 4.1.2, it constitutes a challenge to be able to fully characterize the relative role played by correlated noise sources on the potential of a photometric survey to detect statistically significant transit events, as this analysis will also depend on the details of the observed target populations. In the future, such an assessment will be made using our survey data and a statistically significant sample of targets.

5 SUMMARY AND CONCLUSIONS

We report results of a 1-yr-long photometric monitoring campaign of a sample of 23 nearby ($d < 60$ pc), bright ($J < 12$) M dwarfs carried out in Italy at OAVdA, using small-size (< 1 m class) telescopes. This survey was conceived as a necessary preparatory step towards a long-term search for transiting, small-radius planets around thousands of dM stars, which will be conducted at OAVdA with an array of automated 40-cm telescopes, beginning early 2012. This ‘pilot study’ was designed to achieve two goals: (i) demonstrate the sensitivity to $< 4 R_{\oplus}$ transiting planets with periods of a few days around our programme stars, through a two-fold approach that combines a characterization of the statistical noise properties of our photometry with the determination of transit detection probabilities via simulations; and (ii) where possible, improve our knowledge of some astrophysical properties (e.g. activity, rotation) of our targets through a combination of spectroscopic information and our differential photometric measurements. At a technical level, the results we obtained during the pilot study are instrumental to the accurate design and fine-tuning of several aspects of our upcoming photometric survey, such as the definition of the best observational strategy, the optimization of the target list, and the identification of improvements to be carried out on the pipeline for photometric data reduction and time-series periodicity analysis. Our main findings can be summarized as follows:

(1) *Photometric precision.* We achieve a typical nightly RMS photometric precision of ~ 5 mmag, with little or no dependence on the instrumentation adopted or on the details of the methodology (different comparison stars selection criteria, use of different detrending algorithms) utilized to perform differential photometry

on the targets. We also carried out an analysis of the impact of correlated (red) noise on time-scales of ~ 30 min, which showed that it is typically a factor of ~ 1.3 greater than pure white noise, with a weak dependence on the method used to perform differential photometry. This result reveals that our data are only mildly affected by short-term correlated systematics. The estimated photometric precision degrades to ~ 9 mmag when the ensemble light curves are determined over the typical ~ 2 months duration of the observations for each target. Such degradation is understood in terms of a combination of unmodelled medium-term systematics in our data and intrinsic variability of our target stars.

(2) *Stellar variability analysis.* We searched for periodic transit-like events in the photometric data set for each target using the BLS algorithm. No such signal was recovered for any target. This is an expected result, given the sample size; thus, meaningful constraints/upper limits on the planet fraction as a function of radius and orbital separation cannot be provided. The light curves of our programme stars were inspected for evidence of periodic signals of approximately sinusoidal shape, which could be interpreted as due to the presence of rotating spots on the stellar photosphere. For two stars in our sample, LHS 3445 and GJ 1167A, we found clear evidence of a periodicity in the light curve ascribable to such effect. We determined photometric rotation periods of ~ 0.47 and ~ 0.22 d for LHS 3445 and GJ 1167A, respectively; these estimates were confirmed by the large projected rotational velocities ($v \sin i \sim 25$ km s $^{-1}$ and $v \sin i \sim 33$ km s $^{-1}$, respectively) inferred for both stars based on the analysis of archival high-resolution Keck/HIRES spectra. The estimated inclinations of the stellar rotation axes for LHS 3445 and GJ 1167A agree with those derived using a simple spot model, which successfully reproduces the observed sinusoidal photometric variations in both cases (the dispersion of the post-fitting residuals is of the order of the sample photometric precision). Finally, we detected short-term, low-amplitude flaring events in the differential photometric measurements of LHS 3445 and LHS 2686 (the latter not known to be a flare star). LHS 3445 was observed flaring three times, and two flares were recorded almost consecutively during the same night, with an approximately equal decay time of ~ 4.5 min, possibly a case of homologous flares.

(3) *Sensitivity to small-radius transiting planets.* We carried out large-scale simulations of transit signals (of periods in the range 0.5–5 d and depths in the range 0.5–2 per cent in flux units) injected in the actual (nightly reduced) photometric data for our sample. A total of 400 000 light curves were analysed for each target using a real-life transit events search algorithm (BLS). The study of the BLS transit recovery rates and overall performance for a subsample of stars with good, fair and poor phase coverage highlighted the capability of BLS to identify the correct period (when multiple transits were observed) even for signals with depth close to the typical photometric precision of the data (~ 5 mmag), albeit with low statistical confidence, as well as some of its performance limitations which are driven by the specific choice of its most relevant setup parameters. We expressed our main findings in terms of two easy-to-use comparison metrics, that is, transit detection probabilities and phase coverage. We found a quasi-linear relationship between the two quantities. Based on the BLS algorithm, there appears to be a limit of ~ 90 per cent in the probability of detecting a transit even when the phase coverage approaches 100 per cent. Around stars in our sample with good phase coverage (> 50 per cent), we would have had > 80 per cent chances of detecting companions with $P < 1$ d and transit depths > 0.5 per cent in flux units. Correspondingly, around these stars we would have been sensitive to companions with radii as small as ~ 1.0 – $2.2 R_{\oplus}$.

The main findings reported here provide useful information for the purpose of the design and implementation of the operations of a ground-based M dwarf transit survey, with the aim of maximizing the chances for small-radius planet detection and improving our understanding of several astrophysically interesting properties of M dwarfs, particularly when investigated by means of statistical analyses of large stellar samples. Together with other similar efforts carried out by other groups, such as the pioneering MEarth programme, the photometric data base populated by our survey data will be of great help, for example (i) to improve the characterization of nearby M dwarf stars, when combined with *Gaia*'s exquisitely accurate astrometry (e.g. Sozzetti 2011); and (ii) to optimize the target selection criteria for red dwarfs which might be included in next-generation space-based transit survey programmes, such as *TESS* (Ricker et al. 2010) and *PLATO* (Rauer & Catala 2011) or which might be selected for spectroscopic characterization of planetary atmospheres of transiting planets found orbiting cool, nearby stars with future space-borne infrared observatories such as *EChO* (Tinetti et al. 2011) and *FINESSE* (Swain 2010).

A forthcoming paper will present in detail all relevant aspects of the upcoming survey, including overall system description, operation control software, target selection criteria, robust reduction pipeline and archiving.

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NEW VARIABLE STARS DISCOVERED FROM THE WESTERN ITALIAN ALPS. I.

OBSERVATIONS FROM FIELDS $12\text{hr} < \text{RA} < 24\text{hr}$

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Abstract: We present 20 new variable stars discovered at the Astronomical Observatory of the Autonomous Region of the Aosta Valley in the course of observations carried out from April to October 2010. The list of the newly discovered stars comprises 19 pulsating variables (two of them should be classified as Delta Scuti and 16 as Mira Ceti-type/Semi-Regular pulsators), and one W UMa eclipsing binary system. Our proposed variability classification relies on the properties of the optical differential light curves that we obtained using less than 1-meter class telescopes.

1. INTRODUCTION

We announce the discovery of 20 new variable stars (19 pulsating stars and one eclipsing binary system). The data discussed here are based on observations carried out at the Astronomical Observatory of the Autonomous Region of the Aosta Valley (OAVdA), in the Western Italian Alps, from April to October 2010, using less than 1-meter class optical telescopes. These data are only a part of our conspicuous database of photometric measurements collected since December 2009, and other new variable stars that we found will be published in a second paper (Giacobbe et al., in preparation). On December 2009 we started a one-year-long photometric survey of a small sample of nearby M dwarfs with the main goal of monitoring their optical microvariability over a period of several weeks, to assess in particular the implications for the detection of small-size transiting planets. This observing campaign, which we defined as a 'pilot study', represents a preparatory step toward the beginning of the project APACHE (A Pathway towards the Characterization of Habitable Earths), a new long-term survey of thousands of red dwarfs in the northern-hemisphere aimed at the detection of rocky planets using the photometric transit method (Damasso et al., 2011). The variables discussed here are stars which were present in the target fields observed during the pilot study.

2. INSTRUMENTATION AND METHODOLOGY

The observations for the pilot study were carried out using three small-class optical telescopes equipped with CCD cameras. Their main characteristics are summarized in Table 1. Every instrument was equipped with a set of BVRI standard filters. The data coming from the 250mm telescope were collected using an I filter, while the 400 and 810mm telescopes made use of R filters. This choice of the filters is a consequence of the primary aim of our survey, i.e. the photometric monitoring of red dwarfs. In this paper we discuss data collected with the 250 and 810mm telescopes, while in Giacobbe et al. (in preparation), where results from fields $00\text{hr} < \text{AR} < 12\text{hr}$ are presented, also data from the 400mm are shown.

The reduction and analysis of the CCD images were performed by the software package TEEPEE (Transiting Exoplanets PipEline) developed by the authors. A detailed description of the first version of

the TEEPEE pipeline, containing the basic functions preserved in the updated versions, is given in Damasso et al. (2010). The final result of the data processing is the generation of the differential light curves, obtained making use of aperture photometry, of all the stars in the CCD field which were automatically recognized in every frame of the series. In this way we were able to identify the variable stars present in each field after a visual inspection of the light curves. On the Y-axis of each light curve is indicated the differential magnitude obtained as the difference between the average instrumental magnitude of the selected comparison stars and the instrumental magnitude of the target. Using this convention, epochs of minimal differential magnitudes correspond to epochs of minimal brightness of the target.

The variables presented here showed a clear (or at least unambiguous) photometric behavior easily ascribable to one of the GCVS variability types. We discarded the objects with a low S/N ratio, the ones showing a type of variability not easy to classify or transit-like signals recorded at only one epoch, which are unuseful to determine the orbital period of the eclipsing system.

The updated version of TEEPEE package used to process the data is improved concerning the methods for the selection of the optimal aperture radius and set of reference stars for each observing session. Up to 12 different apertures are tested and the best set of comparison stars is automatically determined from a list of the 100 brightest objects in the field, excluding the ones too close to the CCD borders. The method we used to determine the best set of comparisons consists primarily in sorting the list of the possible 100 reference stars on the base of the RMS of their light curves, obtained from differential photometry with the other 99 candidate references. The aperture and set of reference stars selected at the end of the data processing are the ones which give the smallest RMS for the entire light curve of the object of interest. This means that the set of the best comparison stars found automatically changes on nightly basis for a particular object, and we did not use the same ensemble of comparisons for each observing session. That is the reason why we do not provide here the reference stars for each target.

In § 3.2 we discuss variables which show periods longer than 30 days. For these stars we produced light curves relative to the whole period of observation (66 days), obtained running TEEPEE over all the nights at once, i.e. treated as they were a single (long) observing session. The differential photometry was automatically performed on both newly discovered and already known variables using the best set composed of 39 comparison stars, which are detailed in Table 3.

The time series analysis of the light curves has been performed using two computer programs. One is PERIOD04 (<http://www.univie.ac.at/tops/Period04/>), which is a software to perform discrete Fourier transformation. Denoting with ω_i a significant frequency calculated with the Fourier decomposition, with A_i the corresponding amplitude of the frequency peak in the periodogram, and with ϕ_i the phase constant, the light curve of a target can be approximated, for each value of time t , with the analytical function $F(t) = C + \sum A_i [\sin(2\pi(\omega_i t + \phi_i))]$, where C is a zero-point constant and the sum is over all the significant frequencies calculated.

The second software is the PERIOD Time-Series Analysis Package (version 5.0; <http://www.starlink.rl.ac.uk/star/docs/sun167.htm/sun167.html>), which is a part of the STARLINK project, for analysis with the Lomb-Scargle algorithm implemented in for astronomical data processing (<http://starlink.jach.hawaii.edu/starlink>). The uncertainties in the variability periods which we report are internal minimum errors as evaluated by the software.

For some variables we performed a sinusoidal fit to their light curves, which we show in the plots. The fit algorithm used is implemented in the PERIOD package, fixing the period of the sine function to the one evaluated with the Lomb-Scargle procedure.

3. RESULTS AND DISCUSSION ON THE NEW VARIABLE STARS

The type of variability that we suggest for each object is necessarily based only on the characteristics showed by its differential light curve, because the discovery of such variables emerged from data collected for a different purpose and could not be improved with follow-up observations.

To confirm that our findings are really new variable stars, we checked the following Web-based catalogues: VizieR (<http://vizier.u-strasbg.fr/>), the International Variable Star Index

(<http://www.aavso.org/vsx/index.php>), the General Catalogue of Variable Stars (<http://www.sai.msu.su/groups/cluster/gcvs/gcvs/>), and the ASAS catalogue of variable stars (<http://www.astrouw.edu.pl/asas/?page=acvs>).

We adopted the books of Sterken and Jaschek (1996), Percy (2007) and Aerts et al. (2010) as the main resources to propose a classification for the new variable stars we observed.

The types of variability are coded according the GCVS classification. For each object we adopted the standard magnitudes reported by the NOMAD-1 catalogue, without correcting for absorption.

Table 2 summarizes the main information about the new variables found, including the suggested types of variability and the periods we were able to evaluate for the stars which clearly show periodical changes in their light curves.

In the following sections we discuss each variable star separately, according the order in Table 2. We divide the discussion in four paragraphs, each devoted to a particular field.

3.1 NOMAD-1 1367-0306809

This object was monitored for 13 nights starting from May 24th until July 18th, 2010, using the 250mm telescope. Due to its $V \sim 14$ magnitude and the small aperture of the telescope, the quality of the data for this star is not so good as for other targets in the field. We performed Fourier decomposition of the photometric time series, which then appears to be consistent with that of a pulsating star. We found 2 significant frequencies: $F1 = 5.78616777$ cycle/day (corresponding to a period $P = 0.172826$ days), and $F2 = 3.42487131$ cycle/day (corresponding to a period $P = 0.291982$ days). The frequency $F2$ represents the peak value in the periodogram calculated over the residuals O-C, obtained from the difference between the observed data points and the corresponding ones calculated with a sinusoidal fit using $F1$. The corresponding amplitudes and phase factors for $F1$ and $F2$ are: $A1 = 0.0162772765$, $\Phi1 = 0.19464$, $A2 = 0.0170448468$, $\Phi2 = 0.386117$. The zero-point factor is $C = 0.994236538$. In Fig. 1 we show the original light curve folded according the frequency $F1$ (plot a), the corresponding periodogram (plot b), the residuals O-C, folded according to the frequency $F2$ (plot c), and the frequency content of the residuals (plot d).

On the base of our data and the color information available from catalogues, we can not suggest a specific classification for this variable, only considering it a stellar pulsator with a good confidence.

3.2 A FIELD RICH OF MIRA AND SEMI-REGULAR VARIABLES

The new variable stars grouped in this paragraph were discovered in a field rich of red variables already reported in literature. In Fig. 2 we show the light curves that we obtained from our data for the known Mira-type variables KR Sge, LL Sge, LM Sge, LV Sge, LX Sge (Rosino and Guzzi, 1978), NSVS J1914429+190818 (Woźniak et al., 2004), and for the slow irregular L variable NSVS J1913242+192533 (Woźniak et al., 2004). On the AAVSO site, the latter object is suggested to have a period of 68 days which our data do not show, strengthening the hypothesis that this target is an irregular L variable. In order to support our hypothesis concerning the classification of the new stars discussed in this section, for comparison we report the color indexes of some of the Mira-type variables already known in the field (from NOMAD-1 photometry): $V-J = 10.953$, $V-H = 12.227$, $V-K = 12.966$ (LL Sge); $V-J = 7.289$, $V-H = 8.487$, $V-K = 8.927$ (LM Sge); $V-J = 10.469$, $V-H = 11.727$, $V-K = 12.464$ (LV Sge); $V-J = 8.551$, $V-H = 9.663$, $V-K = 10.269$ (LX Sge).

All the data from this field were collected using the 250mm telescope during observations spanning 66 days. The periods that we suggest for the new long-period variables should all be considered as tentative. The periodograms have been calculated assuming as the maximum frequency the Nyquist frequency ($F_N = 724$ cycle/day), and no significant peaks are present out of the frequency range selected for the plots (from 0 to 10 cycle/day).

3.2.1 NOMAD-1 1095-0380434

This is probably a red giant star with color indexes $V-J = 6.008$, $V-H = 7.118$ and $V-K = 7.53$. Fig. 3 shows the data for this object, which appears to be a SR (Semi-Regular) pulsating star with an estimated period $P \sim 39$ days and a peak-to-peak amplitude of ~ 0.056 mag (as estimated from a sinusoidal fit). The data are folded according the ephemeris $HJD(\text{phase}=0) = 2,455,371.51438 + P \cdot N$.

3.2.2 NOMAD-1 1093-0380200

This is a highly red star with color indexes $V-J=9.047$, $V-H=10.352$ and $V-K=11.134$. Fig. 4 shows the light curve for this star, which is very similar to the one observed for the Mira-type star LV Sge (Fig. 2) and is characterized by a steady dimming of nearly 1 mag over two months. We suggest for this star a classification as a Mira or SR variable.

3.2.3 NOMAD-1 1095-0380572

This is probably a red giant star with color indexes $V-J=7.698$, $V-H=8.874$ and $V-K=9.378$. Fig. 5 shows the data for this object, for which we may suggest a classification as SR pulsating star. The peak-to-peak amplitude is ~ 0.33 mag, as estimated from a sinusoidal fit.

3.2.4 NOMAD-1 1095-0381014

This is probably a red giant star with color indexes $V-J=7.548$, $V-H=8.672$ and $V-K=9.148$. Fig. 6 shows the data for this object, which appears to be a SR pulsating star with a tentative period $P \sim 54$ days and a peak-to-peak amplitude of ~ 0.2 mag (as estimated from a sinusoidal fit). The data are folded according the ephemeris $HJD (\text{phase}=0) = 2,455,371.51438 + P \cdot N$.

3.2.5 NOMAD-1 1095-0381250

This is probably a red giant star with color indexes $V-J=7.559$, $V-H=8.701$ and $V-K=9.156$. Fig. 7 shows the data for this object, which does not show a periodicity less than 66 days. This star may be classified as a Mira or SR variable.

3.2.6 NOMAD-1 1090-0387525

This is probably a red giant star with color indexes $V-J=7.461$, $V-H=8.628$ and $V-K=9.124$. Fig. 8 shows the data for this object, which appears to be a SR pulsating star with an estimated period $P \sim 42$ days and a peak-to-peak amplitude of ~ 0.24 mag (as estimated from a sinusoidal fit). The data are folded according the ephemeris $HJD (\text{phase}=0) = 2,455,371.51438 + P \cdot N$.

3.2.7 NOMAD-1 1093-0381534

This is probably a red giant star with color indexes $V-J=8.404$, $V-H=9.589$ and $V-K=10.108$. In Fig. 9 the light curve is showed, which does not show a periodicity less than 66 days. This star may be classified as a Mira or SR variable.

3.2.8 NOMAD-1 1095-0382124

This is probably a red giant star with color indexes $V-J=7.182$, $V-H=8.367$ and $V-K=8.842$. Fig. 10 shows the data for this object, which appears to be a SR pulsating star with a tentative period $P \sim 54$ days and a peak-to-peak amplitude of ~ 0.16 mag (as estimated from a sinusoidal fit). The data are folded according the ephemeris $HJD (\text{phase}=0) = 2,455,371.51438 + P \cdot N$.

3.2.9 NOMAD-1 1090-0388621

This is a highly red star with color indexes $V-J=10.823$, $V-H=12.102$ and $V-K=12.706$. In Fig. 11 the light curve is showed, which does not show a clear periodicity less than 66 days. This star could be classified as a Mira or SR variable.

3.2.10 NOMAD-1 1091-0387997

This is probably a red giant star with color indexes $V-J=8.163$, $V-H=9.39$ and $V-K=9.893$. Fig. 12 shows the data for this object, which may be a M/SR pulsating star.

3.2.11 NOMAD-1 1093-0382699

This is probably a red giant star with color indexes $V-J=7.318$, $V-H=8.469$ and $V-K=9.0$. Fig. 13 shows the data for this object, which may be a M/SR pulsating star with a tentative period $P \sim 63$ days and a peak-to-peak amplitude of ~ 0.36 mag (as estimated from a sinusoidal fit). Data are folded according the ephemeris $HJD (\text{phase}=0) = 2,455,371.51438 + P \cdot N$.

3.2.12 NOMAD-1 1090-0389865

This is probably a red star with color indexes $V-J=8.021$, $V-H=9.27$ and $V-K=9.81$. In Fig. 14 the light curve is showed, which does not show a clear periodicity less than 66 days. This star may be classified as a Mira or SR variable.

3.2.13 NOMAD-1 1094-0383234

This is probably a red giant star with color indexes $V-J=6.008$, $V-H=7.118$ and $V-K=7.53$. Fig. 15 shows the data for this object, which appears to be a SR pulsating star with a period $P \sim 45$ days and a peak-to-peak amplitude of ~ 0.18 mag (as estimated from a sinusoidal fit). Data are folded according the ephemeris $HJD (\text{phase}=0) = 2,455,371.51438 + P \cdot N$.

3.2.14 NOMAD-1 1092-0387428

This is a highly red star with color indexes $V-J=8.542$, $V-H=9.682$ and $V-K=10.289$. Fig. 16 shows the original light curve, which is very similar to the one of the star in Fig. 4 and is characterized by a monotonic dimming of nearly 1.2 mag over two months. We suggest for this star a classification as a Mira or SR variable.

3.2.15 NOMAD-1 1091-0389915

This is probably a red giant star with color indexes $V-J=7.167$, $V-H=8.32$ and $V-K=8.781$. Fig. 17 shows the data for this object, which appears to be a SR pulsating star with a tentative period $P \sim 62$ days and a peak-to-peak amplitude of ~ 0.24 mag (as estimated from a sinusoidal fit). The sinusoidal fit to this light curve reveals that its profile is asymmetric. Data are folded according the ephemeris $HJD (\text{phase}=0) = 2,455,371.51438 + P \cdot N$.

3.2.16 NOMAD-1 1092-0388944

This is probably a red giant star with color indexes $V-J=6.504$, $V-H=7.713$ and $V-K=8.168$. Fig. 18 shows the data for this object, which appears to be a SR pulsating star with some changes in the amplitude of the light curve. From our data we can only guess a possible periodicity of ~ 30 days. It is probably a SRb variable, but it would be necessary to observe more cycles in order to properly define its variability type.

3.3 NOMAD-1 1077-0767537

This star was observed with the 250mm telescope. We performed Fourier decomposition of the light curve, finding 2 significant frequencies: $F1=7.45248337$ cycle/day (corresponding to a period $P=0.134183$ days), and $F2=4.52912947$ cycle/day (corresponding to a period $P=0.220793$ days). The frequency $F2$ corresponds to the peak value in the periodogram calculated over the residuals O-C, obtained from the difference between the observed data points and the corresponding ones calculated with a sinusoidal fit using $F1$. The corresponding amplitudes and phase constants are: $A1=0.072678217$, $\Phi1=0.492082$, $A2=0.0247829231$, $\Phi2=0.99022$. The zero-point factor is $C=1.00239438$. In Fig. 19 we show the light curve folded according the frequency $F1$ (plot a), the corresponding periodogram (plot b), the residuals O-C, folded according the frequency $F2$ (plot c), and the periodogram with the frequency content of the residuals (plot d). Considering that the peak-to-peak amplitude is ~ 0.15 mag and that this star is characterized by color indexes $B-V=0.55$, $V-R=0.29$, $V-J=0.832$ and $V-K=1.18$, which are compatible with a main sequence late-F star, we suggest for this pulsator a classification as a DSCT.

3.4 NOMAD-1 1617-0165649

This object was observed for 37 nights by the 810mm telescope and clearly shows the properties of an eclipsing binary of W UMa type. The estimated rotation period of the components is $P=0.35517 \pm 0.00001$ days. Fig. 20 shows the folded data (averaged in 200 bins), with ephemeris $HJD = 2,455,440.54030 + P \cdot N$. It is evident from the plot the presence of asymmetries close to the minima and maxima of the light curve. Fig. 21 shows four different epochs of observations which demonstrate that the shape of the light curve changed from epoch to epoch. This variability should be attributed to the presence of spotted regions on the surfaces of both stars. Our hypothesis is based on the fact that W Uma-type objects are usually heavily spotted systems, as theoretically predicted by Binnendijk (1970), who was the first to propose that dark spots exist on the surfaces of W UMa eclipsing binary systems to explain the asymmetry and variability of

the light curves at different epochs, and later demonstrated by doppler imaging (see for instance Hendry & Mochnecki, 2000).

3.5 NOMAD-1 1616-0162705

This object was observed for 37 nights by the 810mm telescope and it appears to be a purely radial pulsator with a period $P=0.10073\pm0.00001$ days. In Fig. 22 we show the folded light curve (80 bins), according the ephemeris $HJD(\text{min})=2,455,482.39845+P*N$, and the periodogram. The shape of the curve appears highly symmetric and the peak-to-peak amplitude is ~ 0.033 mag (evaluated with a sinusoidal fit, which is superposed to the data in the first panel of Fig. 22). The color indexes are $B-V=0.68$, $V-J=1.058$ and $V-K=1.361$ which, taking into account the reddening, are compatible with a very-late F main sequence star. We suggest that this star may be classified as a DSCT variable.

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Table 1 – Summary of the main characteristics of the telescope systems used in OAVdA for the pilot study, a preparatory campaign for the upcoming APACHE survey.

Optical scheme	Telescope		CCD camera		Resulting configuration	
	Aperture (mm)	Focal ratio	Sensor area (pixel)	Pixel area (μm)	FoV (arcmin)	Plate scale ("/pixel)
Reflector Maksutov	250	f/3.80	2184×1472	6.8×6.8	52.10×35.11	1.43 (binning 1×1)
Reflector Ritchey-Chrétien	400	f/7.64	1024×1024	24×24	26.4×26.4	1.55 (binning 1×1)
Reflector Ritchey-Chrétien	810	f/7.90	2048×2048	15×15	16.3×16.3	0.48 (binning 1×1)

Table 2 – Summary of the new variable stars discussed in this paper.

Star ID NOMAD-1	Star ID GSC2.3	RA (J2000)	DEC (J2000)	Vmag (NOMAD-1)	Types of suggested variability (GCVS codes)	Delta mag R (mag)*	Estimated period (days)**
1367-0306809	N4CJ000080	17:54:04	46:42:04	13.84	pulsator	~0.05	0.172826 (frequency F1) 0.2919818 (frequency F2)
1095-0380434	N26S095788	19:12:46	19:31:42	14.66	SR	0.056	~39
1093-0380200	N26S074080	19:12:49	19:20:49	16.88 (GSC2.3)	M/SR	~0.8	-
1095-0380572	N26S094790	19:12:51	19:31:11	17.97	SR	0.33	-
1095-0381014	N26S096123	19:13:08	19:31:58	15.99	SR	0.2	~53
1095-0381250	N26S094065	19:13:17	19:30:38	16.01	M/SR	0.31	-
1090-0387525	N26S044948	19:13:24	19:04:44	17.97	SR	0.24	~42
1093-0381534	N26S071251	19:13:42	19:19:10	16.9	M/SR	~0.29	-
1095-0382124	N26V001429	19:13:52	19:32:36	16.54	SR	0.16	~55
1090-0388621	N26S041190	19:14:01	19:02:13	17.59	M/SR	0.31	-
1091-0387997	N26S055576	19:14:22	19:10:56	17.05	M/SR	0.38	-
1093-0382699	N26S070220	19:14:29	19:18:49	16.5	SR	0.36	~63
1090-0389865	N26S045637	19:14:42	19:05:09	16.21	M/SR	~0.27	-
1094-0383234	N26S090324	19:14:49	19:29:04	16.86	SR	0.18	~45
1092-0387428	N26S068589	19:15:13	19:17:57	17.97	M/SR	~1.3	-
1091-0389915	N26S047973	19:15:31	19:06:31	15.05	SR	0.24	~62
1092-0388944	N26S060821	19:16:06	19:13:41	15.93	SR(b)	~0.11	close to 30 days?
1077-0767537	N0LW000410	22:40:30	17:43:59	14.3	DSCT	0.15	0.134183 (frequency F1) 0.220793 (frequency F2)
1617-0165649	N0WB000244	23:05:55	71:44:20	13.58	EW	0.42	0.35517 ± 0.00001
1616-0162705	N0WB000269	23:07:12	71:40:27	13.1	DSCT	0.033	0.10073 ± 0.00001

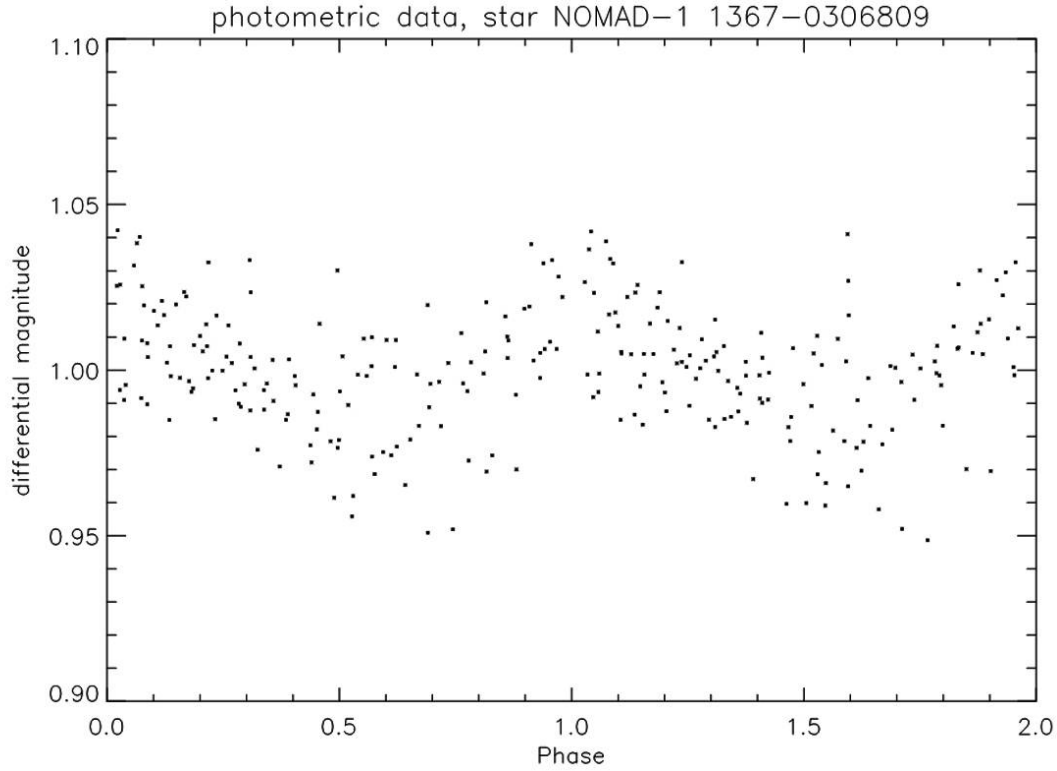
*For the long-period variables, this represents the magnitude range for the epochs spanning 66 days. For the variables for which we performed a sine fit we provide the estimated peak-to-peak amplitude.

**For the long-period variables, these represent tentative estimations assuming constant periods.

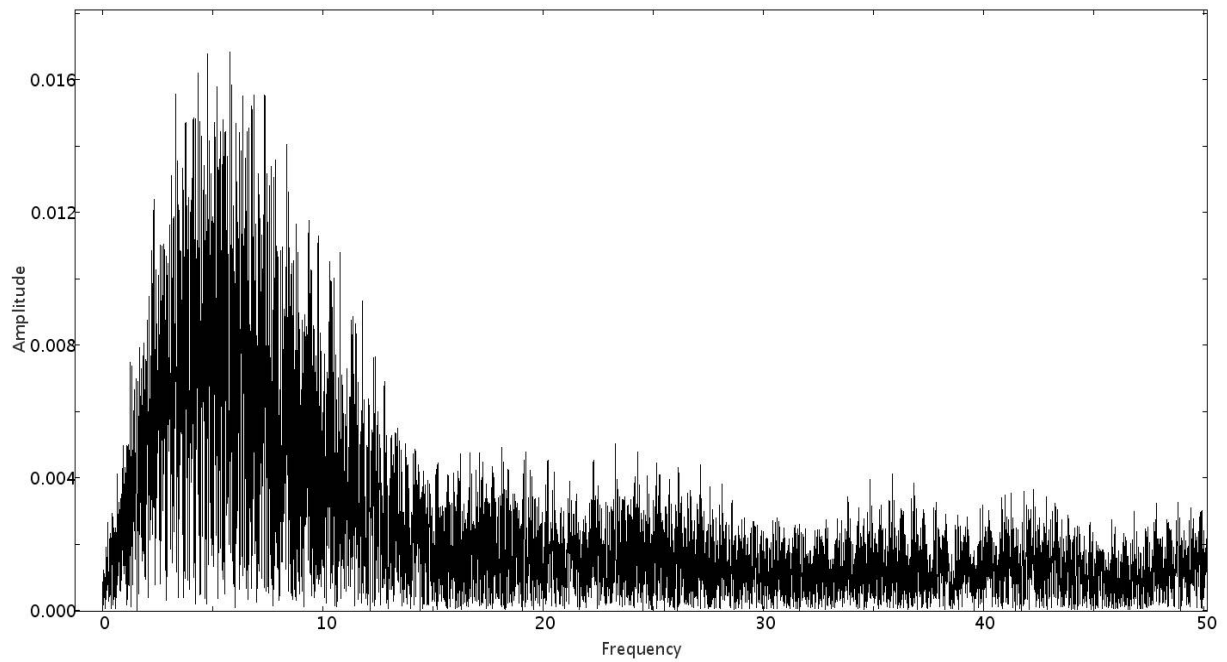
Table 3 – Summary of the comparison stars used to produce the aperture differential light curves in § 3.2.

Star ID	RA (J2000)	DEC (J2000)
HD 179585	19:12:26	19:12:30
NOMAD-1 1094-0380020	19:12:48	19:27:50
HD 349865	19:12:49	19:14:09
NOMAD-1 1093-0380254	19:12:51	19:23:30
NOMAD-1 1093-0380321	19:12:54	19:23:43
NOMAD-1 1095-0380824	19:13:01	19:32:08
HD 230897	19:13:03	19:27:54
NOMAD-1 1092-0383952	19:13:06	19:17:10
HD 349866	19:13:10	19:06:17
NOMAD-1 1091-0386017	19:13:12	19:08:52
NOMAD-1 1094-0380742	19:13:17	19:27:03
NOMAD-1 1092-0384276	19:13:18	19:14:33
NOMAD-1 1095-0381269	19:13:18	19:34:24
NOMAD-1 1094-0380805	19:13:19	19:24:19
NOMAD-1 1092-0384504	19:13:27	19:13:28
HD 230917	19:13:27	19:16:44
NOMAD-1 1090-0388005	19:13:40	19:04:51
NOMAD-1 1091-0386917	19:13:44	19:11:32
NOMAD-1 1094-0382002	19:14:02	19:27:02
HD 349904	19:14:05	19:25:51
HD 230964	19:14:19	19:23:15
NOMAD-1 1092-0385942	19:14:20	19:12:44
NOMAD-1 1092-0385932	19:14:20	19:13:35
NOMAD-1 1095-0382811	19:14:21	19:31:03
NOMAD-1 1093-0382587	19:14:24	19:20:57
NOMAD-1 1090-0389434	19:14:28	19:05:43
NOMAD-1 1094-0382867	19:14:35	19:28:42
NOMAD-1 1094-0382904	19:14:36	19:27:10
LHS 3446	19:14:39	19:18:21
NOMAD-1 1093-0382957	19:14:39	19:19:53
NOMAD-1 1093-0383117	19:14:45	19:18:48
NOMAD-1 1092-0386657	19:14:46	19:13:25
NOMAD-1 1090-0390061	19:14:48	19:03:42
NOMAD-1 1092-0387379	19:15:11	19:15:05
NOMAD-1 1091-0389571	19:15:18	19:11:16
HD 231005	19:15:22	19:02:06
NOMAD-1 1090-0391122	19:15:22	19:04:01
TYC 1607-1253-1	19:15:25	19:13:16

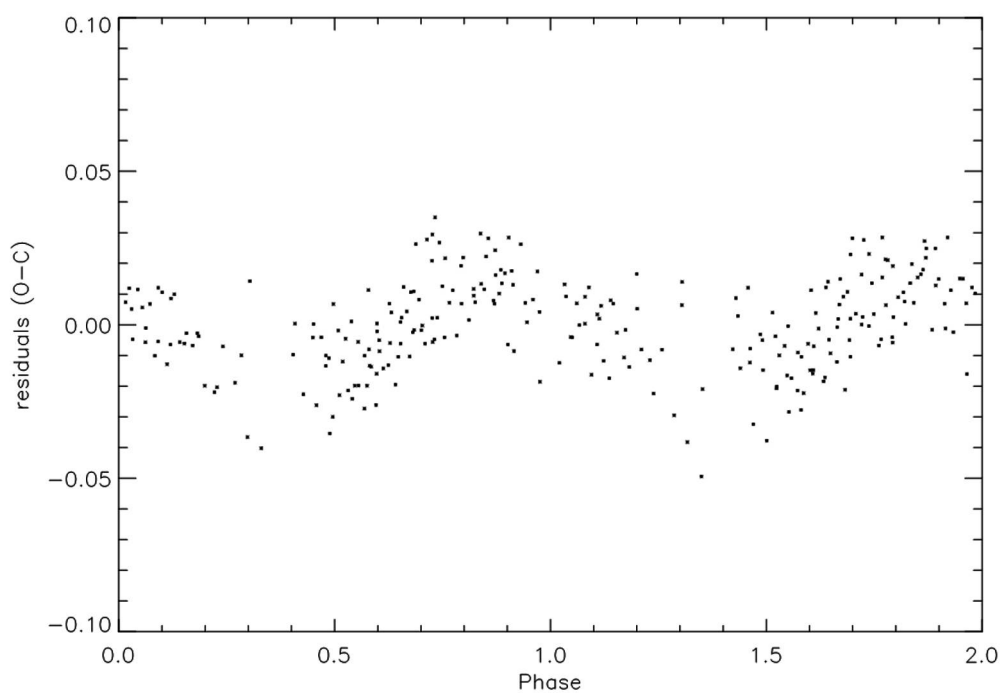
Figure 1 – (a) Light curve of the pulsating star NOMAD-1 1367-0306809 phased according the peak frequency $F1=5.78616777$ cycle/day. (b) Periodogram showing the frequency content of the original data. (c) Residuals O-C phased according the frequency $F2=3.42487131$ cycle/day, showing that they contain a significant periodicity. (d) Periodogram showing the frequency content of the residuals. (e) Finding chart for the target.



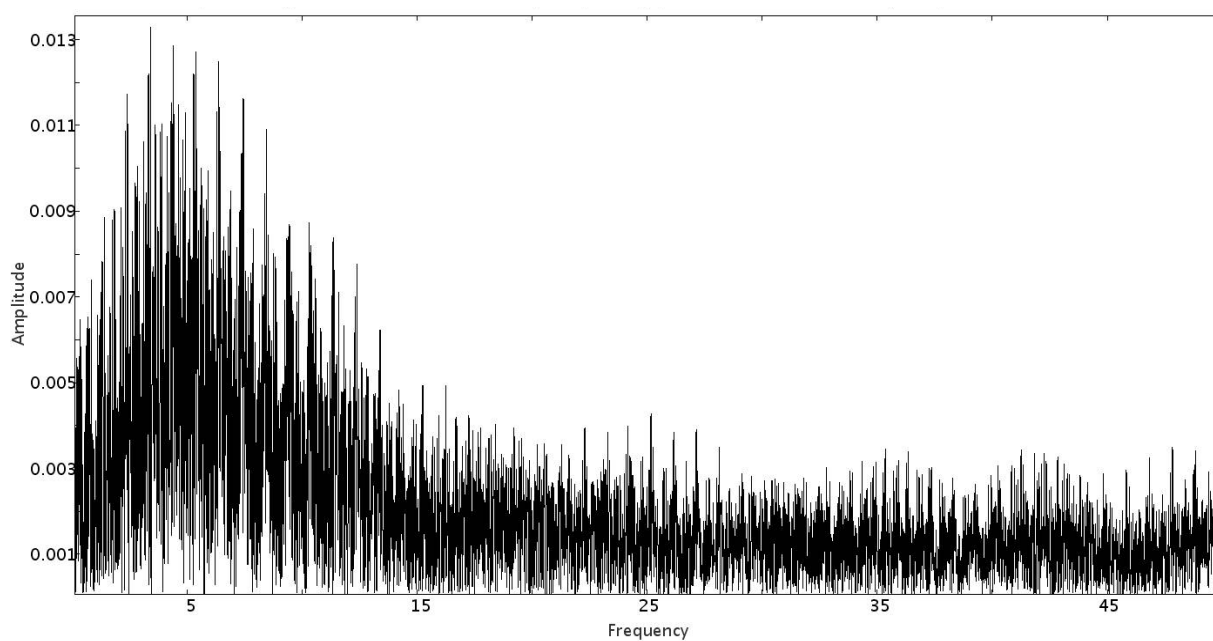
(a)



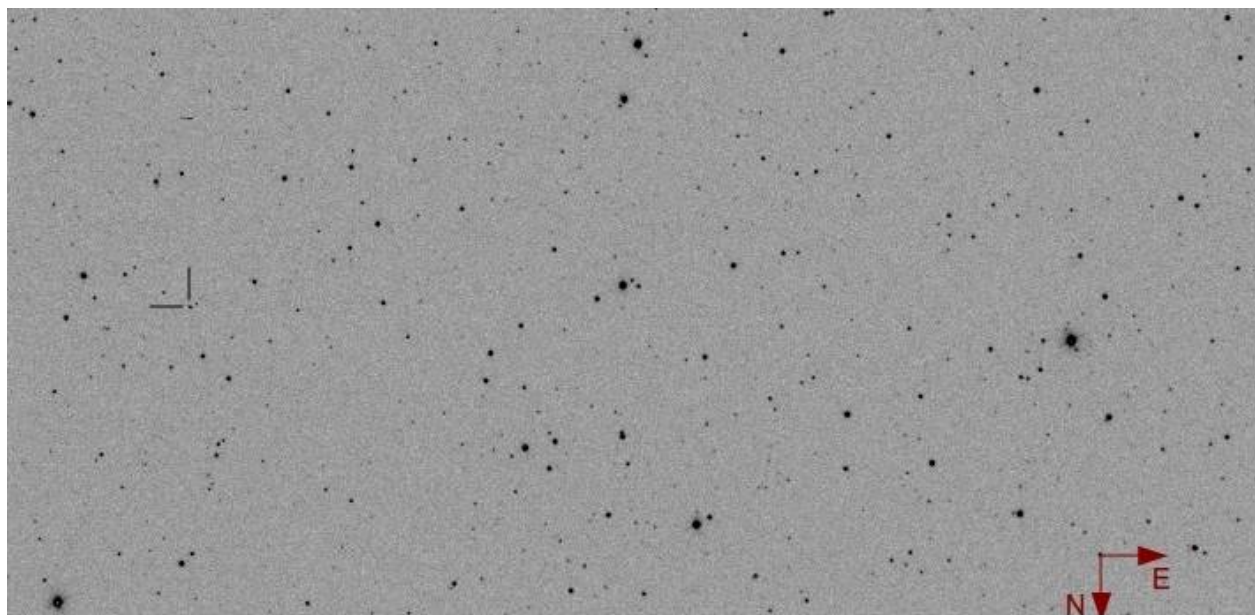
(b)



(c)

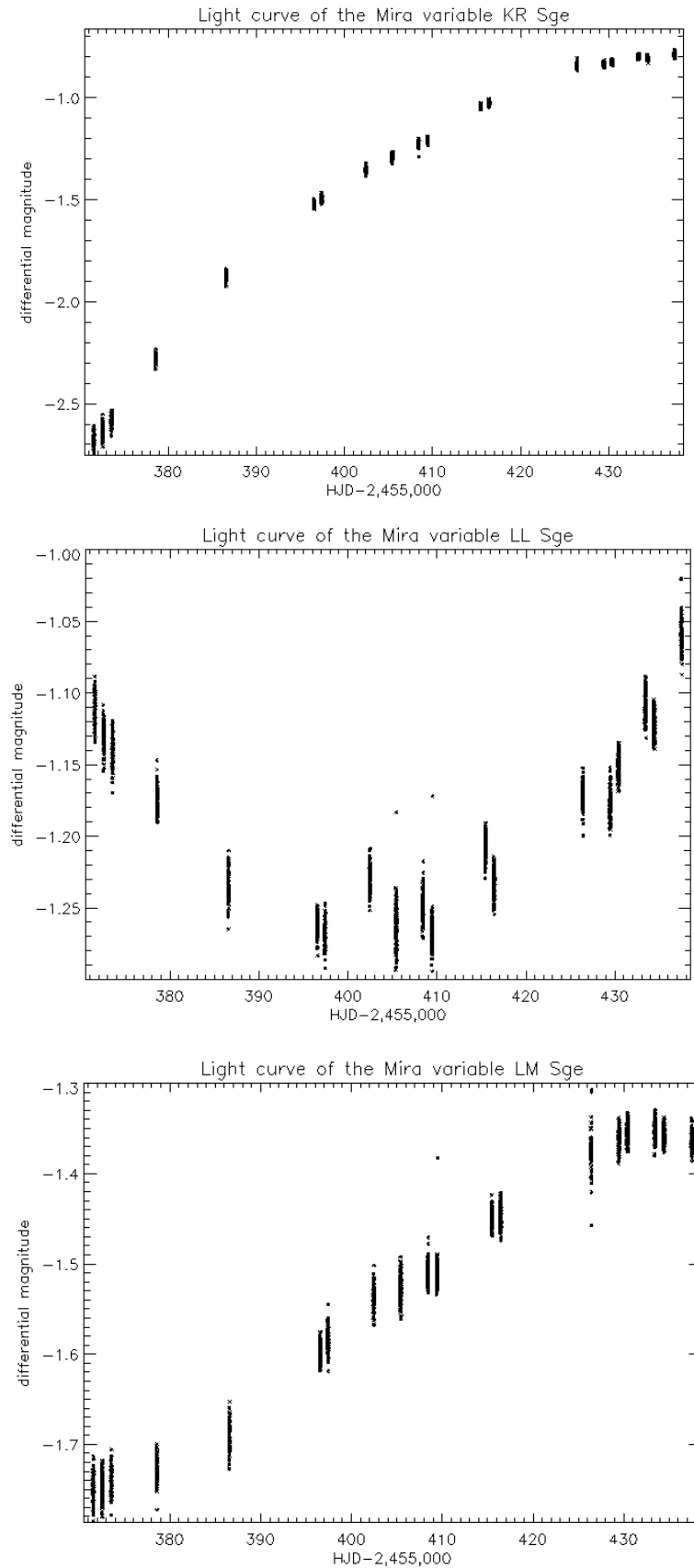


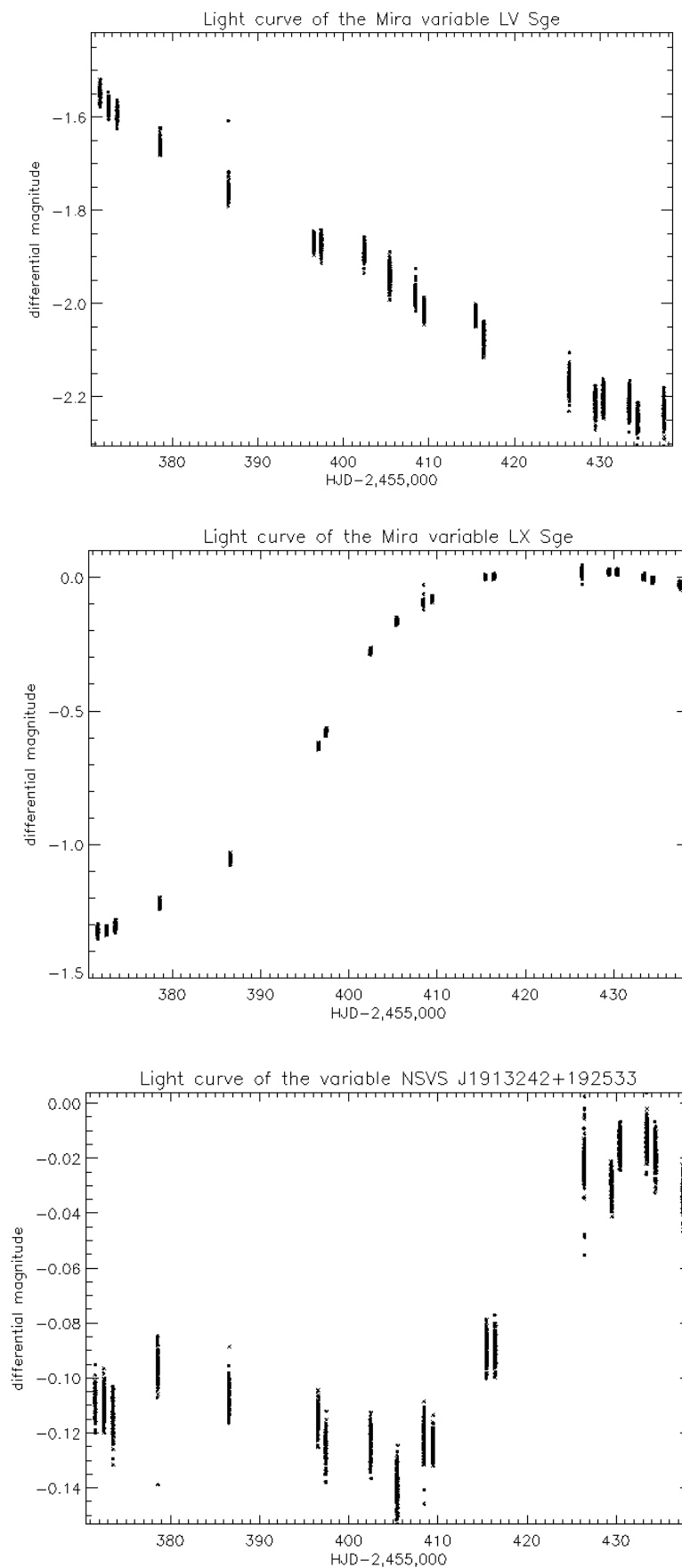
(d)



(e)

Figure 2 – Light curves of the known red variables KR Sge, LL Sge, LM Sge, LV Sge, LX Sge, NSVS J1913242+192533 and NSVS J1914429+190818. The quality of our data proves the reliability of the results provided by our pipeline TEEPEE.



(Fig. 2 continued)

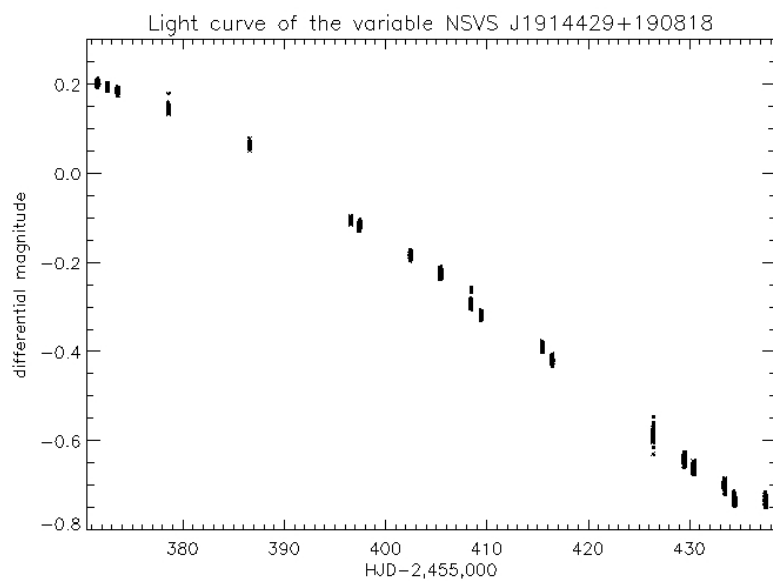
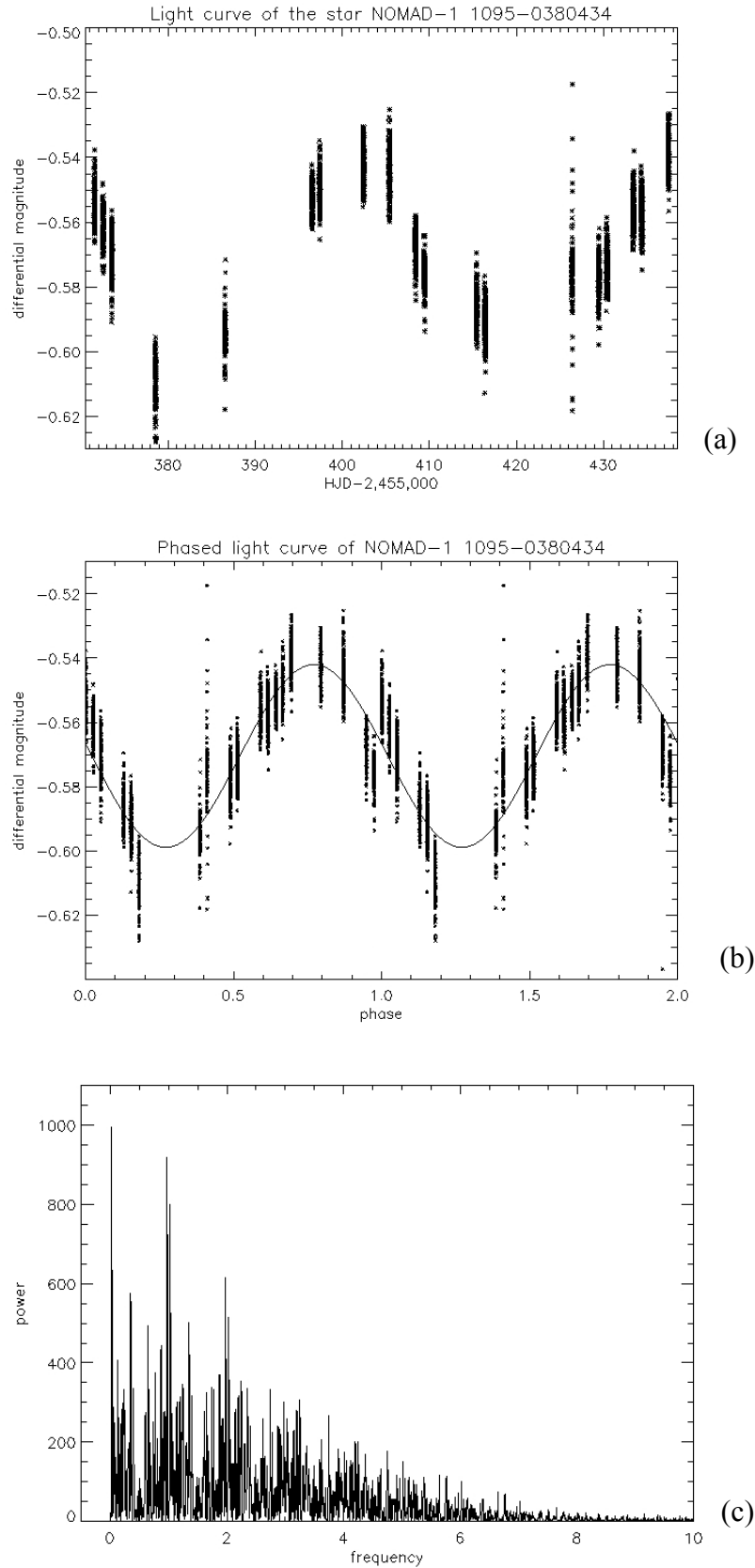
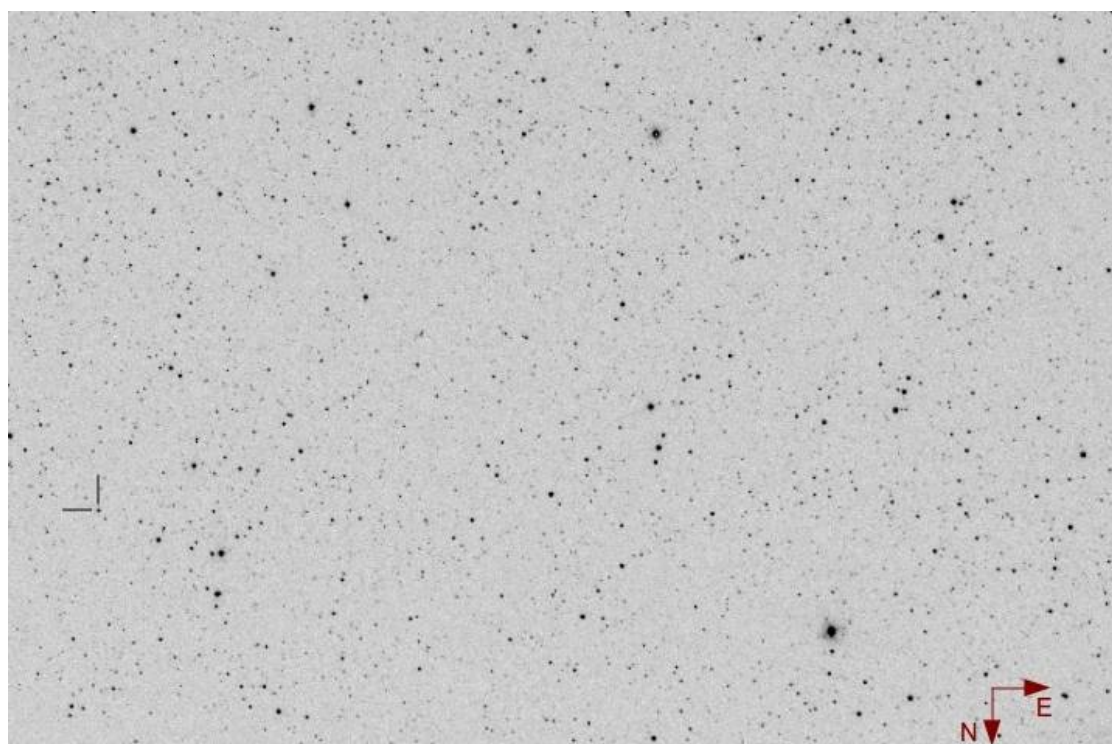
(Fig. 2 continued)

Figure 3 – (a) Original light curve of the star NOMAD-1 1095-0380434. (b) The phased light curve. Overplotted is the best fit sine curve. (c) The Lomb-Scargle periodogram. The peak frequency corresponds to the period P indicated in Table 2. (d) Finding chart for the target.





(d)

Figure 4 – (Up) Light curve of the star NOMAD-1 1093-0380200. This is probably a Mira or a SR pulsator. (Down)

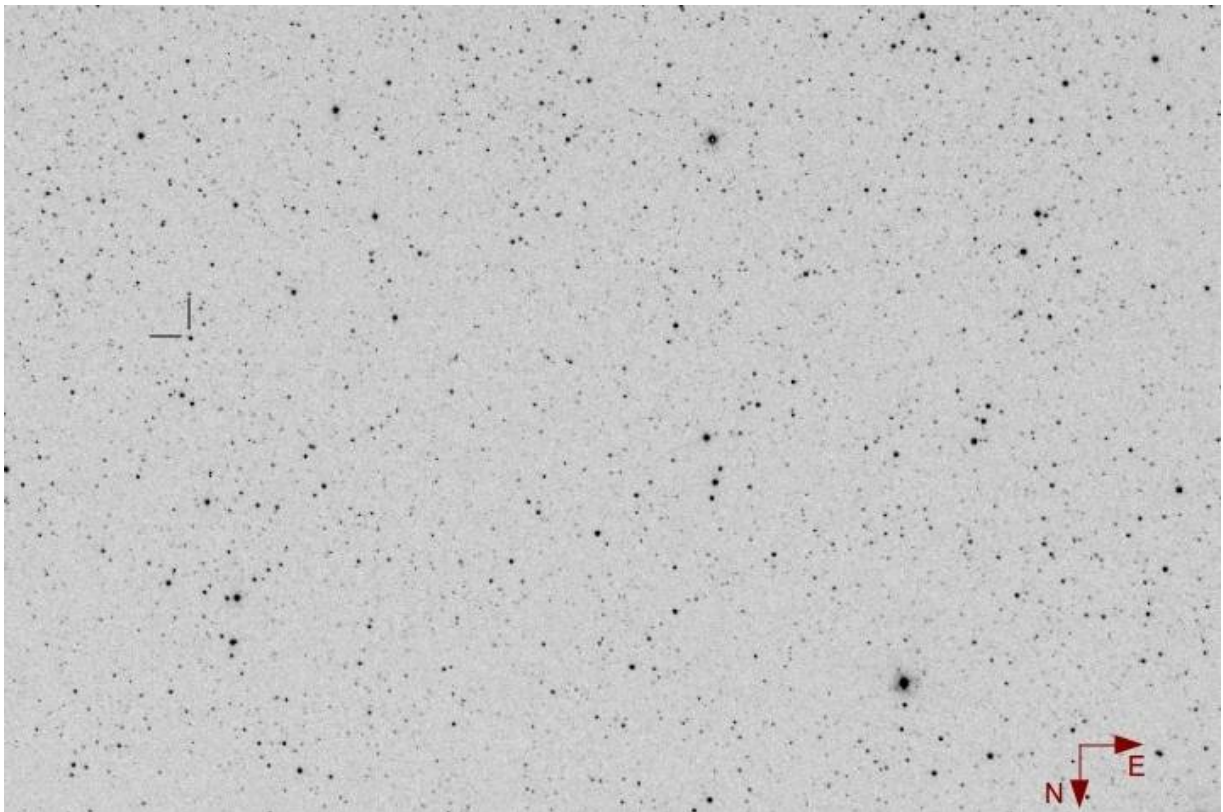
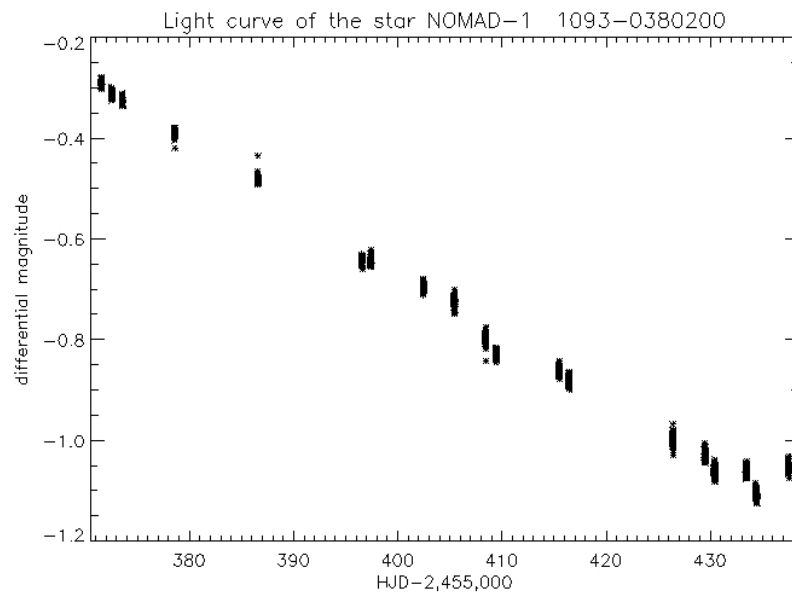


Figure 5 – (Up) Original light curve of the star NOMAD-1 1095-0380572. (Down) Finding chart for the target.

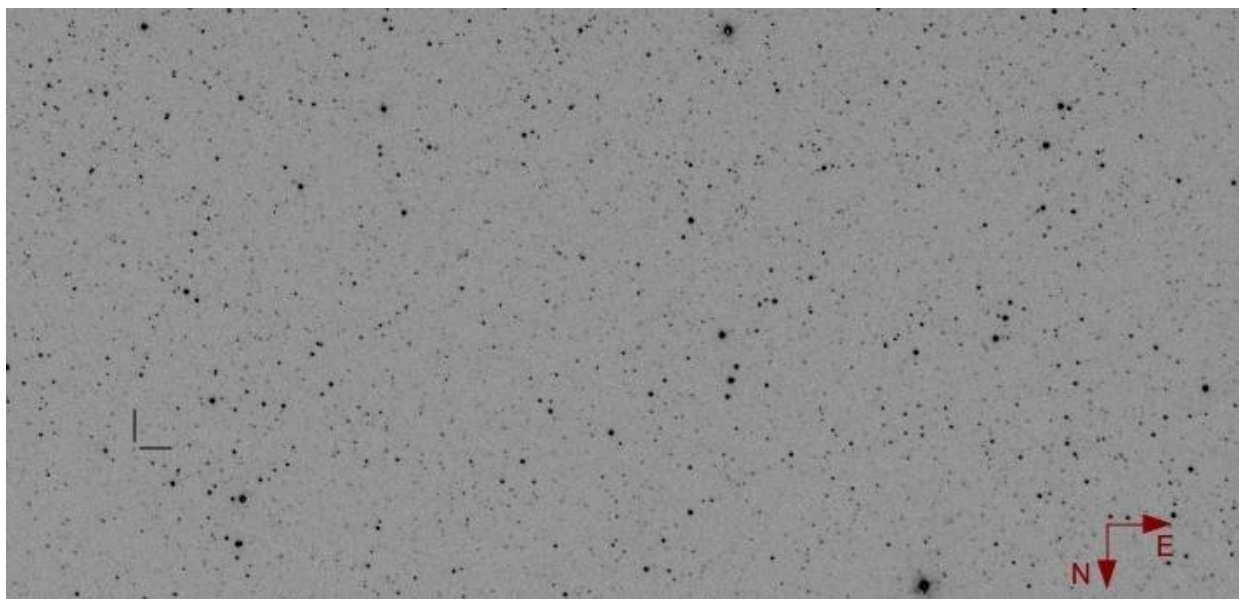
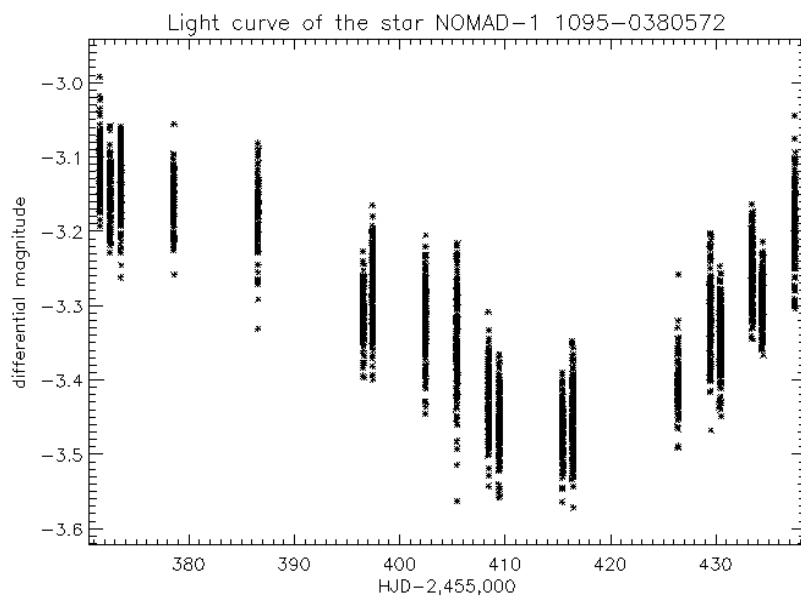
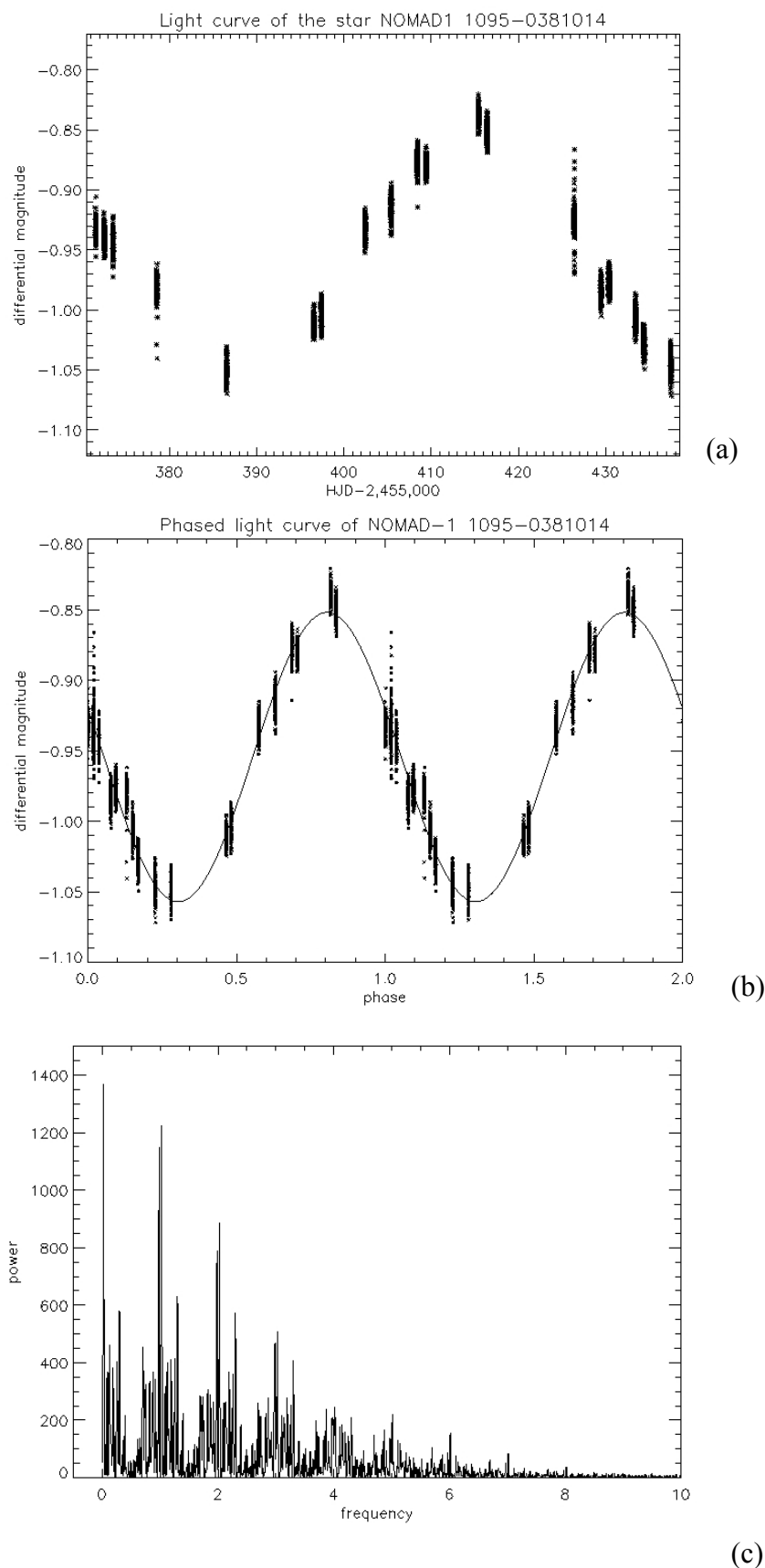
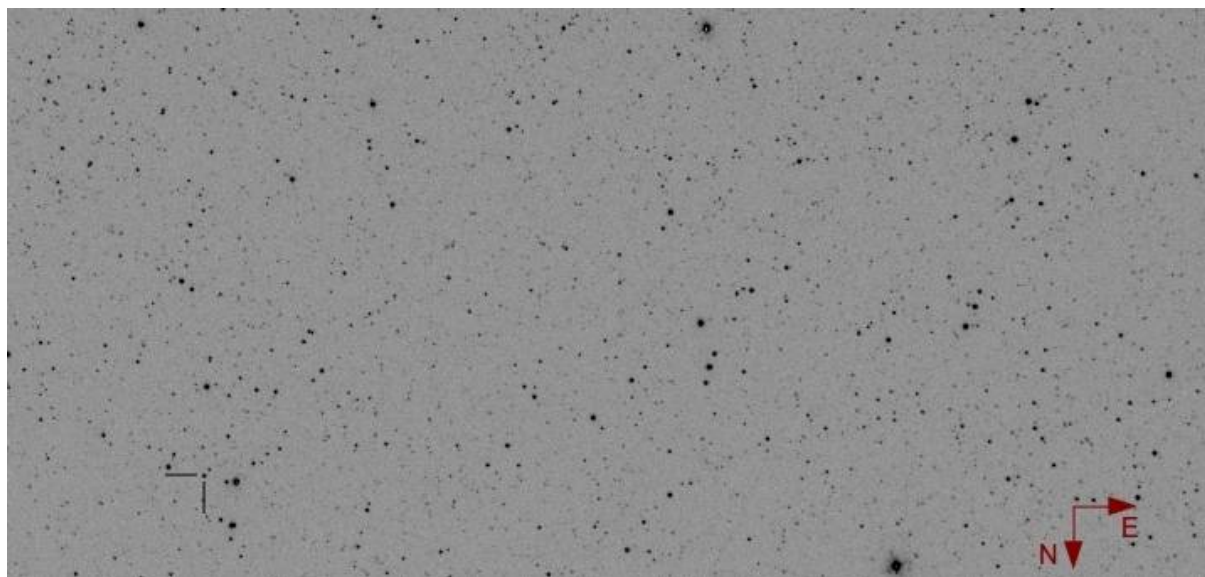


Figure 6 – (a) Original light curve of the star NOMAD-1 1095-0381014. (b) The phased light curve. Overplotted is the best fit sine curve. (c) The Lomb-Scargle periodogram. The peak frequency corresponds to the period P indicated in Table 2. (d) Finding chart for the target.





(d)

Figure 7 – (Up) Light curve of the star NOMAD-1 1095-0381250. This is probably a Mira or a SR pulsator. (Down) Finding chart for the target.

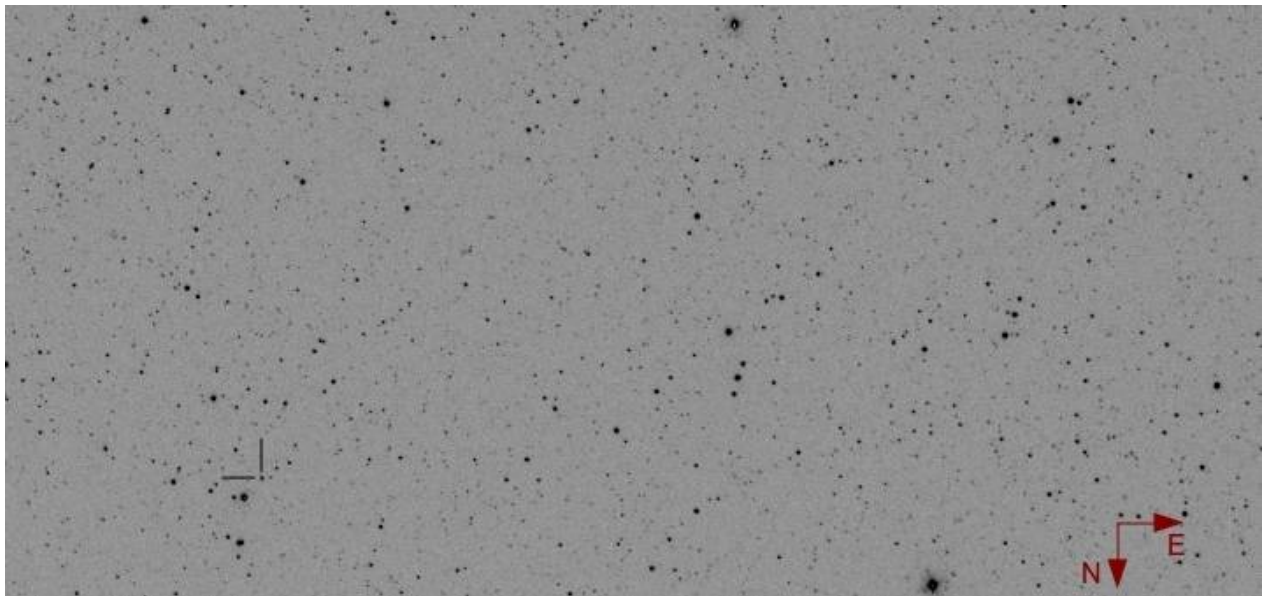
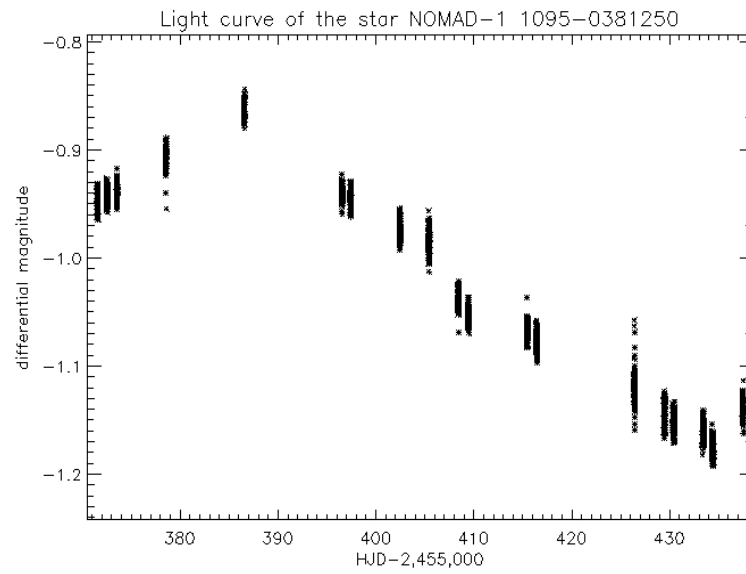
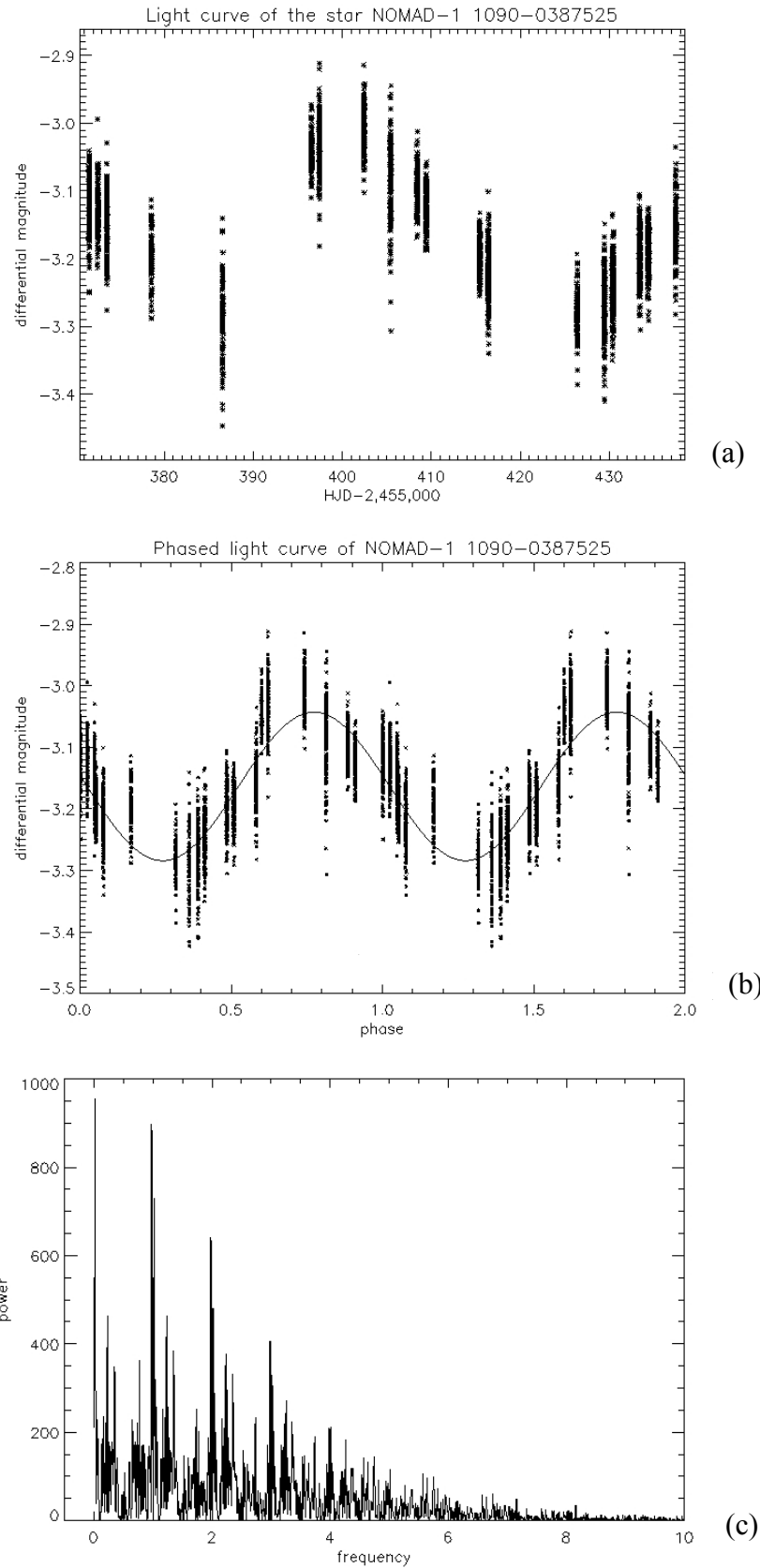
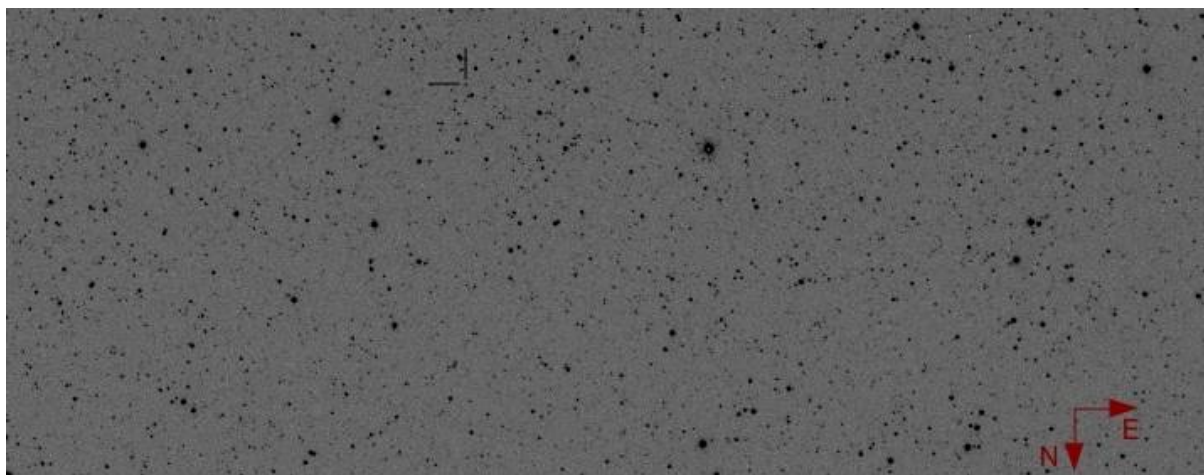


Figure 8 – (a) The original light curve of the star NOMAD-1 1090-0387525. (b) The phased light curve. Overplotted is the best fit sine curve. (c) The Lomb-Scargle periodogram. The peak frequency corresponds to the period P indicated in Table 2. (d) Finding chart for the target.





(d)

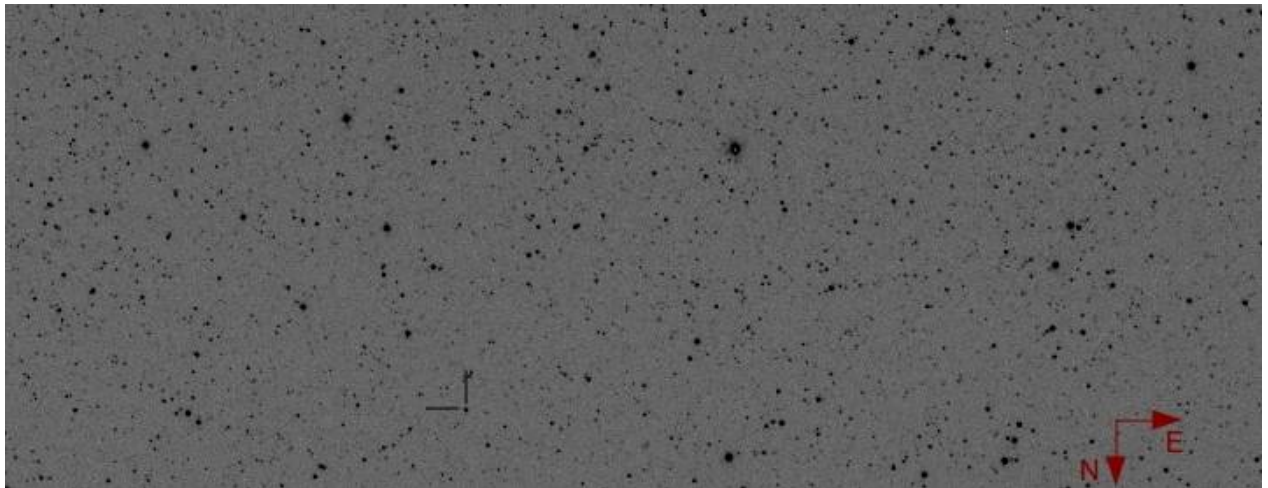
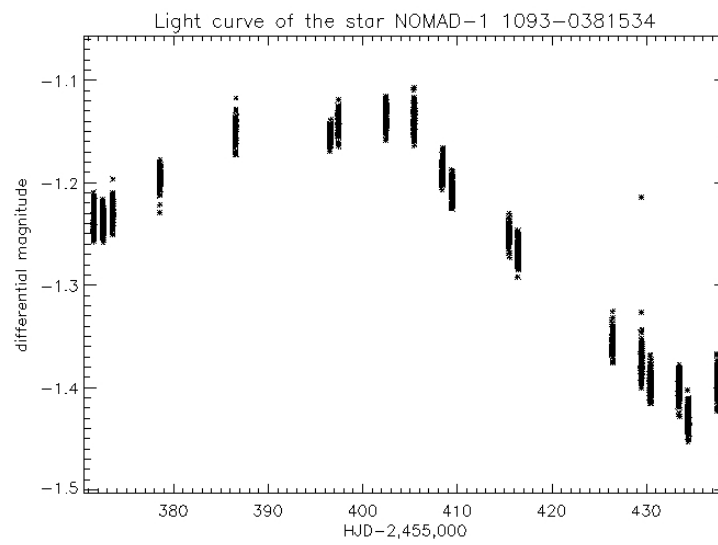
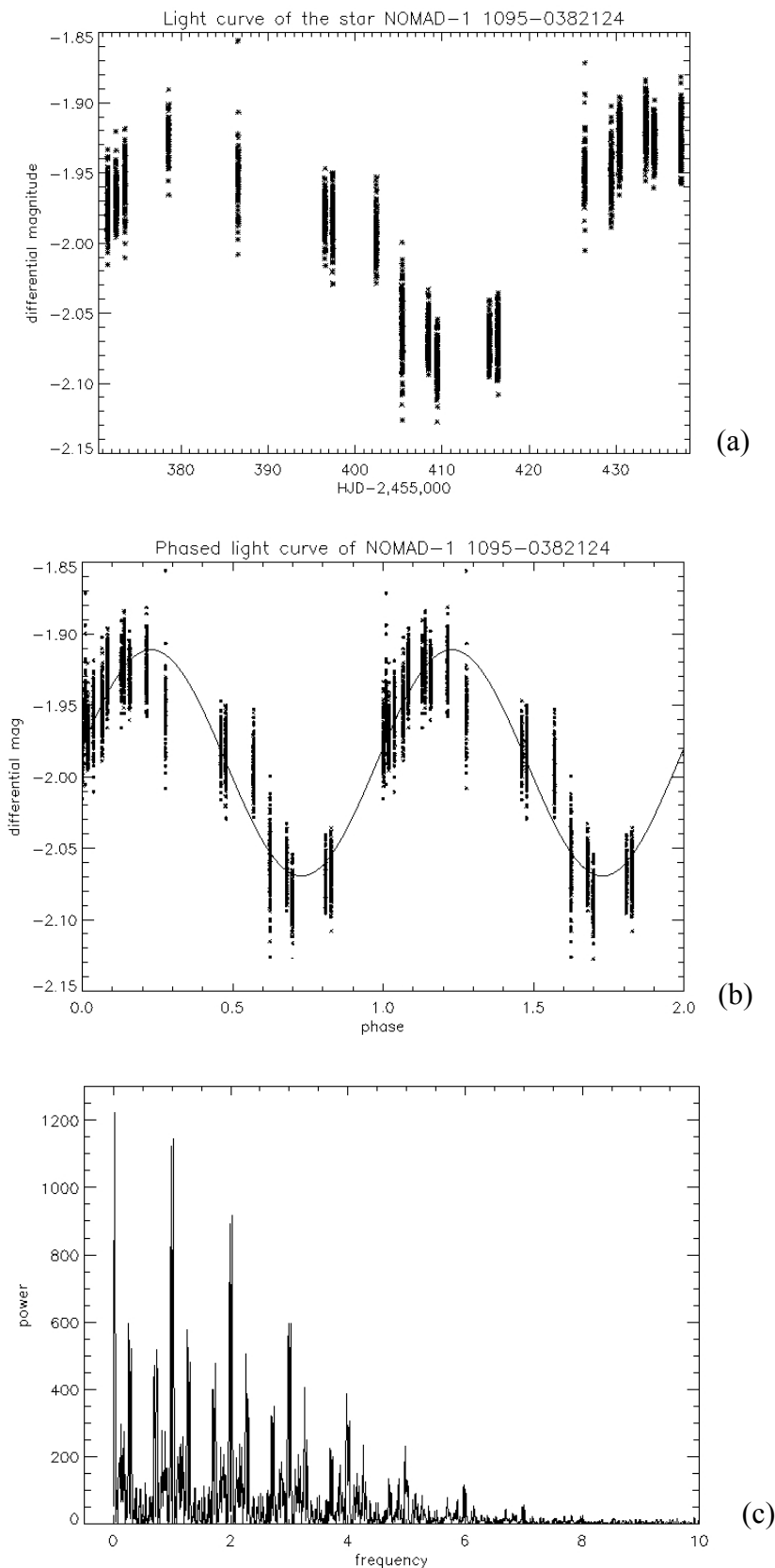
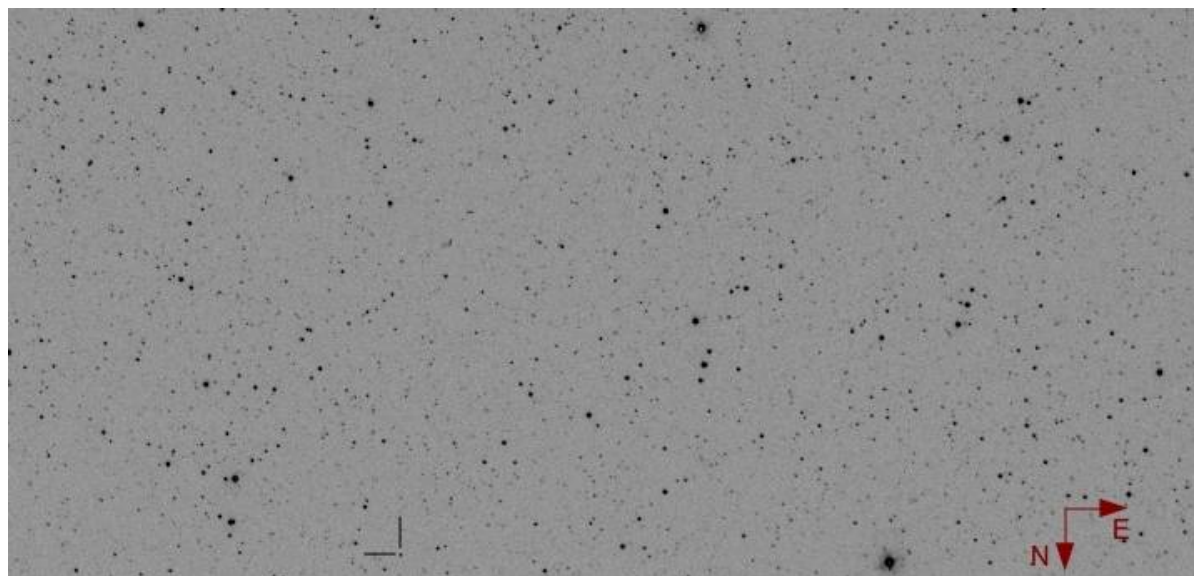
Figure 9 – Light curve of the star NOMAD-1 1093-0381534.

Figure 10 – (a) Original light curve of the star NOMAD-1 1095-0382124. (b) The phased light curve. Overplotted is the best fit sine curve. (c) The Lomb-Scargle periodogram. The peak frequency corresponds to the period P indicated in Table 2. (d) Finding chart for the target.





(d)

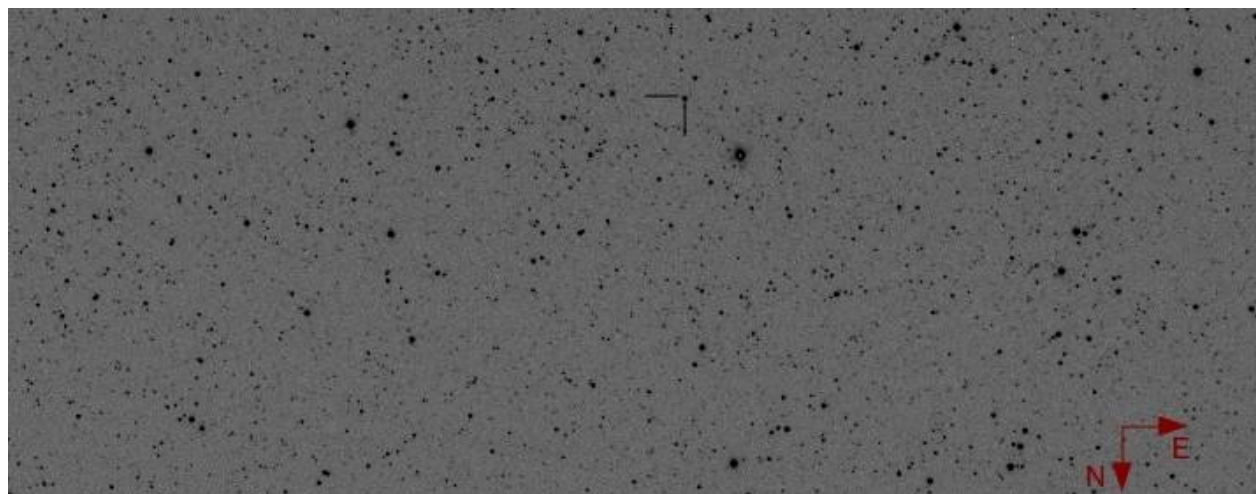
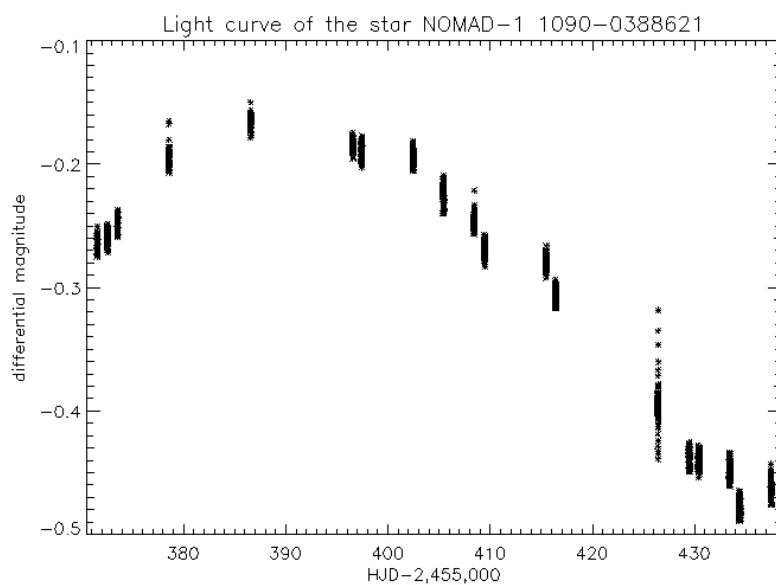
Figure 11 – (Up) Light curve of the star NOMAD-1 1090-0388621. (Down) Finding chart for the target

Figure 12 – (Up) Original light curve of the star NOMAD-1 1091-0387997. (Down) Finding chart for the target.

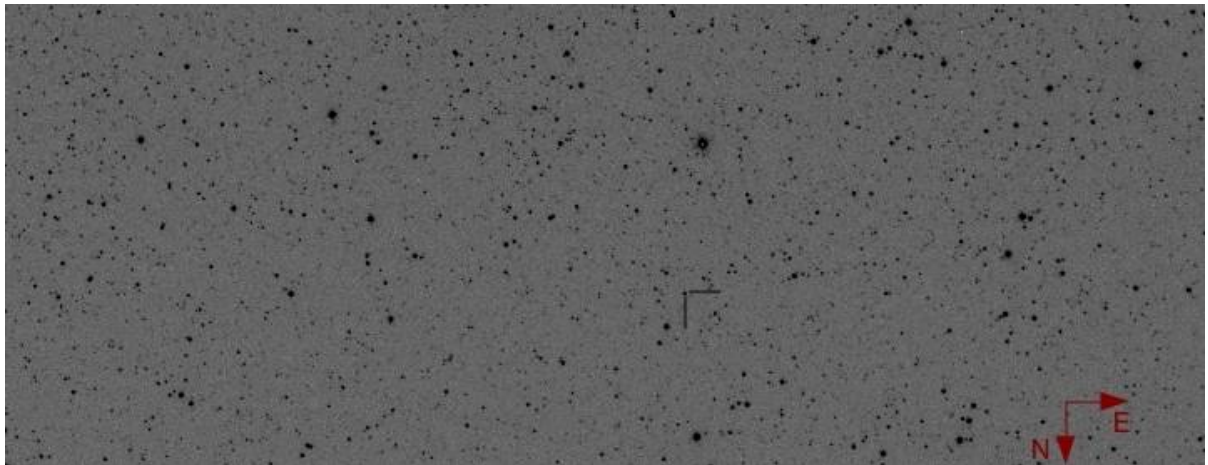
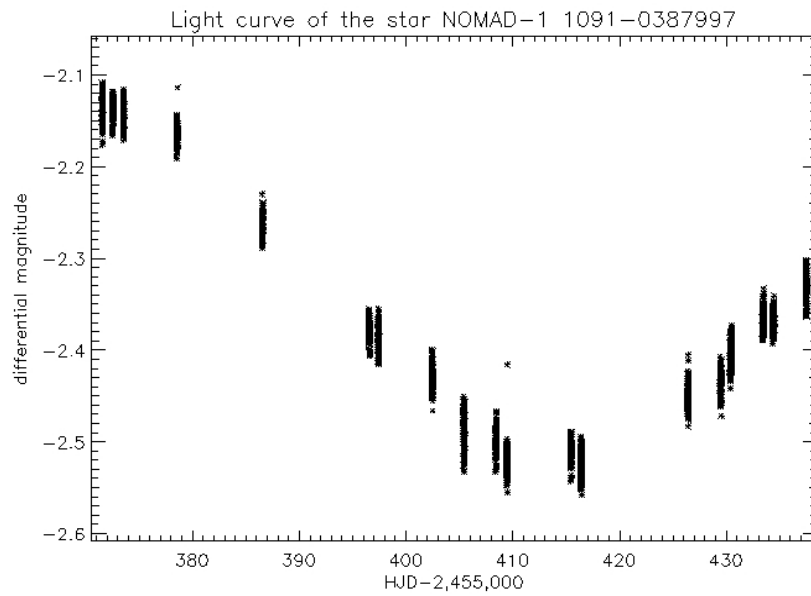
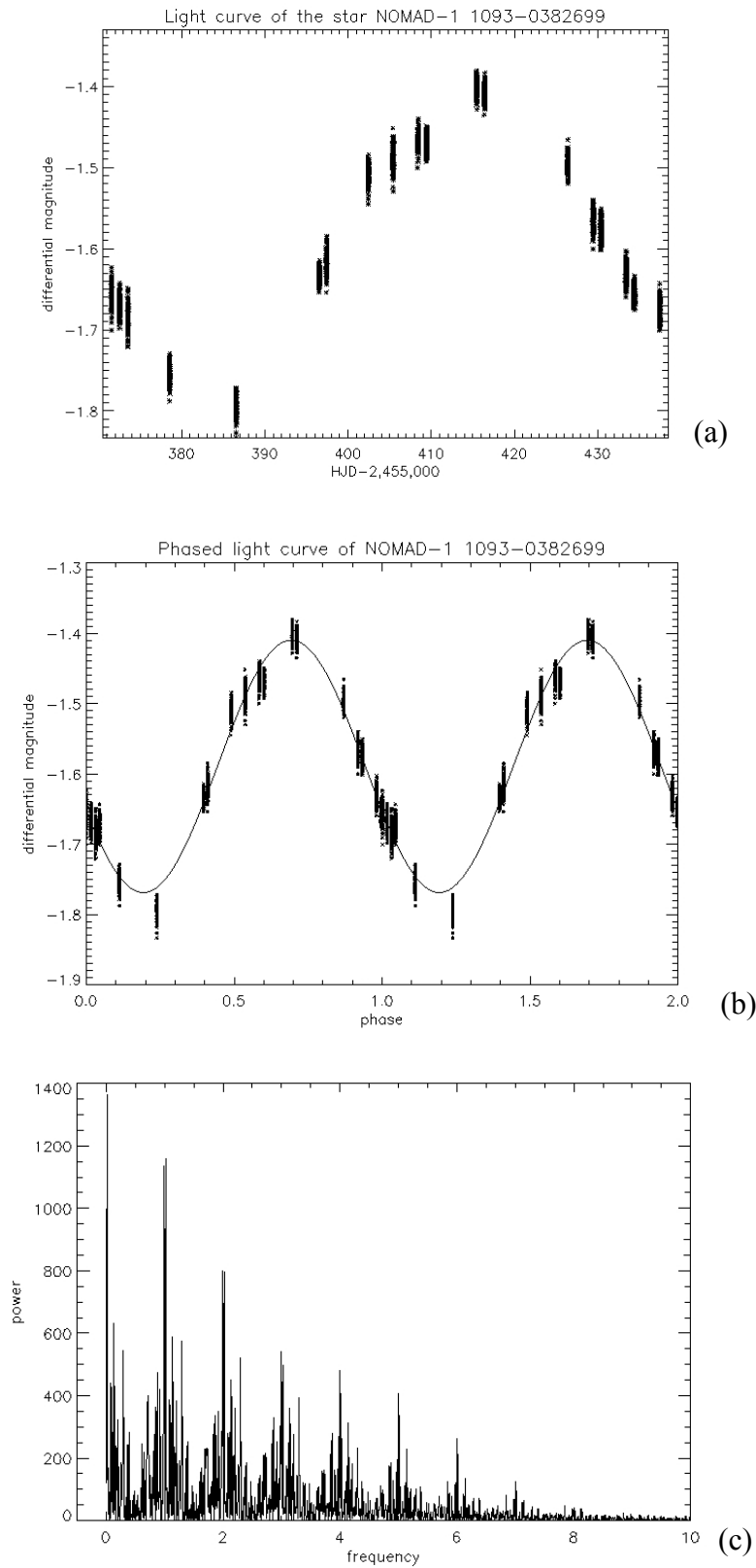
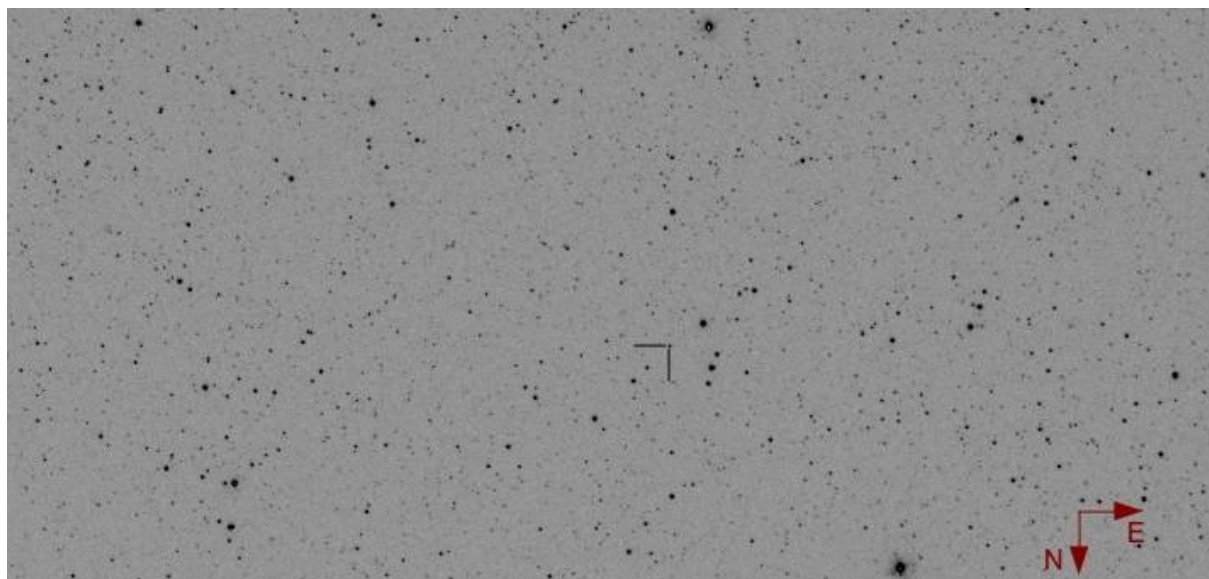


Figure 13 – (a) Original light curve of the star NOMAD-1 1093-0382699. (b) The phased light curve. Overplotted is the best fit sine curve. (c) The Lomb-Scargle periodogram. The peak frequency corresponds to the period P indicated in Table 2. (d) Finding chart for the target.





(d)

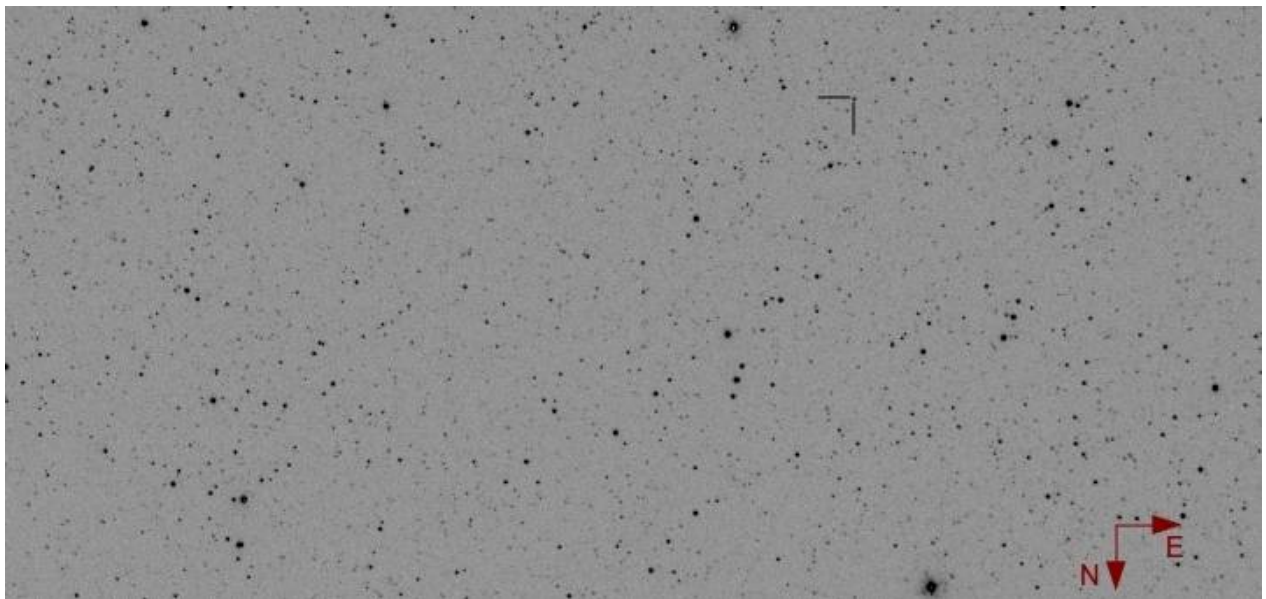
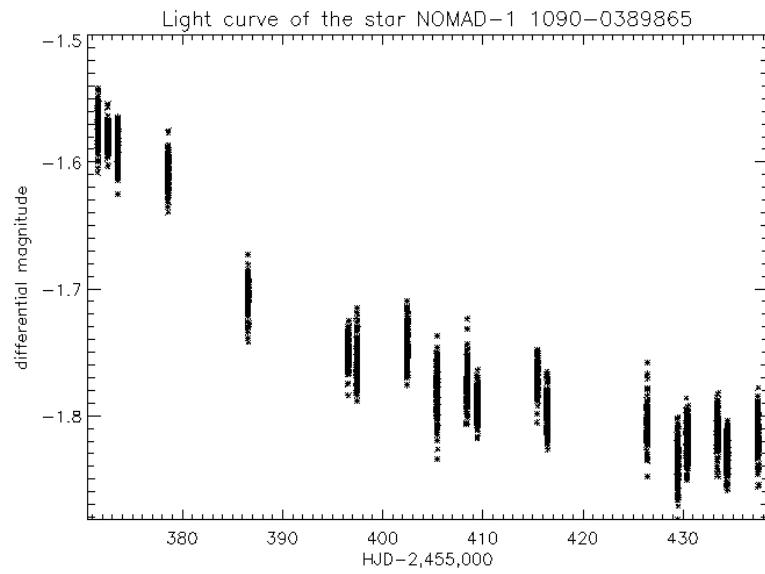
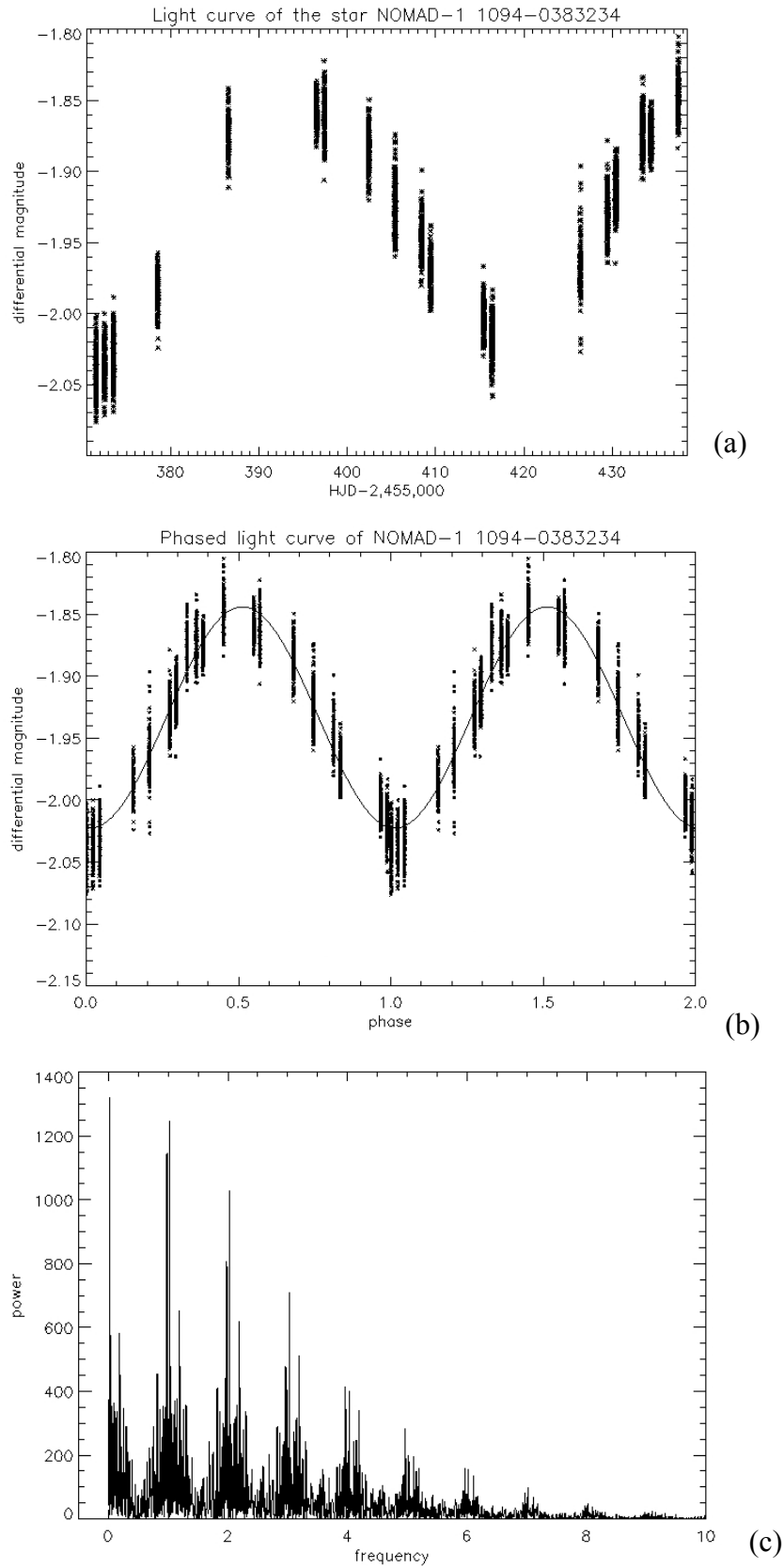
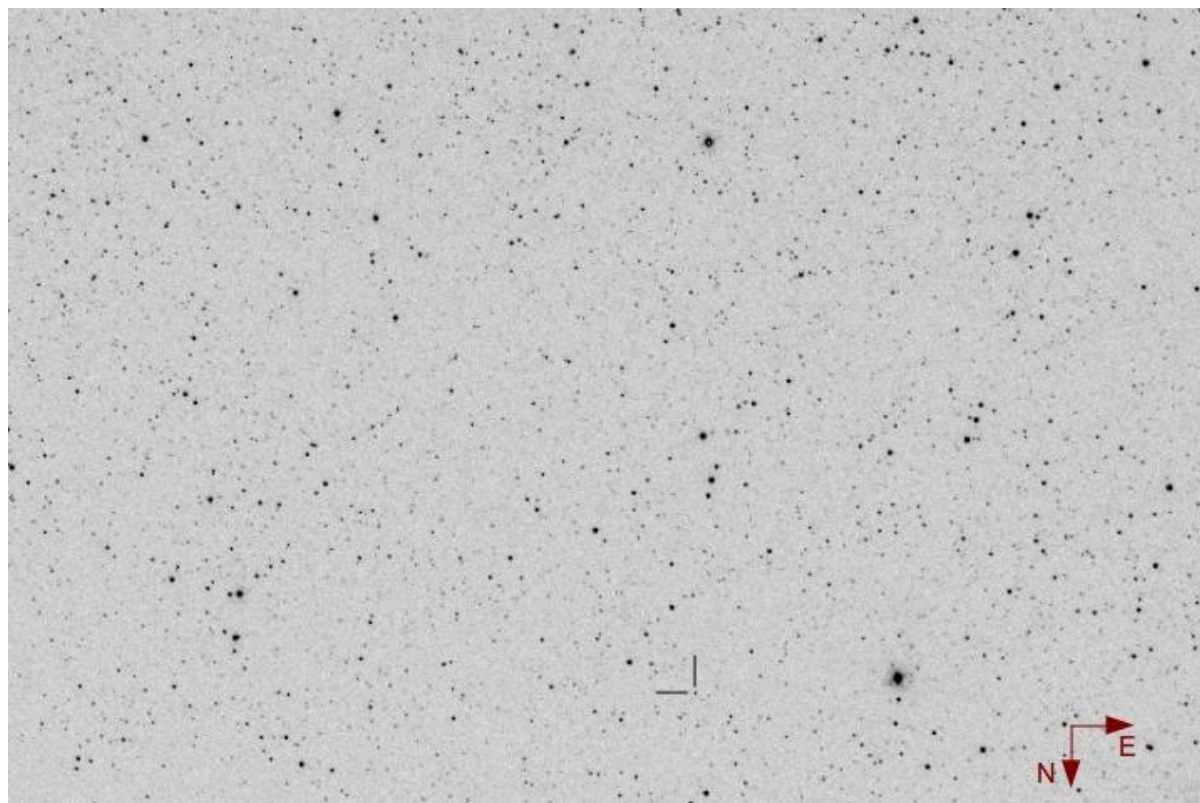
Figure 14 – (Up) Light curve of the star NOMAD-1 1090-0389865. (Down) Finding chart for the target.

Figure 15 – (a) Original light curve of the star NOMAD-1 1094-0383234. (b) The phased light curve. Overplotted is the best fit sine curve. (c) The Lomb-Scargle periodogram. The peak frequency corresponds to the period P indicated in Table 2. (d) Finding chart for the target.





(d)

Figure 16 – (Up) Light curve of the star NOMAD-1 1092-0387428. This is probably a Mira or a SR pulsator. (Down) Finding chart for the target.

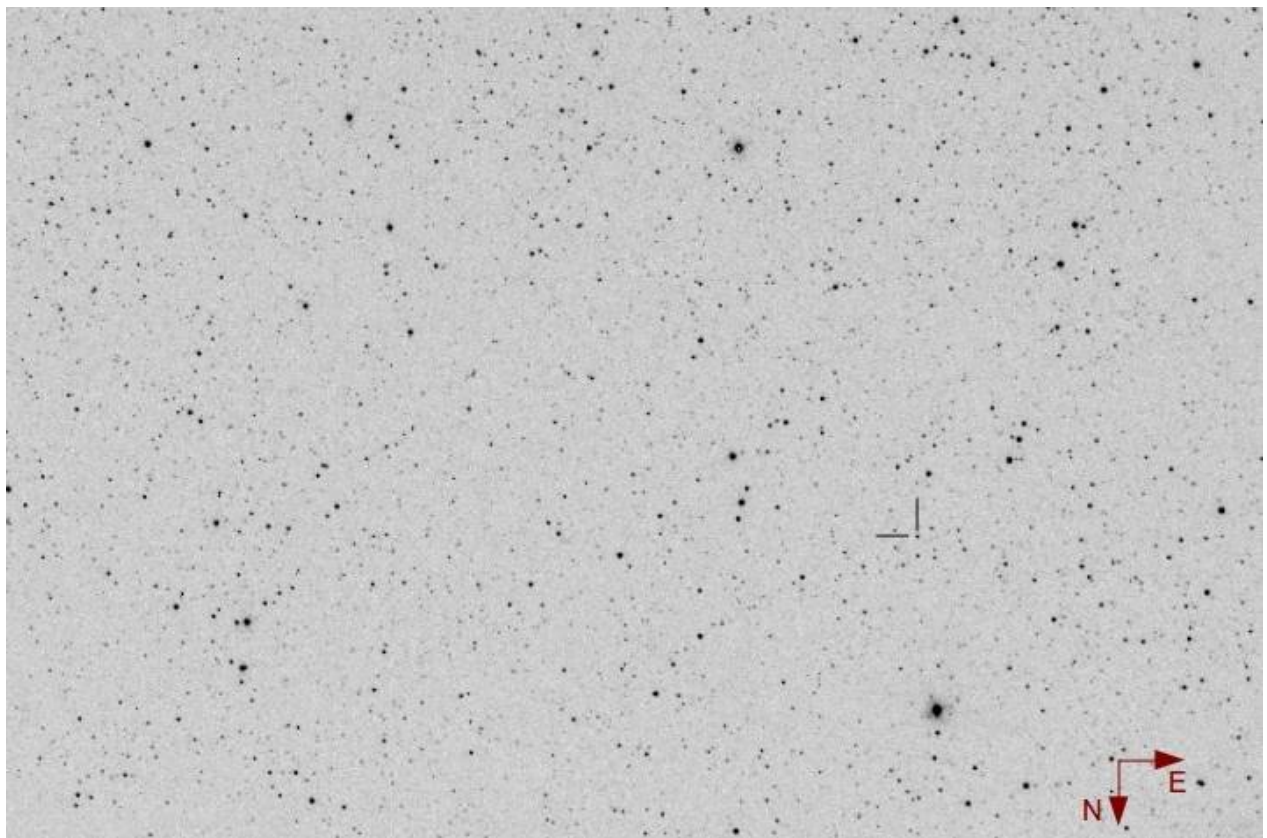
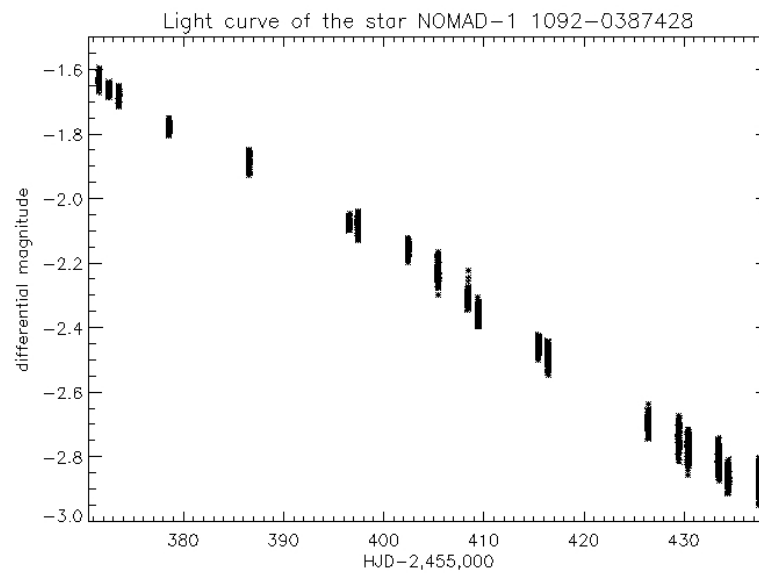
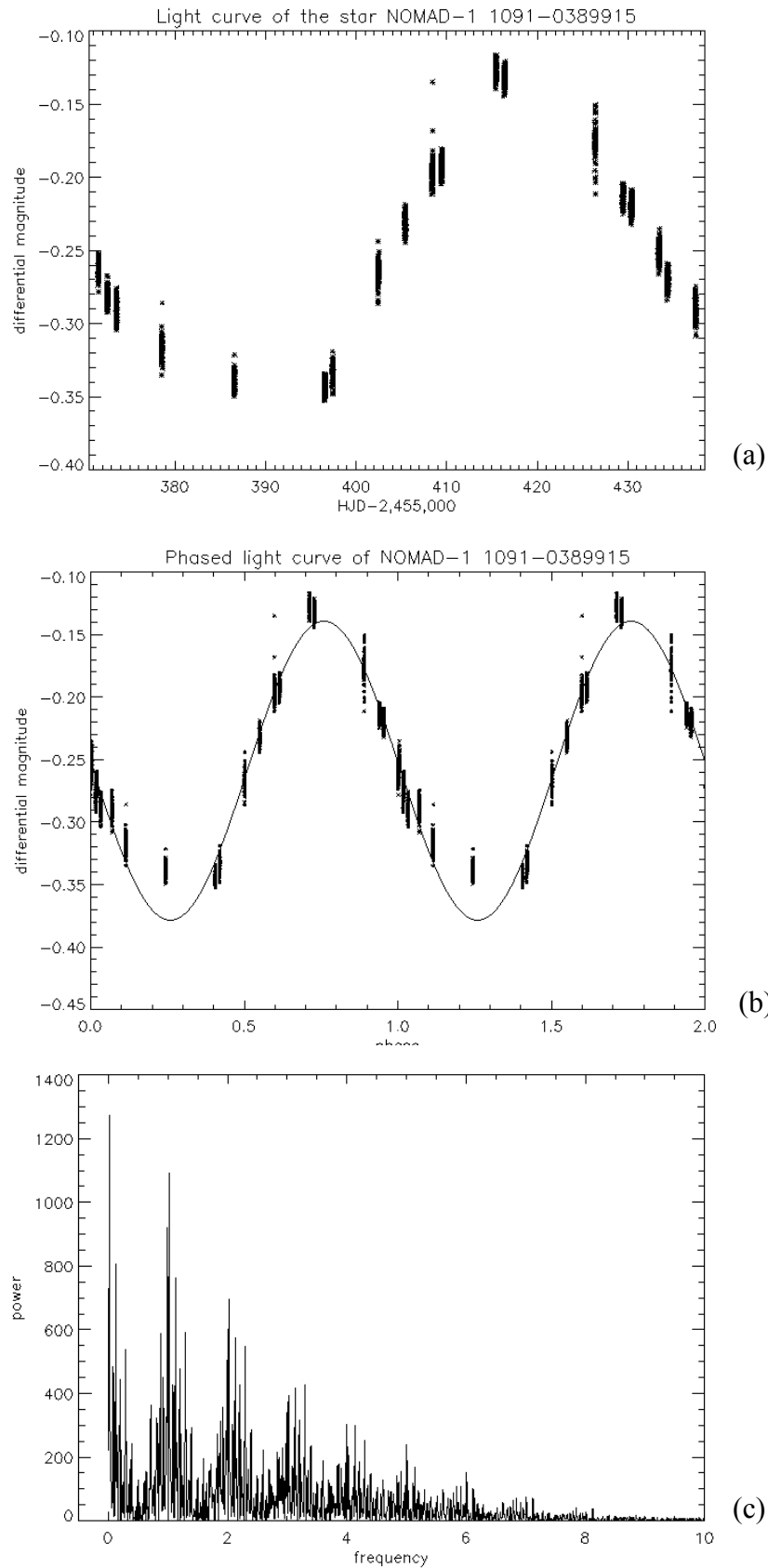
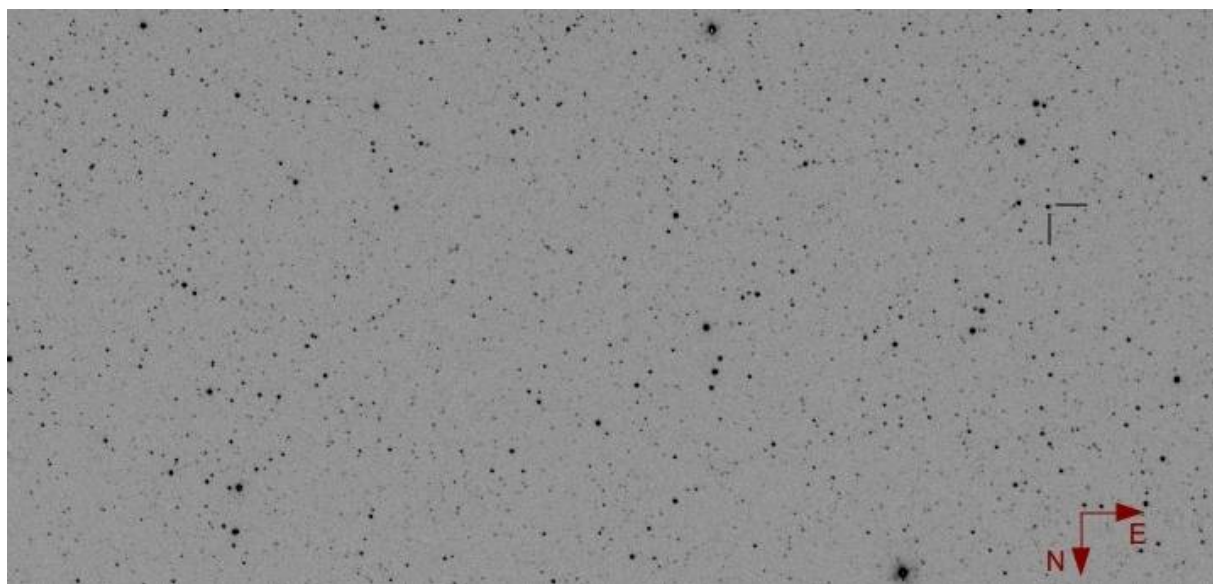


Figure 17 – (a) Original light curve of the star NOMAD-1 1091-0389915. (b) The phased light curve. Overplotted is the best fit sine curve. (c) The Lomb-Scargle periodogram. The peak frequency corresponds to the period P indicated in Table 2. (d) Finding chart for the target.





(d)

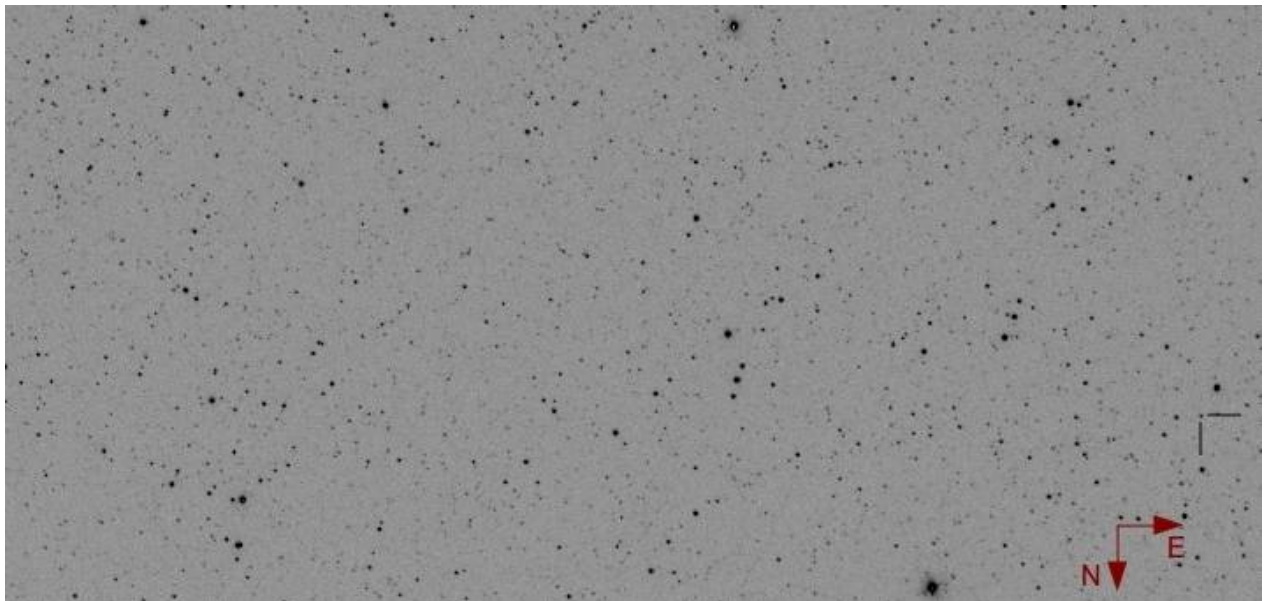
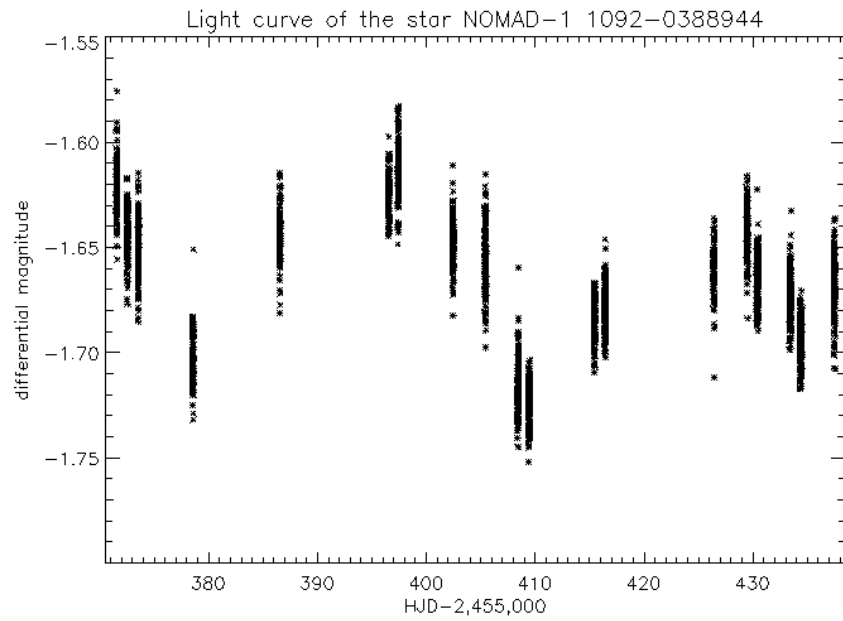
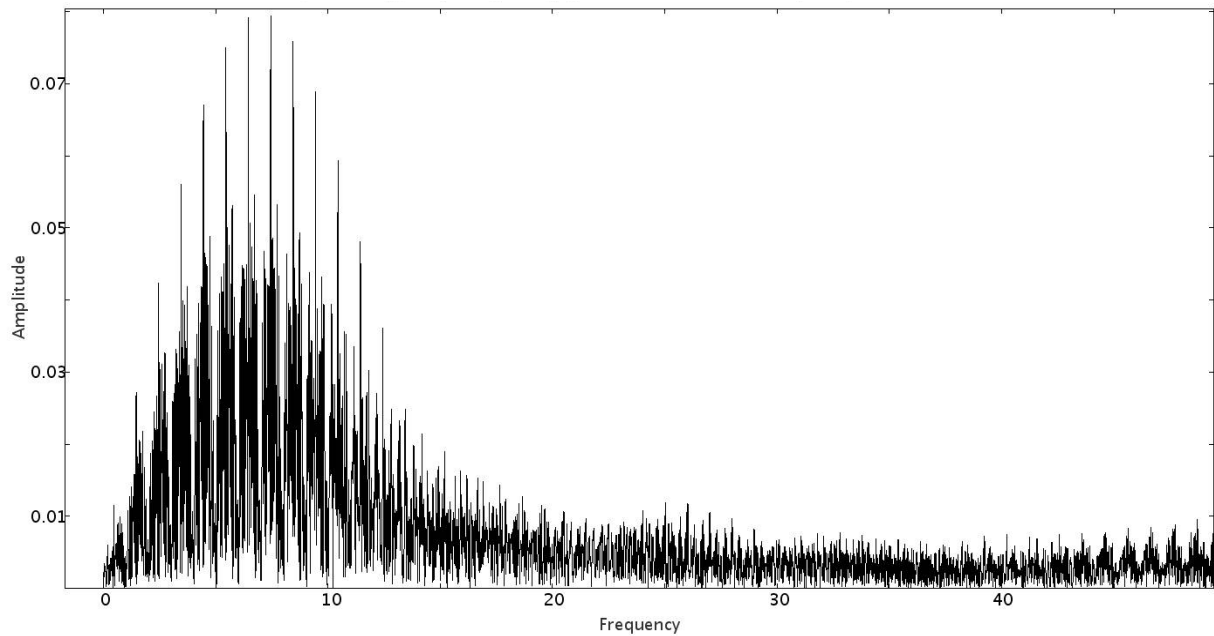
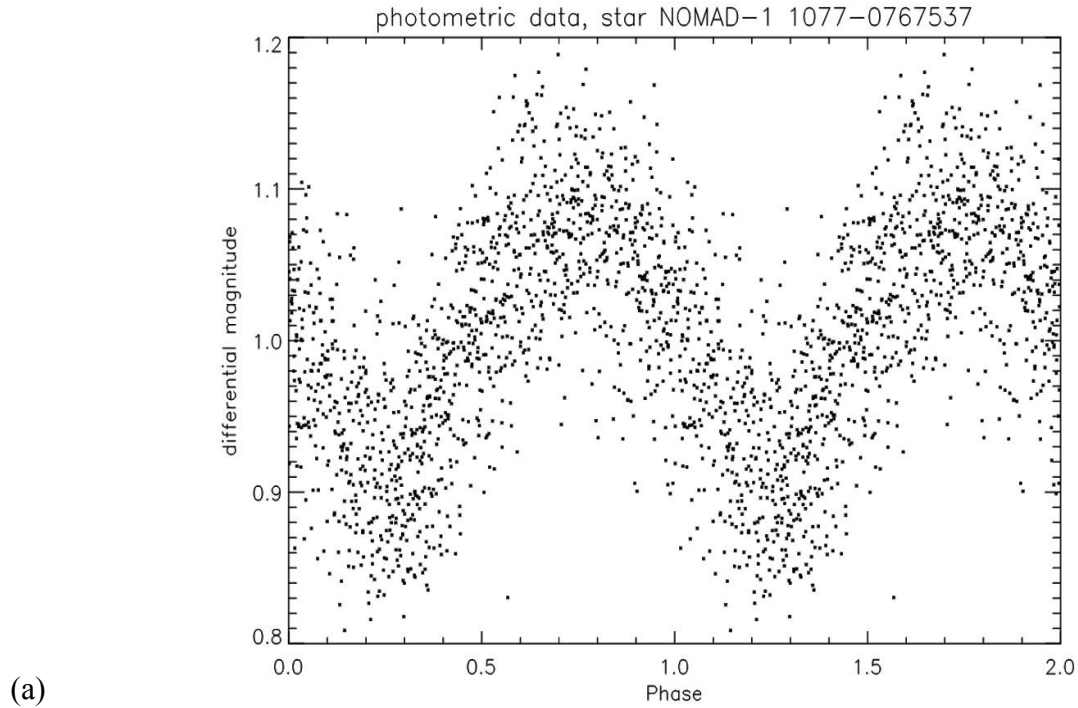
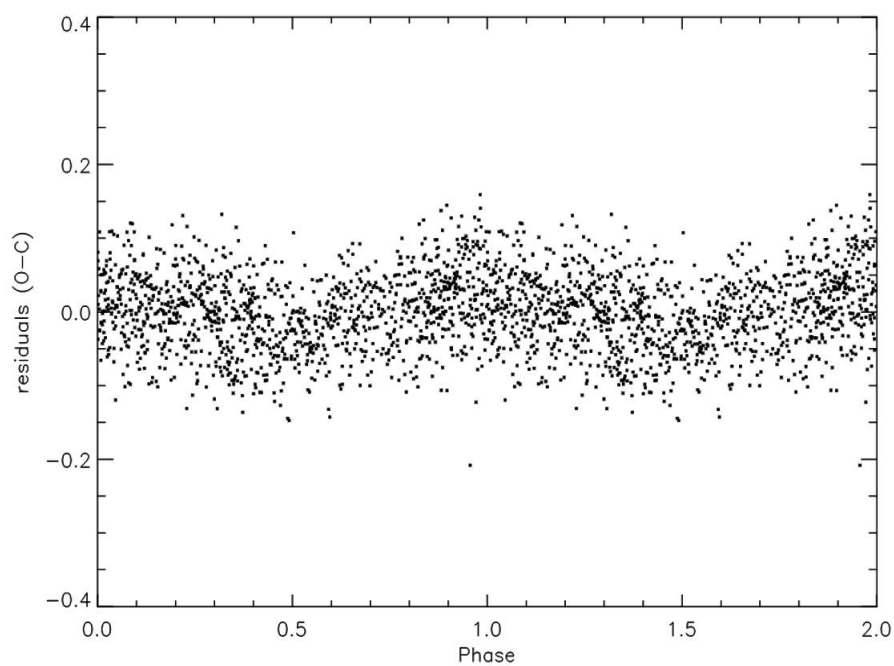
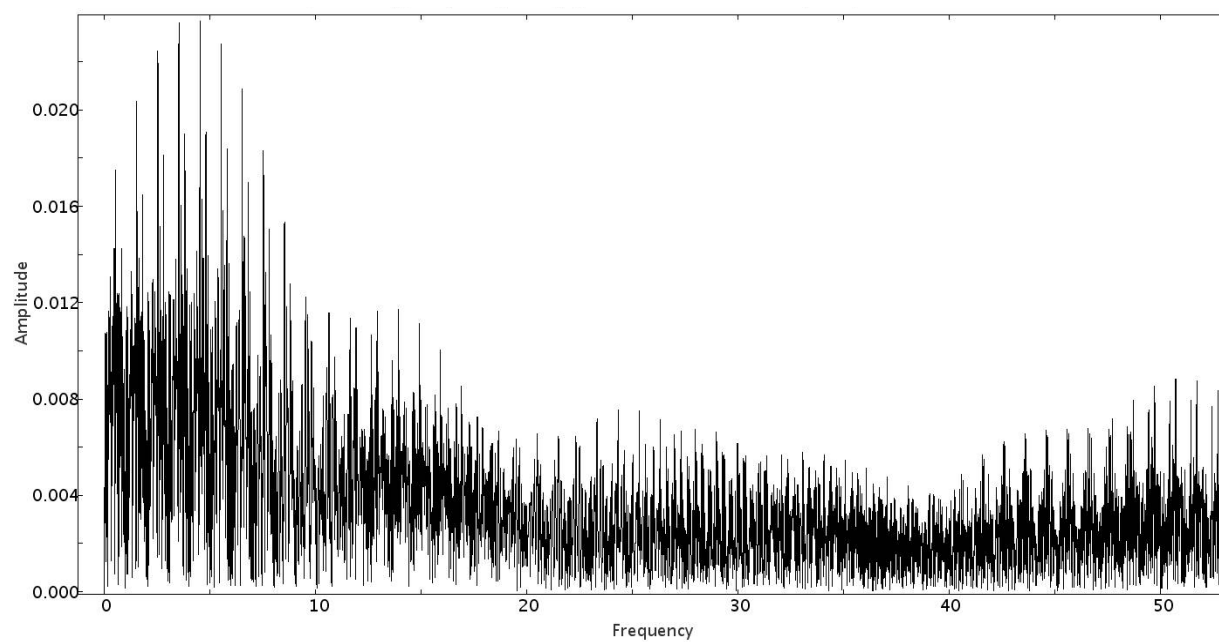
Figure 18 – (Up) Light curve of the star NOMAD-1 1092-0388944. (Down) Finding chart for the target.

Figure 19 – (a) Light curve of the pulsating star NOMAD-1 1077-0767537 phased according the frequency $F1=7.45248377$ cycle/day. (b) Periodogram showing the peak corresponding to $F1$. (c) Residuals O-C phased according the frequency $F2=4.52912947$ cycle/day, showing that the residuals contain a significant periodicity. (d) Periodogram related to the Fourier analysis of the residuals, showing the peak corresponding to $F2$. (e) Finding chart for the target.

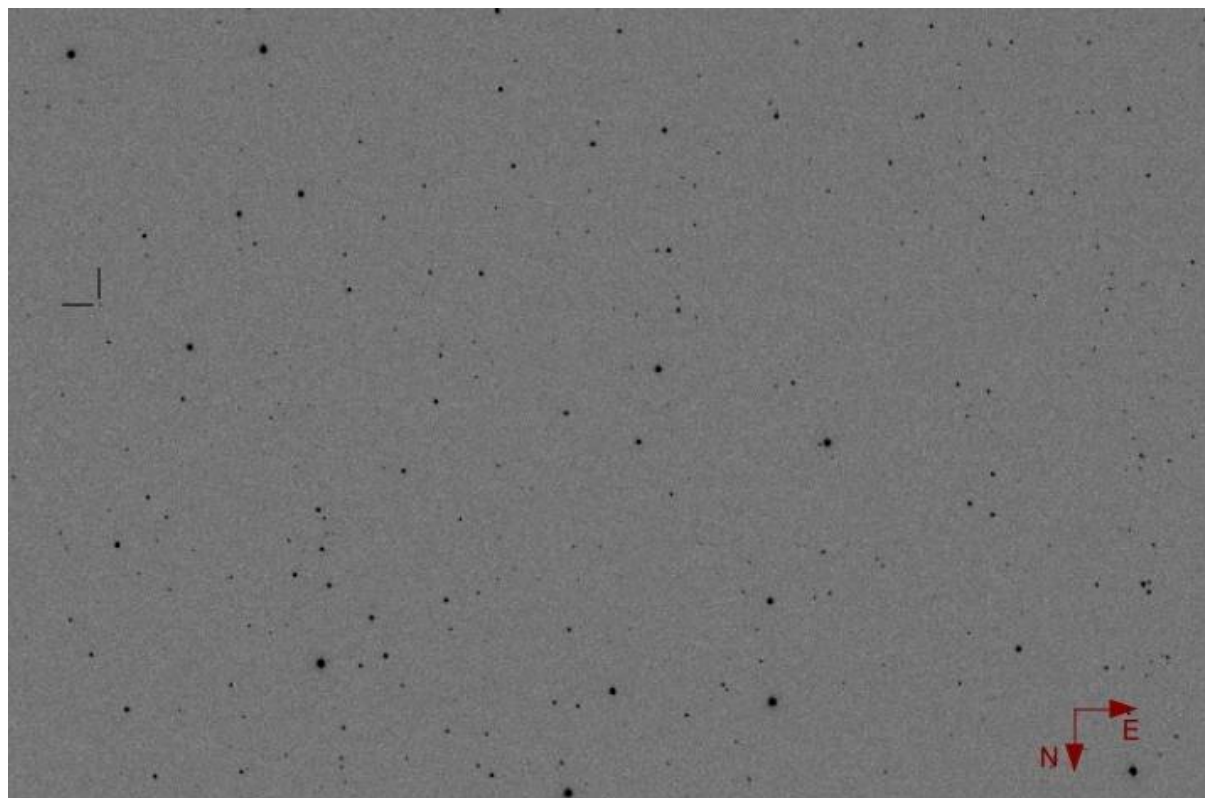




(c)



(d)



(e)

Figure 20 – (Up) Folded light curve of the object NOMAD-1 1617-0165649. (Down) Finding chart for the target.

The object can be classified as a W UMa eclipsing binary system. Data correspond to 37 nights of observations and are averaged in 200 bins.

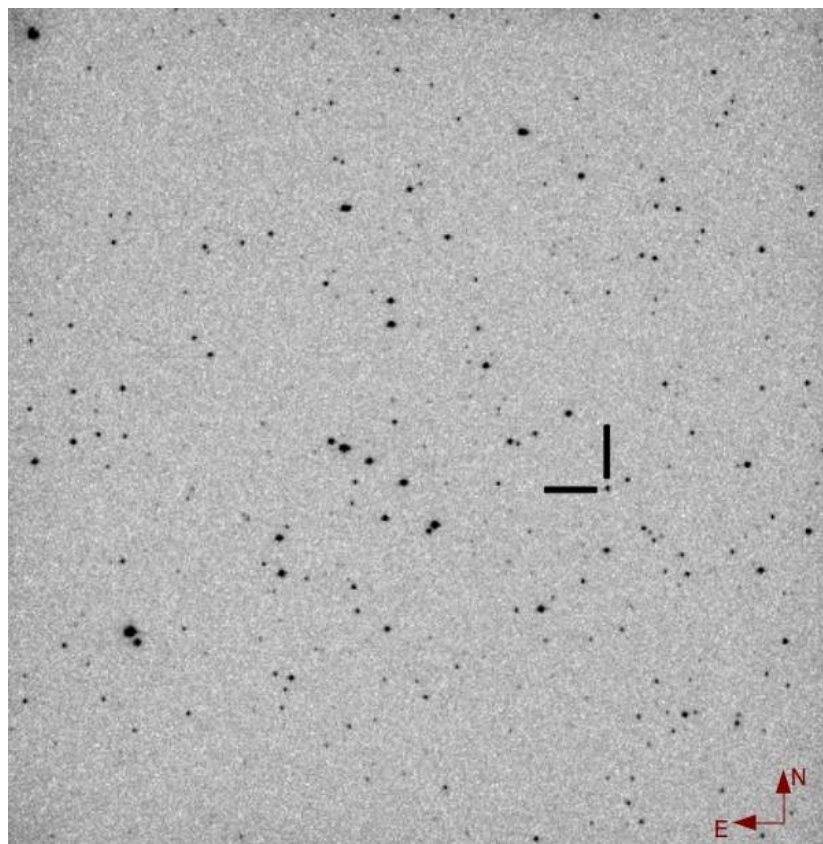
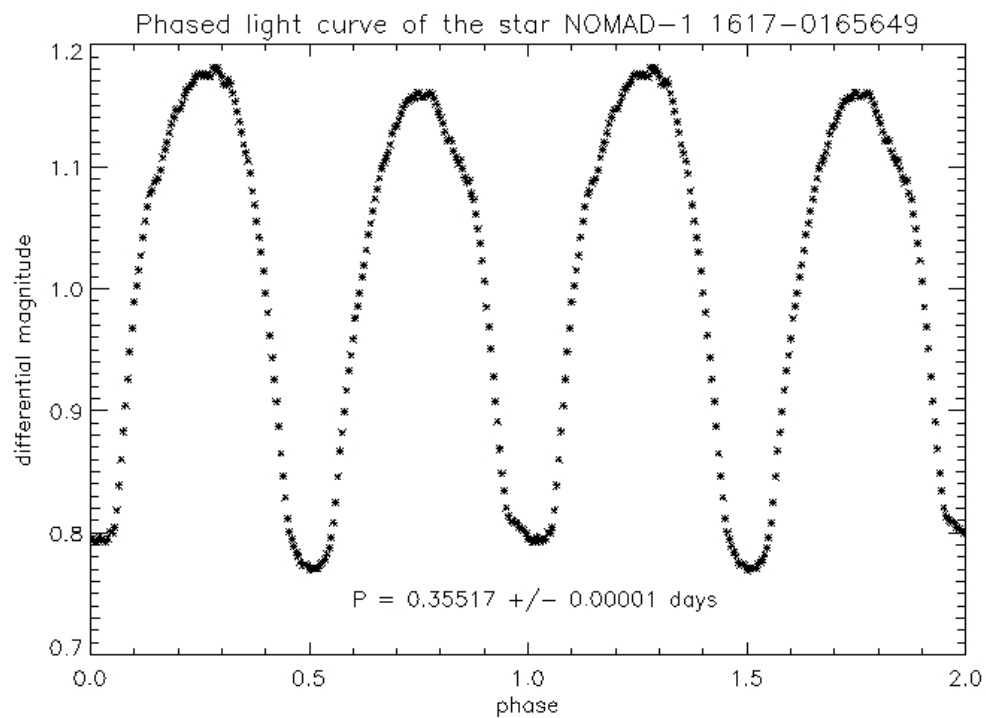
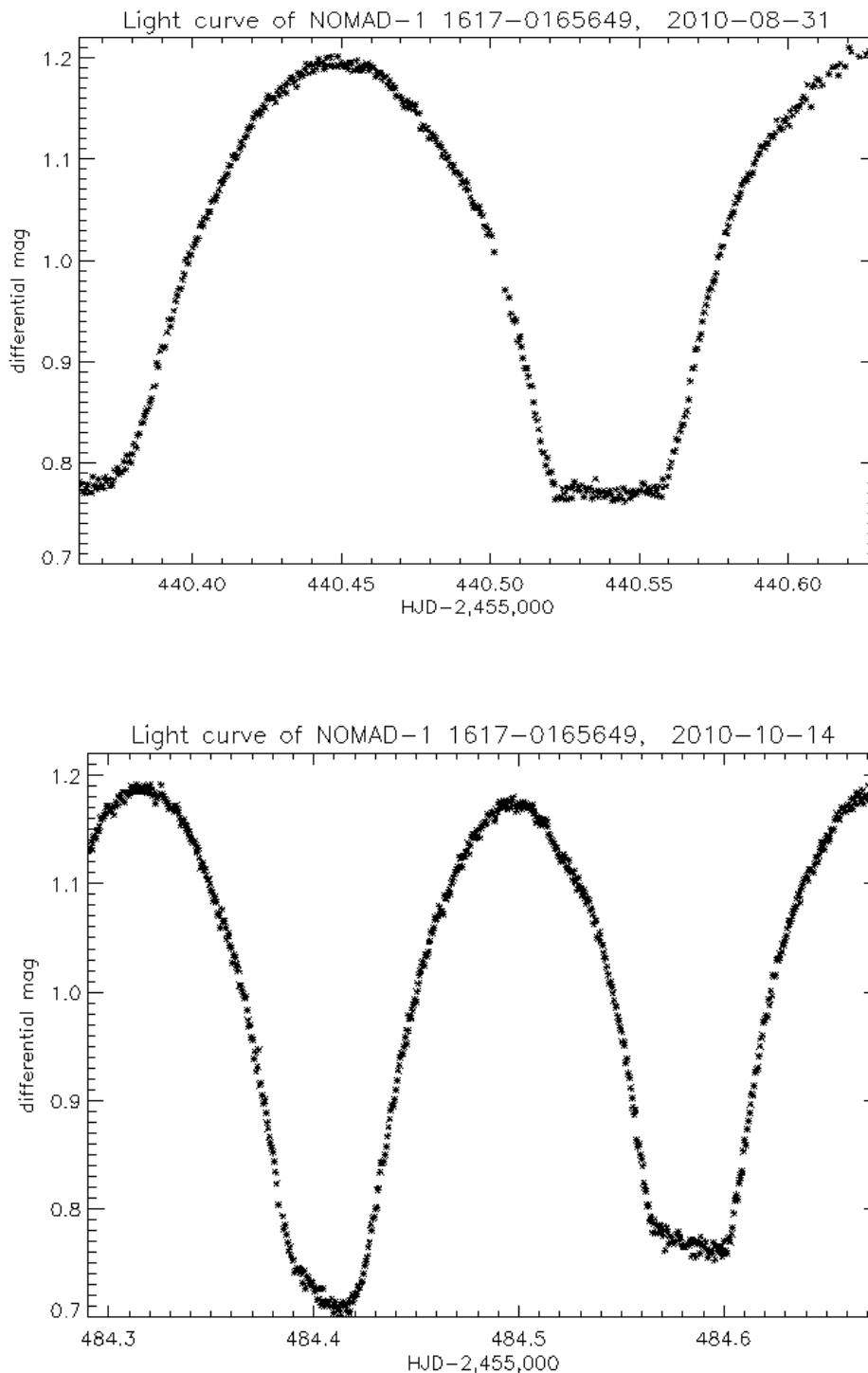


Figure 21 – Single-night light curves of the object NOMAD-1 1617-0165649. Changes from epoch to epoch in the shape of the minima is clearly evident, as for asymmetries in the parts corresponding to the maxima (this explain the global asymmetries present in the folded light curve of Fig. 20). This can be due to the presence of dark spots on the surfaces of both the system components. The epoch of observation is indicated at the top of each plot.



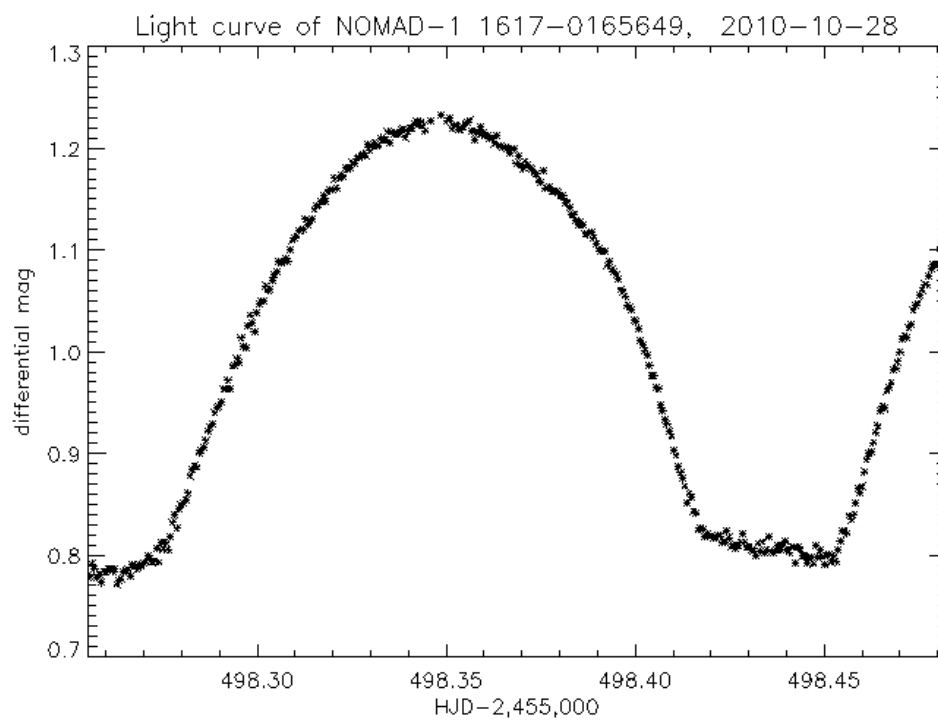
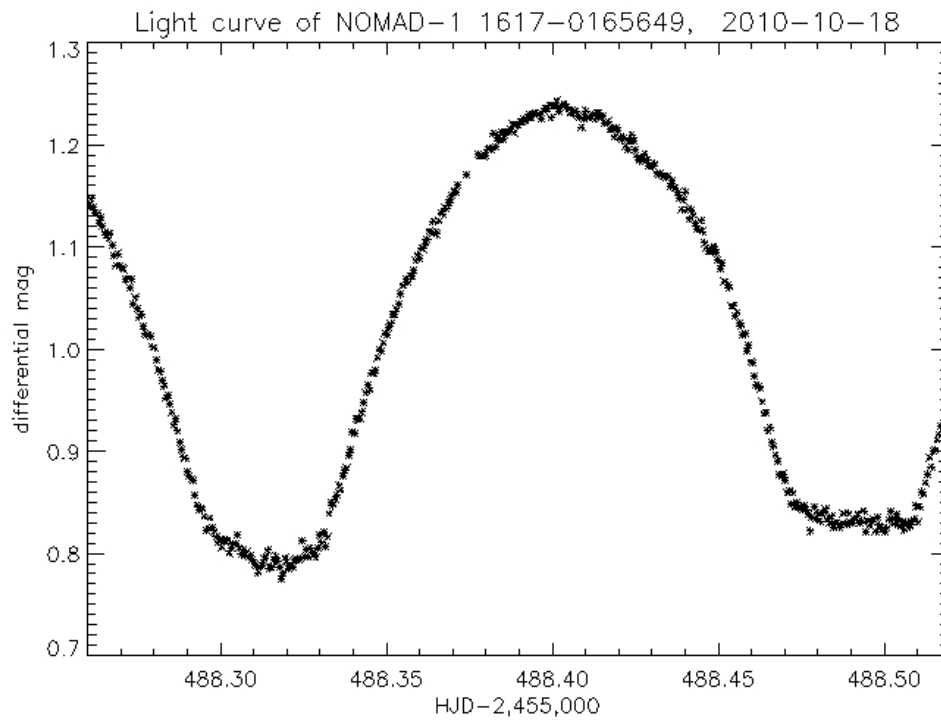
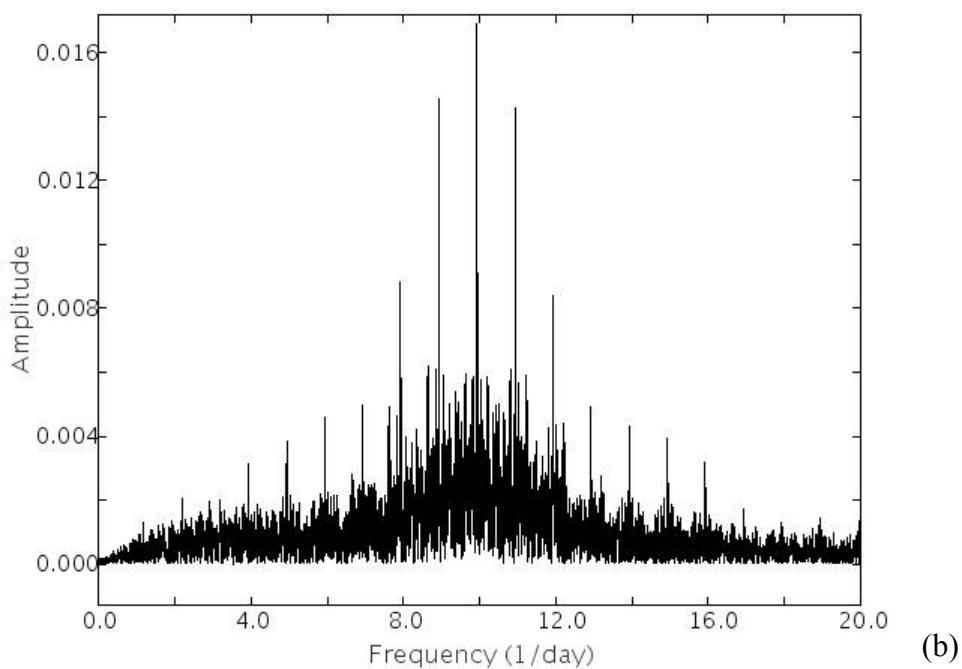
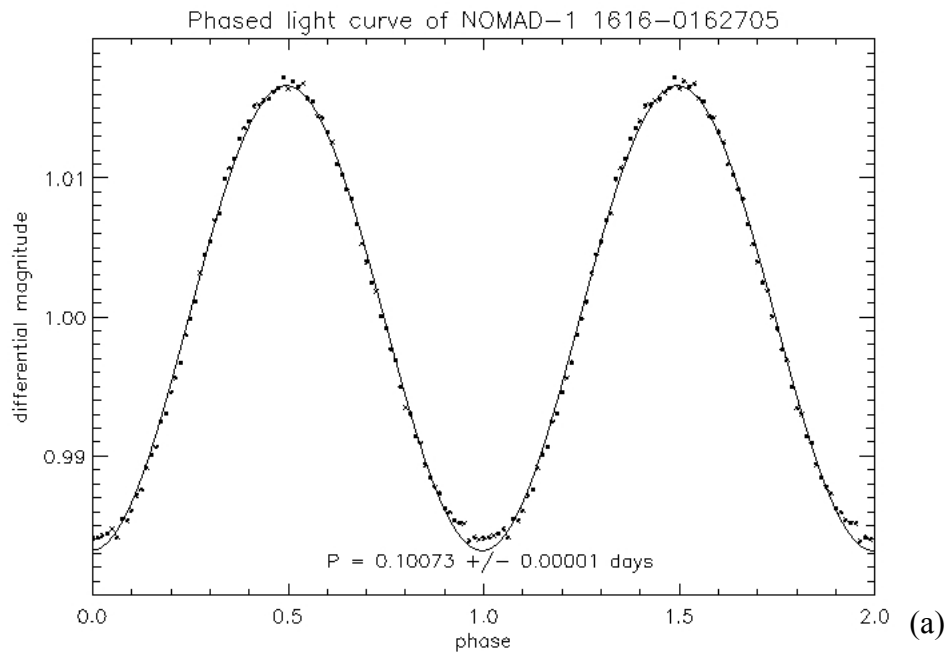
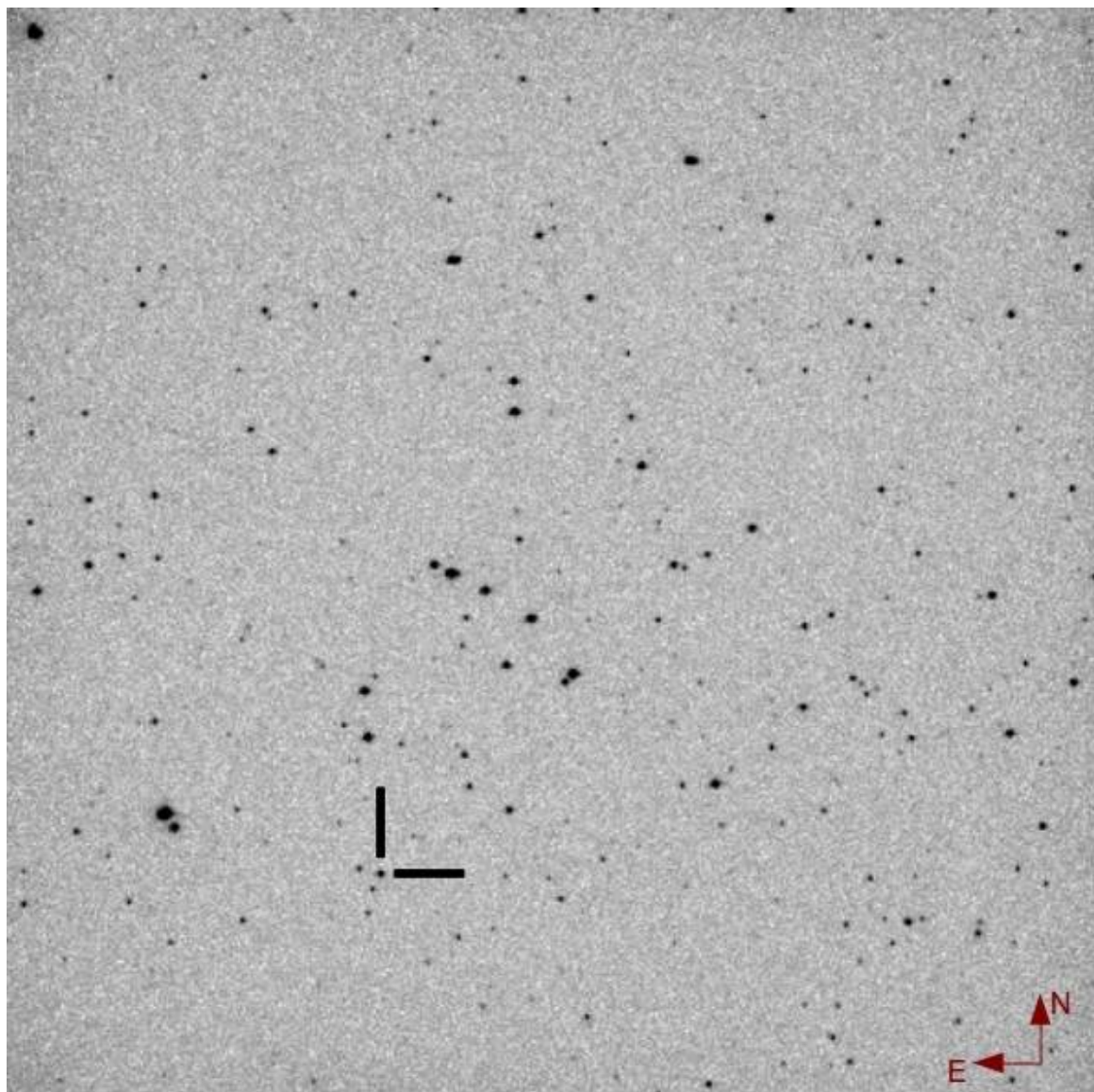
(Fig. 21 continued)

Figure 22 – (a) Folded light curve of the star NOMAD-1 1616-0162705 with the best fit sine curve superposed. (b) The periodogram showing the peak corresponding to the folding period $P=0.10073$ days. (c) Finding chart for the target. The star may be classified as a Delta Scuti pulsating variable.





(c)

VSX J071108.7+695227: a Newly Discovered Short-period Eclipsing Binary

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Abstract We report the discovery of an EW variable, VSX J071108.7+695227, with a short orbital period of ~ 0.238 day. This period is very close to the lower limit of ~ 0.22 day that has been found for EW systems. Here we present and discuss photometric and spectroscopic data of the variable, collected at the Astronomical Observatory of the Autonomous Region of the Aosta Valley and at the Asiago Astrophysical Observatory. The light curves show some asymmetries and the spectra suggest a dK4 classification for the two components. It could be interesting to carry out further observations of this system at different epochs because such systems frequently show variations in period and in the features of the light curve.

1. Introduction

We report the discovery of VSX J071108.7+695227 (= 2MASS J0711 0876+6952276), a short-period eclipsing binary system. We classify it as an EW type variable. This variable, located in the constellation Camelopardalis (R.A. 07^h 11^m 08.76^s; Dec. +69° 52' 27.6"; epoch J2000.0), was discovered thanks to photometric observations performed at the Astronomical Observatory of the Autonomous Region of the Aosta Valley (OAVdA), and at the Asiago Observatory. The system has an estimated orbital period of ~ 0.238 day.

The variable deserves further investigation mostly because the assessed period is very short and pretty close to the sharp cut-off at the lower limit of ~ 0.22 day found by Norton *et al.* (2011) for these binaries. Only a minor percentage of EW variables have periods shorter than ours. For example, Rucinski (2006) found that only a few tens out of the 4,638 EW systems of the ASAS sample have a period shorter than or similar to ours, Weldrake *et al.* (2007) found only two out of fifty-eight short period eclipsing binaries to have $P < 0.238$ day, and Miller *et al.* (2010) about ten out of 533. To date, the largest sample of EW systems with a period shorter than ours is made up of the fifty-three EW binaries with $P < 0.2314$ day listed by Norton *et al.* (2011). Moreover, such close systems show several features that change over time, as the orbital period and the shape of the light curves, as we discuss below.

All this considered, we pursued a photometric and spectroscopic analysis of our variable aimed at better characterizing its physical properties. We determined B, V, and R light curves, we assigned the two components to a spectral type, we looked for possible activity indicators in the spectra like emission lines, and we sought asymmetries in the light curves.

2. Instrumentation and methodology

Since the end of 2008, at the OAVdA is underway the implementation of an extensive observational campaign aimed at finding small-sized extrasolar planets around M dwarfs using the photometric transit method (Damasso *et al.* 2010; Giacobbe *et al.* 2012). The first observations of VSX J071108.7+695227 were performed at the end of December 2011, during the commissioning tests of the new telescope array which will be used for a five-year survey of hundreds of M dwarfs in the solar neighborhood. The array is composed of four identical 40-cm $f/8.4$ Ritchey-Chrétien telescopes, each on a 10 MICRON QCI2000 mount and equipped with a FLI ProLine 1001E CCD camera.

After the discovery, we photometrically followed up on the binary system with the main telescope present in OAVdA, an 81-cm $f/7.9$ Ritchey-Chrétien coupled to a back-illuminated CCD camera FLI ProLine PL 3041-BB and standard BVRI filters. The sensor is 2048 px $\times$ 2048 px, with a pixel area of $15 \times 15 \mu\text{m}^2$. The system has a FoV of 16.5×16.5 arcmin² with a

plate scale of 0.48"/pixel (binning 1×1). We present and discuss here the data collected with this telescope. In Figure 1 we present one of our frames and indicate our system.

2.1. Photometric data

The scientific frames taken during the discovery night and the follow-up observations were reduced and analyzed with the software package TEEPEE (Transiting Exoplanets PipEline) developed by some of the authors. A detailed description of the basic functions of the TEEPEE pipeline is provided in Damasso *et al.* (2010). In short, the final result of the data processing is the generation of the differential light curves of all the stars in the CCD field which were automatically recognized in every frame of the series. The ensemble photometry is obtained testing up to twelve apertures. The best set of comparison stars is automatically determined for a pre-selected target from a list of the 100 brightest objects found in the field, excluding the ones too close to the CCD borders. The aperture and set of reference stars selected at the end of the data processing are the ones which give the smallest RMS for the entire light curve of the object of interest.

Figure 2 (a, b, c) shows the normalized differential light curves of VSX J071108.7+695227 obtained in B, V, and R filters on January 16, 2012, during the follow-up observations with the 81-cm telescope. The differential magnitudes are calculated as the difference between the average instrumental magnitudes of the comparison stars and the instrumental magnitudes of the variable star. The comparison stars automatically selected by the TEEPEE pipeline for each filter are listed in Table 2. The light curves clearly unveil the EW variability type for the object and the observations cover almost 1.75 times the orbital period of the two components of the system, which we estimated to be ~ 0.238 day using the Fast Chi-Squared algorithm described in Palmer (2009) and freely available at <http://public.lanl.gov/palmer/fastchi.html>. Figure 3 shows the normalized V-band light curve folded according to the orbital period. The zero epoch is $HJD(0) = 2455943.438$.

We estimate a mean V magnitude for the object through the relations described in Pavlov (2009), which use the $J-K$ color index from the 2MASS catalogue (Skrutskie *et al.* 2006) and the U_f and U_a magnitudes from the UCAC-3 catalogue (USNO 2012):

$$V_f = 0.531 \cdot (J-K) + 0.906 \cdot U_f + 0.95 \pm 0.08 \quad (1)$$

$$V_a = 0.529 \cdot (J-K) + 0.9166 \cdot U_a + 0.83 \pm 0.08 \quad (2)$$

Averaging the two values found from (1) and (2) results in $V = 14.37$, where $J = 12.631$, $K = 11.923$, $U_f = 14.366$, and $U_a = 14.396$.

Using the following conversion relations between the USNO A2.0 (Monet *et al.* 1998) and Landolt BR magnitudes (Kidger 2003):

$$B = 1.097 \cdot \text{USNO}(B) - 1.216 \quad (3)$$

$$R = 1.031 \cdot \text{USNO}(R) - 0.417 \quad (4)$$

where $\text{USNO}(B)=14.8$ and $\text{USNO}(R)=13.9$, we obtained $B=15.0$ and $R=13.9$.

Moreover, the star also appears in the APASS catalogue (AAVSO 2012), which provides other estimates for B and V magnitudes: $B=15.485 \pm 0.368$; $V=14.468 \pm 0.289$.

2.2. Spectroscopic data

To better characterize the variable and look for possible activity indicators like emission lines, on January 26, 2012, we took nine consecutive spectra with the 182-cm Copernico telescope at the Asiago Observatory (<http://www.pd.astro.it/asiago/>), using the AFOSC CCD camera. Two different optical configurations were used (grism3 and grism8) with different dispersion and spectral coverage. The main features of these configurations are summarized in Table 1. We took five spectra using the grism3 and four with the grism8.

In Figure 3 we overplotted (solid and dashed) vertical lines corresponding to the orbital phases at which the nine spectra of the system were collected. It can be seen that the first ones (with both configurations) were taken at maximum brightness. They are shown in Figure 4. The other spectra do not show sizeable differences as compared to these, at least at the low dispersion accessible to us. It can be noticed, however, that they were taken at a not very different phase.

3. Discussion

At the epoch of our observations the light curves of the variable showed some clear asymmetries, as expected from such short-period systems. The most significant is an evident O'Connell Effect as the magnitude of the two maxima is different (Davidge and Milone 1984). The conventional way to assess the size of this effect is to measure the peak magnitude after the primary (deepest) minimum subtracted from the peak magnitude after the secondary minimum. From Figure 2 we derive that $\Delta B \sim \Delta V \sim \Delta R \sim +0.05$. Furthermore, a closer inspection of the B curve reveals a small "shoulder" along the rise towards both the secondary maxima. This is possibly due to the occurrence of starspots.

In fact, it is well-known that that EW variables are usually heavily spotted systems, as theoretically predicted by Binnendijk (1970). He was the first to propose that dark spots exist on the surfaces of the components to explain the asymmetry and variability of the light curves at different epochs. This hypothesis was later demonstrated by Doppler imaging (see for instance Hendry and Mochnecki 2000). One of the authors of the present paper already dealt with this issue and detected the presence of starspots in light curves taken at different epochs of one EW variable with an orbital period of ~ 0.355 day (Damasso et al. 2011).

Starspots are a possible explanation of the O'Connell Effect as well, but there is much uncertainty in this respect (Wilsey and Beaky 2009).

It would be interesting to collect new data of this system at different epochs to put in evidence possible evolutions that our data, taken during a single night, cannot reveal. In particular, short-period systems like ours can show variations in period or in the shape of the light curves, like an inversion of the primary and secondary maxima leading to an O'Connell Effect with opposite sign (see for example the case of V523 Cas treated in Zhang and Zhang 2004).

Let us now turn to the discussion of the spectroscopic data. The spectra in Figure 4 display the typical shape of K stars, without any evident superposition of different spectral types. This suggests that both components have similar spectra and surface temperatures. This is in accordance with the fact that the minima in the light curves are almost equal in deepness.

W UMa binaries are expected to be located within or in proximity of the main sequence stars (Bilir *et al.* 2005). This can be confirmed by our spectra: the prominence of the MgH band around 5200 Å and the tooth-shaped MgH feature around 4770 Å strongly suggest that the stars are dwarfs (Gray and Corbally 2009, p. 262).

To obtain a more precise classification, we resorted to the lines highlighted in Figure 4(c): the CaI line at 6162 Å, the BaII-Fel-CaI blend at 6497 Å, and the H α line at 6563 Å. The latter directly correlates with temperature, while the first two inversely correlate with temperature, so that the CaI or BaII-Fel-CaI blend to H α ratio is a useful temperature indicator.

Although in late-type stars it is often difficult to spot out an actual continuum to refer to, we calculated the equivalent widths of these three lines which are only indicative. They are:

$$W\lambda(\text{CaI}) = 1.7 \text{ \AA}$$

$$W\lambda(\text{blend}) = 0.8 \text{ \AA}$$

$$W\lambda(\text{H}\alpha) = 0.4 \text{ \AA}$$

We decided to compare our spectra to the ones tabulated by Allen and Strom (1995) because they possess a spectral coverage and resolution quite similar to ours. The CaI to H α ratio suggest a dK4 classification.

A further clue as to how to classify the two stars can be given by the slight difference in depth of the two minima. Such difference is nearly equal to 0.05 magnitude, that is, $\sim 4.7\%$ in flux. Calling $T_{1,2}$ the surface temperatures of the two components we can roughly infer that $(T_1 / T_2)^4 \sim 1.047 \rightarrow T_1 / T_2 \sim 1.012$, that is, the component 1 is hotter than the component 2 by 1.2 %. At temperatures between 4000 and 5000 K this means a difference of ~ 50 K. Unfortunately, the surface temperature of lower main sequence stars is not easy to calculate and within a same spectral type there can be a variance of more than 100 K (see for example Casagrande *et al.* 2006). Hence, the calculated temperature

difference cannot be safely assumed as to testify a difference of spectral type between the two components. In the end, we rest upon a dK4 classification for both components. In addition, this conclusion is consistent with a classification based on the color indices: according to Cox (2000) a dK4 star is expected to have $J-H = 0.58$ and $H-K = 0.11$, and our variable has $J-H = 0.583$ and $H-K = 0.125$.

Furthermore, we can try to deduce the masses of the two stars. If we call a the overall semi-major axis of the system (that is, the sum of the two semi-major axes with respect to the center of mass) expressed in AUs, T the period expressed in years, and $M_{1,2}$ the masses of the two components expressed in solar units, we have:

$$a^3 = T^2(M_1 + M_2) \quad (5)$$

From our photometric data we deduce $T = 0.238 \text{ day} = 6.516 \times 10^{-4} \text{ yr}$. A mid-K dwarf typically has a mass $M \sim 0.7 - 0.75$; assuming $M_1 + M_2 = 1.45$, it results that $a \sim 1.27 \times 10^6 \text{ km}$.

Assuming both components to have a radius $R 0.75 - 0.8$ with respect to the Sun, that is, about $5 \times 10^5 \text{ km}$, we have $a \sim 2.5R$. This is fine because W UMa variables are supposed to be almost touching each other.

Moreover, one could ask how large a Doppler broadening such an orbital pattern would entail in spectra. Let us assume a circular orbit. At the time of maximum in the light curve we should have an overall Doppler broadening of the order of:

$$\Delta\lambda / \lambda = v / c = 2\pi a / (Tc) = 1.29 \times 10^{-3} \quad (6)$$

If we consider the $H\alpha$ line at $6563\text{\AA}$ we have that $\Delta\lambda \sim 8\text{\AA}$, that is, the width of the line should extend about from 6554.5 to $6571.5\text{\AA}$. If we consider the CaI line at 6162 we have $\Delta\lambda 8\text{\AA}$, that is, the width of the line should extend about from 6154 to $6170\text{\AA}$. These values are consistent with our spectra, but because of the low dispersion we can attain we believe we cannot draw any sure conclusion in this respect.

We finally looked for possible activity indicators in the spectra like emission lines, but we found none at the level of resolution accessible to us.

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Table 1. Optical configurations used to acquire the spectra of the variable.

<i>Configuration</i>	<i>Spectral coverage</i>	<i>Mean dispersion</i>	<i>Resolution</i>
grism3	~3700 – ~5850Å	~2.1Å/px	~650
grism8	~5950 – ~8000Å	~2.0Å/px	~1900

Table 2. Comparison stars used for differential photometry in B, V, and R bands.

<i>Star</i>	<i>R.A.</i>			<i>Dec.</i>			<i>Band</i>
	<i>h</i>	<i>m</i>	<i>s</i>	<i>°</i>	<i>'</i>	<i>''</i>	
UCAC-3 320-037770	07	09	19.041	+69	55	06.66	B V
UCAC-3 320-037772	07	09	21.093	+69	56	00.27	B
UCAC-3 320-037776	07	09	24.095	+69	56	59.02	B V R
UCAC-3 320-037779	07	09	28.970	+69	51	43.34	B R
UCAC-3 320-037783	07	09	32.398	+69	50	57.44	B
UCAC-3 320-037784	07	09	32.649	+69	58	42.06	B
UCAC-3 320-037787	07	09	34.315	+69	49	49.11	B V R
UCAC-3 320-037794	07	09	42.534	+69	50	59.13	B
UCAC-3 320-037795	07	09	43.173	+69	54	42.21	B
UCAC-3 320-037798	07	09	45.939	+69	55	15.41	B
UCAC-3 320-037799	07	09	47.551	+69	52	26.48	B
UCAC-3 320-037820	07	10	09.948	+69	55	17.80	B
UCAC-3 320-037821	07	10	11.189	+69	50	45.90	B
UCAC-3 320-037823	07	10	14.455	+69	50	34.28	R
UCAC-3 320-037827	07	10	20.912	+69	49	40.04	B V R
UCAC-3 320-037828	07	10	21.806	+69	52	30.72	B
UCAC-3 320-037831	07	10	23.959	+69	51	24.78	B R
UCAC-3 320-037835	07	10	31.401	+69	53	52.17	B
UCAC-3 320-037849	07	10	38.339	+69	57	18.61	B
UCAC-3 320-037857	07	10	42.666	+69	49	14.61	B
UCAC-3 320-037860	07	10	44.576	+69	51	52.55	B
UCAC-3 320-037862	07	10	47.011	+69	51	35.23	B
UCAC-3 320-037867	07	10	54.909	+69	52	17.17	B V R
UCAC-3 320-037871	07	11	03.636	+69	52	31.88	B
UCAC-3 320-037876	07	11	07.800	+69	51	27.49	B V
UCAC-3 320-037881	07	11	10.879	+69	51	29.52	B V
UCAC-3 320-037885	07	11	14.572	+69	56	07.65	B V R
UCAC-3 320-037896	07	11	27.544	+69	48	08.74	B
UCAC-3 320-037901	07	11	32.558	+69	52	03.82	B V R
2MASS 07110649+6947296	07	11	06.492	+69	47	29.61	B
2MASS 07094405+6952413	07	09	44.051	+69	52	41.40	B

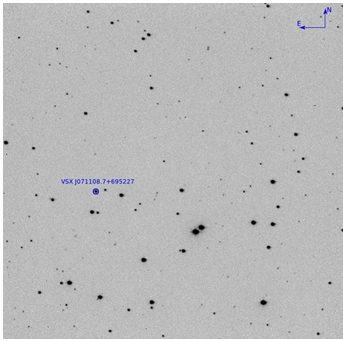


Figure 1. The star field of VSX J071108.7+695227, with the variable star target highlighted. The scale of the image is 16.5×16.5 arcmin². North is up and east is to the left.

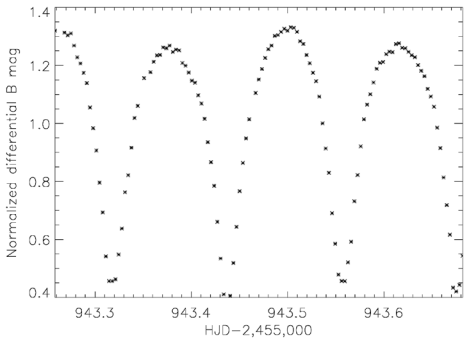


Figure 2a. Differential light curve of the variable star VSX J071108.7+695227 in B filter. The data were collected on January 16, 2012.

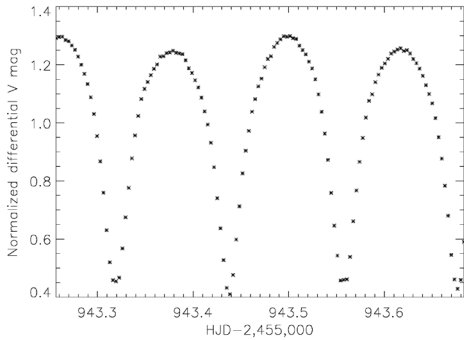


Figure 2b. Differential light curve of the variable star VSX J071108.7+695227 in V filter. The data were collected on January 16, 2012.

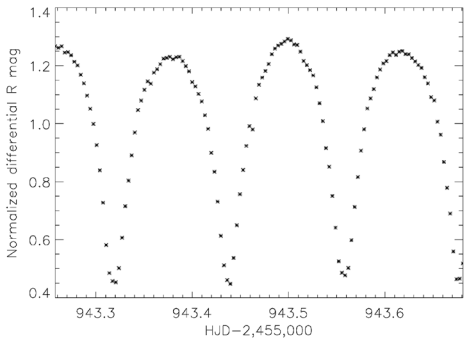


Figure 2c. Differential light curve of the variable star VSX J071108.7+695227 in R filter. The data were collected on January 16, 2012.

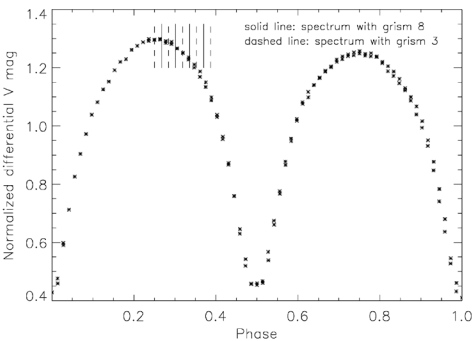


Figure 3. Differential light curve of VSX J071108.7+695227 in V band folded according to the orbital period ~ 0.238 days.

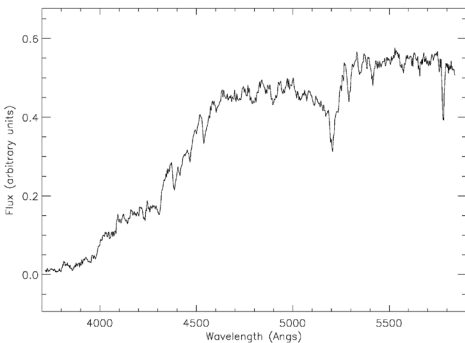


Figure 4a. Spectra of the variable star VSX J071108.7+695227 at maximum brightness, taken with grism3. The mid epoch of the exposure is HJD 2455953.493615.

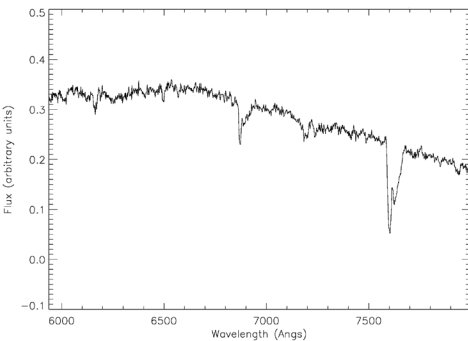


Figure 4b. Spectra of the variable star VSX J071108.7+695227 at maximum brightness, taken with grism8. A magnified region is displayed in Figure 4c. The mid epoch of the exposure is HJD 2455953.497677.

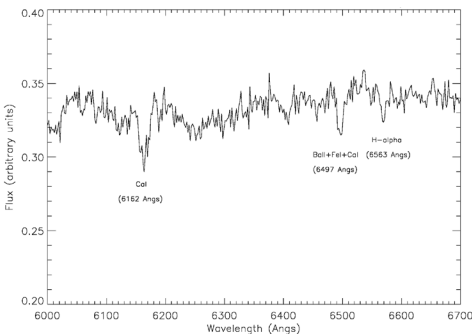


Figure 4c. A magnified region of the spectra of the variable star VSX J071108.7+695227 at maximum brightness, taken with grism8. The mid epoch of the exposure is HJD 2455953.497677.

Chapter 3

The APACHE Project: survey operations

3.1 Introduction

This Chapter is dedicated to the description of the main features of the APACHE survey, as they have been conceived and maintained along the first observing season. A general introduction to the principal characteristics of the Project can be found in [Sozzetti et al. \[2013\]](#), which represents the very first paper introducing the community to APACHE. The paper is attached to the end of the Thesis manuscript and it forms an integral part of this Chapter. Here I describe in greater detail the many facets of the work done to make the survey operational, in particular those for which I have given the main contributions. Specifically, I am the main responsible for the definition and maintaining of the APACHE Input Catalogue (AIC), I have given a relevant contribution in testing and debugging the hardware and the software tools and in defining an appropriate observing strategy. At the end of the Chapter I will describe in detail the pipeline for data reduction and analysis, which can be considered as an evolution of the one described in [Damasso et al. \[2010b\]](#) and also used for the pilot study [[Giacobbe et al., 2012](#)]. The version of the pipeline software discussed here, from which all the results presented in [Chapter 4](#) and [Chapter 5](#) have been obtained, has been entirely developed by myself.

3.2 Building the APACHE Input Catalogue

A bearing wall of the APACHE survey is represented by the list of M dwarfs that are eligible for observations during the campaign. We paid much attention to the

definition of the APACHE Input Catalogue (AIC), first setting up a wide list of potential targets based on general criteria related to the geographical coordinates of the OAVdA (and the constraints imposed by the surrounding mountains) and to the field of view of the CCD cameras, and then defining a ranking list based on the available information about the properties of the stars collected cross-correlating several stellar catalogues. At the end, each star has been characterized by a final score which set its observing priority. The AIC is an 'open' catalogue, as the observing priorities of the targets that are constantly updated on the basis of new data published in literature or gained from ongoing surveys parallel to APACHE (discussed below), which provide fresh information about the physical properties of the stars. In fact, being a targeted survey, as opposite to a wide-field survey, a strong point of APACHE is the a-priori knowledge of as much detail as possible on the stars of interest. Moreover, up to now the strategic synergy established since Summer 2012 between APACHE and the GAPS programme (see Chapter 5) has been a relevant reason for greatly increasing the observing priority of several targets (i.e. those in common with the high-resolution spectrograph HARPS-N). With the GAPS observations in progress, the spectroscopic data already revealed that some targets are not M dwarfs but stars of different spectral type (and/or luminosity class), and that others are actually multiple systems. These objects have been removed from the observing schedule of APACHE. A similar help is secured from the ARDS survey, as introduced later in this Section. Here I shortly describe the criteria followed for building the AIC and the works we referred to collect as much information as possible about the targets. All the M dwarfs in the AIC come from the catalogue of 8889 bright cool stars compiled by [Lépine and Gaidos \[2011\]](#). This high number of stars does not impose us relevant restrictions in defining the criteria for selecting a reasonable number of APACHE targets. Taking into account the geographical coordinates of the OAVdA and some environmental constraints, we first selected a sub-list of targets that 1) have positive Declination, 2) are visible for at least 45 days in a row and 3) are observable for at least 3 hours/night in a row, with an altitude > 40 degrees during this time lapse. We consider the timespan of one month as the minimum requirement for monitoring a target during an observing season, in order to increase the chance of detecting more than one single transit and confirm the existence of the event, possibly estimating the orbital period of the companion. For a similar reason, by observing a target for at least 3 hours per night there is the chance of observing a complete or partial transit event. By applying these constraints, the number of potentially good stars reduces to 4806. In a second step, we discarded 378 stars for which a very bright object falls in the field of view of the APACHE telescopes. This avoids blooming effects which are not predictable and could contaminate the flux in the circular apertures used to

perform the photometry of the targets and comparison stars. The selection was made cross-correlating the coordinates of the potential targets with those of the objects listed in the Bright Star Catalog¹, used as a source of basic astronomical and astrophysical data for stars brighter than magnitude 6.5, considering a search radius of 11 arcmin (i.e. placing the target in the centre of the FoV, as it actually happens during the observations. The FoV of the APACHE telescopes is 26'x26'). The third and final selection filter we applied concerns the need of assuring a minimum number of potentially good comparison stars to be used in the ensemble differential photometry of the targets. APACHE will observe hundreds of fields for which it is not possible to identify a-priori stars bright enough and with a low level of photometric variability that could be safely used as comparison. For this reason, we have selected only those stellar fields which contain at least three potentially good reference stars, i.e. stars whose J flux (from the 2MASS Catalogue) is similar to that of the target. Defining F_J the flux of a target M dwarf in band J , our requirement for a field star to be considered a possible comparison is that its J -flux is between $0.3F_J$ and $1.5F_J$. This selection criteria filters out ~ 1100 M dwarfs, leading to a final list of 3298 possible targets. As expected, several discarded M dwarfs are among the brightest in the original list and lie in a FoV with no suitable number of comparison stars. To devise a preliminary ranking list, we searched for published information about several physical properties of the stars. First, it is important to have an accurate spectral classification, to be quite confident that we are observing an early-to-mid type M dwarf, the spectral range of interest for APACHE. [Lépine and Gaidos \[2011\]](#) provide a tentative classification based on photometric information, which is necessarily only approximate and subject to a non-negligible uncertainty. In a following work, [Lépine et al. \[2013\]](#) improved the spectral classification of the brightest stars ($J < 9$) of the [Lépine and Gaidos \[2011\]](#) catalogue by analysing newly acquired low-resolution spectra. In addition to this work, we cross-checked the PMSU catalogues ([Reid et al. \[1995\]](#), [Hawley et al. \[1996\]](#), [Gizis et al. \[2002\]](#)), those of [Bochanski et al. \[2005\]](#), [Riaz et al. \[2006\]](#), [Shkolnik et al. \[2009\]](#), [Houdebine \[2010\]](#), [Reiners et al. \[2012\]](#) and the list of M dwarfs published in the [DwarfArchives.org](#) Web site² (and references therein). M dwarfs with a reliable spectral classification rank higher in our list. The observing priority further rises if 1) the star is known to be a slow rotator, according to measurements of its projected rotational velocity $v \sin i$; 2) it has a low chromospheric activity as measured by the equivalent width of the H_α line (positive sign: emission; negative sign: absorption); 3) it is not known as a bright X-ray source, by verifying its inclusion in the ROSAT bright source all-sky catalogue [[Voges et al., 1999](#)]. A

¹<http://tdc-www.harvard.edu/catalogs/bsc5.html>

²<http://spider.ipac.caltech.edu/staff/davy/ARCHIVE/index.shtml>

slow rotator and a star with a low activity level is to be preferred because, for the spectroscopic follow-up required to measure the mass of a transiting planetary candidate, the measurements of the radial velocity variations are less affected by the line broadening and the intrinsic jitter due to stellar activity. To get information about $v \sin i$, we have cross-checked the catalogues of [Glebocki and Gnacinski \[2005\]](#), [Houdebine \[2010\]](#) and [Reiners et al. \[2012\]](#). We have flagged as slow rotators stars with a measured $v \sin i < 15 \text{ km s}^{-1}$. The information about the equivalent width of the H_α line (sign and values) has been obtained from the PMSU catalogues ([Reid et al. \[1995\]](#), [Hawley et al. \[1996\]](#), [Gizis et al. \[2002\]](#)), and those of [Bochanski et al. \[2005\]](#), [Riaz et al. \[2006\]](#), [Jenkins et al. \[2009\]](#), and [Shkolnik et al. \[2009\]](#). Very recently, we have also performed a cross-check with the spectroscopic catalog of M dwarfs from the LAMOST pilot survey ([Yi et al. \[2013\]](#)). For each spectrum of this catalogue, spectral subtype and equivalent widths of the H_α line are provided. Since Summer 2012, an important support to APACHE, at present especially as a resource for updating the AIC, is a low-resolution spectroscopic survey of M dwarfs which is conducted at the Astrophysical Observatory of Asiago. The project ARDS (Asiago Red Dwarf Survey) is a collaboration between the APACHE Team and colleagues of the Dept. of Physics and Astronomy of the University of Padova and INAF-OAPa, and its main goal is the spectroscopic characterization of a sample of M dwarfs (for instance, their chromospheric activity and the determination of a reliable spectral classification) selected from the Apache Input Catalogue among those that lack information from other catalogues. We have been using the fresh information coming from the ARDS spectra to modify the observing bonus of the targets in the AIC, for instance by ranking higher a star with evidence of H_α absorption or lower a star showing H_α emission. Initially, the survey was conducted by using the 122 cm and 182 cm telescopes at the Asiago Observatory, then the observations have been restricted to the 182 cm telescope and to the faintest stars in the AIC ($J > 9$). This change in the observing strategy was imposed by the publication of a spectroscopic catalogue by [Lépine et al. \[2013\]](#), which is focused on M dwarfs brighter than $J=9$, so that the ARDS catalogue is composed by a list of targets complementary to that of [Lépine et al. \[2013\]](#).

To favour those stars not yet monitored by other observing campaigns, we checked the inclusion of the M dwarfs in past or ongoing high-precision Doppler surveys ([Wright et al. \[2004\]](#), [Bonfils et al. \[2013\]](#)) excluding those already known to host planets that do not show transits. Moreover, because APACHE puts first the observation of stars with possibly no stellar companions, which could represent a complication for a RV follow-up in case of a transit detection, we have excluded from the schedule those targets known to be spectroscopic binaries (e.g. [Shkolnik](#)

[et al. \[2009\]](#)). To exclude the presence of very close visual (and possibly physical) companions, we have also taken into consideration the results of the AstraLux M dwarf multiplicity survey ([Janson et al. \[2012\]](#)), which uses high-resolution imaging to look for multiplicity in the range 0.08-6 arcsec from the star. Finally, by cross-checking the 2MASS catalogue we have flagged those targets that have at least one field star of similar magnitude within a radius of 15 arcsec. Taking into consideration the typical seeing at our site (median value 1.7 arcsec) and the pixel scale of the CCD cameras (1.5 arcsec/pixel), in some circumstances such a close object could blend with the target and prevent reliable aperture photometry. We do not exclude a-priori these problematic fields but, if selected for the observations, then they are visually inspected and considered for rejection. The last, but not least, parameter that we have considered for the definition of the ranking list is the expected number of observations of each target by the Gaia satellite, which has been successfully launched and is supposed to provide a very relevant contribution to the extrasolar science ([Sozzetti et al. \[2001\]](#), [Sozzetti \[2013\]](#)). According to the scanning law of Gaia, it is possible to calculate the number of expected transits over a certain field after the nominal 5 years of mission. We have assumed that targets with a number of Gaia observations greater than 100 have higher priorities when building the APACHE schedule because they will be characterized by a very accurate trigonometric parallax. This means that it will be possible to measure the stellar intrinsic luminosity, mass and radius. If APACHE discovered transiting planets around bright targets, these updated values for the host stars (especially the radius) would imply a precise determination of the planet radius. Combined with exquisite RV data (e.g. those collected with the HARPS-N spectrograph), the bulk density of the planet could be precisely determined (e.g. [Anglada-Escudé et al. \[2013\]](#)).

In summary, all the informations collected about the potential APACHE targets result in a series of 'bonus' and 'malus' that determine their final score, from which the nightly observing schedule is built. Since Spring 2013, 25 more targets have been added to the AIC and with the maximum priority in the schedule. These are bright stars which are scheduled also on HARPS-N in the framework of the GAPS Project 5. Initially, these stars were not selected in the AIC because of lack of a suitable number of comparison stars in the FoV. We have overcome this problem by observing them in the V-band, where they are in general fainter than other field stars, instead of the I_c-band adopted for all the other targets. As a final remark, we note that the AIC has 322 targets in common with those in the MEarth catalogue.

3.3 Assessing masses, radii and effective temperatures of the APACHE targets

The determination of fundamental stellar parameters with great precision, as radius and mass, is very important to characterize an exoplanet, because usually the uncertainties in the host star mass and radius dominate the uncertainties in the planet mass and radius, and hence in the planetary bulk density. The precise characterization of a planet host star is in general a very complicated task, in that it combines empirical measurements with evolutionary and atmospheric stellar models. This is particularly difficult for M dwarfs because the theoretical models can not yet reliably describe the stars' properties, for example because the effects of their strong stellar magnetic fields are poorly known. A description of the challenges in assessing the physical parameters of M dwarfs can be found, for example, in [Rojas-Ayala et al. \[2013\]](#), [Fernandez et al. \[2009\]](#), [Kraus et al. \[2011\]](#) and [Birkby et al. \[2012\]](#) (and references therein), with the latter three papers discussing in detail (and providing contrasting results about) the discrepancy, known since long time, between the predicted and observed radii of low-mass binary stars.

Despite this Thesis does not address the issue of the determination of M dwarfs physical parameters, nonetheless we have considered useful to provide an estimate of mass and radius for the stars in the APACHE Input Catalogue, in particular because the stellar radius is a required parameter when evaluating the sensitivity of the survey to transit signals of different depth, thus to planets of different size. The APACHE Team is presently performing this analysis after the first observing season (to appear in a paper in preparation) by injecting fake transits of different depth in real light curves of different targets characterized by a different noise level and phase coverage. Those signals are then recovered by using the BLS algorithm [\[Kovács et al., 2002\]](#), then applying a statistical analysis as described in [Giacobbe et al. \[2012\]](#). Before entering the details of the analysis, it is necessary to define some sub-lists of stars from the AIC we have used for this work. Out of the 3323 M dwarfs composing the AIC, a subset of 2498 have good estimates for visible V magnitudes obtained from a cross-check with the APASS photometric catalogue [\[Henden et al., 2009\]](#), that are in general more precise than those listed in [Lépine and Gaidos \[2011\]](#), and color indices $V-J$, $V-H$ and $V-K$. We call *S1* this subset. Only 170 stars in our AIC have a measured trigonometric parallax, thus they are the only for which it is possible to know the distance and the intrinsic brightness with good precision. We call *S2* the subset including these stars.

3.3.1 The radii of the *APACHE* M dwarfs

The stellar radii can be measured through four different methods: 1) The Stefan-Boltzmann Law, provided one knows about the surface temperature and the intrinsic brightness of a star: only for the *S2* stars we can proceed this way; 2) Interferometric techniques; 3) Eclipsing binaries; 4) The development of stellar models. Apart from method 4) that lies beyond the scopes of the present work, it must be noticed that only a few M dwarfs radii have been measured via method 2) to date [Ségransan et al., 2003], [Demory et al., 2009]. Actually, the small radii of these stars makes them a secondary target for this kind of measures. Moreover, only a few data have been collected from eclipsing binaries. Thus, for our purpose we resorted to the Stefan-Boltzmann Law, and it becomes a matter of estimating the effective temperature T_{eff} and intrinsic brightness of our stars. A large amount of data is available about effective temperatures of red dwarfs. Casagrande et al. [2008] supply relations tying several visible and infrared color indices to T_{eff} . Accurate data about these color indices are available for the *S1* stars and as a first step we could derive the T_{eff} of these stars from such relations. Casagrande et al. do not include any metallicity dependence in their relations, because their M dwarf sample is made up of stars lying in the solar neighbourhood and they are supposed to be disk stars. Moreover, the same authors observe an increasing scatter in T_{eff} below 2800 K, due to a larger metallicity influence, but for higher temperatures they point out that "with the exception of $B-V$, none of the colour-temperature transformations has strong dependence on the metallicity $[M/H]$ above 2800 K, and therefore our relations are not likely to be affected much as metallicities for M dwarfs improve" (page 595). We felt confident we could employ these relations safely, and we obtained T_{eff} for the stars in the *S1* sample. A different line of attack is pursued by Lépine et al. [2013]. Here T_{eff} for several M dwarfs is derived fitting observed to synthetic spectra. We compared the temperatures derived from the relations of Casagrande et al. [2008] to those worked out by Lépine et al. [2013] for a subsample of 390 stars for which both estimates were available, noticing an overall good agreement with only a few stars whose temperature differs by a 10% in the two cases. As we can avail ourselves with good data about color indices for most of our stars (subset *S1*), whilst good spectroscopic data are in shorter supply, we decided to utilize the T_{eff} worked out from Casagrande et al. relations, reassured by the good agreement between the two methods. Although we derived T_{eff} for the *S1* stars, i.e. most of the AIC objects, we could work out the intrinsic brightness of the *S2* stars alone, i.e. a small percentage of the overall number. Anyway, we went on this way utilizing empirical bolometric corrections given by Casagrande et al. (2008, page 595) together with the trigonometric parallaxes listed in Lépine and

Gaidos [2011]. Figure 3.1 shows the relation $\text{Log}(\text{luminosity})$ vs. $\text{Log}(T_{eff})$ for the *S2* stars ('plus' symbol). In lack of any precise information about the distance of the other stars of our Input Catalogue, we subsequently worked out a $\text{Log}(T_{eff})$ Vs. $\text{Log}(\text{Luminosity})$ relation fitting these data points. A quadratic fit was finally chosen and it is depicted in Fig. 3.1 ('empty square' symbol). It tends to underestimate luminosities for larger T_{eff} values, and to overestimate them for lower T_{eff} values, but it looked like the best possible choice in our case. Using this fit we then deduced the brightness of all the *S1* stars, for which we have a T_{eff} assessment. At this point, we worked out the stellar radii by using the Stefan-Boltzmann Law. In Fig. 3.2, the radii distribution for *S1* stars is shown in the first plot, while the plot in the middle shows the radii distribution for the *S2* star list, with radii calculated via the accurate luminosities deduced by parallaxes and not from the best-fit quadratic function. Finally, in the plot at the bottom we compared the radii for the *S2* stars worked out via both methods, to provide an overall assessment of the consistency of the results. It can be seen that the fitted radii are underestimated for larger values and overestimated for lower ones. Generally speaking, it is clear that fitting luminosities and radii the way we did introduces a certain degree of imprecision because it abruptly approximates the complex structure of the main sequence in the M dwarfs region. The radius we get for a star is then to be considered only as a "working radius", a sort of statistical mean value for that temperature.

3.3.2 The masses of the APACHE M dwarfs

To work out masses, we turned to the relations supplied for low-mass stars by Delfosse et al. [2000] (pag. 220). They tie a stellar mass M to its absolute magnitude in V , J , H and K bands and to the $V-K$ color index. Although exploiting the color index would allow us to deduce the mass for the *S1* stars, we were reluctant to do so because the V magnitudes have been much improved since the time of Delfosse et al. calibrations and perhaps their relation could not fit equally well the new values. Moreover, V magnitudes are pretty metallicity-sensitive as compared to the infrared ones for our stars, thus we rather turned to the $M-M_J$, $M-M_H$ and $M-M_K$ relations (where M_x : absolute magnitude in band x) and, by averaging the three estimates, worked out masses for the *S2* stars, or -more precisely- for the subset of these whose J , H , K values fall within the validity range of Delfosse et al. relations. We call *S3* this subset and it includes 170 stars. To get a mass for the stars in the *S1* list, we decided to find a best-fit relation between the mass and T_{eff} , a stellar parameter for which we have an estimate. In Fig. 3.3 we show the masses as a function of T_{eff} for the *S3* stars, il Log-Log scale, with oveplotted the

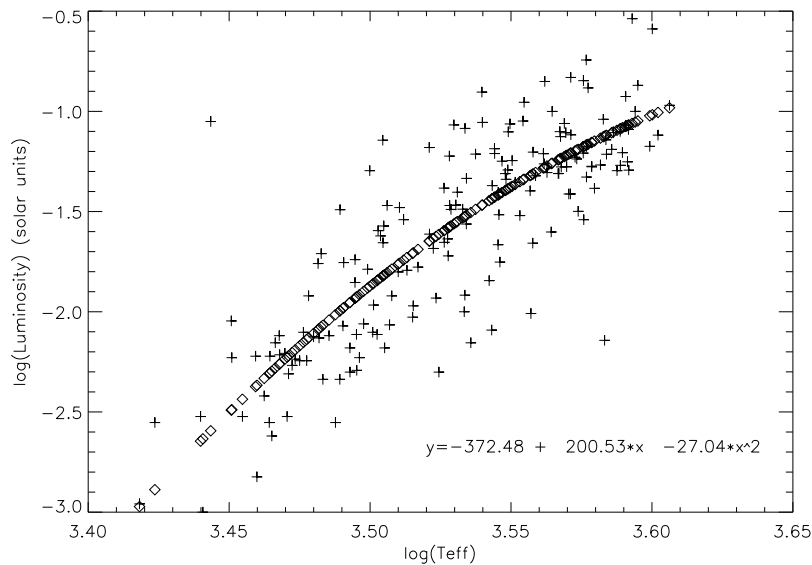


FIGURE 3.1: Luminosity vs. Effective temperature for 170 red dwarfs of the APACHE Input Catalogue ('plus' symbol) with measured trigonometric parallax, with the estimate of the parameters obtained from empirical relations as described in the text. Superposed ('empty square' symbol) is the result of a quadratic best-fit, with the corresponding adopted quadratic relation indicated in the plot. This relation has been used to assess the luminosity of 2498 stars in the AIC with estimated T_{eff} .

best-fit quadratic relation ("square" symbol). This empirical relation was used to calculate the mass of the stars in the *S2* list from their T_{eff} . It can be seen that our fit overestimates masses at low T_{eff} and underestimates them at higher T_{eff} . Finally, we compared the masses calculated through the Delfosse et al. relations and through our fit for the *S3* stars, to gain an overall assessment of the consistency of the results (see Fig. 3.4). We found a fairly good agreement. Afterwards, we considered the work by [Bayless and Orosz \[2000\]](#), in which the authors deal with the eclipsing binary 2MASS J05162881+2607387, whose components are both low-mass dwarfs. This offers the rare occasion to directly estimate both masses and radii of the stars. The authors, utilizing their data as well as other recent mass and radius determinations for low-mass binaries, work out a mass-radius relation. It is interesting to determine the stellar radii for the *S3* stars exploiting this relation to compare them with the one deduced via the Stefan-Boltzmann Law. The agreement is acceptable but not so tight. The radii worked out following [Bayless and Orosz \[2000\]](#) are, in general, smaller, and we found this quite surprising because they state that the radii of the 2MASS J05162881+2607387 components are larger than the model predictions. We discussed whether it was the case to work out radii from the [Bayless and Orosz \[2000\]](#) relations instead of following the Stefan-Boltzmann Law line of attack. We decided not to do this, because the relation by [Bayless and Orosz](#)

[2000] builds upon a very small amount of data, albeit they have the undeniable advantage of being accurate ones.

3.4 Main specifications of the APACHE hardware and software control system

APACHE employs an array of five small-size telescopes hosted on a single platform with electronically controlled roll-off enclosure. Four telescopes are working since the start of the scientific observations, on July 2012, while the fifth has been installed lately and started observations on March 2013. The array is composed of identical Carbon Truss 40 cm f/8.4 Ritchey-Chrétien telescopes, each with a GM2000 10-MICRON german mount and equipped with a FLI Proline PL1001E-2 CCD Camera and Johnson-Cousins V, R and I filters. This configuration is characterized by a pixel scale of ~ 1.5 arcsec/pixel and a field of view of 26×26 arcsec². Except for a small number of targets, all the M dwarfs are observed using the I_c filter. These systems guarantee a state-of-the-art quality performance: negligible temperature gradients and a quantum efficiency QE of about 80% in the whole wavelength range of interest. A very relevant step in building APACHE has been the choice and implementation of the software control system for the telescope array. The open source observatory manager RTS2³ [Kubnek et al., 2004], [Kubnek, 2010] has been our choice for its high-level performances. RTS2 is running in many other Observatories worldwide and it is very suitable for the APACHE needs because it allows, among others, the possibility of including dynamic (and circular) scheduling of the observations. RTS2 manages the observations by dividing the observing run in separate temporal 'states' during which only some specific operations are performed. During the 'dusk state', the telescopes take dark and flatfield frames, while during the 'night state', that starts after the epoch of the astronomical twilight, scientific images of the targets are acquired. The last fraction of the observing run is represented by the 'dawn state', during which the telescopes take again dark and twilight flatfield frames. RTS2 is installed separately on every PC which manages each telescope of the array, thus each observing station is run independently by the others. With this modular architecture, the astronomers/operators can easily manage the operations of a single observing station in case of problems. During the first season, we have worked to make the software control system very stable. At regime, only few preliminary operations have to be made manually before starting the observations, which then go on automatically. Every night, the FITS files collected

³<http://www.rts2.org/>

by each telescope are transferred from the local PCs to the workstation HP Storage Works X1600 12TB used as Network Attached Storage (NAS) system, which are connected together via Intranet 1 GB/s. More details about the survey hardware and the design of the software for system control can be found in [Christille et al. \[2013\]](#).

Concerning my role in the implementation phase of RTS2, I have been involved only marginally in the (very hard) computer engineering work necessary to adapt the software to our needs (for which the APACHE Team took advantage of the valuable collaboration of P. Kubánek), but I have provided a very relevant contribution in debugging during several nights spent in testing the whole system.

3.5 Observing strategy

After 4 years of operations, the definition of an appropriate observing strategy turned out to be a critical point for the expected performances of the MEarth survey, as explained in [Berta et al. \[2013\]](#). This is especially true for a survey conducted from a single site and lacking of a connection to a network of Observatories located at different longitudes. In preparing APACHE, we have defined a strategy maintained along the first season. Here I just describe its main characteristics, pointing out that we are not yet in the conditions for heavily revising it after only one year of operations, although the results from the first year at regime are being investigated to identify the main critical points to be promptly modified. Before starting the night observations, just after the instruments have been switched on, they automatically acquire the necessary calibration images (dark and twilight flat-field frames), until the 'night state' begins. As said, this operation is repeated just before dawn. As regards to the flatfields, we are developing the method described by [Surma \[1993\]](#), which aims to produce an optimal master flatfield free from the shutter shading effects, by deconvolving the intrinsic CCD flatfield and the camera's 2D shutter function using flatfield frames taken at different exposures. This method is tailored to each single target, because the function to use for calculating a master flatfield depends on a target exposure time. By now, we are still testing this algorithm and it has not been yet included in the pipeline as a standard procedure. At the beginning of each observing run, a list of targets to be monitored is produced for each telescopes, by selecting those stars in the AIC having the highest scores in the ranking. Separate lists are loaded on the PCs of each telescope, and the targets are observed after the epoch of the astronomical twilight. Before these observations the focusing of the telescopes takes place, that lasts about 10 minutes. This is done

by pointing a fixed region in the sky, very close to the Polaris and containing an adequate number of stars, and several frames are acquired by moving the focuser around the optimal focus position of the encoder that was found in the previous night. These images are then processed to extract from each one an average value for the FWHM of the field stars. A fit with a second order polynomial function is then performed on the FWHM values expressed as a function of the encoder focuser positions, and the minimum of this function is calculated. At the end, the focusers are moved to the encoder positions corresponding to the minimum values of the best-fit. The secondary mirror is never moved during this phase, because the range of encoder steps is wide enough for each focuser to reach the optimal focus position, which remains unchanged during all the observing session. A target star is always observed by the same telescope and usually it stays in schedule for at least 1.5 months in a row. One main point in arranging the schedule on a nightly basis is that it is 'circular': a telescope must come back to observe a star after a timespan not longer than 25 minutes, to collect a suitable number of data for a transit to be detected if it is in progress (which is assumed to typically last 2 or 3 hours). During this interval, the telescope points different fields, taking three consecutive images for each target before moving to a new one, and the number of the observed stars depends on their exposure times (fixed). We set to three the number of exposures per target per pointing to minimize the effects produced by a changing seeing, and for light curve analysis we use the average value of the corresponding extracted instrumental magnitudes. If in a particular night a star is located at a distance <40 degrees from the Moon, this star is not selected for that observing run. Another constraint related to the celestial coordinates of a target is that it is observed only if its altitude above the horizon is greater than 30 degrees, in order to limit the noise introduced in the photometric data by the effects of high airmass. When the altitude falls below this limit, the star is discarded and a new one enters the schedule. On average, in winter time a single telescope can observe more than 10 different stars every night. A relevant detail of our observing strategy is the importance of having the target always located in the centre of the CCD chip at each exposure. This is of great relevance in order to minimize the systematics due to an (inevitably) imperfect flat-fielding correction. To guarantee a precise pointing, when a telescope reaches the target field a short-time exposure is acquired and fed to the software **Astrometry.net**⁴ [Lang et al., 2010], which provides a real-time astrometric calibration of the image. From the output of the **Astrometry.net** code and by using the J2012 coordinates of the target, the corrections to be applied for locating the star in the centre of the CCD sensor are calculated and sent to the mount, which responds accordingly. Usually, the astrometric calibration fails when

⁴<http://astrometry.net/>

thick veils/clouds are present over the stellar field. When this happens, new images are taken at increasing exposure times (in steps of 5 seconds) until **Astrometry.net** resolves the image. We fixed a limit of 25 seconds as longest exposure to correct the telescope pointing. Whether this limit is reached, the system skips the target and switches to the next one in the schedule. *APACHE* does not use yet an "alarm mode" strategy, according to which if a star shows in real-time evidence of a transit in progress, all the telescopes or at least another one are immediately pointed to that star for an intensive follow-up. Despite we have developed the software TSE which performs real-time photometry as a part of the *APACHE* data reduction and analysis pipeline (see next Section), a robust protocol for entering a "follow-up mode" that minimizes the probability for a false alarm has not been drafted yet. As a part of our strategy, since the beginning of the observations we have included in the schedule some stars known to host a transiting planet. These stars have been kept under observation for several weeks with the goal of testing our capability in detecting the transits and retrieving the main features of the signals, like the orbital period and the depth. We have selected stars with signals of different depth and periodicity below 5 days, in order to test the performances of *APACHE* on the kind of transits we expect to discover. Some results about these extra targets are discussed in Chapter 4.

As a final point, it is interesting to shortly describe the procedure we have implemented for determining the exposures times for each target, that have been kept fixed during the whole season. We have devised a list of M dwarfs from the AIC characterized by different magnitudes in the *J*-band and different *V-K* color index, in order to consider stars of spectral type in the range k7-m5, according to the classification provided by [Lépine and Gaidos \[2011\]](#). During a night with a very good sky, we collected images of these stars with several exposure times, measuring the SNR in each frame. Then, we have calculated for each target the exposure time for which the expected SNR is 200 (SNR=300 for the later spectral types), by fitting the SNR as a function of the exposure times. Finally, we divided the stars in spectral bins ([k7-m1], m2, m3, m4, [m5-m7]) and for each of them we have derived the best-fit relation of the form $A \cdot 10^{(J-B)/2.5}$, where *A* and *B* are constants and *J* is the 2MASS magnitude. This relation provides the optimal exposure time to be used to reach the expected SNR=200 (300 for the spectral bin m5-m7). After the first year of observations, we have realized that, despite this method resulted in an optimal choice for the majority of the targets, for some of them the exposure times can be increased to boost the SNR. In fact, our calibrations were made during a night with very good sky transparency, which is a condition that happens only for some sessions, and we did not take into account the small differences in the focal

length of the five telescopes. While the calculated exposure times avoid by choice that saturation is reached for the target M dwarfs, sometimes the SNR turns out to be less than the optimal value. For some stars, we could sensibly reduce the discrepancy between the observed and expected photometric noise, resulting in less scattered light curves (see Chapter 4). This is a matter for discussion in view of the possible observing strategy revision during the second season.

3.6 Description of the data reduction and analysis packages

I have carried out the data reduction and analysis by using two different pipelines which perform ensemble differential aperture photometry, both developed by myself and based on the same structure that was defined during the preparatory studies to APACHE. The general structure of the pipelines is described in [Damasso et al. \[2010b\]](#) and [Giacobbe et al. \[2012\]](#), so we refer to these papers for the explanations of the main features. Here I recall that the aim of the pipelines is to produce the best possible differential light curve for the target star, by using two different methods for selecting the radius of the aperture and the set of comparison stars which minimize the RMS of the M dwarf photometric time-series. Exclusively for APACHE, I have devised the TSE (Transit SEntinel) package which performs ensemble differential aperture photometry of each target (and field stars) in real-time. This software can be launched at any moment by the observer during the night, by selecting different options showed on a GUI, as reducing the data of all the telescopes at the same time or just those of one particular instrument. By using TSE it is possible to check the evolution of the photometric time-series of the scheduled M dwarfs, even if, as explained, at the moment this tool can not be used yet for taking immediate decisions about changing the observing strategy on the fly in case of a suspected transit signal. This is a point we plan to undertake during the second season. Nonetheless, TSE has been a very useful tool for helping in debugging the RTS2 control system during the first months of observation. By inspecting the light curves produced by the software, it has been possible to detect quickly several malfunctions and to take immediate action for a fine-tuning. Moreover, I have used TSE during the first months of observations to detect flares, which are best detected in light curves collected during a single night, rotational modulation on some target stars and several new variables (see Chapter 4). In its present version, TSE implements two procedures for detrending the light curves. The first is the SysRem algorithm developed by [Tamuz et al. \[2005\]](#), the second is inspired to the 'common mode' correction described by [Berta et al. \[2012\]](#) and used for data

from the MEarth survey. The latter detrending procedure is based on the analysis of the general behaviour of the M dwarf light curves collected by all the telescopes during a night to look for patterns, due to variations in the environmental observing conditions, that have affected a large sample of the observed stars. By evaluating these patterns, they can be used for correcting the photometric time-series of the targets. First, by dividing the total timespan of observation for that night in bins of 30 minutes, an average differential magnitude value is calculated for each bin from the measurements of all the M dwarfs, producing a 'common mode' time-series. Then, the light curve of each M dwarf is considered and for each time stamp a 'common mode' correction is calculated by performing a linear interpolation of the 'common mode' time-series. The differential magnitude correction terms are finally subtracted from the original light curve, producing a detrended time-series. The same procedure is also performed by dividing the M dwarfs according to their $V-J$ color index instead of considering the targets all together. This alternative method should be in principle more accurate because any 30-min averaged variation in the environmental observing conditions is expected to affect stars with different colors in a different way. Then, M dwarfs are organized in three sublists according to their $V-J$ ($V-J < 3$, $3 < V-J < 4$ and $V-J > 4$) and the 'common mode' corrections are calculated and applied separately for each of these samples. A limitation of this alternative procedure is that very few targets can fall in one or more of the three groups, and this determines less reliable differential magnitudes corrections. In summary, TSE produces light curves with and without detrending which can be inspected separately, without any preference for one or the other because I am not yet confident that the detrending methods always produce the best results. Anyway, the 'common mode' corrections in general are of the order of 1 mmag or less.

The second data reduction and analysis pipeline I have developed is a new version of the TEEPEE software (Transiting Exoplanets PipEline), which I have used for an a-posteriori analysis of the data and for studying the photometric variability of the M dwarfs over the whole timespan of observations. The bulk of the results described in Chapter 4 have been obtained by using the TEEPEE package. The pipeline implements the SysRem algorithm for detrending the light curves [Tamuz et al., 2005]. Sysrem is applied to data on a night-by-night basis before running the part of the code which performs aperture differential photometry. Included in the package is the automatic search for transit-like signals with the BLS algorithm [Kovács et al., 2002] and for periodic signals that could be attributed to stellar rotation with the Lomb-Scargle and CLEAN algorithms. If a periodic, sinusoidal-like modulation is detected, TEEPEE includes a procedure for executing a bootstrap analysis to assess how significant the signal is. Besides the target M dwarfs, my version of TEEPEE

performs the analysis of the photometric time-series of field stars to search for and characterize new, interesting variables, as described in Chapter 4.

Mine is not the 'official' version of the TEEPEE pipeline. This fact represents an important characteristic of the APACHE survey. Our team decided to develop other two different software tools to have different results to compare, in order to boost the chances of a planetary transit detection. One alternative version of TEEPEE has been developed by colleagues of the OAVdA, and some differences with mine lie in the way the issue related to the telescope mount flip is corrected⁵ and the way detrending methods are applied to the light curves. The last, independent pipeline was originally developed for different purposes by a colleague at INAF-OATo [Lanteri, 1991], and it has been adapted to work on APACHE data. At present it is used only for test analysis and not yet for a global analysis of the photometric variability of the APACHE targets.

⁵The APACHE photometry -as the MEarth data- is characterized by an avoidable flaw due to the use of german equatorial mounts. When a star moves across the local meridian, the position of the telescope changes, by flipping from east to west, in order to avoid collisions with the support column. This brings about in a X-Y flip of all the stars on the CCD sensor. While the target star falls always on the central pixels of the sensor, the field stars (then, the set of reference stars selected by the pipeline) fall on different pixel region of the chip. Unfortunately, even the best flatfield we can obtain is not able to correct for this effect, and the result is that the light curve of the target is characterized by an offset in correspondence of the time when the mount flip occurs.

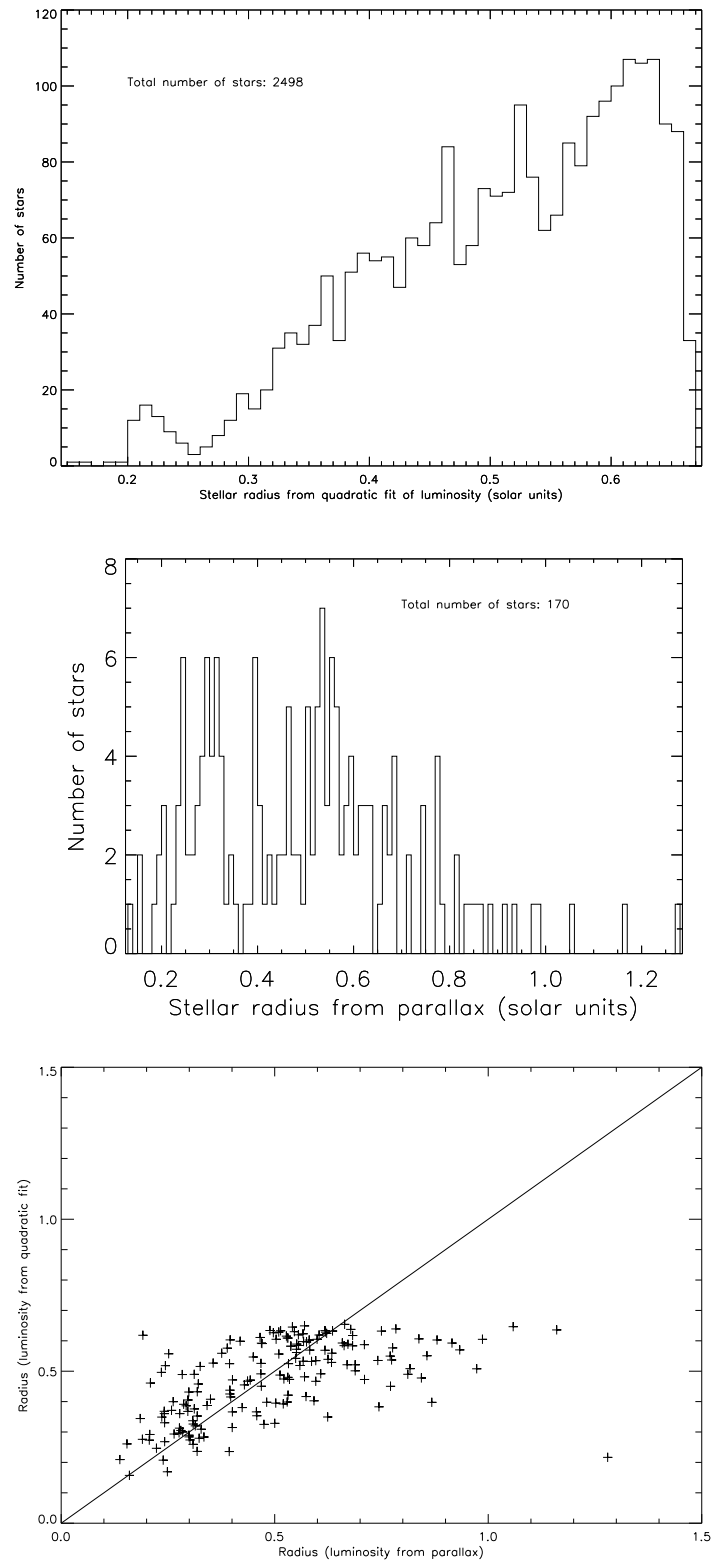


FIGURE 3.2: (*Top*) Distribution of the radii estimated for the *S1* list of M dwarfs from the best-fit quadratic relation providing the stellar luminosity as function of the effective temperature. (*Middle*) Distribution of the radii estimated for the *S2* list of M dwarfs from the Stefan-Boltzmann Law using the luminosities derived from trigonometric parallaxes. (*Bottom*) Comparison between the radius measurements of the previous plot for the *S2* sample with the values obtained using the best-fit quadratic relation.

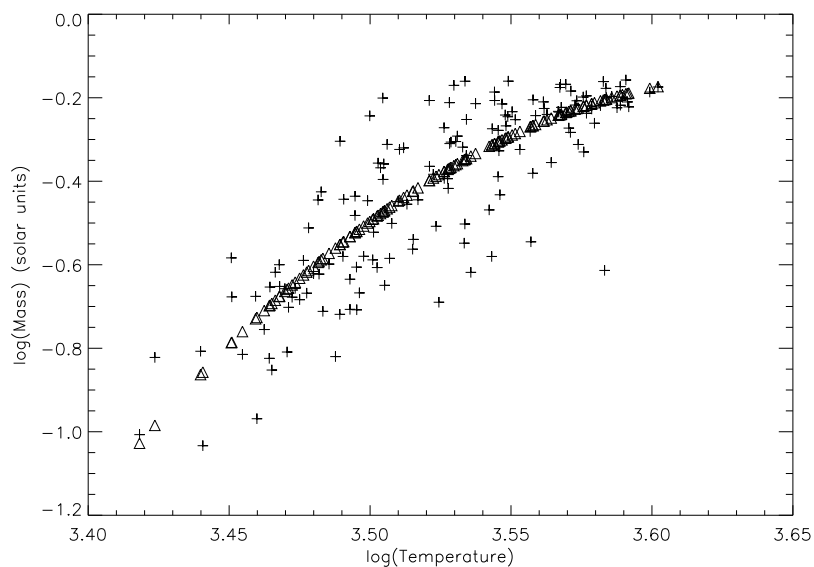


FIGURE 3.3: Masses for 170 stars of the APACHE Input Catalogue with measured trigonometric parallax, as a function of their effective temperature. Data are showed in Log-Log scale. The masses are calculated from the empirical relations of [Delfosse et al. \[2000\]](#), while the effective temperatures are those derived from the calibrations of [Casagrande et al. \[2008\]](#). Overplotted is our best-fit quadratic relation.

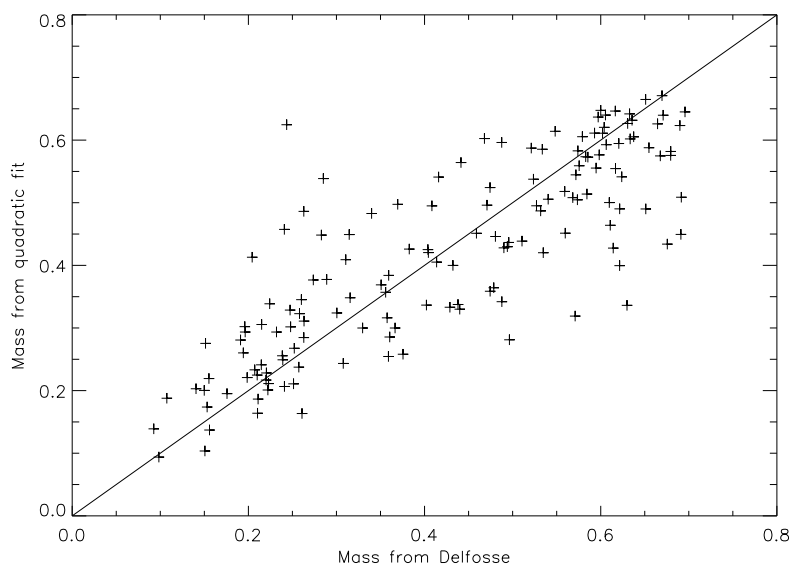


FIGURE 3.4: Match between the masses of the 170 M dwarfs of the *S3* sub-list derived from the empirical relations of [Delfosse et al. \[2000\]](#) (abscissa) with those calculated from the best-fit quadratic relation showed in Fig. 3.3 (ordinate).

The APACHE Project

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Abstract. First, we summarize the four-year long efforts undertaken to build the final setup of the APACHE Project, a photometric transit search for small-size planets orbiting bright, low-mass M dwarfs. Next, we describe the present status of the APACHE survey, officially started in July 2012 at the site of the Astronomical Observatory of the Autonomous Region of the Aosta Valley, in the Western Italian Alps. Finally, we briefly discuss the potentially far-reaching consequences of a multi-technique characterization program of the (potentially planet-bearing) APACHE targets.

1. INTRODUCTION

M dwarf stars, with masses $M_{\star} \leq 0.6 M_{\odot}$, make up the vast majority of the reservoir of nearby stars within $\sim 25\text{--}30$ pc. These stars have not traditionally been included in large numbers in the target lists of radial-velocity (RV) searches for planets for two main reasons: 1) their intrinsic faintness, which prevented Doppler surveys in the optical from achieving very high radial-velocity precision ($< 5\text{--}10$ m/s) for large samples of M dwarfs (e.g., Eggenberger & Udry 2010, and references therein), and 2) their being considered as providers of very inhospitable environments for potentially habitable planets (e.g., Tarter et al. 2007; Scalo et al. 2007, and references therein). These two paradigms are now shifting. There are several important reasons for such a change in perspective, which can be summarized under two main themes.

First, the observational evidence gathered by ultra-high-precision space-borne photometric surveys (e.g., Kepler) indicates that the frequency of low-mass planets, i.e. Neptunes and Super-Earths, is an increasing function of decreasing stellar mass (Howard et al. 2012; Dressing & Charbonneau 2013). This result has recently been strengthened by the findings of ground-based RV programs carried out with state-of-the-art facilities (e.g., HARPS): Super-Earths with $M_p \leq 10 M_{\oplus}$ within the Habitable Zone¹ (HZ) of low-mass stars appear ubiquitous (Bonfils et al. 2013). Given that the identification of a rocky, habitable planet is the essential prerequisite to its possible characterization as an actual life-bearing

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¹ In its standard definition, the Habitable Zone corresponds to the range of distances from a given star for which water could be found in liquid form on a planetary surface (Kasting et al. 1993).

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celestial object, it is thus clear why low-mass M dwarfs, seen for long as providers of inhospitable environments for life (Scalo et al. 2007, and references therein), are now being moved at the center of the stage in the exoplanets arena. Consensus is growing among the astronomers' community that the first habitable rocky planet will be discovered (and might have been discovered already!) around a red M dwarf in the backyard of our Solar System.

Second, the sample of the nearest ($d < 25\text{--}30$ pc), relatively bright ($J < 9\text{--}10$) M dwarfs is amenable to combined studies with a wide array of observational techniques, which can be exploited at the best of their potential providing the opportunity to characterize the architecture of planetary systems across orders of magnitude in mass and orbital separations in a way that's not readily achievable for Solar analogs. For example, the possibility to reach detection of short-period transiting rocky planets from the ground with modest-size telescopes (30–50 cm class) is guaranteed by the small radii of M dwarfs, leading to deep transits ($\Delta mag \gtrsim 0.005$ mag) for the case of planets with $2 \leq R_p \leq 4 R_\oplus$ (e.g., Charbonneau et al. 2009). In addition, as we have discussed above, the favorable mass ratios allow for detection of rocky, potentially habitable planets with the RV technique, thanks to the moderately large amplitudes of the RV signals (a few m/s). Analogously, at intermediate separations ($\approx 1\text{--}4$ AU) high-precision astrometry becomes sensitive to planets in the mass range between Neptune and Jupiter (e.g., Casertano et al. 2008). Finally, the favorable planet-star contrast ratios provided by the low intrinsic luminosity of M dwarfs allows for improved detectability thresholds of giant planets at wide separations ($> 5\text{--}10$ AU) with direct imaging techniques (e.g., Bowler et al. 2012). For the same reason, atmospheric characterization of transiting low-mass Super-Earths can be achieved for this sample (e.g., Tessenyi et al. 2012). Systematic studies of planetary systems orbiting low-mass stars can thus crucially inform planet formation and evolution, structural and atmospheric models, particularly when seen in connection with the properties of the hosts (e.g., Ida & Lin 2005; Mordasini et al. 2012a,b; Seager & Deming 2010, and references therein).

However, not all physical properties of low-mass stars are known precisely enough for the purpose of the detection and characterization of small-radius planets. Worse still, some of the characteristics intrinsic to late-type dwarfs can constitute a significant source of confusion in the interpretation in planet detection and characterization measurements across a range of techniques. First of all, there exist discrepancies between theory and observations in the determination of the sizes of M dwarfs, typically on the order of 10%–15% (Ribas 2006; Torres et al. 2010, and references therein). Second, there are at present difficulties in spectroscopically determining with a high degree of precision M dwarf metallicities, as M-dwarf spectra are dominated by chemically complex molecular features that make the identification of the continuum in an M dwarf spectrum challenging, rendering line-based metallicity indicators unreliable (Woolf et al. 2009; Rojas-Ayala et al. 2010). Third, our understanding of the age-rotation-activity connection for field M dwarfs with age greater than $t \sim 0.5$ Gyr (e.g., Jenkins et al. 2009; West & Basri 2009) is still subject to rather large uncertainties due to the sparseness of the data. Fourth, as measurements of chromospheric activity indicators (H α line) have shown how the fraction of active M dwarfs increases as a function of spectral sub-type (e.g., Bochanski et al. 2005; West et al. 2011), activity-related phenomena such as stellar spots, plagues, and flares become increasingly a matter of concern for planet detection and characterization programs targeting late-type stars.

All the above considerations clearly underline how achieving the goal of the detection *and* characterization of low-mass, potentially habitable, rocky planets around low-mass stars requires the construction of a large (all-sky) sample of nearby, relatively bright M dwarfs with well-characterized properties. This will necessitate the combined use of time-series of spectroscopic, astrometric, and photometric data of high quality. In particular, the jitter levels will have to be quantified in detail for each target individually, as the jitter properties may vary from star to star within the same spectral class, as suggested by recent findings based on high-precision Kepler photometry (e.g., Ciardi et al. 2011) and high-resolution, high-S/N spectroscopy (e.g., Zechmeister et al. 2009). In the following, we summarize the preparations for and present first results from APACHE (A PATHway to the Characterization of Habitable Earths), a new ground-based photometric transiting search for small-size planets around

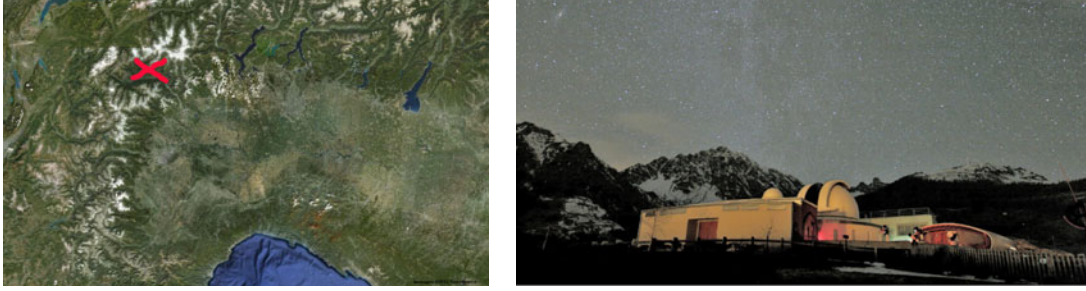


Figure 1. *Left:* map of northern Italy with the red cross marking the approximate location of the OAVdA in the Western Italian Alps. *Right:* a night view of the Aosta Valley Observatory.

thousands of bright, nearby early- to mid-M dwarfs. The APACHE project is a collaboration between INAF-Osservatorio Astrofisico di Torino (INAF-OATo) and the Astronomical Observatory of the Autonomous Region of the Aosta Valley (OAVdA). APACHE utilizes an array of five 40-cm telescopes at the OAVdA site, in the western Italian Alps (Fig. 1, left and right panels). The survey, with official kick-off in July 2012, will last for five years.

2. THE SITE CHARACTERIZATION STUDY

In this work (Damasso et al. 2010), we carried out a detailed site characterization study at the OAVdA site, aimed at establishing its potential to host the APACHE project. For the purpose of the site testing campaign, we gathered R -band photometric and seeing measurements utilizing different instruments available at the site. We gauged site-dependent observing conditions such as night-sky brightness, photometric precision, and seeing properties. Public meteorological data were also used in order to help in the determination of the actual number of useful observing nights per year.

We measured V -band night-sky brightness and extinction levels not dissimilar from those registered at other good observing sites. The median seeing over the period of in situ observations (a few months) was found to be $\approx 1.7''$ (Fig. 2, left panel), and rather stable. However, given the limited duration of the observations, we did not probe any possible seeing seasonal patterns or the details of its possible dependence on other meteorological parameters, such as wind speed and direction. The fraction of fully clear nights per year amounts to 39%, while the total of useful nights increases to 57%, assuming a (conservative) cloud cover of not more than 50% of the night. Based on the analysis of photometric data collected over the period of 2009 May-August for three stellar fields centered on the transiting planet hosts WASP-3, HAT-P-7, and Gliese 436, we achieved seeing-independent best-case photometric precision ~ 3 mmag (rms) in several nights for bright ($R < 11$ mag) stars (see Fig. 2, right panel for an example). A median performance ~ 6 mmag during the observing period was obtained for stars with $R < 13$ mag.

3. THE PILOT STUDY

The pilot study (Giacobbe et al. 2010) was focused on a year-long photometric monitoring campaign, using small-size instrumentation (25–80 cm class telescope systems), of a sample of 23 bright ($J < 12$ mag), cool M0-M6 dwarfs with good parallaxes from the TORino Parallax Program (TOPP; Smart et al. 2010). The primary objectives we set out to achieve in this study were *a)* to demonstrate sensitivity to $< 4 R_{\oplus}$ (i.e., smaller than radius of Neptune) transiting planets with periods of a few days around our sample, through a two-fold approach that combines a characterization of the statistical noise properties of our photometry with the determination of transit detection probabilities via simulations, and

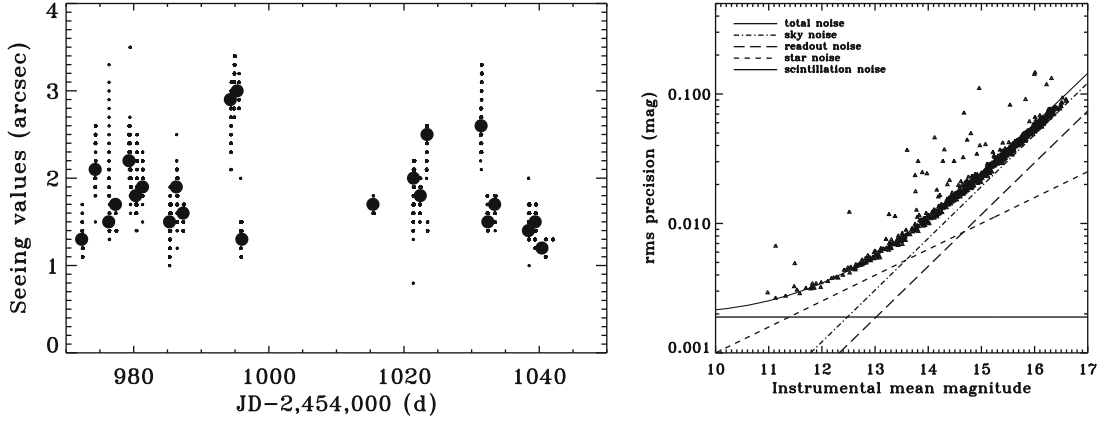


Figure 2. *Left:* the distribution of seeing measurements over the whole period of observation reported in Damasso et al. (2010). The small black stars show individual data points, each corresponding to an average seeing value over a 1 min interval. The large filled circles indicate the median seeing value for each night. *Right:* photometric errors (rms) vs. instrumental mean magnitude in the field of the planet-hosting star WASP-3 during a good observing night (Damasso et al. 2010). The various contributions to the expected photometric noise, according to an analytic error budget model, are also shown. Pictures reprinted with permission from Damasso et al. (2010).

b) where possible, to better our knowledge of some astrophysical properties (e.g., activity, rotation, age) of our targets through a combination of spectroscopic and astrometric information and our differential photometric measurements.

We achieved a typical nightly rms photometric precision of ~ 5 mmag, with little or no dependence on the instrumentation used or on the details of the adopted methods for differential photometry, and gauged the degradation levels in the precision with respect to a pure white noise regime due to the presence of correlated (red) noise in our data. Based on a detailed stellar variability analysis, *a*) we detected no transit-like events (an expected result given the sample size); *b*) we determined < 1 day photometric rotation periods for two of the M dwarfs in the sample, in agreement with the large projected rotational velocities inferred for both stars based on the analysis of archival spectra, and found consistency of the estimated inclinations of the stellar rotation axes with those derived using a simple spot model (see Fig. 3, left panel). For two stars in the sample we recorded short-term, low-amplitude flaring events. Finally, based on simulations of transit signals of given period and amplitude injected in the actual (nightly reduced) photometric data for our sample, we derived a relationship between transit detection probability and phase coverage (see Fig. 3, right panel). We found that, using the BLS search algorithm, even when phase coverage approached 100%, there was a limit to the detection probability of $\approx 90\%$. Around program stars with phase coverage $> 50\%$ we would have had $> 80\%$ chances of detecting planets with $P < 1$ day inducing fractional transit depths $> 0.5\%$, corresponding to minimum detectable radii in the range $\sim 1.0\text{--}2.2 R_{\oplus}$.

4. THE APACHE INFRASTRUCTURE

APACHE employs an array of five 40-cm class telescopes hosted on a single platform with electronically controlled roll-off enclosure (see Fig. 4, left panel). The availability of a single movable enclosure and of much of the associated support infrastructure makes the OAVdA a site essentially unique in Europe and will afford a very substantial cost saving for the project. The arrangement of the array has been defined so as to maximize sky coverage during campaign operations (see Fig. 4, right panel). The telescope array is composed of five identical Carbon Truss 40-cm f/8.4 Ritchey-Chrétien telescopes, with a GM2000 10-MICRON mount and equipped with a FLI Proline PL1001E-2 CCD Camera and

Hot Planets and Cool Stars

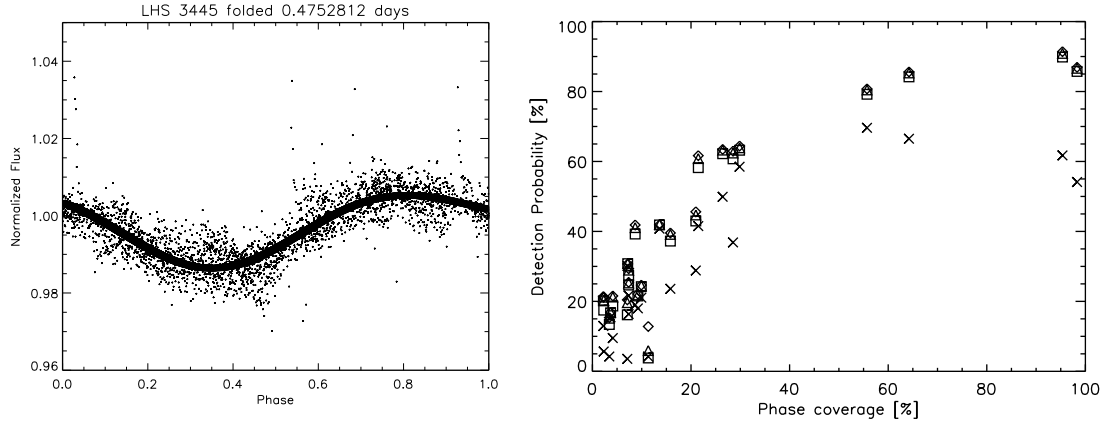


Figure 3. *Left:* photometric data for the dM star LHS 3445 folded according to its probable rotation period ($P = 0.472$ days). Overplotted is a best-fit single-spot model, as discussed in Giacobbe et al. (2012). *Right:* average detection probability as a function of average phase coverage for $P < 1.0$ days. Pictures reprinted with permission from Giacobbe et al. (2012).

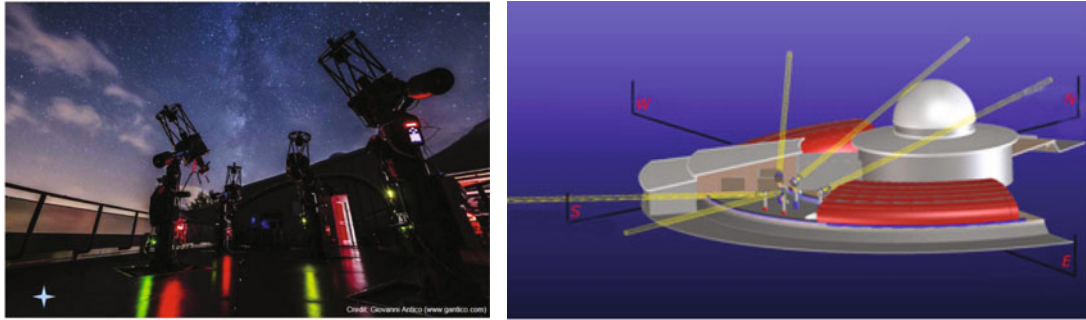


Figure 4. *Left:* close-up night view of the APACHE telescope array. *Right:* a cartoon visualizing the exact arrangement of the APACHE telescopes within the OAVdA platform.

Johnson-Cousins R & I filters. These systems guarantee state-of-the-art quality performance: negligible temperature gradients, QE 80% in the whole wavelength range of interest. The open source observatory manager RTS2 (Kubanek 2010) is the choice for the high-level software control of the five-telescope system, including dynamic scheduling of the observations (for details, see Christille et al., this volume). Provisions have been made for the hardware of relevance for the APACHE operations control, data acquisition, processing centre and backup, which is necessary to accommodate the high data rate: two HP Z600 Workstation and one HP EliteBook 8740w Mobile Workstation as control PCs and workstations for data analysis, one HP Storage Works X1600 12TB as Network Attached Storage (NAS), connected together via Intranet 1 GB.

5. SURVEY DESIGN: INPUT CATALOGUE AND OBSERVING STRATEGY

The APACHE Input Catalogue (AIC) of M dwarfs is constructed starting from the all-sky sample of 8889 bright ($J < 10$) low-mass stars in Lépine & Gaidos (2011). The final AIC is composed of

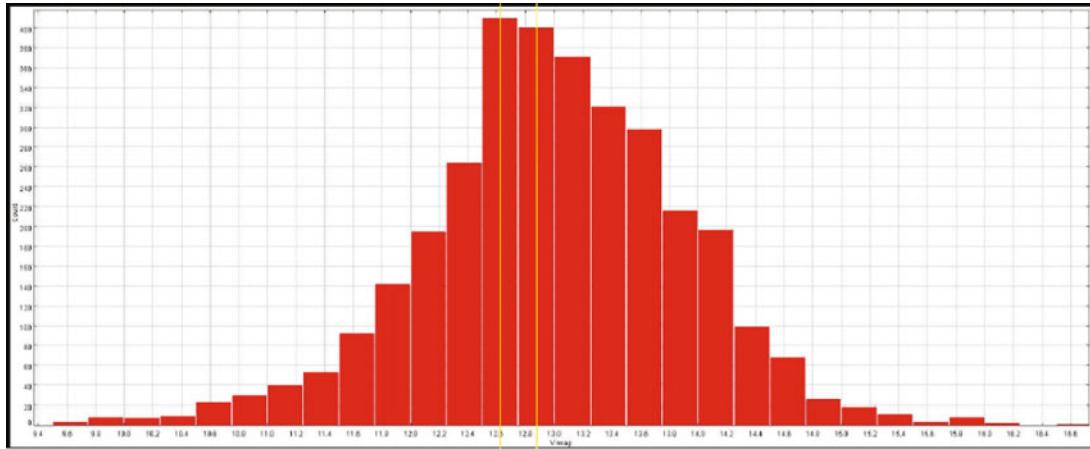


Figure 5. V mag distribution of the APACHE target sample.

~ 3000 targets selected on the basis of their visibility from the OAVdA site and the availability of a suitable number of potentially good comparison stars in the telescopes' field-of-view. Moreover, cross-correlation with approximately two dozen catalogues was performed to get further information about the targets, such as a precise determination of spectral class, their projected rotational velocity $V \sin i$, their level of chromospheric activity, X-ray emission, the presence of binary companions detected either spectroscopically or by direct imaging, or astrometry, or a combination of these techniques. Based on accurate parameterization of Gaia's scanning law, the number of the Gaia transits scheduled was associated to each target. Based on all available information, a prioritized list was defined for the purpose of scheduling with the APACHE telescopes. The final optical magnitude distribution of the sample peaks at $V \approx 13$ mag, with a median of $V \sim 14$ mag (Fig. 5). The vast majority of targets is bright enough to allow for a host of additional characterization measurements, in case of positive detections of transiting planets. As a synergetic example, a carefully selected sub-sample of APACHE targets is currently the objective of high-precision RV monitoring with the HARPS-N spectrograph on the Telescopio Nazionale Galileo (TNG) as part of the long-term Global Architecture of Planetary Systems (GAPS) programme.

We built upon the experience matured with the pilot study to define and then refine the details of the observing strategy for the APACHE survey. Taking into account the use of synthetic transits, by assuming different numbers of consecutive exposures (from 1 to 4) and different temporal samplings (intervals of 20 through 50 minutes between two sets of consecutive pointings of the telescope on the same target), we evaluated the transit detection probabilities for stars with different average phase coverages in a given interval of possible orbital periods. The results of this analysis prompted us to adopt an initial observing strategy consisting of 3 exposures every ~ 20 minutes, to be eventually revisited as the survey unfolds.

6. THE FIRST SIX MONTHS OF OPERATIONS

Official survey operations started in July 2012, and the project evolution can be followed through its official website at <http://apacheproject.altervista.org>. With six months of data collected in hand, we can begin to look at some statistics of the survey. Approximately 100 fields have been observed thus far, with each APACHE telescope typically observing a dozen targets each night. The weather pattern of the Summer and Fall seasons has confirmed the expected fraction ($\sim 50\%$) of useful nights.

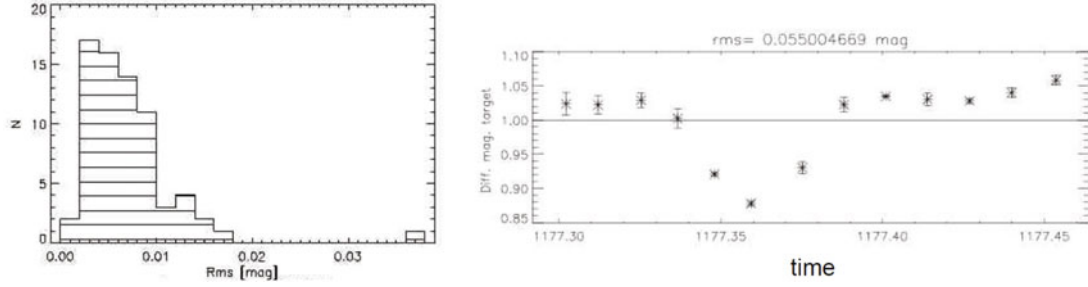


Figure 6. *Left:* rms photometric precision distribution for a sample of ~ 100 APACHE targets observed during the first six months of survey operation. *Right:* APACHE#1 independent discovery lightcurve of an eclipsing binary first reported by Kiraga (2012).

Using the robust TEEPEE pipeline for the reduction and analysis of the photometric data (Giacobbe et al. 2012), we performed differential aperture photometry on the ensemble of targets observed to-date. The resulting distribution of the rms photometric precision for the sample (Fig. 6, left panel) has a median of ~ 5 mmag, attesting of the quality of the data. We independently discovered (Fig. 6, right panel) a new eclipsing binary amongst our targets, that was published by Kiraga (2012) while we were performing a preliminary analysis on the data.

In parallel, we are developing the pipeline TSE (TEEPEE Sentinel) which is designed to perform real-time differential photometry of the targets during each night. Once fully developed and tested, TSE will be used for a prompt identification and assessment of interesting signals, triggering real-time changes in the observing strategy such as high-cadence follow-up of ongoing possible events (magnifying the sensitivity to long-period planets).

A significant update to the AIC is now ongoing, based on the latest spectroscopic information for many of the APACHE targets published by Lépine et al. (2013). The repercussions are particularly non-negligible in the M0-M1 sub-spectral type regime, with many objects being spectroscopically recognized as earlier-type dwarfs.

7. SUMMARY

APACHE is the first Europe-based transit search for small-radius planets orbiting, bright, nearby M dwarfs. It draws on the pioneering work carried out by the MEarth project (Nutzman & Charbonneau 2008), in that it adopts a one target per field approach and the corresponding constraints on the observing strategy optimized for the array of five APACHE telescopes and the chosen site characteristics. It extends and complements MEarth in the Northern hemisphere, in that it targets early- to mid-M dwarfs, conceding in detectable planet radius for fixed photometric precision but focusing by construction on a target sample that's in principle more favourable for atmospheric characterization work in case of positive detection. After the first six months of operations, the program is delivering the expected quality in differential photometric precision. The synergy potential between APACHE, Doppler (e.g., HARPS-N), and astrometric (e.g., Gaia) techniques is potentially huge (see, e.g., Sozzetti, this volume), and the APACHE optical lightcurves of thousands of M dwarf stars will contribute directly to create a database of uniquely well-characterized low-mass stars in the solar neighborhood, inclusive of exoplanets with precise mass and radius determinations orbiting M dwarfs bright enough to enable detailed characterization of the planetary interior structure and atmospheres with upcoming space-borne observatories (e.g., CHEOPS, EChO, JWST).

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Chapter 4

The APACHE Project: preliminary results from the first observing season

4.1 Introduction

The implementation of the hardware and software tools for the APACHE survey has been a long and hard work, and since the time of the telescopes' first light I was really curious to see what we could harvest after the first months of observation. So much curious to finally reap the first fruits that I took the decision of spending a fourth year working on the PhD. This Chapter describes some of the results of the first season of survey, which will be included in a forthcoming publication where we will present in great detail the APACHE Project to the community, then including also material discussed in Chapter 3. First, here I present global results about several M dwarfs, describing in particular what we can learn about their variability as measured by the APACHE photometry, which is a major issue of my Thesis. Some peculiar targets are discussed separately: from the analysis of their light curves we have measured their rotation periods, and for some of them we have detected flares. In the last part of the Chapter I introduce the discovery and first characterization of several variable stars in the fields of the target M dwarfs, an interesting by-product of the survey that I have investigated with great interest. I wish that this Chapter could demonstrate, in addition to the huge effort made for developing all the tools for data analysis, the potential of the APACHE survey in assuring the community with an invaluable database of original photometric measurements, which can be used with benefit for a better understanding of the physics of cool stars.

4.2 Search for transit-like signals in the light curves of the APACHE M dwarfs

As stated elsewhere, my efforts in analysing the data of the first observing season have been focused mainly on the characterization of the photometric variability of the targets in terms of stellar activity, which is the main topic this Chapter is about. Anyway, the APACHE survey has been designed with the primary goal of detecting transit signals in the light curves of a accurately selected sample of M dwarfs. In this Section I illustrate my contribution in the data analysis finalized to the detection of transit-like signal candidates in the light curves of the targets that I could analyze homogeneously up to now. The results of this study must be considered as preliminary, and they will be matched to the results obtained from the analysis of the light curves produced by the alternative pipelines developed by other members of the APACHE Team. I have searched for transit-like signals by using an improved version¹ of the Box-fitting Least Squares (BLS) algorithm [Kovács et al., 2002]. I have restricted the search to planetary orbital periods less than 5 days, and the number of tested frequencies has been 10000. Finally, I have set to 100 the number of phase bins required by the algorithm and the range of transit duration (expressed as fraction of the tested period) between 0.007 and 0.1. For the analysis I have considered the basic outputs of the algorithm: the best period found, the corresponding signal depth and transit fractional duration, and the Signal Detection Efficiency (SDE), which is a parameter that tries to quantify how much the best period is significant under the hypothesis of a transit-like signal. A simple way to calculate the SDE is through the relation

$$\text{SDE} = \frac{B_{\text{pow}} - \overline{Pow}}{\sigma_{\text{pow}}} \quad (4.1)$$

where B_{pow} is the spectral power density corresponding to the best test frequency, $\overline{Pow}$ is the average of all the spectral power densities in the periodogram, and σ_{pow} is their RMS value. According to this formula, the SDE is a measure of how far from the average value is the highest power density peak in the periodogram, expressed in units of the RMS distribution of the power densities. Kovács et al. [2002] suggest that an SDE greater than 6 can be considered as indicative of a significant detection. Keeping in mind that the light curve of each significant transit candidate, folded according to the best period found, is visual inspected, rather than relying only to a single value for the SDE, that could be not enough robust, I have introduced two alternative SDE estimates. The first is calculated using the relation

¹http://www.lpl.arizona.edu/~bjackson/idl_code/eebls.pro

$$\text{SDE} = \frac{D_{B_{pow}}}{\sigma_{transit, B_{pow}}} - \text{Mean}\left(\frac{D_{oth}}{\sigma_{transit}}\right) \quad (4.2)$$

where $D_{B_{pow}}$ is the transit depth (in magnitudes) estimated by BLS which corresponds to the best period, and D_{oth} is the transit depth estimated for any other tested period. Both are expressed relative to $\sigma_{transit}$, which is the RMS of the points in the transit portion of the light curve folded according to the tested period. The second, alternative estimate for the SDE is calculated using the relation

$$\text{SDE} = \frac{D_{B_{pow}}}{\sigma_{oot, B_{pow}}} - \text{Mean}\left(\frac{D_{oth}}{\sigma_{oot}}\right) \quad (4.3)$$

where now σ_{oot} is the RMS of the light curve points which fall out-of-transit, while the other parameters are defined as for the relation (4.2). The idea underlying this analysis is that a promising transit candidate, which should deserve a detailed investigation, should have significant values for all the three estimates of SDE, complemented by plausible values for the transit depth and duration. Moreover, the candidate period, under the hypothesis that it is not too long as compared to the total timespan of observations and number of useful data (Table ??, must be excluded if it corresponds to a peak in the spectral window function. When the ensemble of these data supports the possibility that there is a real transit signal in the light curve of a target, the data are examined in detail. In Table 4.1 are summarized the results of the BLS analysis applied to a sub-sample of targets observed during the first season. At this stage only the results from non-detrended light curves are presented and without considering the correction to compensate seeing variations. Results are showed for the two methods used to calculate the light curves, which generally select different aperture radii and sets of comparison stars, with some exceptions when both methods produce the same results. We can learn how to correctly interpret these results by looking at the targets with known transits that APACHE has monitored during the first season. Among these, a target having an SDE greater than 6, as calculated from (4.1), is WASP-3, known to host a planet with orbital period $P=1.8468372$ days (<http://exoplanet.eu>). For this target the other two SDE estimates have a positive value, which is compatible with the possibility of a real transit signal. As for WASP-33, another star with a planet orbiting around once every 1.21986967 days, the SDE calculated through (4.1) is less than 6, while the alternative SDE estimates are positive but not so high. We notice that our estimates of the orbital periods are good for both the planets WASP-3b and WASP-33b compared to the latest published values. The target Apache 6 has an estimated transit period of nearly 4.5 days with an $\text{SDE}>6$ (according to the relation (4.1)), which can be considered a-priori a reliable value because this target has been monitored for long time (see Table 4.2). However, the estimated transit

depth is negative, thus ruling out the possibility for a real transit present in the light curve. As a general comment, looking at the Table 4.1 there are targets for which all the parameters seem indicate the presence of a possible transit signal, that have not been confirmed after a visual inspection of the folded light curves. This tells us that the automatic procedure for identifying the most promising transit candidates has to be improved, by finding more accurate selection criteria.

TABLE 4.1: Results of the BLS algorithm applied to the light curves of a sample of M dwarfs observed by APACHE during the first season. The analysis has been performed on differential magnitude time series (no detrended) obtained with two different selection methods for the aperture radius and set of comparison stars. For each photometric method three different estimates of the Signal Detection Efficiency (SDE) are provided (as explained in the text), together with the best orbital period, transit depth and fractional duration estimated by the BLS algorithm.

	Photometric method 1						Photometric method 2					
Star name	Period (days)	Depth (mag)	Fractional duration	SDE (4.1)	SDE (4.2)	SDE (4.3)	Period (days)	Depth (mag)	Fractional duration	SDE (4.1)	SDE (4.2)	SDE (4.3)
apache 1019	1.7406	0.0044	0.0569	3.68	0.548	0.9390	3.0003	-0.00	0.0621	4.05	-2.81	-0.90
apache 1158	1.0002	0.0220	0.0190	3.83	-0.623	2.5860	1.0002	0.02	0.0189	4.62	-0.62	2.27
apache 1427	3.3378	-0.1248	0.1300	2.03	-0.676	-0.0506	3.3456	-0.13	0.1241	1.91	-0.73	-0.00
apache 1449	0.9810	-0.0051	0.4078	3.97	-0.075	-1.2169	0.9314	0.01	0.0904	1.98	-0.66	0.60
apache 1684	1.8889	-0.0077	0.0847	3.67	-1.416	-0.6266	1.8889	-0.01	0.0847	3.67	-1.22	-0.40
apache 1705	3.4483	-0.0166	0.0074	3.58	-5.062	-2.3971	3.7202	-0.01	0.0437	3.33	-1.78	-1.26
apache 1729	1.1913	0.0083	0.0290	4.30	2.281	1.2892	1.3194	0.03	0.0052	4.29	2.02	4.03
apache 1739	1.1052	0.0068	0.0716	3.56	0.523	1.2406	0.8515	-0.01	0.1493	3.33	-2.09	-1.40
apache 1770	3.1104	0.0163	0.0124	2.47	4.791	2.5603	1.0382	0.01	0.2038	2.91	-0.08	2.15
apache 1782	4.9652	0.0490	0.0013	2.59	-3.722	3.4825	4.9652	0.05	0.0013	2.59	-3.72	3.48
apache 1866	1.8298	0.0177	0.0081	2.13	-3.561	2.0021	1.4850	0.01	0.0133	2.45	2.49	2.05
apache 2116	4.9044	-0.5050	0.0021	1.25	-0.437	-3.7363	4.9044	-0.51	0.0021	1.23	-0.45	-3.72
apache 2155	0.9782	0.3591	0.0353	2.76	0.147	1.5763	0.9782	0.36	0.0353	2.76	0.10	1.58
apache 2173	1.3305	-0.0178	0.0547	4.31	-0.675	-0.8376	1.3305	-0.02	0.0547	4.28	-0.18	-0.50
apache 2240	1.0205	-0.0189	0.0079	3.43	1.292	-2.1646	1.0205	-0.02	0.0079	3.43	1.29	-2.16
apache 2400	1.9837	0.1115	0.0491	6.29	-	0.3097	1.9837	0.11	0.0491	6.53	-	0.38
apache 2459	3.5199	-0.0240	0.0054	5.35	-1.373	-1.7488	4.4924	-0.13	0.0005	4.52	0.16	-7.19
apache 2570	1.6664	0.0156	0.0098	3.34	0.004	1.5515	4.7893	-0.04	0.0012	3.41	0.33	-4.06
apache 2586	0.9551	-0.0283	0.0055	3.34	1.035	-5.7618	2.5873	-0.01	0.0245	3.09	-1.50	-1.76

Continued

apache 2650	1.0005	0.0201	0.0869	5.27	7.821	-0.2521	1.0005	0.02	0.0869	5.27	7.82	-0.25
apache 2784	3.7244	0.0220	0.0019	3.71	-1.073	2.7964	1.6795	0.02	0.0063	5.62	-0.84	2.52
apache 2923	1.0885	-0.0334	0.0033	5.05	0.692	-6.5661	2.1758	-0.04	0.0017	4.80	-11.39	-6.39
apache 2965	3.6010	0.4188	0.0057	4.14	54.309	3.6599	3.6010	0.42	0.0057	4.14	54.31	3.66
apache 3083	2.8074	0.0053	0.0365	3.80	1.736	0.7927	2.1013	0.06	0.0007	5.36	-0.05	6.23
apache 3110	1.2796	-0.0050	0.0818	4.20	-1.567	-1.4745	1.7715	0.01	0.0163	4.05	3.80	1.51
apache 3126	1.0018	0.0051	0.1341	4.95	0.031	0.6367	2.3137	0.01	0.0220	5.26	0.01	1.18
apache 3248	1.4110	0.0100	0.0258	4.11	0.737	1.4393	2.1839	0.01	0.0346	5.16	3.11	0.73
apache 33	3.1486	-0.0077	0.0130	3.67	-0.964	-1.1364	1.9818	0.00	0.1479	3.12	0.83	0.49
apache 3305	0.8852	-0.0077	0.0974	3.18	-10.985	-2.9638	0.8868	-0.01	0.0778	1.45	-8.35	-0.56
apache 3308	4.9652	-0.0755	0.0006	3.40	2.011	-7.9607	1.0005	0.05	0.0372	3.81	1.77	2.69
apache 347	2.6810	-0.0314	0.0026	1.80	0.710	-3.8859	2.6810	-0.03	0.0026	1.80	0.71	-3.89
apache 379	4.0617	-0.0326	0.0014	4.11	1.673	-3.6693	1.0206	0.04	0.0039	4.85	0.08	5.03
apache 57	3.3523	-0.0229	0.0031	1.04	-0.443	-2.9054	1.4215	0.02	0.0148	2.66	-0.57	1.50
apache 647	1.0180	-0.0988	0.0017	4.88	-0.922	-10.0634	1.0180	-0.10	0.0017	4.88	-0.92	-10.06
apache 735	1.0692	-0.0070	0.2245	4.68	0.693	-0.0986	1.1477	-0.01	0.1917	3.61	1.51	-0.41
apache 850	2.5753	0.0083	0.0348	3.43	1.289	0.9717	2.2462	0.02	0.0371	3.02	1.36	1.43
apache 915	1.9873	0.0057	0.0512	4.68	1.630	1.2041	1.9826	0.01	0.0538	4.22	2.76	1.03
apache 981	1.0294	-0.0056	0.1758	4.06	-0.307	-0.4597	4.4248	-0.01	0.0106	3.64	-1.35	-1.30
apache 1040	4.8497	-0.0713	0.0008	2.49	-0.684	-7.8956	3.4819	-0.03	0.0108	2.62	-0.81	-1.49
apache 1041	2.2624	0.0134	0.0122	4.04	3.462	2.2043	2.6969	-0.01	0.0226	3.59	-2.27	-1.82
apache 1267	3.0230	0.0062	0.0325	4.77	1.120	1.1936	4.9505	0.06	0.0003	5.42	-0.42	8.17
apache 1436	2.5873	-0.1006	0.0359	1.61	-0.243	-0.5824	2.5873	-0.10	0.0359	1.61	-0.24	-0.58
apache 1511	2.5025	0.0185	0.0202	4.36	1.724	1.5778	4.6062	0.02	0.0080	4.06	1.49	1.56
apache 1551	3.5149	0.0059	0.0354	3.56	3.650	1.9326	1.9455	-0.02	0.0057	3.14	-3.45	-3.54
apache 1557	3.2765	-0.0534	0.0031	2.85	8.998	-3.8423	1.0880	-0.05	0.0216	2.99	-2.23	-2.18

Continued

apache 160	4.6685	-0.0175	0.0022	4.14	0.263	-2.8932	1.7150	-0.01	0.0387	4.11	-1.92	-1.37
apache 1642	0.9985	0.0228	0.0611	1.48	-0.072	-0.9133	0.9909	0.01	0.2215	4.57	6.72	0.72
apache 17	2.1173	-0.0053	0.0320	4.55	-2.246	-0.8623	2.1173	-0.01	0.0320	4.55	-2.25	-0.86
apache 1925	0.9940	-0.0063	0.1039	5.44	-3.075	-1.5239	0.9975	0.01	0.1954	4.95	-0.85	-0.04
apache 2077	1.1294	-0.0205	0.0332	3.32	-0.579	-1.1729	1.5272	-0.02	0.0246	4.30	-1.84	-2.05
apache 2691	0.8933	-0.0268	0.0250	3.67	-0.547	-0.7252	2.4408	0.05	0.0046	2.83	0.43	2.53
apache 2773	1.9877	-0.0078	0.0407	3.17	-1.295	-1.1650	4.2391	0.02	0.0022	3.41	5.90	3.26
apache 2995	2.4384	-0.0559	0.0005	5.82	0.292	-10.8631	3.3234	0.07	0.0003	6.10	-0.30	8.79
apache 301	1.0464	0.0242	0.0209	2.41	5.998	1.3211	1.0464	0.02	0.0209	2.41	6.00	1.32
apache 3117	1.0848	-0.0459	0.0071	3.75	0.415	-5.2477	1.0848	-0.05	0.0071	3.26	0.27	-5.58
apache 3122	4.2337	0.0604	0.0065	4.46	22.531	12.1661	4.2337	0.06	0.0065	4.46	22.53	12.17
apache 3300	1.6650	-0.0347	0.0050	4.63	0.550	-2.9184	1.6650	-0.03	0.0050	4.63	0.55	-2.92
apache 6	4.4743	-0.2400	0.0002	7.04	2.786	-12.2371	4.4743	-0.24	0.0002	7.04	2.79	-12.24
apache 833	3.6563	-0.1249	0.0032	5.80	5.134	-3.9649	3.6563	-0.12	0.0032	5.77	4.11	-3.93
apache 932	3.7509	-0.0336	0.0059	3.69	-111.462	-2.6211	3.7509	-0.02	0.0104	3.77	-8.72	-1.80
WASP-48	1.0958	-0.0037	0.0990	4.52	-1.247	-1.1438	2.8281	0.01	0.0192	4.32	1.03	1.23
WASP-3	1.8467	0.0105	0.0373	7.25	1.611	1.0353	1.8471	0.01	0.0374	4.09	2.49	0.74
GJ 3470	3.7383	0.0097	0.0170	3.84	1.844	1.3250	3.7467	0.01	0.0205	3.98	2.90	1.16
WASP-33	1.2197	0.0142	0.0591	4.69	0.555	1.0222	1.2197	0.01	0.0463	4.20	0.82	1.28

4.3 Seasonal photometric variability of a sample of APACHE targets

Here I summarize the results of the photometric analysis that I have performed homogeneously with my version of the TEEPEE pipeline for most of the M dwarfs observed during the first season. An interesting paper to be considered as a reference for the aims of the work discussed in this Section is that of [Goulding et al. \[2012\]](#), where the photometric variability in J -band of a sample of M dwarfs from the WFCAM survey is analyzed. I first present two tables containing the main results which can be of use for estimating the level of variability of each of the APACHE targets. Table 4.2 shows general informations about the observations carried out for a total of 132 M dwarfs, as the number of observing dates, the timespan during which a target has been scheduled, and the number of good photometric points used in the analysis. Table 4.3 contains selected results from the light curve analysis of the stars in Table 4.2 covering the whole timespan of observations: the expected median theoretical photometric noise, which is calculated using the relation (3) in [Damasso et al. \[2010b\]](#); the mean light curve RMS calculated over all the nights of observations (thus, defined as 'intra-night RMS'), and the RMS of the seasonal photometric time-series, i.e. the complete set of data points collected over the timespan of observations. The intra-night and seasonal RMS are provided for both the methods applied by TEEPEE for selecting the best aperture radius and set of comparison stars used for deriving the light curve of the targets (i.e. both aperture radius and set of comparison stars are generally different for each method). It is the seasonal light curve RMS which should provide information about the long-term photometric variability of an M dwarf, by a direct comparison with the expected theoretical noise level. A global picture of what the survey has yield after the first season can be drawn by looking at the results presented in Fig. 4.1 and Fig. 4.2. In the first two plots of Fig. 4.1 the mean light curve RMS calculated on a nightly basis for all the targets in Table 4.2 is compared to the expected median noise, and both are plotted as a function of the median instrumental magnitudes of the M dwarfs. In particular, the second plot shows the ratio between the observed 'intra-night' RMS and the expected noise, from which it is possible to see that an anticorrelation exists with the median instrumental magnitudes, with the brightest stars having a measured photometric noise greater than the theoretical value. This result is indicative of the existence of a systematic trend, which is evident also in the results showed in the last couple of plots in Fig. 4.1, where the mean 'intra-night' RMS of the M dwarfs light curves and the median expected noise are plotted versus the color index $V-K$. We can conclude that the brightest and early-type M dwarfs that

APACHE has observed during the first season appear affected on a nightly basis by a noise level higher than expected, and a plausible explanation is that, instead of being due to the intrinsic activity of the stars, this behaviour should be related to the short-time exposures used for these stars that could determine a non-optimal set of reference stars, in terms of their number and their flux. For that reason, while the survey was already ongoing we have decided to observe in V-band some targets in common with the GAPS project which were not included previously in the AIC (Chapter 5). In V-band the exposure times for the brightest targets can be increased to reach the same SNR as for I-band and the field stars are on average brighter in V, thus the number of potentially good comparison stars with SNR comparable to that of the target can be increased, resulting in less noisy light curves. When considering the RMS of the light curves calculated over the whole timespan of observations and plotted as a function of the instrumental magnitudes (first couple of plots in Fig. 4.2), the results just described do not appear: the differences between the observed and expected noise do not depend on the magnitude, with more than half of the targets that have an RMS greater than the theoretical noise level. The second couple of plots of Fig. 4.2 shows that several M dwarfs with color index less than ~ 4.7 exhibit a noise level greater than expected which actually could be due to the intrinsic long-term activity. It would be important to understand why some targets have large RMS, because for these stars the detection of transits of small size planets is obviously more complicated. If there are complications due to the survey set-up, then to find quickly a solution is one of the high priority points of discussion when we will revise the APACHE observing strategy. The simulations we are carrying out to assess the sensitivity of the APACHE telescopes in detecting transit signals due to planets with different sizes as a function of the noise level in the light curves (the results will appear in a paper now in preparation), will be very useful to produce a clearer picture and to modify some aspects of the observing strategy. Some examples of seasonal differential light curves of some selected targets are showed in Fig. 4.3, to illustrate the final product of the TEEPEE pipeline applied to the APACHE M dwarfs. All the targets discussed here have been monitored in I_c band. Each plot contains the no-detrended photometric time series obtained by using the two methods applied by the TEEPEE package, which for these examples produce very similar results. Each point of a light curve represents the average value of a time series obtained during a single night, and the error bars are the RMS of the single-night light curve. The time stamps used are the average values of the time interval over a single night during which the star has been monitored. The first plot is related to the star number 216 of the AIC, which shows a clear change in luminosity over a period longer than 100 days. The second plot shows the time series of the star number 301, which is interesting because it is a target also of the

GAPS survey and for which we have collected a lot of photometric data points. It can be seen that this star has increased its luminosity with time with respect to the first half of the first observing season. The next diagram shows another example of a star also included in the GAPS target list, the M dwarf Apache 932, which after a data gap of ~ 90 days showed a light curve more scattered and with an average increase of the luminosity. The fourth diagram shows the photometric data for the APACHE star number 1117. This star has been observed for 7 days in a row and the light curves seem to have a sinusoidal-like modulation which could be attributed to the rotation of the star around its axis (see next Section for rotational periods measured for some APACHE targets). This evidence is also confirmed by the light curves detrended with the SysRem algorithm (not showed). It is interesting to note the small peak-to-peak amplitude of the light curve, which is less than 0.01 mag, and the small error bars of the intra-night mean differential magnitudes, revealing very good measurements for this target. In conclusion, it is likely that this M dwarf has a rotational period of ~ 7 days, but it will be possible to confirm this finding by collecting data for more cycles. The next plot of Fig. 4.3 shows the light curves of the M dwarf number 1925 in the AIC, which shows an increase in luminosity after a gap of ~ 200 days. Apache 1925 is also interesting because it showed a transit-like feature during one night of observation, which unfortunately we did not detect a second time until now. The light curve showing that feature is illustrated in Fig. 4.4. The second to last plot refers to the star number 2097, with the light curves that appear to have an oscillating modulation with a reliable period in the range $40 \div 50$ days, but it has been not possible to detect a clear evidence for rotational periodicity. The last example of a seasonal differential photometric series is that of the star number 2173 of the AIC, which is another star in common with the GAPS survey. From the plot it is possible to notice that the light curve scatter is greatly increased after a gap of ~ 260 days in the observations, which could be attributed to an increase in the atmospheric activity of the star.

TABLE 4.2: Summary of the main information of a sample of M dwarfs observed by APACHE during the first season (Part 1). Almost all the targets with the highest number of data points and which have been observed for longer are those in common with the GAPS programme (see Chapter 5).

Name	observing dates	Timespan (days)	data points	V-K
apache 1019	36	362	1789	4.26
apache 1449	8	67	284	4.84
apache 1684	18	61	742	4.26
apache 1705	25	129	1039	5.03
apache 1729	38	186	1290	5.26
apache 1739	32	180	1059	4.19
apache 1770	12	29	305	4.17
apache 1782	22	62	924	3.54
apache 1866	23	122	604	4.54
apache 2116	18	57	289	3.67
apache 2173	44	363	1282	3.89
apache 2240	21	34	755	3.86
apache 2400	20	39	579	3.88
apache 2459	48	128	1394	3.66
apache 2570	24	36	1092	5.11
apache 2586	25	39	1135	4.61
apache 2650	39	122	860	3.83
apache 269	2	3	101	3.33
apache 2784	53	382	1696	4.61
apache 3083	54	379	2047	3.68
apache 3110	26	391	833	4.51
apache 3126	75	416	3562	4.03
apache 3248	35	403	1145	5.59
apache 3251	22	376	940	4.69
apache 33	20	56	1146	4.44
apache 3305	7	17	173	-
apache 347	10	26	424	3.92
apache 379	33	407	1523	4.31
apache 57	8	10	282	5.38
apache 647	54	389	3371	4.03
apache 735	3	125	152	3.30
apache 850	24	124	964	3.70

Continued

apache 915	48	357	2418	4.39
apache 981	44	153	2358	4.19
apache 1040	16	96	781	3.61
apache 1041	40	153	1537	4.21
apache 1130	11	37	446	4.22
apache 1147	20	84	755	4.68
apache 1154	8	57	163	4.14
apache 1267	53	268	1853	4.92
apache 1511	55	186	2113	4.99
apache 1551	36	128	1328	5.06
apache 1557	28	112	870	4.49
apache 160	74	196	5045	4.33
apache 1642	7	14	237	5.72
apache 17	67	186	4466	3.73
apache 1925	72	391	1493	5.53
apache 2077	14	96	236	4.07
apache 2679	19	31	567	5.89
apache 2691	37	103	604	3.46
apache 2773	51	135	1667	3.96
apache 284	13	137	211	4.71
apache 2881	3	35	64	3.81
apache 2937	13	58	84	3.51
apache 2995	50	105	2630	3.73
apache 3007	24	51	545	6.02
apache 301	80	421	5116	4.63
apache 3117	46	182	1621	3.76
apache 3122	65	416	4270	3.83
apache 3300	44	106	1331	-
apache 380	4	9	26	4.71
apache 6	50	103	3302	4.10
apache 833	48	155	2263	3.93
apache 932	29	129	1075	3.91
apache 958	9	8	380	5.20
apache 1038	11	30	263	4.74
apache 1100	21	127	962	3.44
apache 1117	7	6	61	5.91
apache 1143	7	6	241	5.18

Continued

apache 1146	36	195	1174	5.95
apache 1206	18	75	1176	4.04
apache 1589	23	99	633	3.80
apache 1597	56	207	1464	4.26
apache 167	16	44	951	4.53
apache 1674	19	101	862	3.89
apache 1680	22	79	516	4.02
apache 1932	24	68	894	5.12
apache 1993	31	165	1046	4.75
apache 207	50	135	2382	3.92
apache 216	79	294	2543	5.83
apache 2290	8	11	337	4.74
apache 2562	42	143	1608	3.75
apache 2698	20	66	657	5.26
apache 2744	25	76	474	4.26
apache 2864	31	119	1254	3.81
apache 2924	37	96	1542	3.63
apache 2970	46	96	1956	4.83
apache 3002	23	60	814	3.52
apache 3035	28	78	845	5.05
apache 3069	43	432	1576	3.74
apache 3093	12	35	302	4.16
apache 3150	29	422	1017	3.59
apache 3219	57	169	3032	3.74
apache 3301	39	104	1368	-
apache 418	74	421	3646	3.79
apache 419	77	416	4177	4.14
apache 611	29	98	1564	4.00
apache 663	18	43	1147	5.49
apache 822	17	74	1158	3.76
apache 832	5	15	232	3.41
apache 961	22	124	821	4.09
apache 1028	17	96	1159	4.07
apache 1051	20	72	1279	3.70
apache 1379	19	116	927	3.66
apache 1618	19	125	854	5.11
apache 1639	23	126	737	5.71

Continued

apache 1707	35	128	1749	4.71
apache 1776	39	152	1457	4.65
apache 21	6	69	233	4.84
apache 2174	14	51	523	4.37
apache 2680	36	117	1523	4.23
apache 2836	46	98	2380	4.56
apache 2893	23	36	1368	4.24
apache 2992	5	4	269	3.74
apache 3027	32	118	1009	5.08
apache 3228	9	108	250	4.68
apache 331	22	144	742	5.10
apache 467	14	93	919	3.44
apache 770	16	63	904	3.78
apache 95	20	131	675	5.21
apache 1174	8	30	243	3.74
apache 1341	5	8	104	4.05
apache 1706	27	94	1168	3.79
apache 1749	19	56	708	3.66
apache 2011	28	120	590	4.70
apache 2042	42	200	917	4.43
apache 2079	46	168	1290	4.34
apache 2097	36	100	771	4.88
apache 2446	58	222	1646	4.22
apache 2529	34	258	988	3.83
apache 2817	51	187	2204	4.15
apache 2961	15	58	440	3.65
apache 991	7	30	183	3.84

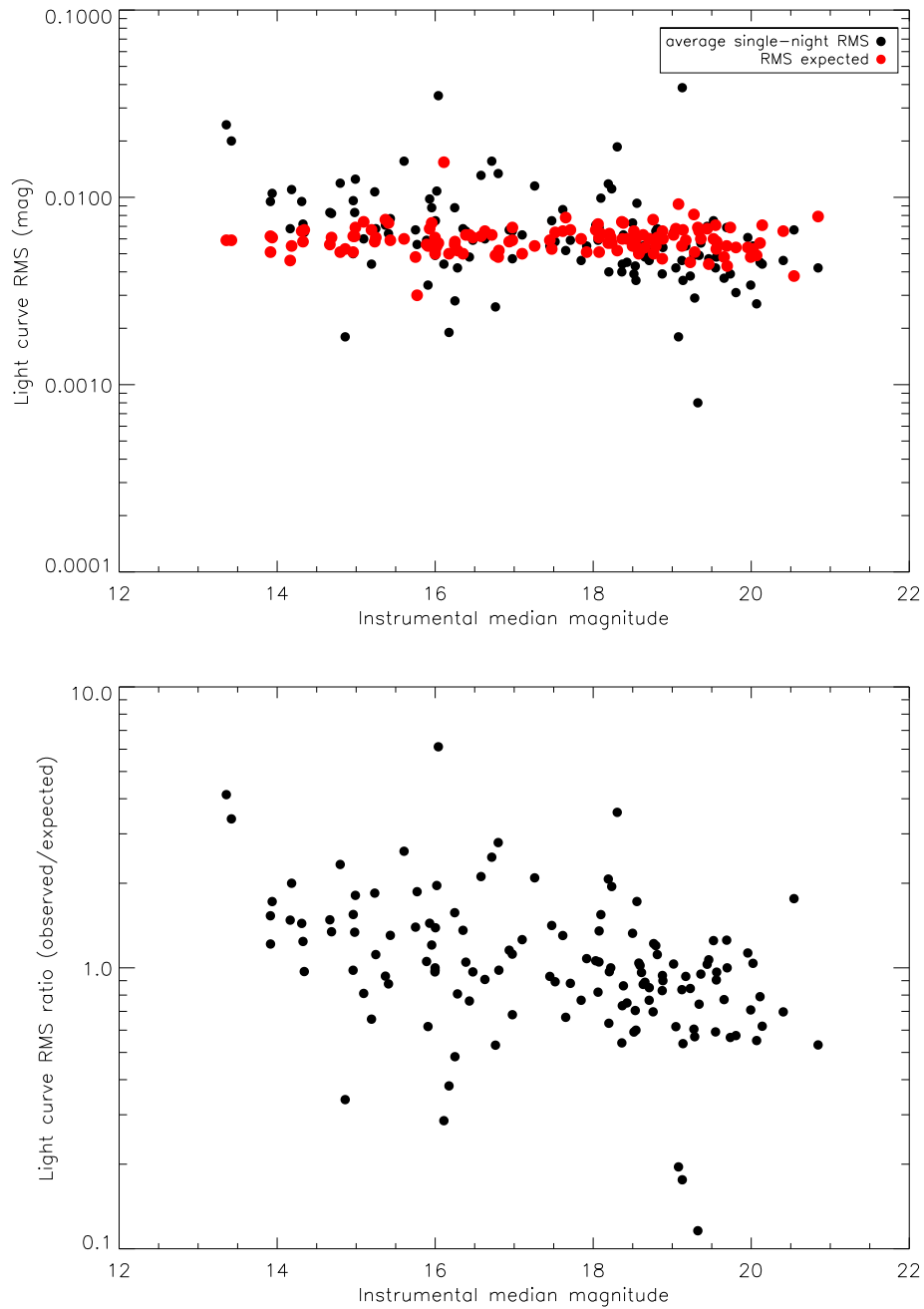
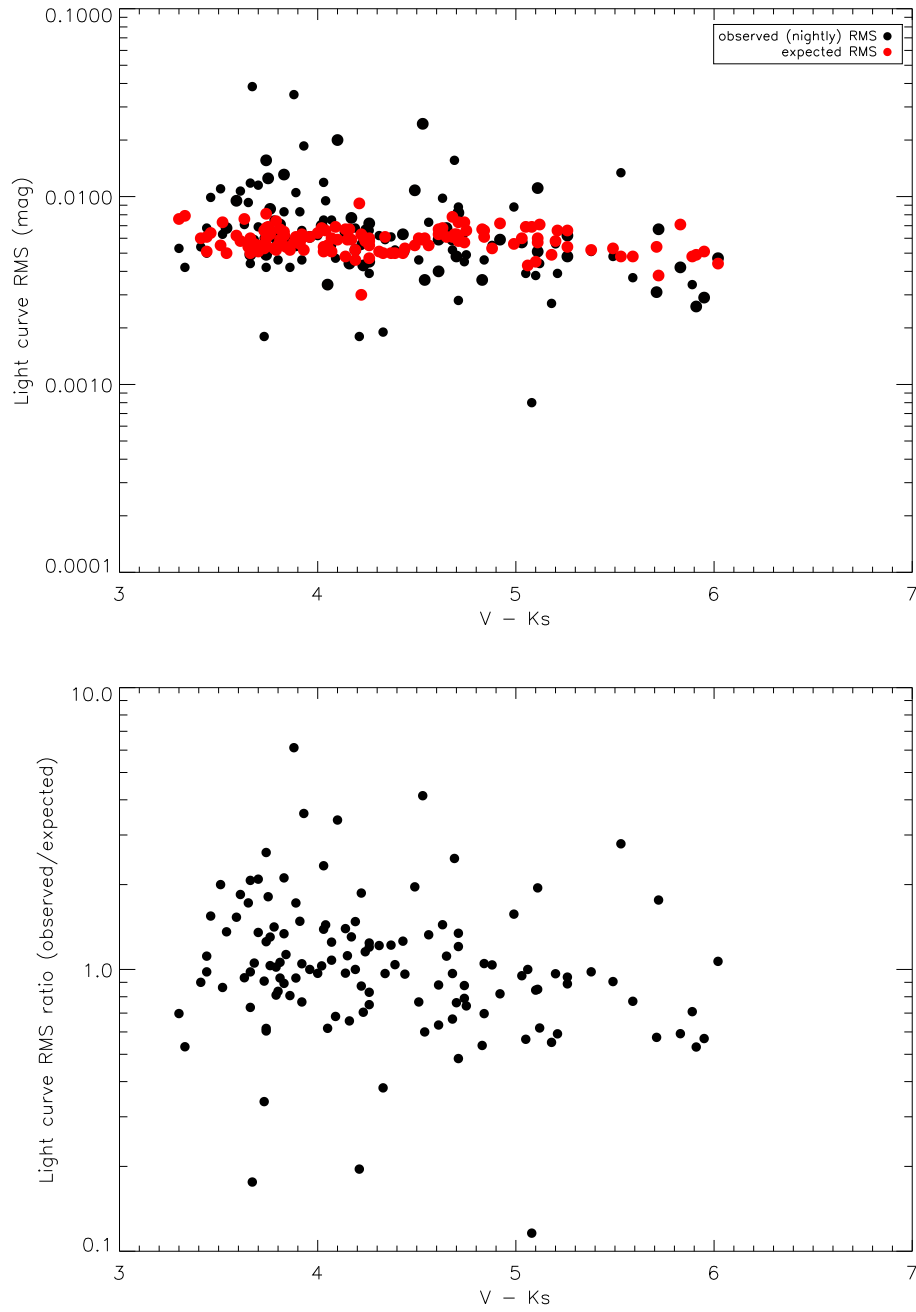


FIGURE 4.1: *First plot.* Average light curve RMS of the APACHE targets observed during the first season (Table 4.2) calculated on a nightly basis (black dots) as a function of the median instrumental magnitude, with overplotted the theoretical photometric noise (red dots). *Second plot.* Ratio of the observed light curve RMS to the expected noise (same as the first plot), plotted as a function of the median instrumental magnitude. *Third and fourth panels.* Same as the previous plots, with data showed as a function of the M dwarfs color index $V-K$ instead of their median instrumental magnitude.

FIGURE 4.1: *continued*

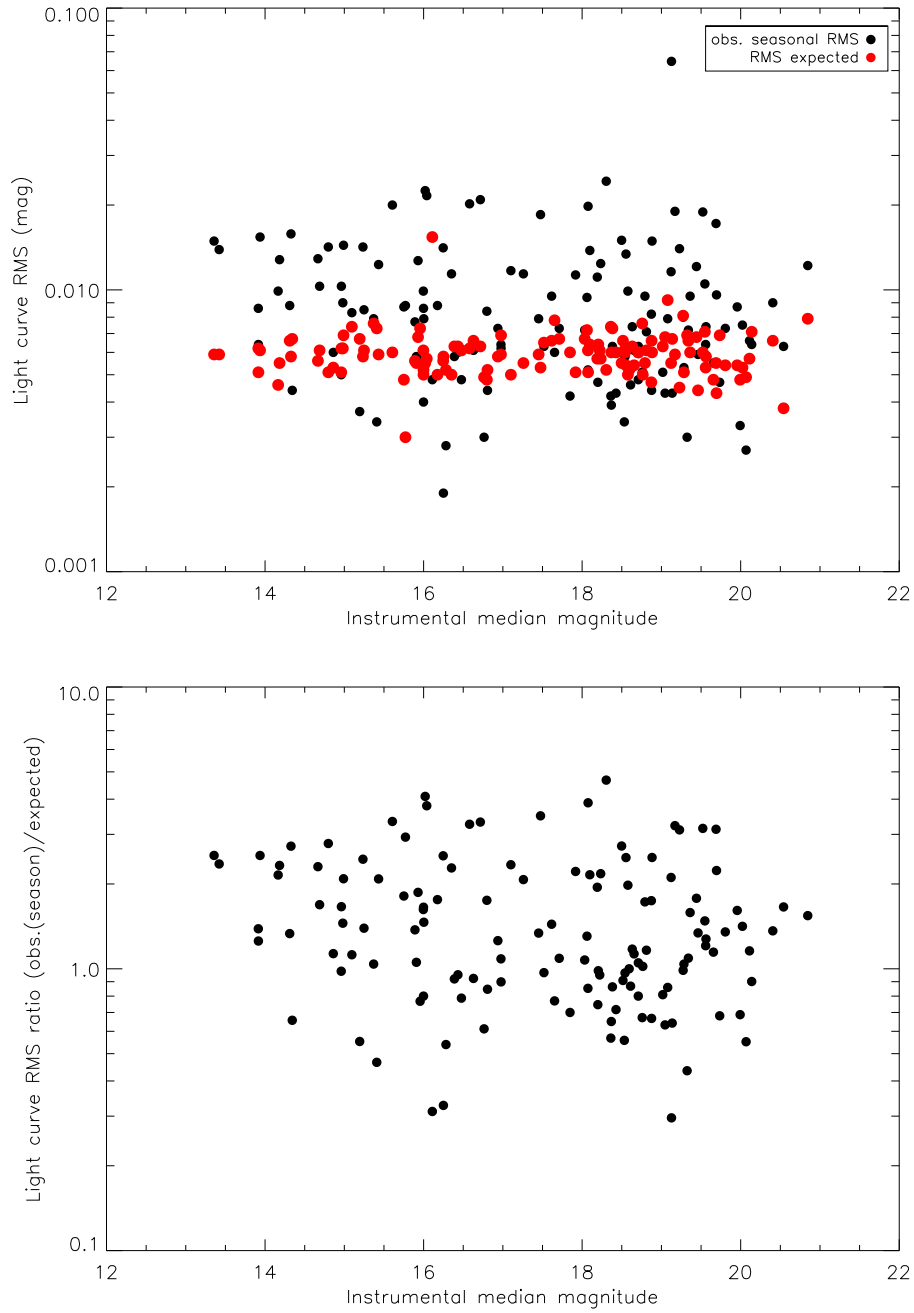
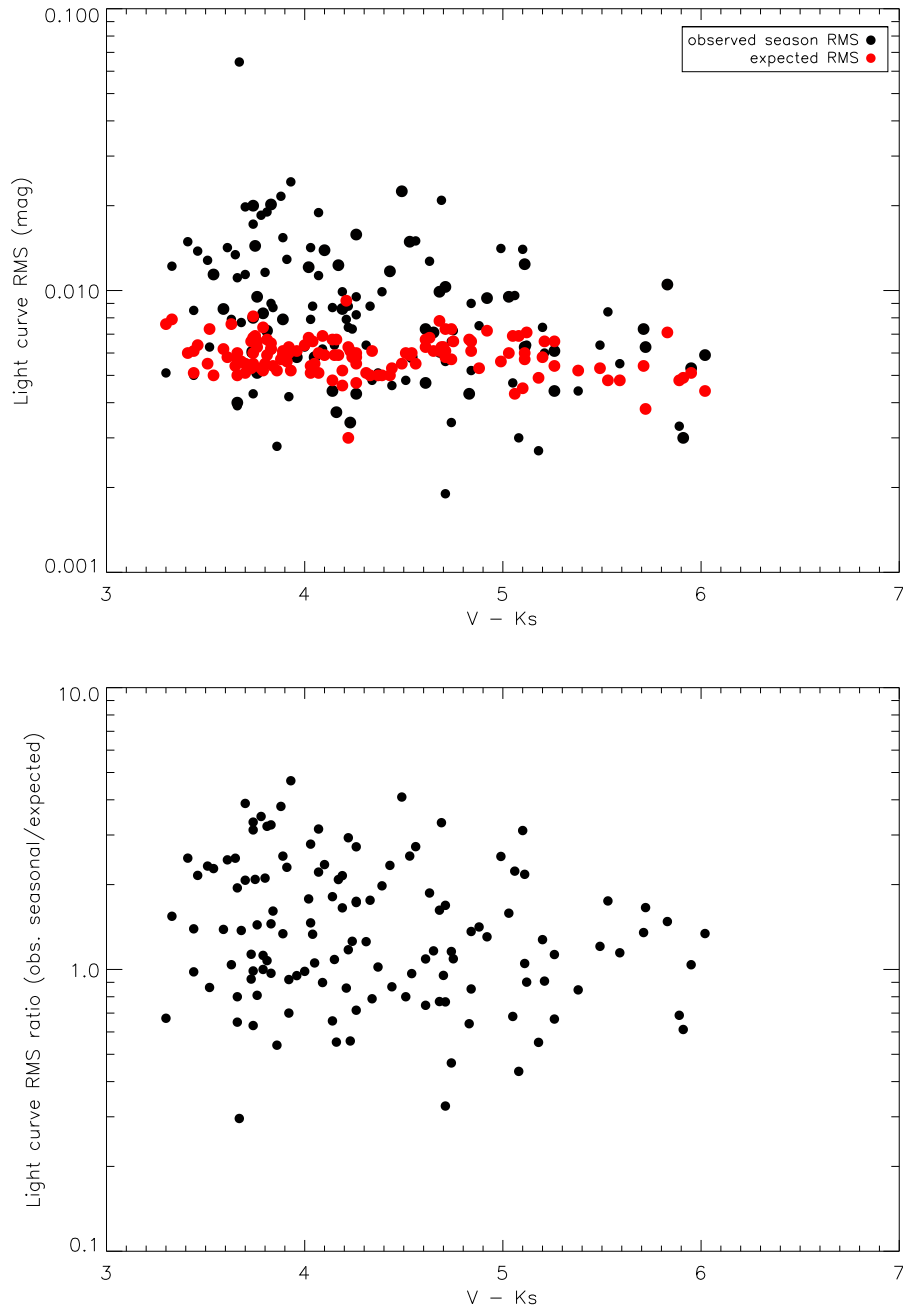


FIGURE 4.2: *First plot.* Seasonal light curve RMS of the APACHE targets observed during the first season (Table 4.2) calculated over the whole timespan of observations (black dots) as a function of the median instrumental magnitude, with overplotted the theoretical photometric noise (red dots). *Second plot.* Ratio of the observed light curve RMS to the expected noise (same as the first plot), plotted as a function of the median instrumental magnitude. *Third and fourth panels.* Same as the previous plots, with data showed as a function of the M dwarfs color index $V-K$ instead of their median instrumental magnitude.

FIGURE 4.2: *continued*

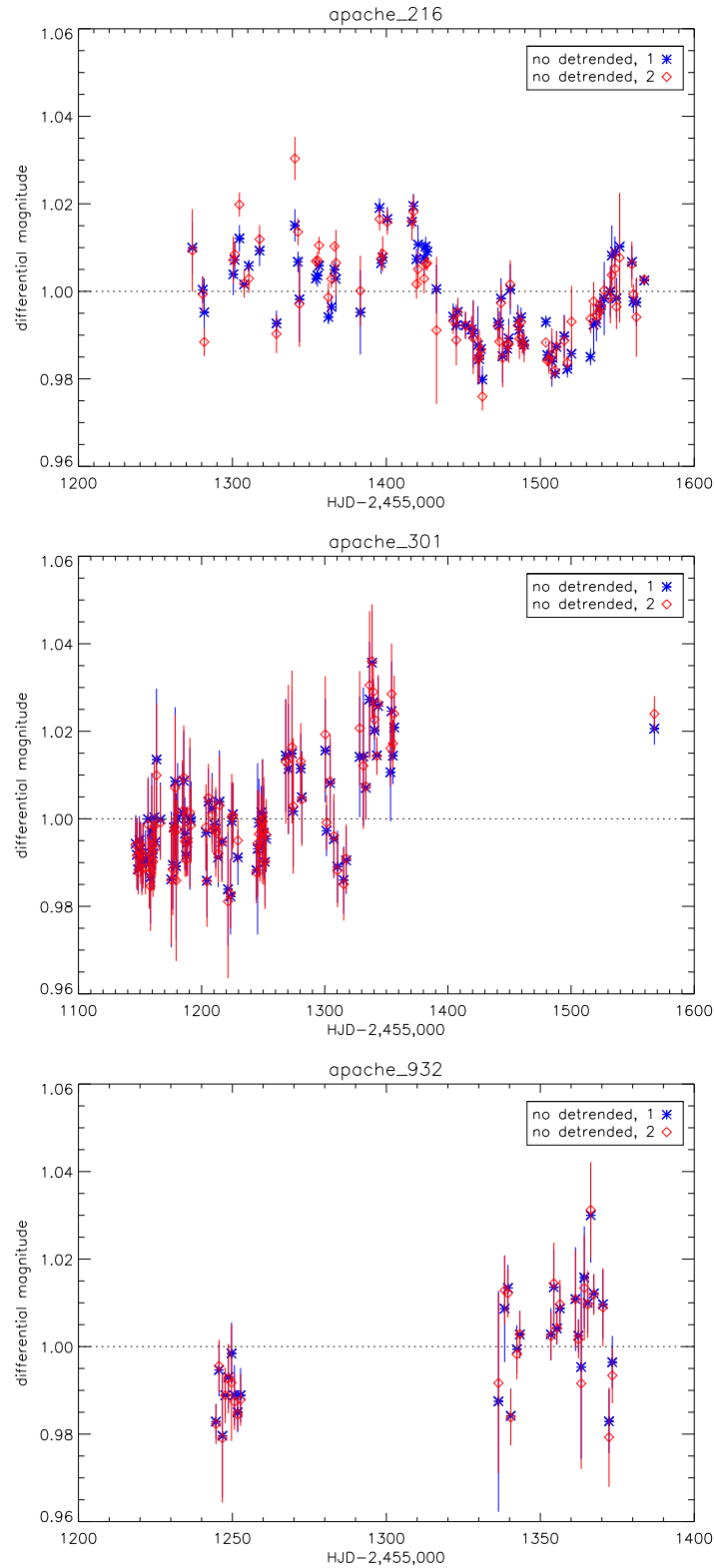
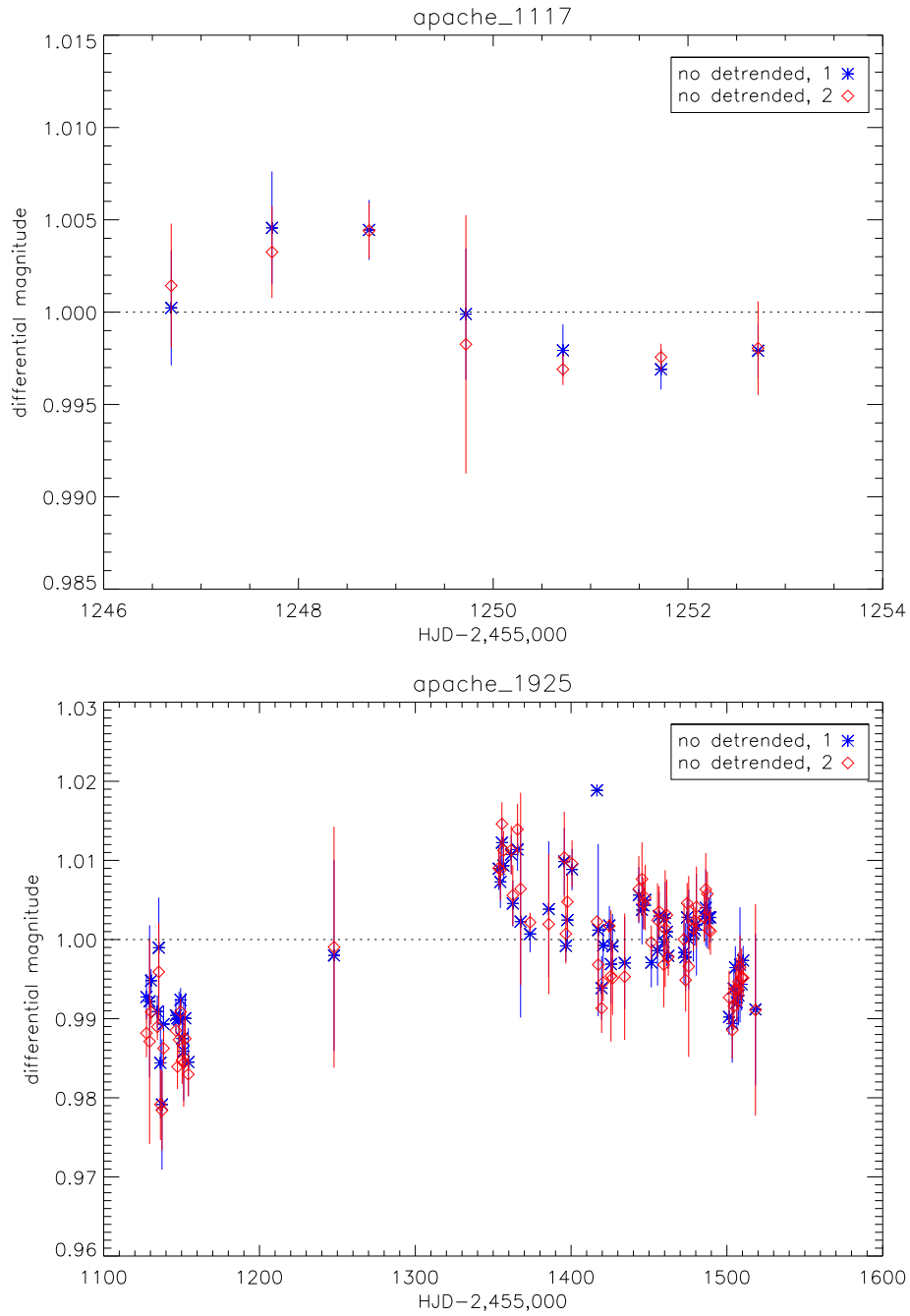
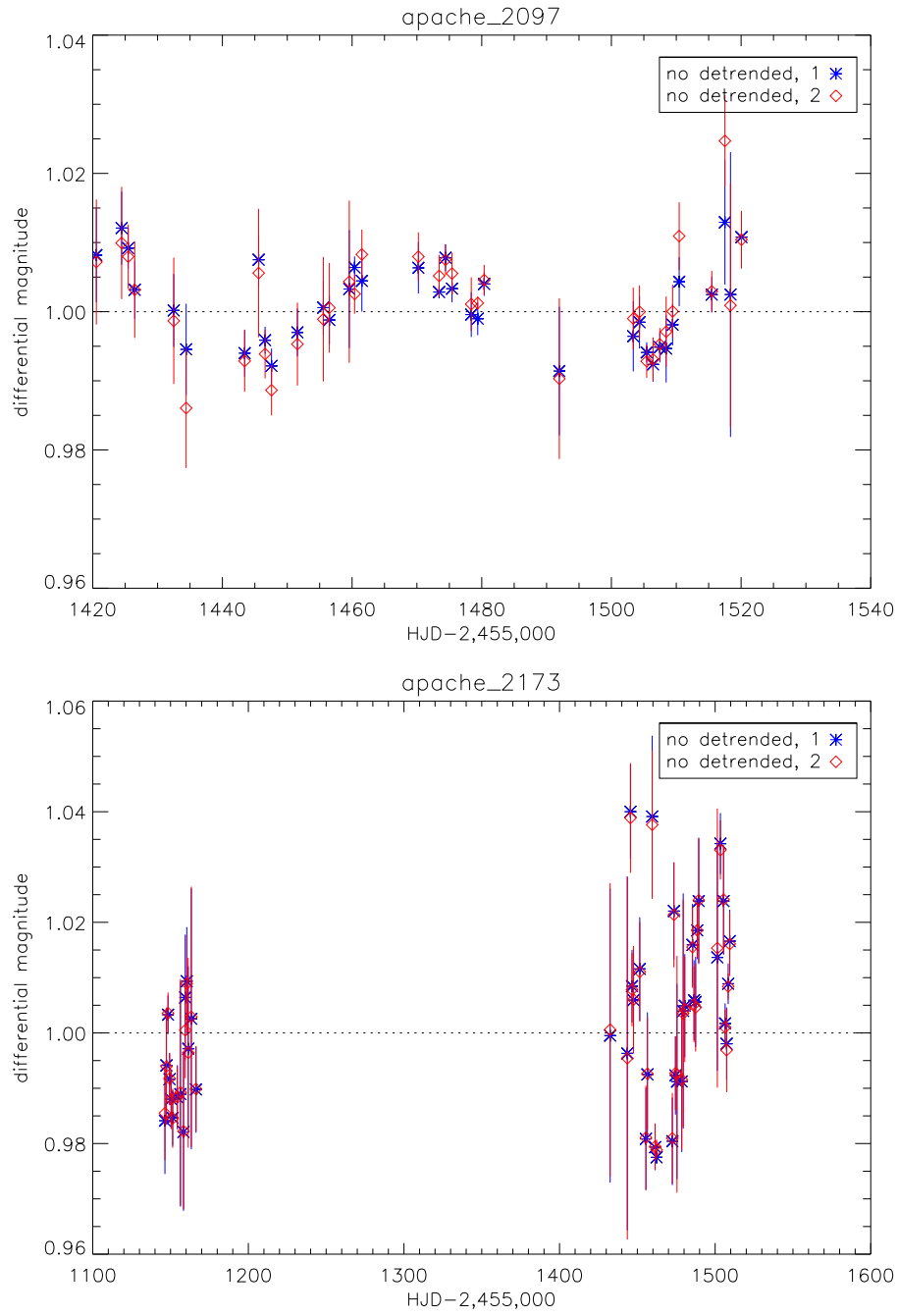


FIGURE 4.3: Seasonal light curves for a limited sample of APACHE targets. These plots represent a complement of the results reported in Tab. 4.2 and 4.3 and show examples of the output of the TEEPEE pipeline. In particular, showed here are the light curves without de-trending obtained by applying the two methods for selecting the best aperture radius and set of comparison stars which are implemented in TEEPEE. Similar plots are available for light curves detrended with the SysRem algorithm.



FIGURE 4.3: *continued*

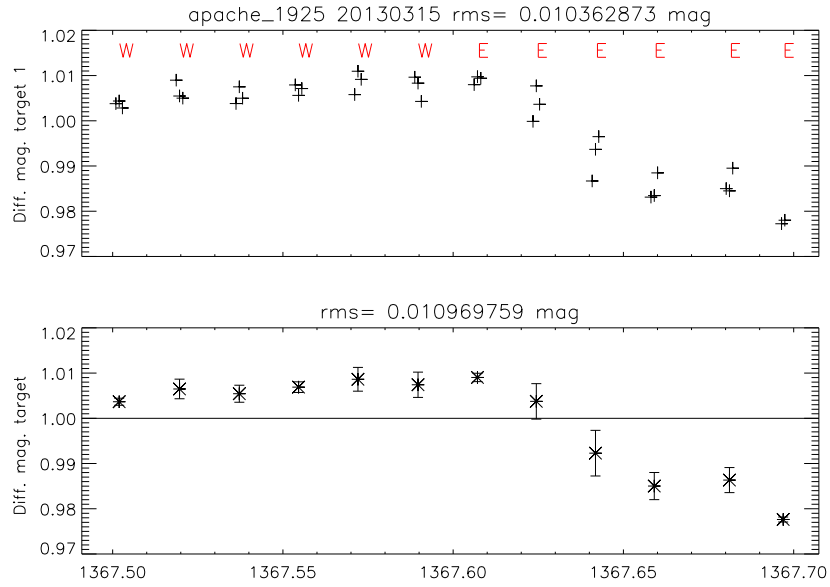


FIGURE 4.4: Differential light curve of the APACHE target number 1925 collected during the night of 2013/03/15 (*abscissa*: HJD). The upper plot shows the complete time series, with data acquired in batches of three consecutive measurements according to the APACHE circular pointing strategy. The second plot shows the data averaged for each batch, with the error bars represented by the RMS of the three measurements in each bin. It can be clearly seen that the star started dimming during the second half of observations, producing a signal which resembles that produced by a transiting companion. Up to now, we could not confirm the real nature of this detection. The capital letters W and E in red indicate the orientation of the telescope mount during the data acquisition. A 180 degrees flip of the mount occurs when the target has passed through the local meridian.

TABLE 4.3: Summary of the main information of a sample of M dwarfs observed by APACHE during the first season (Part 2). Here global results from the photometric analysis are showed, which should provide information about the level of stellar atmospheric activity as seen in the light curves.

Name	Median instr. mag.	Expected median RMS	Mean intra-night RMS (method 1)	Seasonal RMS (method 1)	Mean intra-night RMS (method 2)	Seasonal RMS (method 2)
apache 1019	18.87	0.0047	0.0028	0.0058	0.0039	0.0082
apache 1449	20.40	0.0066	0.0036	0.0069	0.0046	0.0090
apache 1684	18.79	0.0055	0.0075	0.0092	0.0066	0.0095
apache 1705	19.36	0.0060	0.0049	0.0089	0.0057	0.0095
apache 1729	18.65	0.0054	0.0042	0.0053	0.0048	0.0061
apache 1739	15.99	0.0052	0.0044	0.0075	0.0052	0.0086
apache 1770	15.43	0.0059	0.0060	0.0074	0.0077	0.0123
apache 1782	16.35	0.0050	0.0068	0.0114	0.0068	0.0114
apache 1866	18.54	0.0060	0.0037	0.0050	0.0036	0.0058
apache 2116	19.12	0.2187	0.0437	0.1355	0.0385	0.0647
apache 2173	13.93	0.0061	0.0104	0.0158	0.0105	0.0154
apache 2240	16.28	0.0052	0.0042	0.0028	0.0042	0.0028
apache 2400	16.03	0.0057	0.0333	0.0201	0.0349	0.0216
apache 2459	18.19	0.0057	0.0078	0.0076	0.0118	0.0111
apache 2570	18.23	0.0057	0.0090	0.0101	0.0111	0.0124
apache 2586	18.19	0.0063	0.0048	0.0042	0.0040	0.0047
apache 2650	14.98	0.0062	0.0078	0.0088	0.0083	0.0090
apache 269	20.84	0.0079	0.0031	0.0007	0.0042	0.0122
apache 2784	17.71	0.0067	0.0054	0.0082	0.0059	0.0073
apache 3083	15.89	0.0056	0.0056	0.0075	0.0059	0.0077
apache 3110	18.70	0.0060	0.0043	0.0047	0.0046	0.0048
apache 3126	16.00	0.0054	0.0068	0.0068	0.0075	0.0079

Continued

apache 3248	19.65	0.0048	0.0039	0.0051	0.0037	0.0055
apache 3251	16.71	0.0063	0.0081	0.0041	0.0156	0.0209
apache 33	18.61	0.0053	0.0038	0.0041	0.0051	0.0046
apache 3305	18.36	0.0074	0.0041	0.0024	0.0040	0.0042
apache 347	17.84	0.0060	0.0046	0.0042	0.0046	0.0042
apache 379	13.91	0.0051	0.0067	0.0061	0.0062	0.0064
apache 57	16.80	0.0052	0.0041	0.0044	0.0051	0.0044
apache 647	14.79	0.0051	0.0119	0.0142	0.0119	0.0142
apache 735	18.75	0.0076	0.0046	0.0042	0.0053	0.0051
apache 850	18.07	0.0051	0.0047	0.0079	0.0069	0.0198
apache 915	18.57	0.0050	0.0037	0.0060	0.0052	0.0099
apache 981	14.16	0.0046	0.0071	0.0085	0.0068	0.0099
apache 1040	15.23	0.0058	0.0092	0.0105	0.0107	0.0142
apache 1041	19.07	0.0092	0.0017	0.0096	0.0018	0.0079
apache 1130	15.77	0.0030	0.0035	0.0024	0.0056	0.0088
apache 1147	15.99	0.0061	0.0059	0.0099	0.0059	0.0099
apache 1154	15.75	0.0048	0.0059	0.0086	0.0067	0.0087
apache 1267	18.06	0.0072	0.0050	0.0079	0.0059	0.0094
apache 1511	16.24	0.0056	0.0075	0.0149	0.0088	0.0141
apache 1551	19.69	0.0043	0.0015	0.0099	0.0043	0.0096
apache 1557	16.01	0.0055	0.0092	0.0151	0.0108	0.0225
apache 160	16.17	0.0050	0.0020	0.0087	0.0019	0.0088
apache 1642	20.54	0.0038	0.0072	0.0049	0.0067	0.0063
apache 17	16.62	0.0066	0.0060	0.0061	0.0060	0.0061
apache 1925	16.79	0.0048	0.0096	0.0074	0.0134	0.0084
apache 2077	19.52	0.0060	0.0068	0.0176	0.0075	0.0189

Continued

apache 2679	19.99	0.0048	0.0026	0.0028	0.0034	0.0033
apache 2691	18.09	0.0064	0.0087	0.0070	0.0099	0.0138
apache 2773	18.22	0.0061	0.0058	0.0055	0.0061	0.0058
apache 284	14.68	0.0061	0.0068	0.0068	0.0082	0.0103
apache 2881	19.17	0.0059	0.0045	0.0033	0.0055	0.0190
apache 2937	14.18	0.0055	0.0110	0.0128	0.0110	0.0128
apache 2995	14.86	0.0053	0.0016	0.0073	0.0018	0.0060
apache 3007	19.46	0.0044	0.0045	0.0060	0.0047	0.0059
apache 301	15.93	0.0068	0.0095	0.0117	0.0098	0.0127
apache 3117	19.01	0.0063	0.0060	0.0053	0.0065	0.0051
apache 3122	16.58	0.0062	0.0131	0.0202	0.0131	0.0202
apache 3300	14.96	0.0062	0.0096	0.0103	0.0096	0.0103
apache 380	16.25	0.0058	0.0028	0.0016	0.0028	0.0019
apache 6	13.42	0.0059	0.0200	0.0139	0.0200	0.0139
apache 833	18.30	0.0052	0.0185	0.0239	0.0186	0.0243
apache 932	14.66	0.0056	0.0081	0.0124	0.0083	0.0129
apache 958	19.56	0.0058	0.0051	0.0043	0.0056	0.0074
apache 1038	20.11	0.0057	0.0047	0.0065	0.0045	0.0066
apache 1100	15.24	0.0061	0.0071	0.0083	0.0068	0.0085
apache 1117	16.76	0.0049	0.0022	0.0031	0.0026	0.0030
apache 1143	20.06	0.0049	0.0023	0.0028	0.0027	0.0027
apache 1146	19.28	0.0051	0.0029	0.0053	0.0029	0.0053
apache 1206	14.31	0.0066	0.0086	0.0095	0.0095	0.0088
apache 1589	19.12	0.0055	0.0042	0.0099	0.0046	0.0116
apache 1597	18.42	0.0060	0.0045	0.0043	0.0045	0.0043
apache 167	13.35	0.0059	0.0244	0.0149	0.0244	0.0149

Continued

apache 1674	17.45	0.0059	0.0055	0.0079	0.0055	0.0079
apache 1680	19.44	0.0068	0.0070	0.0115	0.0070	0.0121
apache 1932	20.13	0.0071	0.0044	0.0064	0.0044	0.0064
apache 1993	19.33	0.0066	0.0051	0.0072	0.0049	0.0072
apache 207	16.38	0.0063	0.0063	0.0042	0.0066	0.0058
apache 216	19.54	0.0071	0.0038	0.0097	0.0042	0.0105
apache 2290	15.40	0.0073	0.0064	0.0034	0.0064	0.0034
apache 2562	14.98	0.0069	0.0125	0.0144	0.0125	0.0144
apache 2698	18.87	0.0066	0.0062	0.0044	0.0062	0.0044
apache 2744	14.32	0.0058	0.0072	0.0158	0.0072	0.0158
apache 2864	18.03	0.0067	0.0071	0.0072	0.0071	0.0072
apache 2924	15.36	0.0076	0.0061	0.0057	0.0071	0.0079
apache 2970	19.13	0.0067	0.0034	0.0039	0.0036	0.0043
apache 3002	18.38	0.0073	0.0062	0.0069	0.0063	0.0063
apache 3035	19.73	0.0069	0.0038	0.0063	0.0039	0.0047
apache 3069	19.27	0.0081	0.0044	0.0066	0.0049	0.0080
apache 3093	15.19	0.0067	0.0044	0.0037	0.0044	0.0037
apache 3150	13.91	0.0062	0.0089	0.0085	0.0095	0.0086
apache 3219	15.60	0.0060	0.0150	0.0222	0.0156	0.0200
apache 3301	16.10	0.0154	0.0049	0.0051	0.0044	0.0048
apache 418	15.09	0.0074	0.0052	0.0040	0.0060	0.0083
apache 419	14.34	0.0067	0.0065	0.0044	0.0065	0.0044
apache 611	18.20	0.0064	0.0062	0.0063	0.0062	0.0063
apache 663	19.55	0.0053	0.0035	0.0046	0.0048	0.0064
apache 822	17.61	0.0066	0.0084	0.0078	0.0086	0.0095
apache 832	18.88	0.0060	0.0050	0.0106	0.0054	0.0149

Continued

apache 961	16.97	0.0069	0.0050	0.0065	0.0047	0.0062
apache 1028	17.91	0.0051	0.0063	0.0852	0.0055	0.0113
apache 1051	17.25	0.0055	0.0103	0.0097	0.0115	0.0114
apache 1379	18.36	0.0060	0.0035	0.0037	0.0044	0.0039
apache 1618	18.70	0.0060	0.0051	0.0060	0.0051	0.0063
apache 1639	19.80	0.0054	0.0040	0.0073	0.0031	0.0073
apache 1707	15.95	0.0073	0.0071	0.0069	0.0088	0.0056
apache 1776	18.81	0.0061	0.0057	0.0066	0.0068	0.0071
apache 21	18.07	0.0061	0.0054	0.0032	0.0064	0.0052
apache 2174	18.76	0.0050	0.0060	0.0049	0.0061	0.0051
apache 2680	18.53	0.0061	0.0042	0.0034	0.0043	0.0034
apache 2836	18.49	0.0055	0.0052	0.0116	0.0073	0.0150
apache 2893	16.93	0.0058	0.0063	0.0068	0.0067	0.0073
apache 2992	19.04	0.0068	0.0041	0.0037	0.0042	0.0043
apache 3027	19.32	0.0069	0.0008	0.0035	0.0008	0.0030
apache 3228	17.65	0.0078	0.0052	0.0060	0.0052	0.0060
apache 331	19.22	0.0045	0.0036	0.0137	0.0038	0.0140
apache 467	14.96	0.0051	0.0051	0.0052	0.0050	0.0050
apache 770	17.47	0.0053	0.0095	0.0515	0.0075	0.0185
apache 95	18.51	0.0066	0.0034	0.0046	0.0039	0.0060
apache 1174	19.68	0.0055	0.0038	0.0114	0.0069	0.0172
apache 1341	15.90	0.0055	0.0029	0.0059	0.0034	0.0058
apache 1706	18.59	0.0052	0.0057	0.0036	0.0053	0.0052
apache 1749	15.99	0.0050	0.0042	0.0037	0.0049	0.0040
apache 2011	16.43	0.0063	0.0038	0.0044	0.0048	0.0060
apache 2042	17.10	0.0050	0.0063	0.0106	0.0063	0.0117

Continued

apache 2079	16.47	0.0061	0.0060	0.0048	0.0059	0.0048
apache 2097	20.02	0.0053	0.0043	0.0059	0.0055	0.0075
apache 2446	18.63	0.0063	0.0041	0.0046	0.0055	0.0074
apache 2529	17.51	0.0065	0.0052	0.0060	0.0058	0.0063
apache 2817	16.97	0.0059	0.0067	0.0068	0.0066	0.0064
apache 2961	18.55	0.0054	0.0086	0.0132	0.0093	0.0134
apache 991	19.95	0.0054	0.0036	0.0050	0.0061	0.0087

4.4 Stellar rotational periods measured from the APACHE light curves

By observing the same star over a timespan of several weeks, one relevant parameter that can be searched for by analysing the photometric light curve is its rotational period. This can be derived if the light curve of the star shows a periodical sinusoidal-like modulation that can be ascribed to the presence of dark spots and/or bright active regions unevenly distributed on the stellar photosphere. Considering the simplest case of a single spot, the flux of the star changes with time depending on the position of the spot relative to the line of sight, being minimum when the maximum fraction of the cool spot surface becomes visible to the observer. Looking for periodical modulations in light curves that can be interpreted in terms of stellar rotation is a very reliable way to directly measure the rotational period, which is a key observational parameter for stellar evolution, as a diagnostic of the mechanisms responsible for stellar angular momentum loss and internal angular momentum transport. Rotation is also the driving force behind stellar activity, through dynamo production of magnetic fields. Limiting the discussion to M dwarfs, a clear age-rotation-activity relation exists: dM type stars spin down as they age (and this occurs on longer timescale for lower mass stars) and stars with a very fast rotation (down to less than a day) are expected to be young and very active [Delfosse et al., 1998] [Kiraga and Stepien, 2007], [Irwin et al., 2011], [Browning et al., 2010], [Reiners et al., 2012]. Thus, looking for evidence of rotational modulations in the photometric data of the APACHE M dwarfs is an important task to be carried out for two main reasons. First, it is important for characterizing the astrophysical behaviour of cool stars by increasing the existing statistics in literature and, taking into account the main goal of the APACHE survey, it is also necessary for possibly discard from further observations those stars showing short rotational periods. Infact, as already pointed out in §3.2, stars with high activity levels that should show evidence of transit-like signals are the most difficult to be followed-up by monitoring their RV variations, because the stellar activity is an important source of noise in the RV measurements that can make very difficult the detection of a spectroscopic signal produced by a planetary companion. Moreover, those stars showing a modulation in their light curves very close to a sinusoidal shape have their rotation axis which is likely highly inclined and points towards the observer (see the next Section). This circumstance should heavily reduce the probability to observe a planet transiting its parent star because, assuming spin-orbit alignment as a typical configuration of the star-planet system, one can expected to observe a transit with the highest probability when the spin-axis of the star is oriented nearly equator-on with respect to the observer

[Herrero et al., 2012]. The TEEPEE pipeline that I have developed for analysing the photometric data collected by the APACHE telescopes performs an automatic search for sinusoidal-like periodicities in the light curve of the M dwarfs, by first determining the Lomb-Scargle (L-S) [Scargle, 1982, Horne and Baliunas, 1986] and the CLEAN Roberts et al. [1987] periodograms of unbinned and binned (3 consecutive points per bin) data through the use of publicly available IDL codes for these algorithms. The CLEAN procedure deconvolves the spectral window function from the "dirty" discrete Fourier Transform, removing the couplings between physical frequencies and their aliases or pseudo-aliases. As a second step, I analyze in detail only the binned light curves. Up to 30 periods found in the L-S periodogram with the highest peaks, corresponding to a False Alarm Probability (FAP) 0.01 calculated according to the definition in Zechmeister and Kster [2009], are considered for folding the light curve. After a visual inspection of the folded data, I perform a deeper investigation of the nature of the most significant period only when a sinusoidal-like modulation is evident and the period is not too long (then, unreliable) taking into account the total observation timespan and the number of available data points. If a similar, interesting periodicity is found also by the CLEAN algorithm, this corroborates the possibility that the detected period can be ascribed to the rotation of the star. To assess the significance of a 'good candidate' rotational period, first I compute the best-fit sinusoidal curve to the folded data, comparing the RMS of the residuals O-C to the RMS of the original light curve. If the scatter significantly reduces after the removal of the sinusoidal modulation from the folded data, this supports the existence of the signal. Moreover, the analysis of the residuals can reveal the presence of a secondary period, but this has not been found in the handful of stars considered here. The last step performed to statistically confirm/reject a possible rotation period is a classical bootstrap analysis of the data, as described in Kürster et al. [1997] and used in several other studies (e.g. [Endl et al., 2002], [Paulson et al., 2004], [Hatzes and Zechmeister, 2007]). 10000 fake light curves are generated by shuffling (with replacement) the differential magnitudes over the total timespan and keeping fixed the timestamps. A L-S (or CLEAN, where specified) periodogram is then calculated for each bootstrapped light curve, using the same settings adopted for the original photometric time-series. The number of fake light curves for which the maximum peak in the periodogram, for any tested frequency, has a power greater than or equal to that of the most significant period found in the original data, defines the probability that the detected modulation is not real: every random permutation of the data should remove any existing periodicity which is not due to pure white noise, leaving unaffected the frequency contributions due to noise and aliasing. Thus, if none of the 10000 permutations results in a periodogram with power peaks greater than that of the most significant period found in the original

light curve, the astrophysical origin of the periodic signal can be considered having a $\text{FAP} < 10^{-4}$. It should be reminded that an appropriate definition of the FAP as calculated via bootstrap analysis is not a simple task. A conservative interpretation is that there is 1% of probability that the tested period is not of astrophysical origin, by assuming a relative uncertainty of $1/\sqrt{10000}$.

All of the APACHE light curves discussed here have been analysed and processed as I have just described above, confirming the existence of a periodic signal that can be attributed to a rotational modulation. In some cases, the best period found by the CLEAN algorithm has been adopted because the residuals after removing the best-fit sinusoidal curve has the lowest scatter. At the time of writing, I have found evidence of stellar rotation for five M dwarfs. I have performed a search in the archive of Keck Observatory² to look for publicly available HIRES spectra of these stars, with the aim of deriving a measure of the projected rotational velocity $v \sin i$, as done in [Giacobbe et al. \[2012\]](#) for the two M dwarfs LHS 3445 and GJ 1167A analyzed during the pilot study for the APACHE project. Unfortunately this search, that could be very useful in validating the results coming from photometry only and of a simple spot-model applied to the light curves (see next Section), concluded with no results. Figures 4.5 - 4.9 show the light curves of these five targets, folded according the best periods found, and the corresponding periodograms. For the star number 1041 of the AIC (Fig. 4.5), named I06162+7722 after [Lépine and Gaidos \[2011\]](#), the only spectral classification we have is M3V as estimated by the same authors. The star has been observed for a timespan of ~ 5 months from 2012/12/11 to 2013/5/19 and for a total of 41 nights, collecting 1537 useful photometric points. The tentative rotation period of 25.416132 days, found by using the CLEAN algorithm, is quite long compared to the time coverage of the observations and, in absence of other supporting measurements, there is the possibility that the interpretation I provide can be wrong. A bootstrap analysis gives a $\text{FAP} = 0.0001$. The star GJ 3628B (number 1551 of the AIC) (Fig. 4.6) has been monitored for slightly more than 5 months, from 2013/1/22 to 2013/6/2 for a total of 37 nights, collecting 1328 useful data points. The star is classified as M3.5V according to the Palomar/MSU nearby star spectroscopic survey [[Reid et al., 1995](#), [Hawley et al., 1996](#)], while as M5V according to the tentative classification of [Lépine and Gaidos \[2011\]](#). For this star we propose $P = 6.5487847$ days as the candidate rotation period, as found by applying the CLEAN algorithm. The bootstrap analysis produced a $\text{FAP} = 0.0001$, which validates at the highest confidence level the found periodicity. The scatter of the residuals after the subtraction of a sinusoidal fit is sensibly reduced, but looking at the folded curve it can be noticed that the

²<https://koa.ipac.caltech.edu/cgi-bin/KOA/nph-KOAlgin>

points between phases 0.3-06 are not well fitted by a simple sinusoid. This could be the evidence of rapidly evolving starspots/active regions on the stellar photosphere, that changed the shape of the light curve during the timespan of the APACHE observations. The target GJ 4176A (number 2784 in the AIC) (Fig. 4.7) has been observed over a timespan longer than one year, from 2012/7/18 to 2013/8/5, for a total of 54 nights and 1696 useful photometric data. It is classified as M3V both by the Palomar/MSU survey and [Lépine and Gaidos \[2011\]](#). As for the case of the target APACHE 1041, it can be seen that the folded light curve of APACHE 2784 is not optimally sampled at the relatively long period of 25.836742 days found by the Lomb-Scargle algorithm, which then should be considered with care as a trustworthy rotation period, despite it has passed the pipeline checks. The bootstrap analysis resulted in a FAP=0.0001. The target I22006+2715 as named after [Lépine and Gaidos \[2011\]](#) (star number 2961 in the AIC), confirmed as M0V according the new spectroscopic catalog of bright M dwarfs of [Lépine et al. \[2013\]](#), is particularly interesting (Fig. 4.8). Its data showed quite clearly evidence for the existence of a short-period modulation through a visual inspection of the light curves produced on nightly basis by the TSE pipeline. This finding pushed me to process the data collected over the timespan (from 2013/6/15 to 2013/8/16, for a total of 18 nights and 440 useful data points) more quickly than for other stars, revealing the nature of fast-rotator for this target, with a rotation period of 0.524357 days found by the CLEAN algorithm and a folded light curve with a shape very close to a sinusoid. I have then applied a bootstrap analysis to asses the significance of this periodic signal, which resulted in a FAP=0.0001. This circumstance led us to promptly discard the star from further observations aimed at searching for transiting planets. Moreover, this star was selected for spectroscopic observations with the spectrograph HARPS-N within the GAPS programme (Chapter 5), but not yet observed when we identified it as a fast rotator. Following the finding in the APACHE data, it has been removed from the GAPS schedule because it could reveal a high level of jitter in the RV data, then making more difficult the detecting variations due to a small-mass planetary companion. Finally, the star I23513+2344 (as named after [Lépine and Gaidos \[2011\]](#), target number 3276 in the AIC) shows a clear rotational modulation with a period $P = 3.180986$ days, as determined by a L-S analysis (Fig. 4.9). This target, classified as M4V by [Riaz et al. \[2006\]](#), has been observed for 29 nights over a period of ~ 2 months (from 2012/8/26 to 2012/10/24), collecting a total of 1682 useful data points. The bootstrap analysis resulted in a $FAP < 10^{-4}$ for this period. Even if a sinusoidal fit well represents the global variation of the star flux, it can be noticed (as for the star APACHE 1551) that the residuals of the sine fit show an irregular pattern (despite their scatter is nearly half of the original

light curve. Even in this circumstance, this fact can be explained by the presence of one or more starspots/active regions rapidly changing their characteristics.

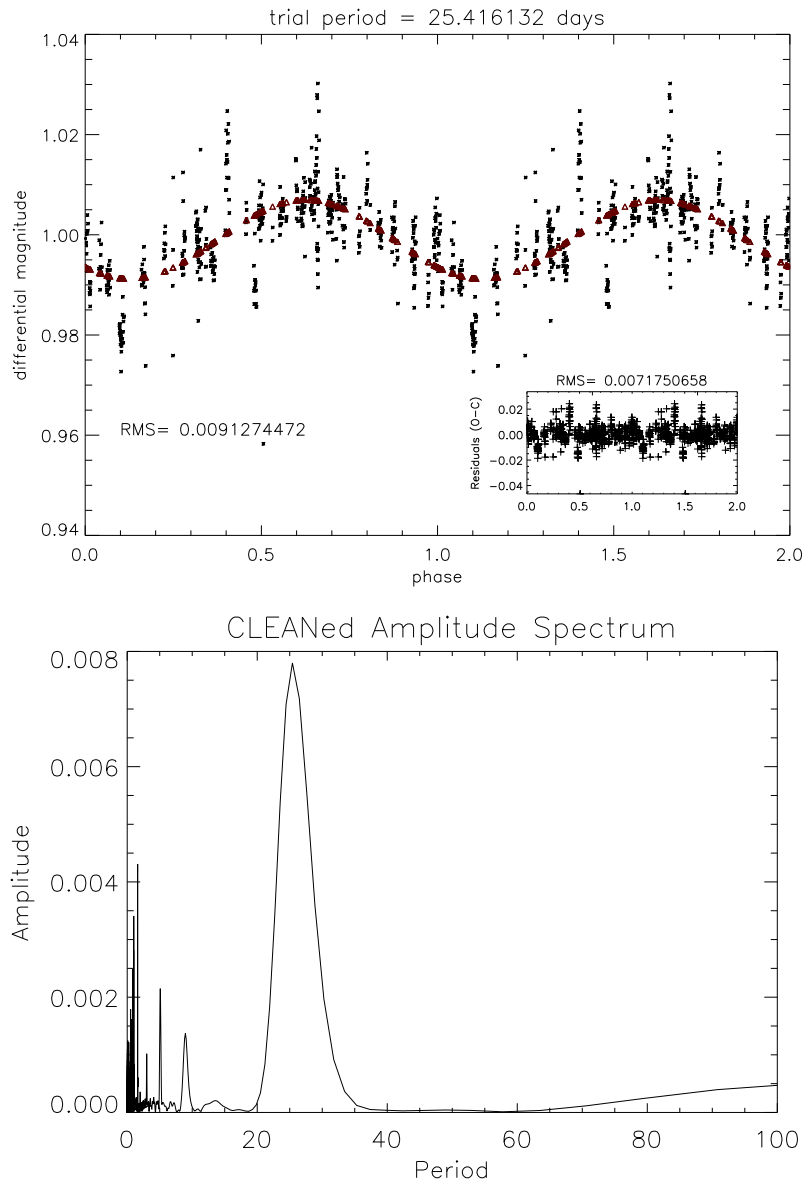


FIGURE 4.5: *Top.* Light curve of the star APACHE 1041 folded according the best period found that can be interpreted as the rotational period of the star around its axis. Superposed (red points) is the best-fit sinusoidal curve with the same periodicity. The residuals after the removal of the sinusoidal fit are shown in the nested, small plot. *Bottom.* CLEAN periodogram of the APACHE 1041 photometric data (periods are expressed in days), showing the dominant peak at $P \sim 25$ days.

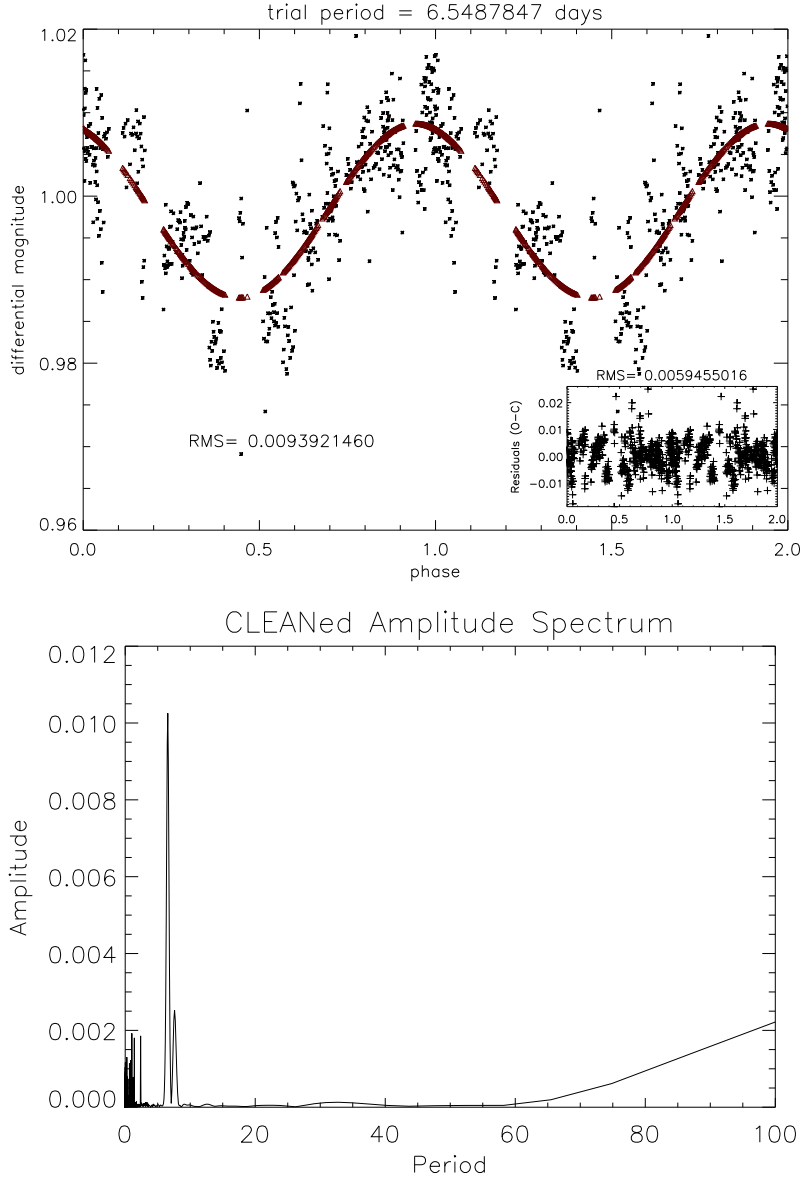


FIGURE 4.6: *Top.* Light curve of the star APACHE 1551 folded according the best period found that can be interpreted as the rotational period of the star around its axis. Superposed (red points) is the best-fit sinusoidal curve with the same periodicity. The residuals after the removal of the sinusoidal fit are shown in the nested, small plot. *Bottom.* CLEAN periodogram of the APACHE 1551 data (periods are expressed in days), showing the dominant peak at $P \sim 6.5$ days.

4.5 Single-spot modelling of rotational light curves

In the paper describing the pilot study [Giacobbe et al., 2012] we discuss a simple model that we have developed for fitting the light curve of a star which shows evidence for rotation, by assuming that the observed sinusoidal-like modulation is due to a single dark spot on the stellar surface. The features (and limitations) of the

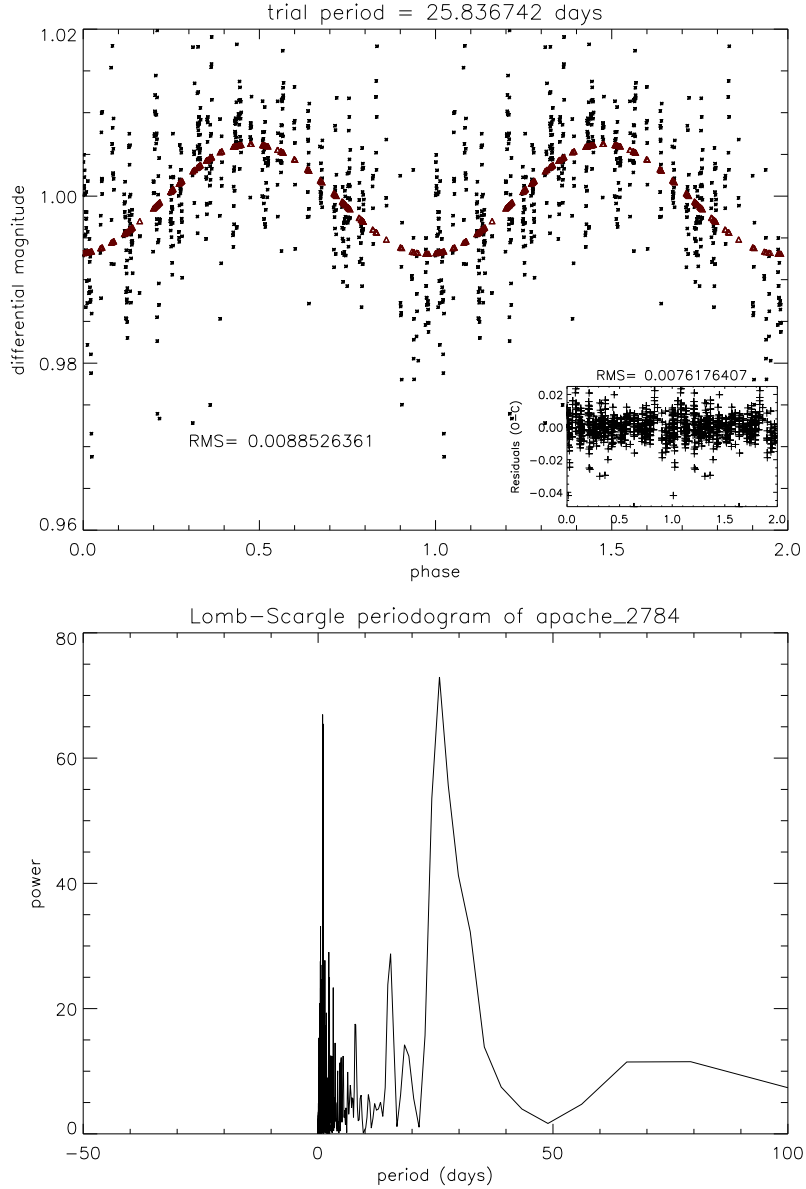


FIGURE 4.7: *Top.* Light curve of the star APACHE 2784 folded according the best period found that can be interpreted as the rotational period of the star around its axis. Superposed (red points) is the best-fit sinusoidal curve with the same periodicity. The residuals after the removal of the sinusoidal fit are shown in the nested, small plot. *Bottom.* Lomb-Scargle periodogram of the APACHE 2784 data, showing the dominant peak at $P \sim 25.8$ days.

model are described in §4.3 of [Giacobbe et al. \[2012\]](#) and I will not repeat them here. I just recall that the free parameters of the model are the inclination angle of the rotation axis i , the spot latitude b , the initial longitude l_0 , and the scalar $f_s r^2$ which, combining the spot contrast f_s with its surface area, as defined by the spot radius r relative to the stellar radius, quantifies the dimming in the light intensity due to the transit of the star spot in front of the observer. Fig. 4.10 shows the folded light

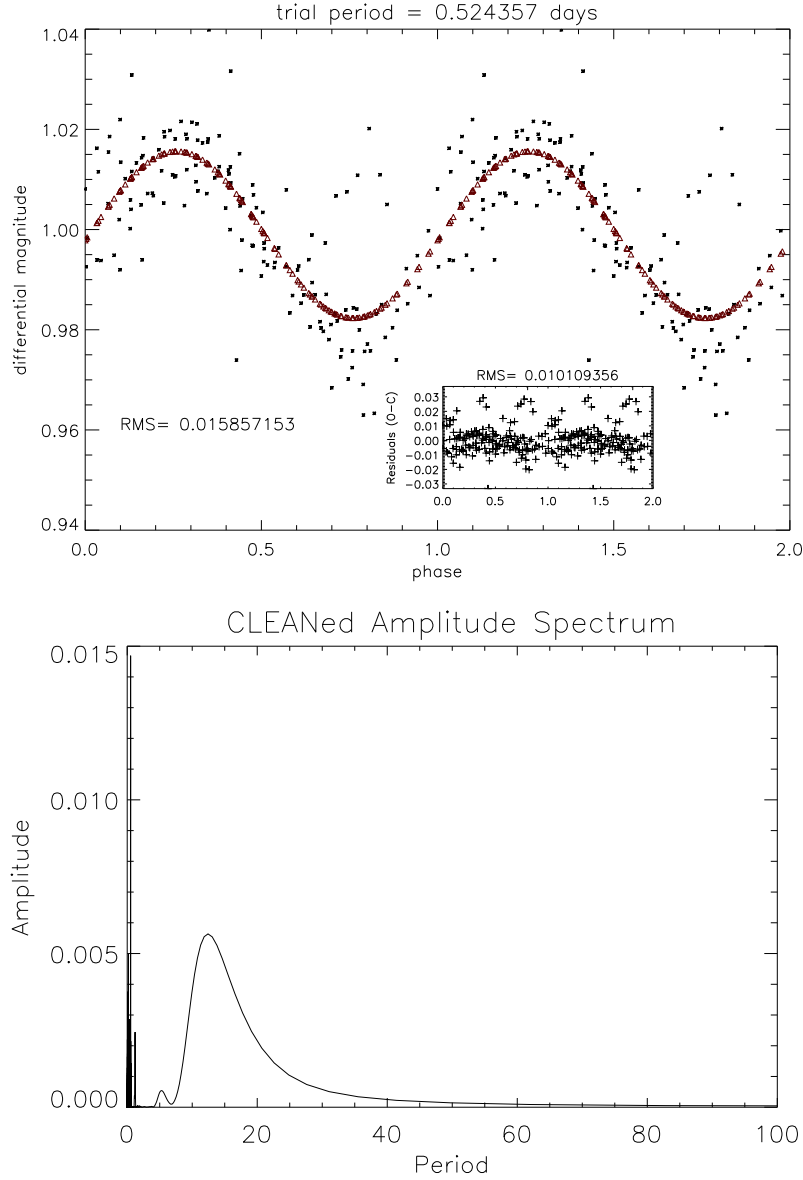


FIGURE 4.8: *Top.* Light curve of the star APACHE 2961 folded according the best period found that can be interpreted as the rotational period of the star around its axis. Superposed (red points) is the best-fit sinusoidal curve with the same periodicity. The residuals after the removal of the sinusoidal fit are shown in the nested, small plot. *Bottom.* CLEAN periodogram of the APACHE 2961 data (periods are expressed in days), showing the dominant peak at $P \sim 0.52$ days.

curves of the five M dwarfs discussed in §4.3 with the result of the single-spot model superposed, while in Tab. 4.4 the best results of the curve-fitting are summarized. The model requires as inputs the effective temperature and radius of the star, which we have estimated as discussed in §3.3. It can be noticed that the model predicts rotation axis which are almost aligned with the star-observer reference line. As stated in §4.4, unfortunately we have not found in public archives spectra for these

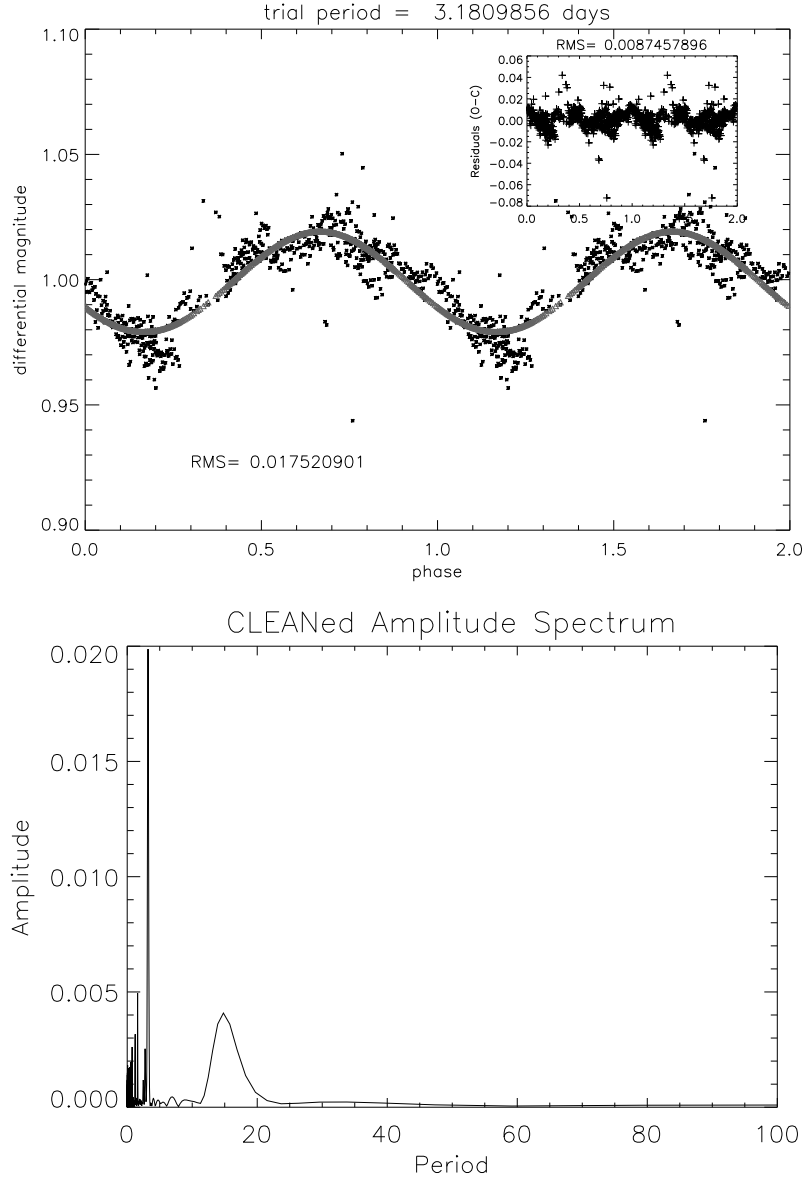


FIGURE 4.9: *Top.* Light curve of the star APACHE 3276 folded according the best period found that can be interpreted as the rotational period of the star around its axis. Superposed (grey points) is the best-fit sinusoidal curve with the same periodicity. The residuals after the removal of the sinusoidal function are shown in the nested, small plot. *Bottom.* CLEAN periodogram of the APACHE 3276 data (periods are expressed in days), showing the dominant peak at $P \sim 3.18$ days.

stars, as we did for the two M dwarfs LHS 3445 and GJ 1167A discussed in [Giacobbe et al. \[2012\]](#) by using data from the Keck/HIRES spectrograph. This has prevented us from combining the photometric rotation periods and the stellar radius estimates with the projected velocities $v \sin i$ measured via spectroscopy to derive independent measurements for the spin-axis inclination angles which can be compared with those obtained with the single-spot model. In the lucky cases of LHS 3445 and GJ 1167A

we found a very good agreement between photometry and spectroscopy estimates, which indicates that the model is able to produce reliable results. In conclusion, the application of our single-spot model to the light curves of the five rotating APACHE M dwarfs must be considered only as an exercise, but also as a robust base for future developments.

TABLE 4.4: Results of a single-spot model applied to the rotational light curves of the five M dwarfs discussed in §4.4 for which we estimated the rotation periods from photometry.

Name	Effective temperature (K)	Radius ($R_{\odot}$)	Axis incl. angle (Degrees)	Spot latitude (Degrees)	$f_s r^2$
apache 1041	3426	0.49	0.10	20	0.19
apache 1551	3070	0.34	0.07	17	0.5
apache 2784	3450	0.50	0.5	44	0.04
apache 2961	3802	0.61	0.13	11	1.6
apache 3276	2982	0.30	0.06	14	1.0

4.6 Stellar flares

Considering the time sampling we have chosen when we have first defined the survey observing strategy (i.e. the same target is re-pointed every ~ 20 minutes), it was not clear a-priori if APACHE could be suited for detecting stellar flares, which usually have decay times of few minutes, as it happened during the pilot study, when the small sample of M dwarfs was monitored with a much shorter time-sampling [Giacobbe et al., 2012]. After the first season, we were able to detect stellar flares for 3 different targets by analysing in real-time the light curves obtained by the TSE pipeline. The stars involved are GJ 3143 (APACHE 331), an M3.5V star according to the Palomar/MSU survey, I09108+3127 (APACHE 1427), an M4V star according to Lépine and Gaidos [2011], and GJ 4196 (APACHE 2864), that Lépine et al. [2013] classify as an M1.5V, in agreement with the Palomar/MSU classification as M1V. The photometric time-series displaying the sudden increase in the stellar luminosity typical of a flare are showed in Fig. 4.11. Each plot refers to a single night, as explained in the figure caption, and each data point in the light curve (represented by the black '+' symbols) is the average of three consecutive exposures. We did not detect more than one flare episode for each star. I have characterized each event following the approach of Hartman et al. [2011], that is, by solving a non-linear least-squares problem with a set of consecutive photometric

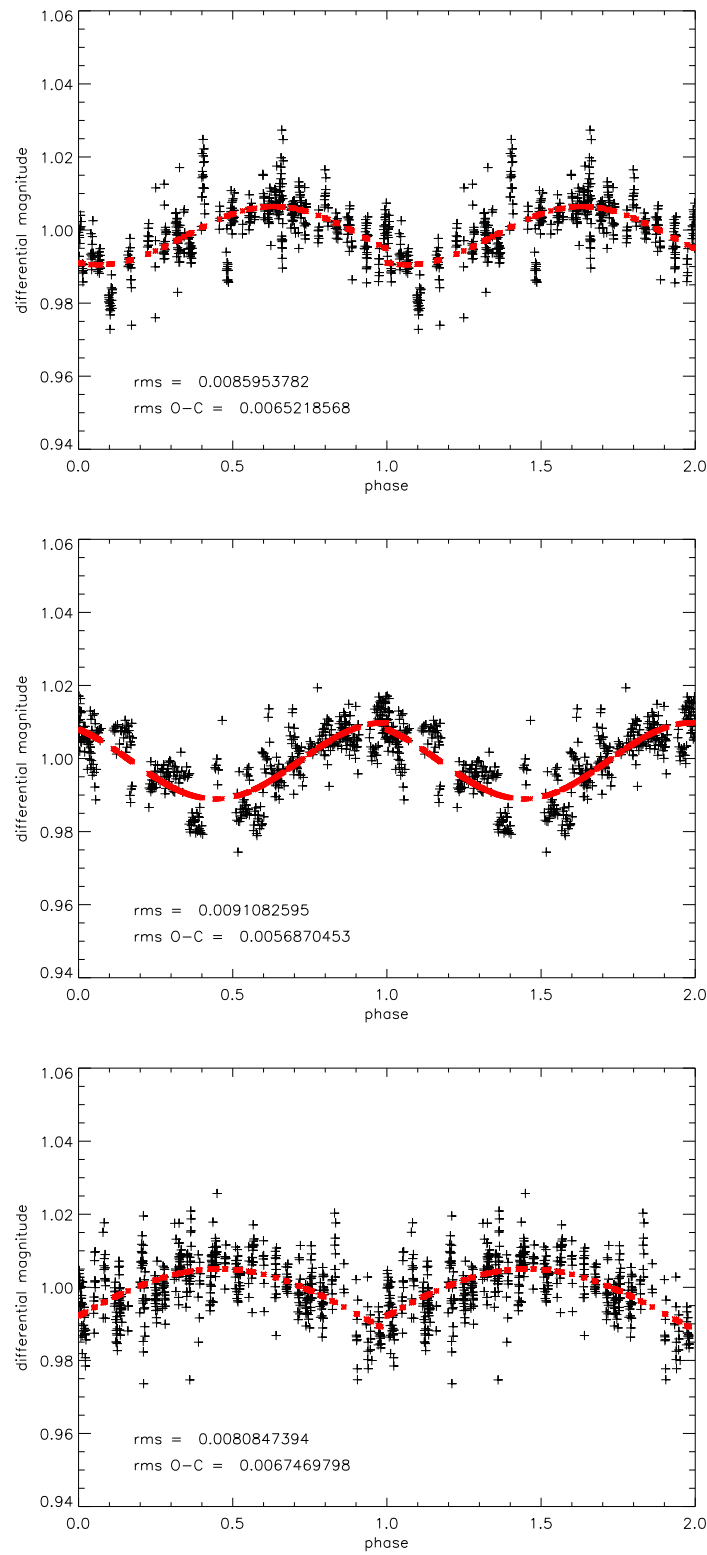
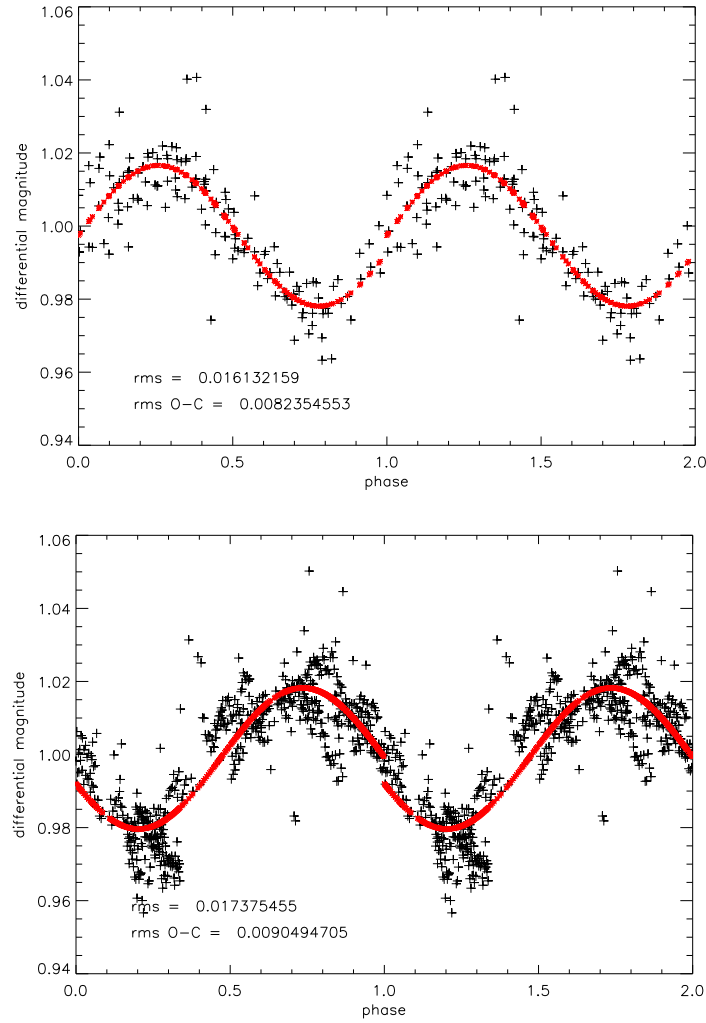


FIGURE 4.10: Light curves of the five M dwarfs discussed in §4.4, folded according to the best rotation periods. Superposed to each plot (red points) is the best-fit light curve predicted by our single-spot model. The RMS of the observed light curve and that of the residuals O-C are indicated. The plots refer to the following targets (from up to bottom): apache 1041, apache 1551, apache 2784, apache 2961, and apache 3276.

FIGURE 4.10: *continued*

measurements starting from the time of recorded maximum brightness t_0 and an exponential model function of the type:

$$\text{mag}(t) = A \times \exp[-(t-t_0)/\tau] + \text{mag}_0 \quad (4.4)$$

with adjustable parameters A , the peak magnitude of the flare relative to the non-flaring magnitude, τ , the decay time-scale, and mag_0 , the differential magnitude of the star before the flare. The least-squares solution was obtained using the IDL code `curvefit`, which is an implementation of the Levenberg–Marquardt method [Marquardt], by looking for the best-fit function of the type $f(x) = A \times \exp(B \times x) + C$, where $x = t - t_0$, after providing guesses for the model parameters A equal to the peak magnitude, B in the range $50\text{--}85 \text{ days}^{-1}$, and mag_0 equal to the average differential magnitude of the post-flare event. The best-fit solutions are overplotted in each panel of Fig. 4.11. The flare events are characterized by decay times which fall in

the range 17-26 minutes, comparable to the average repointing time interval of the APACHE telescopes. APACHE 2864 appears also in the target list of the GAPS programme (Chapter 5), and the information about its activity levels has been considered by the GAPS responsables for a possible exclusion of the target from further spectroscopic investigations. This star was reported to have the H-alpha spectral line in absorption [Gizis et al., 2002], with an average equivalent line width of -0.0361 nm, but it is also classified as a variable of BY Draconis-type by the AAVSO International Variable Star Index VSX. BY Draconis-type variables, as stated in the VSX document describing the variable star type designations, *'are emission-line dwarfs of dKe-dMe spectral type showing quasi-periodic light changes with periods from a fraction of a day to 120 days and amplitudes from several hundredths to 0.5 mag in V. The light variability is caused by axial rotation of a star with a variable degree of non-uniformity of the surface brightness (spots) and chromospheric activity. Some of these stars also show flares similar to those of UV Cet stars, and in those cases they also belong to the latter type and are simultaneously considered eruptive variables'*. Our finding supports the latter classification. For APACHE 2864 we have analysed 1254 useful data collected in 36 nights and over a period of 3 months, without revealing any detectable periodical light changes.

4.7 New variable stars

APACHE is a targeted search, with the main goals of detecting transiting planets around selected M dwarfs and characterizing their variability by collecting hundreds of photometric data points over a typical timespan of several months. Nonetheless, I have always considered very interesting the opportunity of analysing the data of the other stars appearing in the fields of the APACHE red dwarfs, to search for transit-like signals with the BLS algorithm and for interesting variability in their light curves. As described in Chapter 2, I have built the pipelines TSE and TEEPEE so that they can produce automatically the light curves of all the stars detected in the field of view of each APACHE target. By visually inspecting all those photometric time-series for all the APACHE fields that I have analysed during the first season, I have detected several stars which show a clear variability type and I have decided to provide a first characterization of their nature. I need to recall here that the differential light curves of the field stars are obtained by using the same aperture radius and set of comparison stars determined for the target M dwarfs. This is necessary to save computational time, and it means that in general the light curves are not the optimal that can be obtained by selecting that aperture radius and set of reference stars which minimizes the scatter in the star flux. Anyway, because the typical variables I have considered show variations of the order some hundredth of magnitudes and several are much fainter than the target M dwarfs, the comparison stars used for calculating their light curves can be considered a good choice. When detecting a variable star, the first step I take is examining the AAVSO International Variable Star Index Web site³ to check if the variability has been already noticed by someone. For opportunity reasons, I have limited my analysis only to new variable stars, never detected before. Nonetheless, in perspective the APACHE photometric database represents an important source of new, fresh data for those variables already listed in VSX, many of them have been observed for the last time several time ago. However, I have performed a fast analysis of some variable stars already classified with the purpose of testing the reliability of the results of the pipeline, for instance by determining the periods of EW eclipsing variables or RR Lyrae and matching the results with those published. I have always found a very good agreement.

By analyzing the data of the first observing season I have detected more than 80 new variable stars. I have presented and discussed these results on a dedicated paper accepted for publication by the Journal of the American Association of Variable Star Observers [Damasso et al., 2014]. The manuscript of this work is attached at

³<http://www.aavso.org/vsx/>

the end of this Chapter and forms an integral part of the Thesis. While all these new variable stars have just received the formal approval of the AAVSO, there are 9 more variables (not listed in [Damasso et al. \[2014\]](#)) that I have previously analysed in the course of the first season and submitted to the AAVSO. These stars, reported in Tab. 4.5, have been already approved and published online in the VSX database. A sample of their light curves is shown in Fig. 4.12. For the star GSC 02408-01639 and 2MASS J06293956+2815089 I have made use of the SuperWASP Public Archive to improve the estimate of the periods.

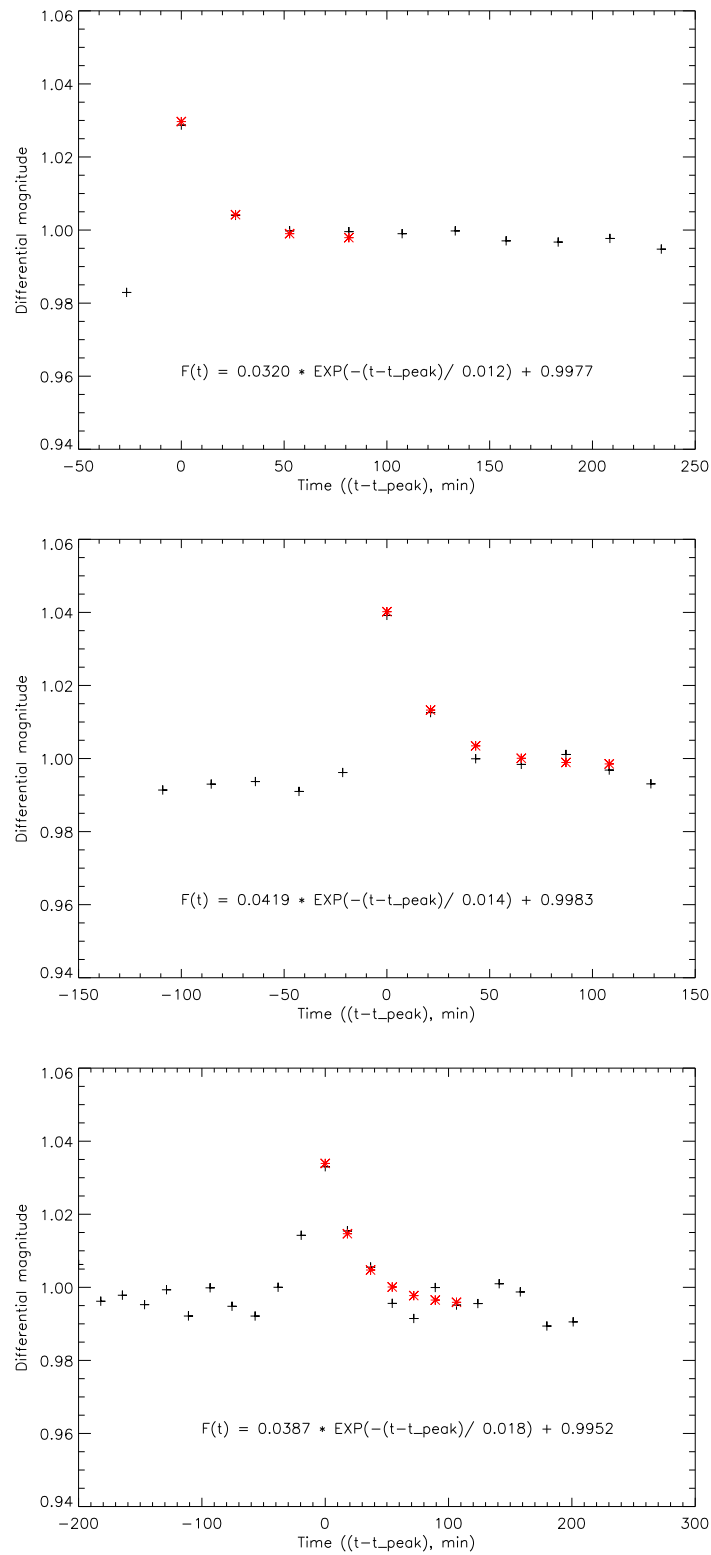


FIGURE 4.11: The three panels show the light curves obtained by using the TSE pipeline for the APACHE targets 331, 1427 and 2864 (from top to bottom, black '+' symbols), observed on the nights 2013/09/13, 2013/04/13 and 2013/07/29 respectively. There are clearly visible impulsive, flaring events detected in the course of the night. Red '*' symbols represent the best-fit solution after applying a flare-model (see text for details), with the resulting best-fit function overplotted.

TABLE 4.5: Variable stars discovered by APACHE during the first observing season, approved by AAVSO and published in the VSX database. The light curves of a sample of these stars are showed in Fig. [4.12](#)

Name	RA (J2000)	DEC (J2000)	Period (days)	Variability type
GSC 02275-00631	10.05815	+31.49170	0.2566	EW
GSC 02408-01639	83.32646	+33.69931	0.0966847	DSCT
2MASS J06293547+2830035	97.39783	+28.50100	0.308	EW
2MASS J06293956+2815089	97.41479	+28.25247	0.36910	EW
CzeV188	297.37458	+31.67761	0.247396	EW
VSX J194934.6+314713	297.39442	+31.78697	0.523	EA
VSX J211426.3+254237	318.60979	+25.71033	0.33706	EW
VSX J214004.5+273835	325.01875	+27.64306	0.289	EW
GSC 04463-01592	331.17146	+67.63944	0.642	EB

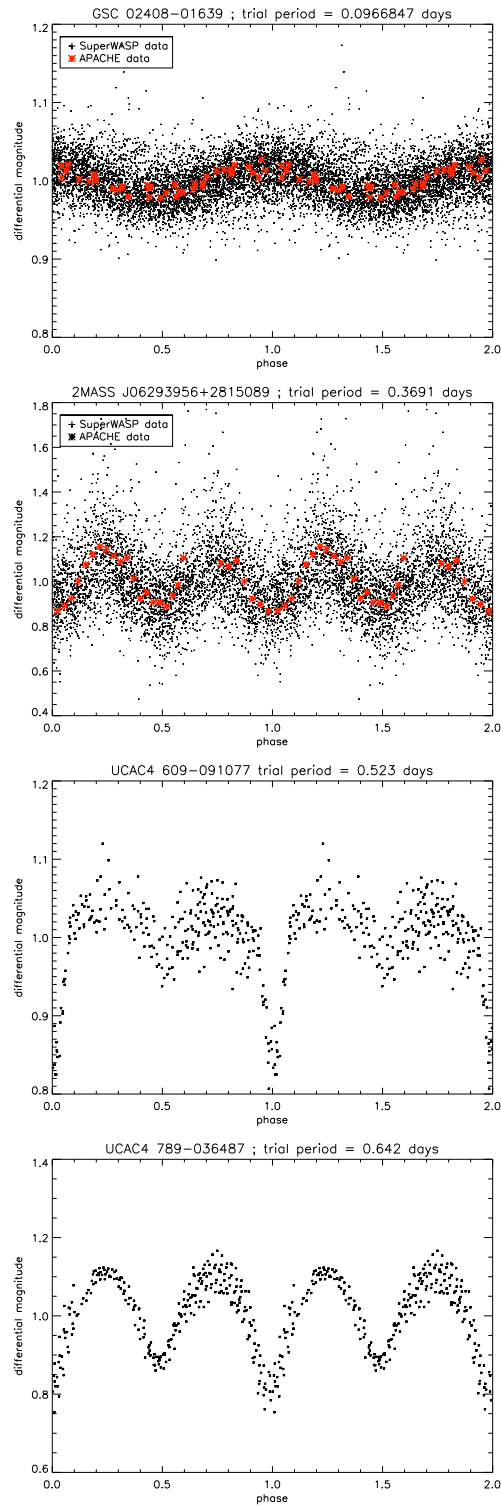


FIGURE 4.12: Sample of light curves of variable stars discovered by APACHE, already approved by the AAVSO and inserted in the on-line VSX database. For GSC 02408-01639 and 2MASS J06293956+2815089 also the data points from the SuperWASP Public Archive are plotted. They have been used to improve the determination of the periods.

New variable stars discovered by the APACHE survey. I. Results after the first observing season

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ABSTRACT

We present more than 80 new variable stars discovered during the first observing season of the APACHE survey. APACHE is a project aimed at detecting extrasolar planets transiting nearby, bright M dwarfs by using an array of small-aperture telescopes. Despite the survey is targeted to a well defined sample of cool stars, we reduce and analyze data also for all the detected field stars. Since July 2012 dozens of different stellar fields have been monitored, leading to the detection of several variables for which we propose a classification and estimate a period, when a periodicity is evident in the data. Thanks to the SuperWASP public archive, we have also retrieved and analyzed photometric data collected by the SWASP survey, which helped us to refine the classification and the period estimation of many variables found in the APACHE database. Some of the variables present peculiarities and thus are discussed separately.

1. Introduction

Since July 2012, at the Astronomical Observatory of the Autonomous Region of the Aosta Valley (OAVdA), located in the Western Italian Alps, is ongoing the project APACHE (A PATHway to the Characterization of Habitable Earths), a new ground-based photometric survey specifically designed to search for transiting, small-size planets orbiting bright, nearby early- to mid-M dwarfs (Sozzetti et al. 2013). APACHE¹ is a collaboration between OAVdA and INAF-Osservatorio Astrofisico di Torino (INAF-OATo), and it will last for five years. The survey utilizes an array of five, automated 40-cm telescopes to monitor hundreds of M dwarfs properly selected from the catalogue of Lèpine & Gaidos

¹<http://apacheproject.altervista.org>

(2011). In parallel with the search for transit-like signals in the light curves of the M dwarfs, we are also analyzing the photometric data of the huge sample of stars that fall in the fields of view of the telescopes, which are centered on the target cool stars, to look for new variable stars. Here we report a list of variables discovered during the first observing season of APACHE. As demonstrated after the first year of operation, the large photometric database collected by APACHE represents a treasure trove for identifying new variable stars which will be constantly scoured.

2. Instruments and methods

The APACHE survey uses an array composed of identical Carbon Truss 40-cm f/8.4 Ritchey-Chrétien telescopes, each with a GM2000 10-MICRON german mount and equipped with a FLI Proline PL1001E-2 CCD Camera and Johnson-Cousins V, R and I filters. This instrument configuration is characterized by a pixel scale of 1.5 arcsec/pixel and a field of view of 26'x26'. Except for a small number of targets which are monitored in V band, all the fields are observed using the I_c filter. The complete catalogue of M dwarfs eligible for observations by the APACHE survey is composed of 3323 targets and has been organized in a ranking list by assigning observing priorities which take into account several factors: for example, the highest priority is given to stars with a reliable spectral classification published in literature; to those that are known to be slow rotators, based on measurements of their projected rotational velocity $v \sin i$; whether they have a low chromospheric activity as measured by the equivalent width of the H_α line and are not known as bright X-ray sources. A slow rotator and a star with a low activity level has to be preferred because, for the spectroscopic follow-up required to measure the mass of a transiting planetary candidate, the measurements of the radial velocity variations are less affected by the line broadening and the intrinsic jitter due to stellar activity. It is interesting

also to mention another parameter considered for the definition of the ranking list. It is the expected number of observations of each target guaranteed by the Gaia satellite, which has been successfully launched and is expected to provide a very relevant contribution to the extrasolar science. According to the scanning law of Gaia, it is possible to calculate the number of expected transits over a certain field after the nominal 5 years of mission. When building the APACHE schedule, we have assumed that targets with a number of Gaia observations greater than 100 have higher priorities because they will be characterized by a very accurate measurements of trigonometric parallax, from which it will be possible to accurately determine fundamental stellar parameters as the intrinsic luminosity, mass and radius, which are necessary for a precise study of any hosted planet.

The APACHE observations are carried out in focus and the exposure times, which are kept fixed during the sessions independently from the seeing, are in the range $3\div180$ seconds, while the magnitudes of the target M dwarfs vary within $8\div16.5$ in V-band and $5.5\div13$ in J-band. The APACHE telescopes use a circular observing schedule, with each target being re-pointed typically ~ 20 minutes after the last observation. This cadence should be optimal for collecting enough data points which fall in the portion of the light curve showing a transit, if it is in progress, that usually is expected to last for $1\div3$ hours. Each time a target is pointed, three consecutive exposures are taken and usually the average value of the corresponding differential magnitudes is used for light curve analysis. In the course of a night the same field is observed as long as its altitude above the horizon is greater than 30 degrees, while it remains in schedule for typically 60 to 90 days in a row.

After the first observing season nearly 150 different stellar fields have been observed, necessarily characterized by a not uniform number of data. We have searched for new variable stars especially considering those fields with the major number of photometric data. For each field we have visually inspected the differential light curves of all the stars

identified, which typically amount to some dozens but in some cases are more than one thousand per field, and processed by the data reduction and analysis pipeline TEEPEE (Transiting Exoplanet Pipeline), developed by the authors mostly in IDL programming language and tailored specifically to provide the user with optimal light curves of the primary target M dwarfs. The TEEPEE package, indifferently applied to data collected during a single night or over the whole timespan of observations, tests up to 12 different apertures and the best set of comparison stars is automatically determined from a list of dozens among the brightest objects in the field, excluding those too close to the CCD borders. The best aperture and set of reference stars selected at the end of the data processing are the ones which give the smallest RMS for the entire light curve of the object of interest. To save CPU time, this procedure is applied once with regard only to the primary M dwarf targets. Thus the aperture and set of comparisons used for determining the differential light curves of the field stars are those selected for the M dwarfs, which usually represent a good choice. Because, as stated, the number of comparison stars is typically high for each field (more than 10 in several cases), we do not provide the complete list for each variable we discuss here. At our site the seeing conditions can vary sensibly from night to night, and typical values for the FWHM of the APACHE images range within $1.5\div 3$ pixels, and the TEEPEE pipeline tests aperture radii in the range $3.5\div 9$ pixels.

3. Results

The aim of this work is providing a list of new variable stars for which we propose tentative classification and, for those showing evidence of periodicity, we produce an estimate of the period. Our conclusions originate only from photometry, and no spectroscopic follow-up has been carried out to improve our knowledge about these objects. For some stars, we considered interesting to provide a detailed, separate discussion (§4). The complete

list of 86 variables discussed in this work is presented in Tab. 1. All of them have been searched in the AAVSO VSX database and 83 can be considered as new genuine discoveries. Three objects are already included in the VSX database. One eclipsing binary system is provided without any information about the orbital period, which we have estimated from our data. Another object is classified in VSX as an eclipsing variable without any information about the orbital period, but our data do not confirm this classification, rather the star appears to be an irregular variable of type L. A variable of L type, as read in the VSX database, is reported with a period of 88 days, but this value is not confirmed by our data. In Fig. 1 we show the corresponding light curves, with those showing periodicity folded according to the best period found through a Lomb-Scargle (L-S) analysis applied to the APACHE data, except in very few cases (as explained below). For this task we used the IDL version of the L-S algorithm². Almost every APACHE light curve presented here has been obtained using the I_c filter, except where specified in the explanatory notes accompanying Table 1. The magnitudes in V band, where not otherwise specified, are those from the APASS survey, which are reported by the UCAC4 catalogue. Several stars appear as having no evidence of periodicity, or with a very poorly defined periodicity which shows only occasionally. Due to this circumstance, we propose these stars to be classified as a variable of L type. The remainder of our list is composed of periodic variables, mostly eclipsing binary systems and some pulsators, with a classification not always clear. To improve the period estimation and to provide a less ambiguous classification where required, we used the SuperWASP public archive -a precious treasure trove now hosted by the NASA Exoplanet Archive³- to recover the light curves of our stars. Nearly 25% of the stars in our sample has thousands of useful SWASP photometric data points that can complement

²<http://www.arm.ac.uk/~csj/idl/PRIMITIVE/scargle.pro>

³<http://exoplanetarchive.ipac.caltech.edu/index.html>

the APACHE dataset with high profit. We performed a L-S analysis to the data from the SWASP survey, specifically using the magnitudes de-trended with the SysRem algorithm (Tamuz et al. 2005). In Tab. 1 we report out of parenthesis the best period found from the SWASP data (when available) which usually, because the timespan and number of data are greater, can be indicated with a number of significant digits higher than for the period derived from APACHE time series (reported in parenthesis). In few cases, we only report the period found from SWASP data, which has been used to obtain the plot in Fig. 1. The position of the last significant decimal digit, both for SWASP and APACHE data, is determined in the following way. We start by folding the light curve using the best period found by the L-S algorithm. Then, by removing the last decimal digit, we fold the data with this truncated period and, by visual inspection, we look at any change in the new phased light curve. If no change is evident, this means that the removed digit is not significant, and we reiterate the process by removing the second to last digit, and so on. When a change in the folded light curve is seen, this means that the removed digit is significant and the process comes to an end.

3.1. Discussion on individual variables

A small subset of variables deserves a closer investigation. The star UCAC4 872-000839 (the first, not numbered object in Tab. 1), showed in the APACHE photometry and on nightly basis a variability similar to that of a pulsating star that we could not characterize with a well-definite period. In Fig. 4 are showed a sample of APACHE light curves of this star collected during single nights. Unfortunately this star is not present in the SWASP archive.

The quite faint star UCAC4 624-036803 (#13 in Tab. 1) appears as an eclipsing binary system already in the APACHE data, and we obtained the best estimate for the orbital

period $P=0.21635$ days from SWASP data. This value is just below the lower limit of ~ 0.22 days for such systems discussed in Norton et al. (2011). This circumstance makes that star an interesting object for follow-up studies, as we have done for a similar variable (Damasso et al. 2012). The highest peak in the L-S periodogram of SWASP data is $P=0.108176$ days, which we have doubled to get the most reliable periodicity. The folded SWASP light curve and the corresponding L-S periodogram in the region of interest are showed in Fig. 3, while data from the APACHE survey are showed in Fig. 1, folded according to the best period found from SWASP photometry.

In the first plot of Fig. 5 data for six nights are showed for the star UCAC4 664-056989 (#15 in Tab. 1). It has been observed by APACHE only for few epochs, and it was not possible to determine a reliable periodicity. By looking at the single-night light curves it can be guessed that the star should be an RR Lyrae-type variable, but a clear classification is not possible. Luckily, this star has been observed by SWASP (id. 1SWASPJ115757.51+423945.5), and we could then propose quite safely a classification as an RRab variable by looking at the light curve characteristics.

The star UCAC4 729-060138 (#35 in Tab. 1) has index color $B-V \simeq 1.0$ according to the APASS photometry, and the dust reddening in the star direction is estimated to be $E(B-V)=0.1$ (Schlafly et al. 2011), thus suggesting that, assuming that the star is a dwarf, it should be a late G to early K type. We propose that this variable should be classified as a rotator. Folding the APACHE data with the best period found (0.688 days) results in a light curve quite scattered in correspondence of the maximum, maybe indicating a change in the amplitude that could be attributed to evolving active regions on the stellar surface. This star is also present in the SWASP database and a L-S analysis resulted in the best period of 0.6902 days. The corresponding folded light curve is showed in Fig 7. The curve from SWASP does not show the kind of amplitude scatter present in the APACHE data.

The star UCAC4 744-062741 (second not numbered object in Tab. 1) shows a clear (and with a complicate pattern) variability for which it was not possible to classify from APACHE photometry alone (first plot in Fig. 6). The number of our data is not sufficient to clearly understand whether this is an eclipsing binary system or, generally speaking, a pulsating variable. The analysis of the SWASP light curve results in the most probable period $P=1.5174$ days, both according to L-S and BLS algorithm (Kovács et al. 2002), and we show the folded data in the second panel of Fig. 6. The analysis of the APACHE data, less numerous than those of SWASP, with the L-S algorithm reveals that the greatest power in the periodogram occurs at $P=1.51$ days (third plot of Fig. 6). Although the shape of both the folded light curves does not allow an immediate explanation, the fact that in effect the same periodicity is obtained from both the dataset would lean towards the interpretation as a modulation due active regions/spots on the stellar surface, and the period of ~ 1.5 days should be considered as the rotation period of the star. Under this hypothesis, the light curve from APACHE, although less sampled, shows less scatter than that from SWASP, and can be useful for observing the details of the flux variations due to features on the stellar atmosphere.

The last object we discuss here is the star UCAC4 588-128603 (#73 in Tab. 1). This star is also included in the SWASP archive. The period analysis of both APACHE and SWASP data results in similar results, but with different significance. We show in Tab. 2 the first significative periods found by the L-S algorithm applied to the two datasets, in order of their significance. While in Fig. 1 we show the APACHE data folded according to the period $P=1.29$ days (which is the fourth in order of significance found in the SWASP data), in Fig. 8 (2nd and 4th plots) we show the APACHE data folded according to the first and second significant periods estimated from the SWASP data, which could be more reliable due to the high number of SWASP data points. The 1st and 3rd panels in Fig. 8 are the corresponding folded light curves of SWASP. It can be seen that both these APACHE

light curves show an interesting modulation that can be related to a particular variability type. In the first case, we should be possibly looking at a rotating star, while if the real period is ~ 0.8 days this would lean towards a pulsating star (RRc type?). In absence of other information, a definitive conclusion can not be drawn.

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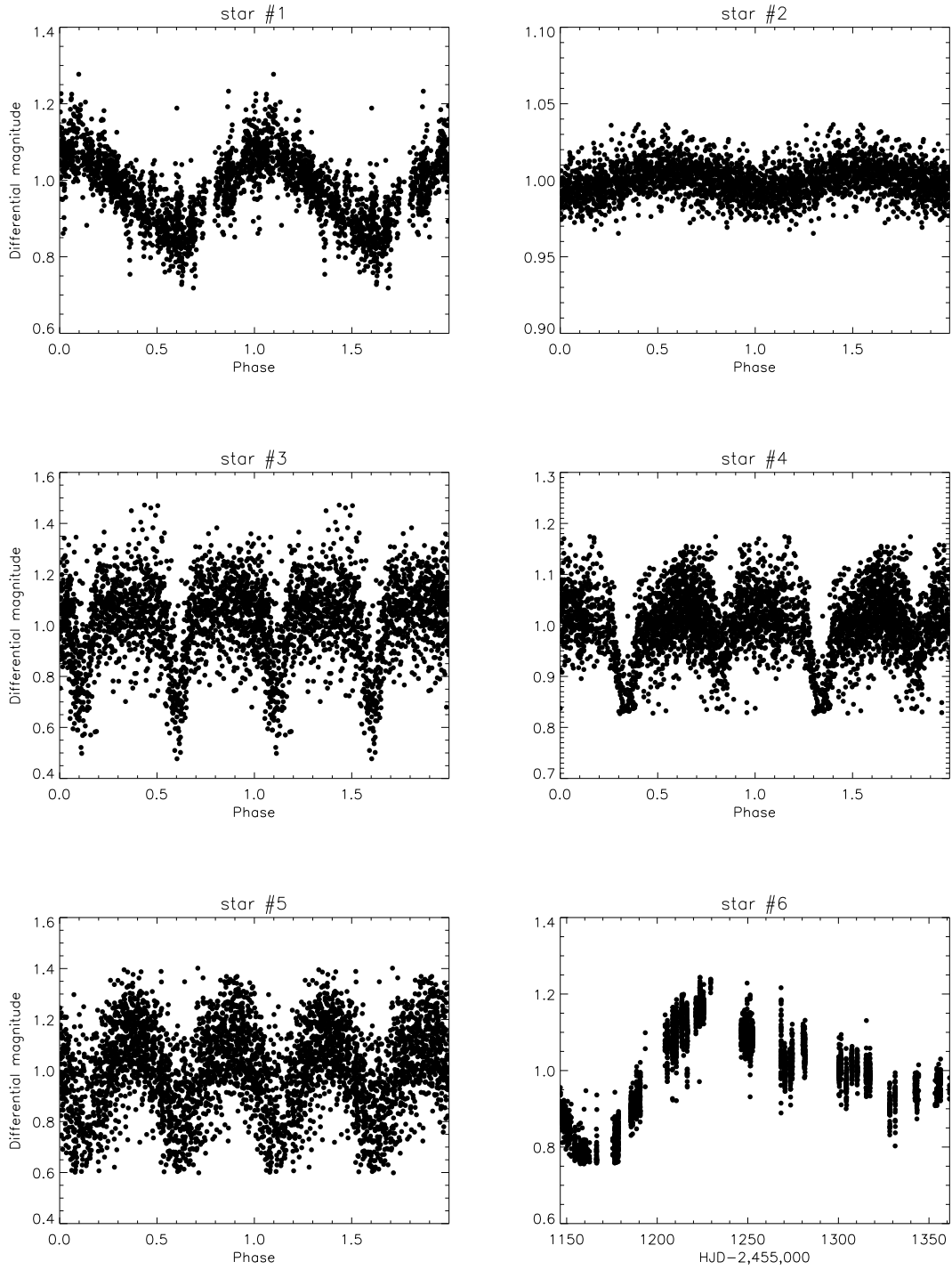


Fig. 1.—: Light curves of the new variables in Tab. 1. They were found during the first observing season of the APACHE survey.

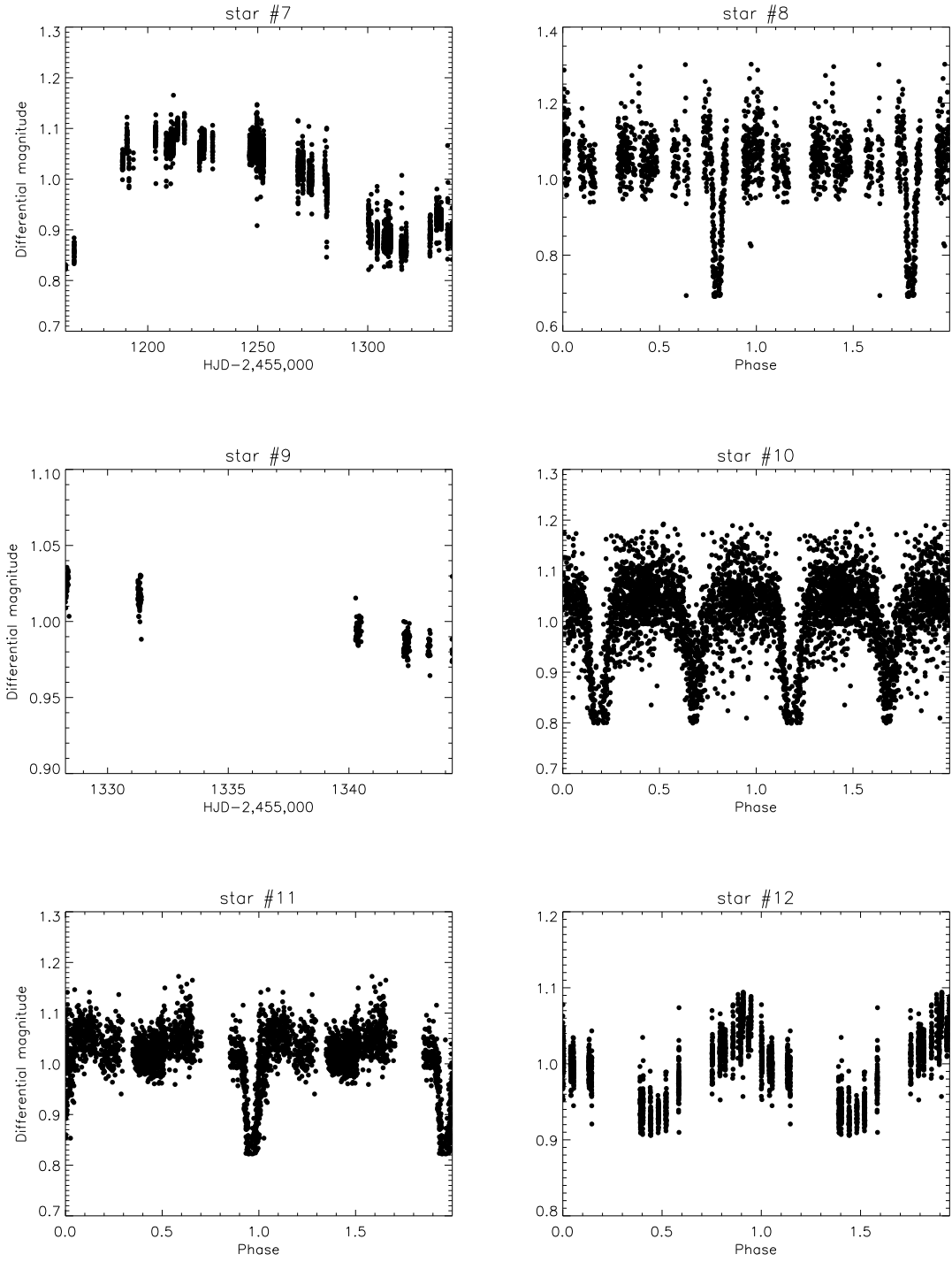


Fig. 1.—: *continued*

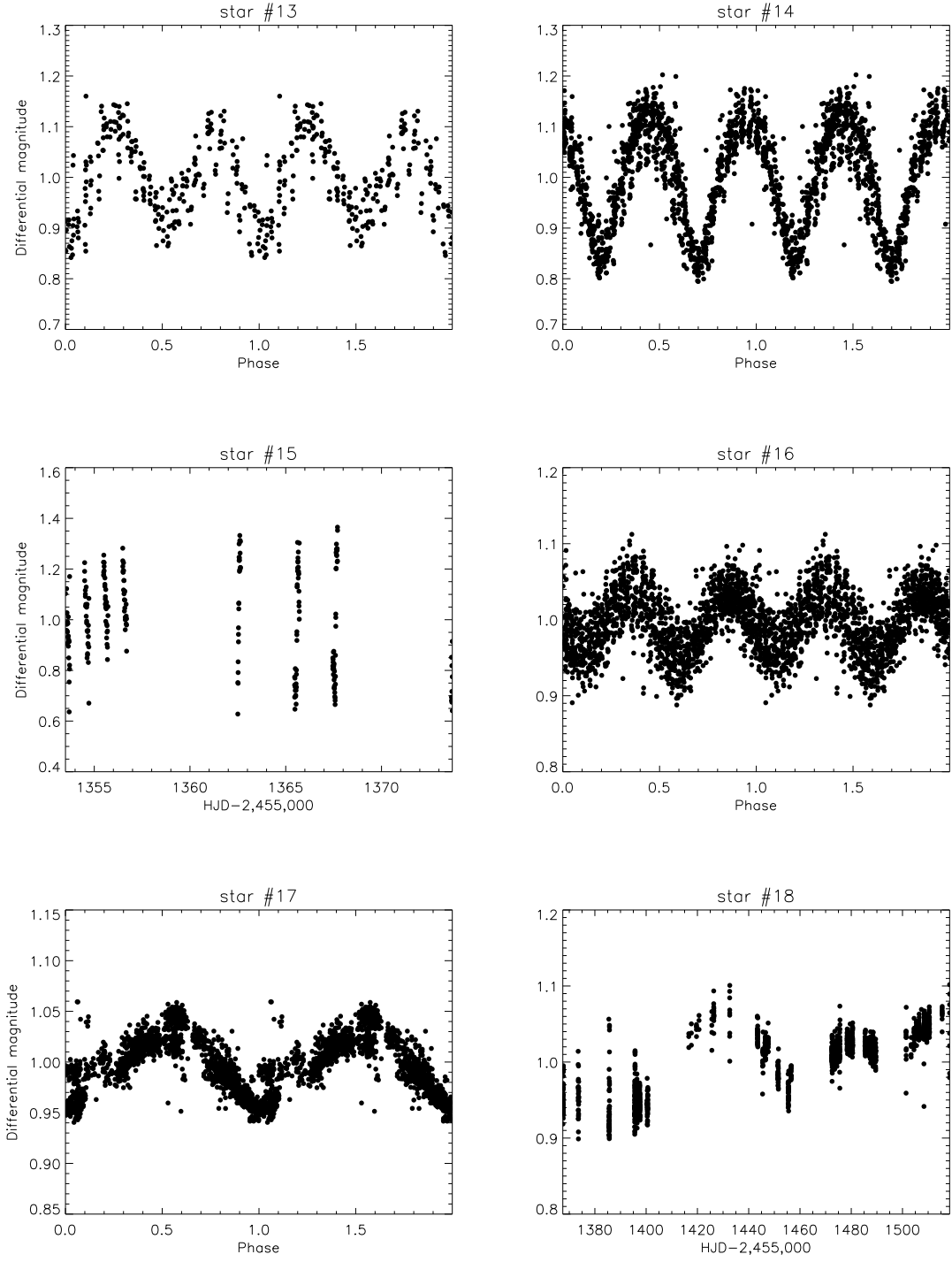


Fig. 1.—: *continued*

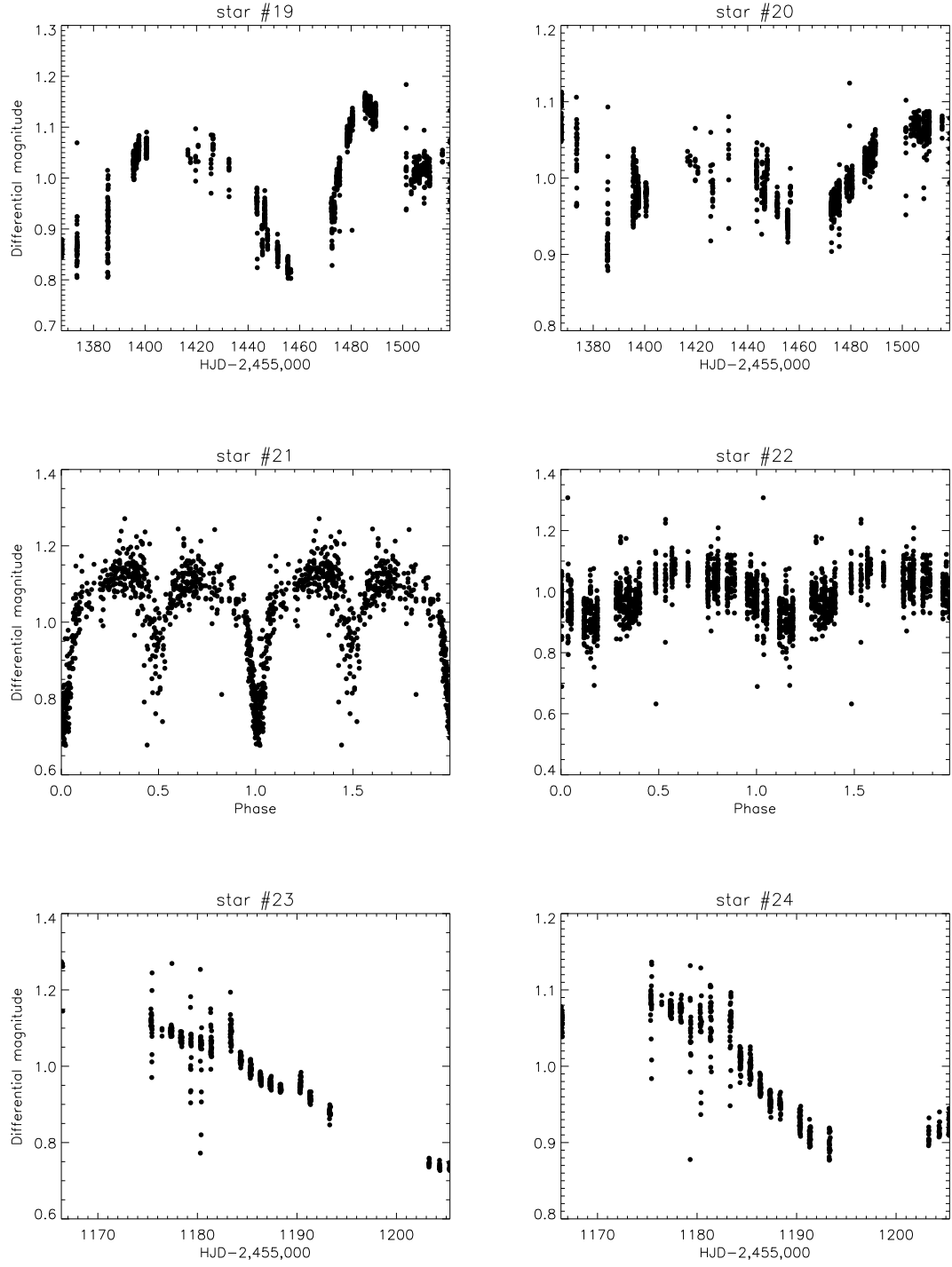


Fig. 1.—: *continued*

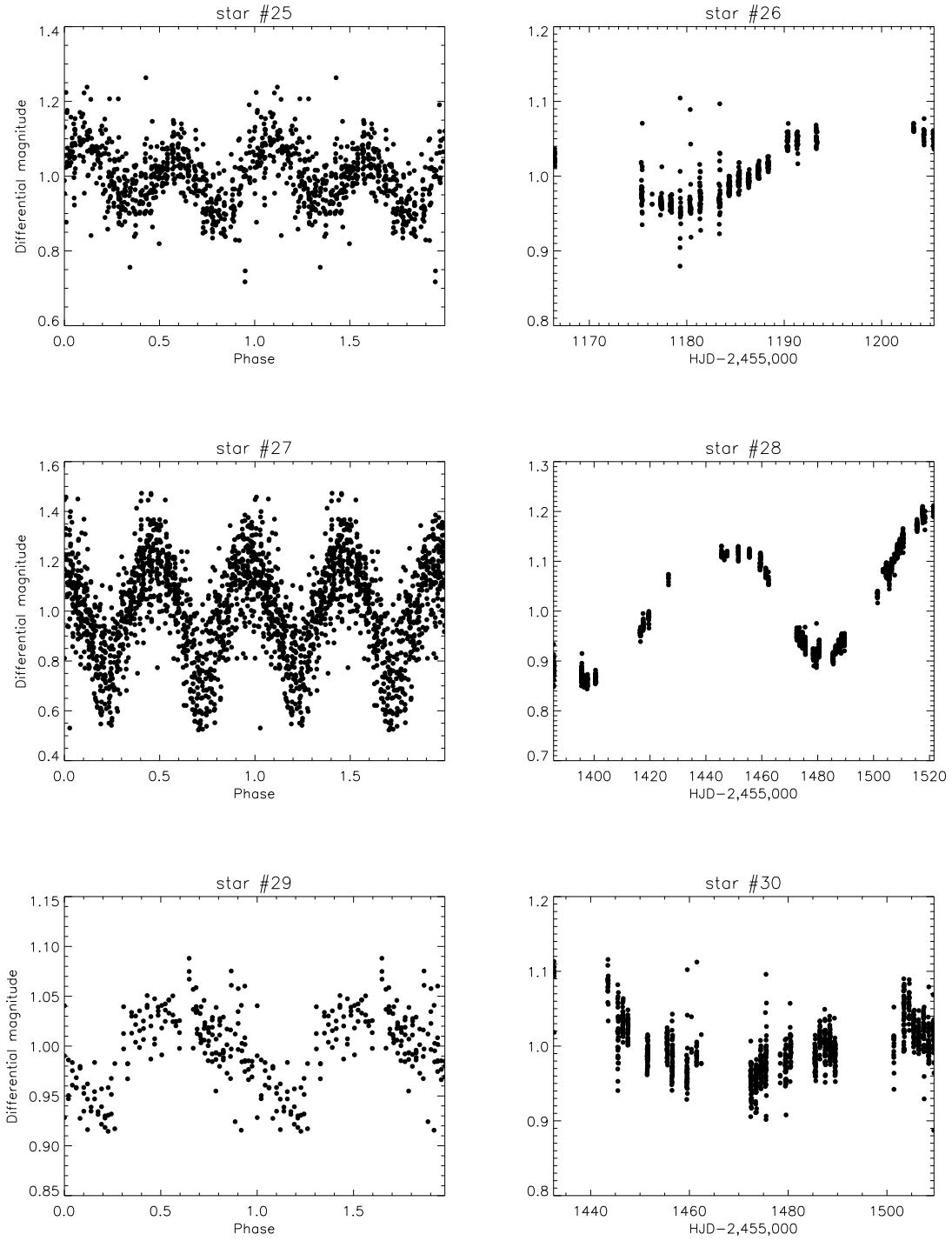


Fig. 1.—: *continued*

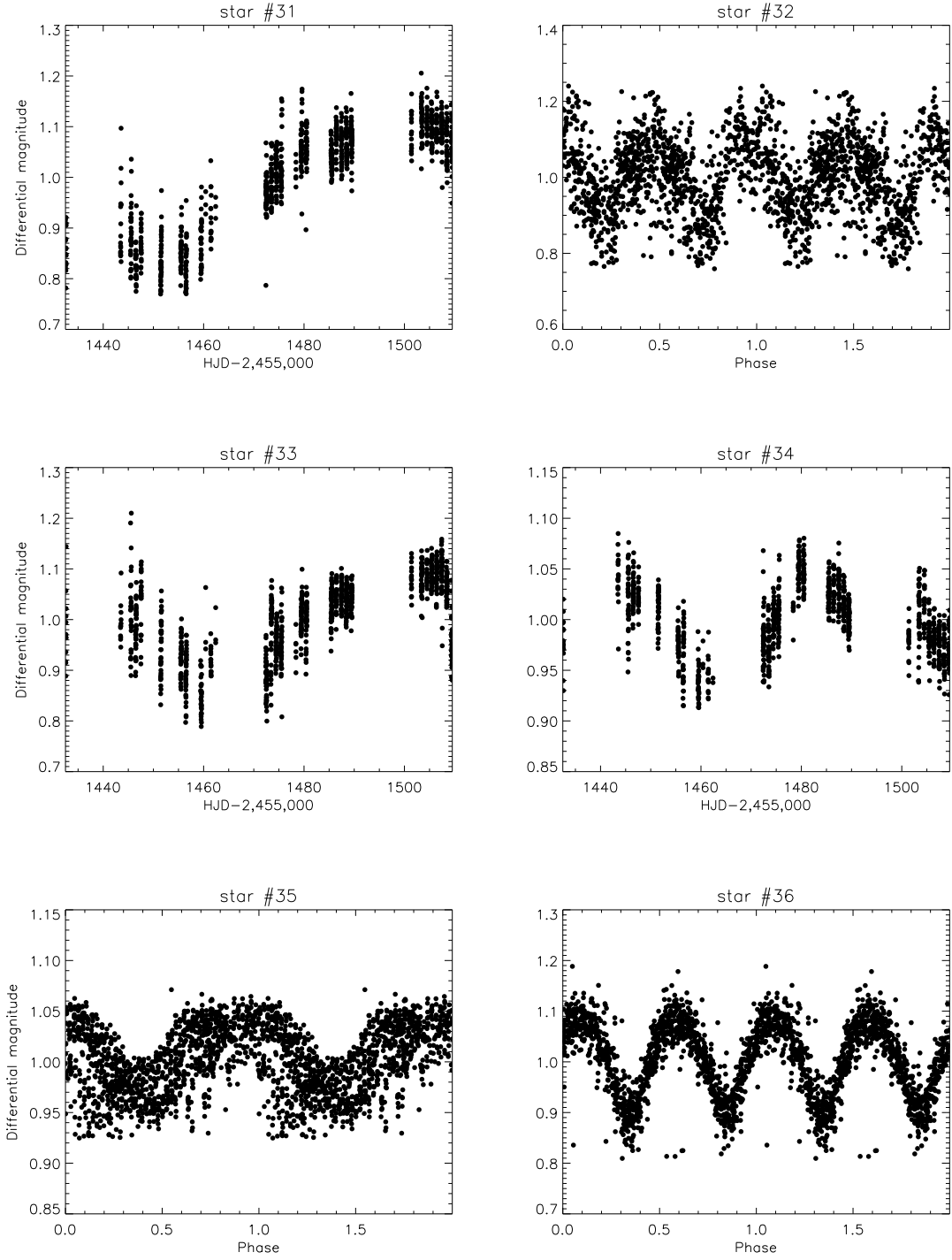


Fig. 1.—: *continued*

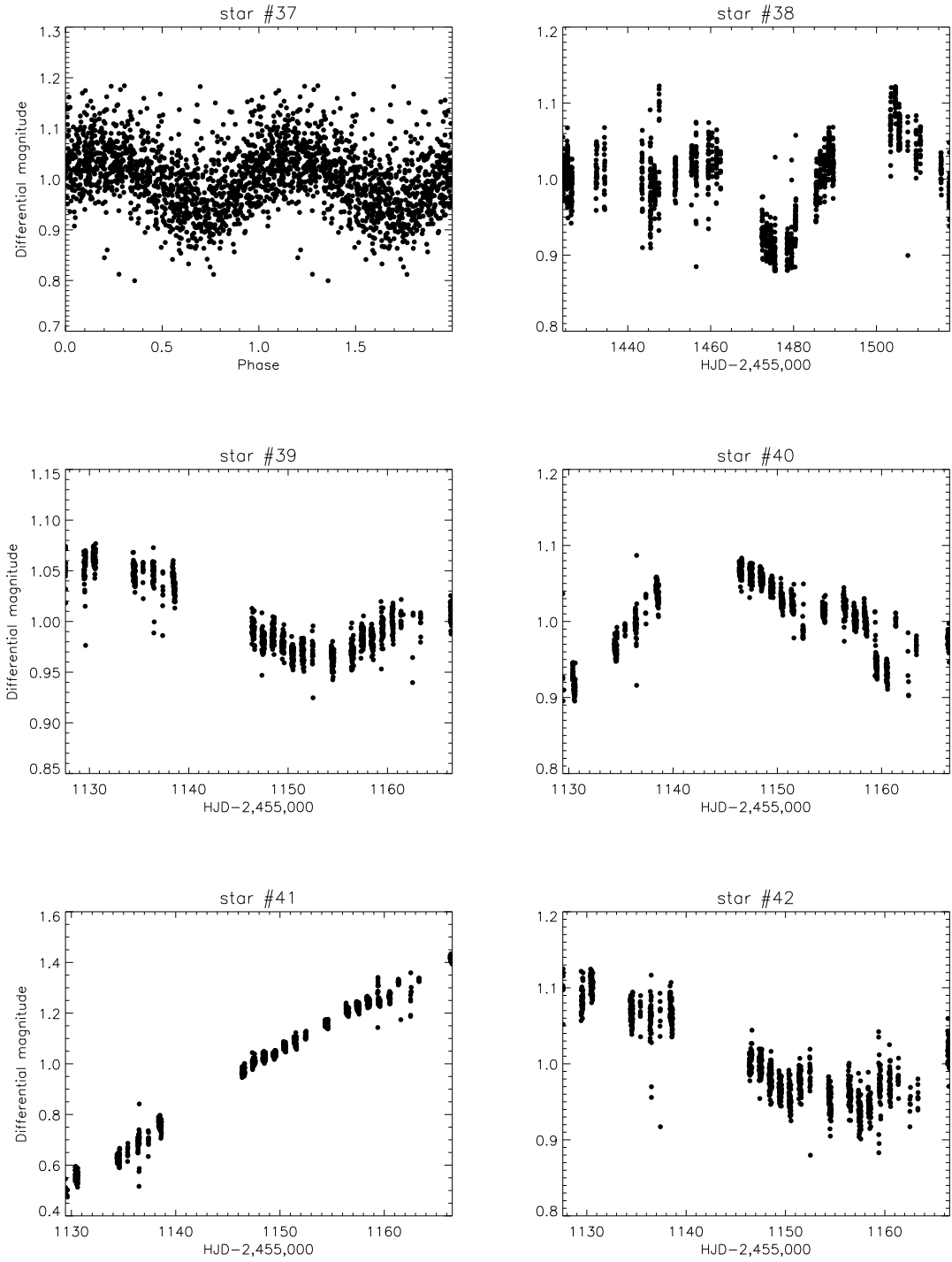


Fig. 1.—: *continued*

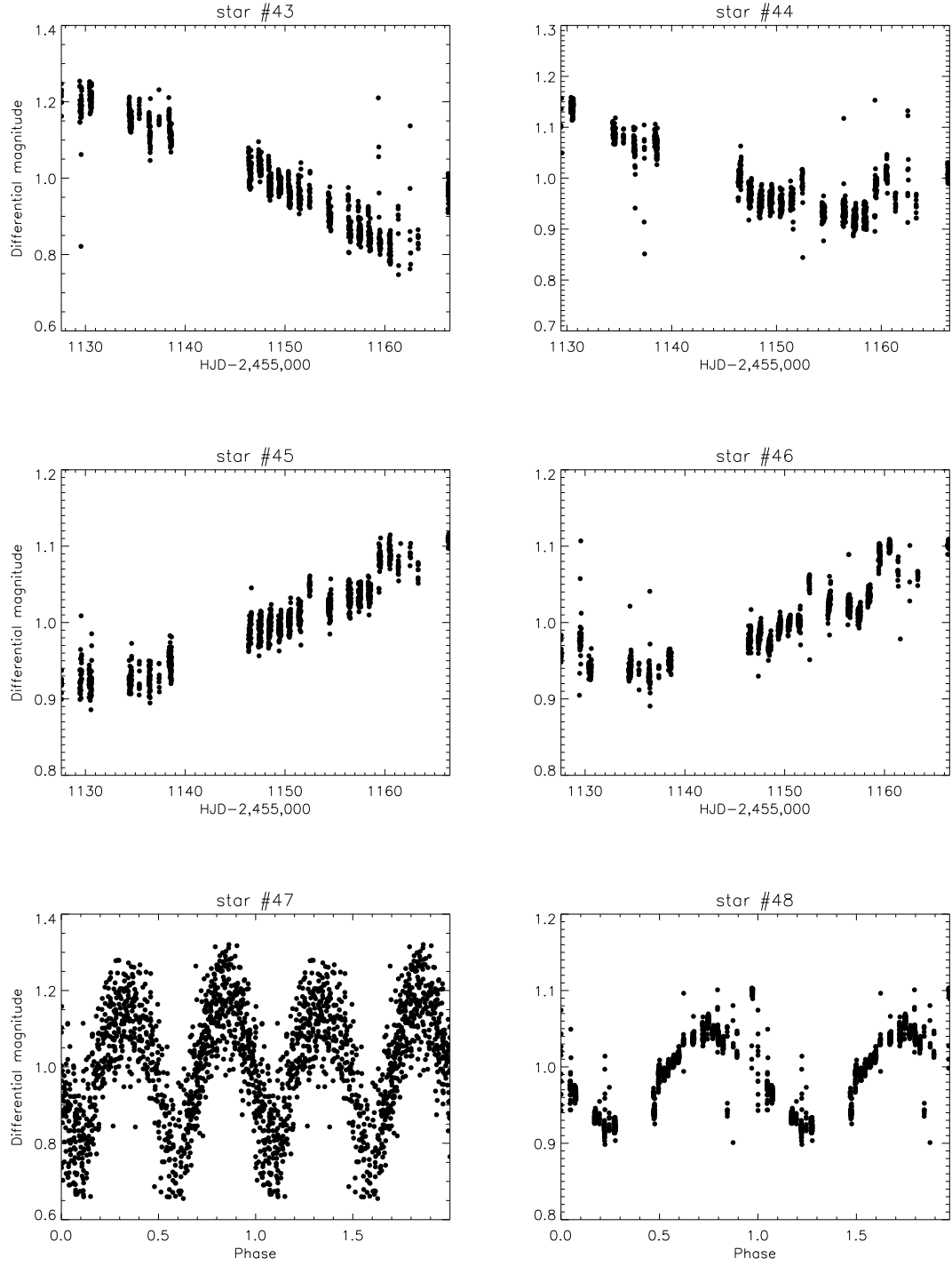


Fig. 1.—: *continued*

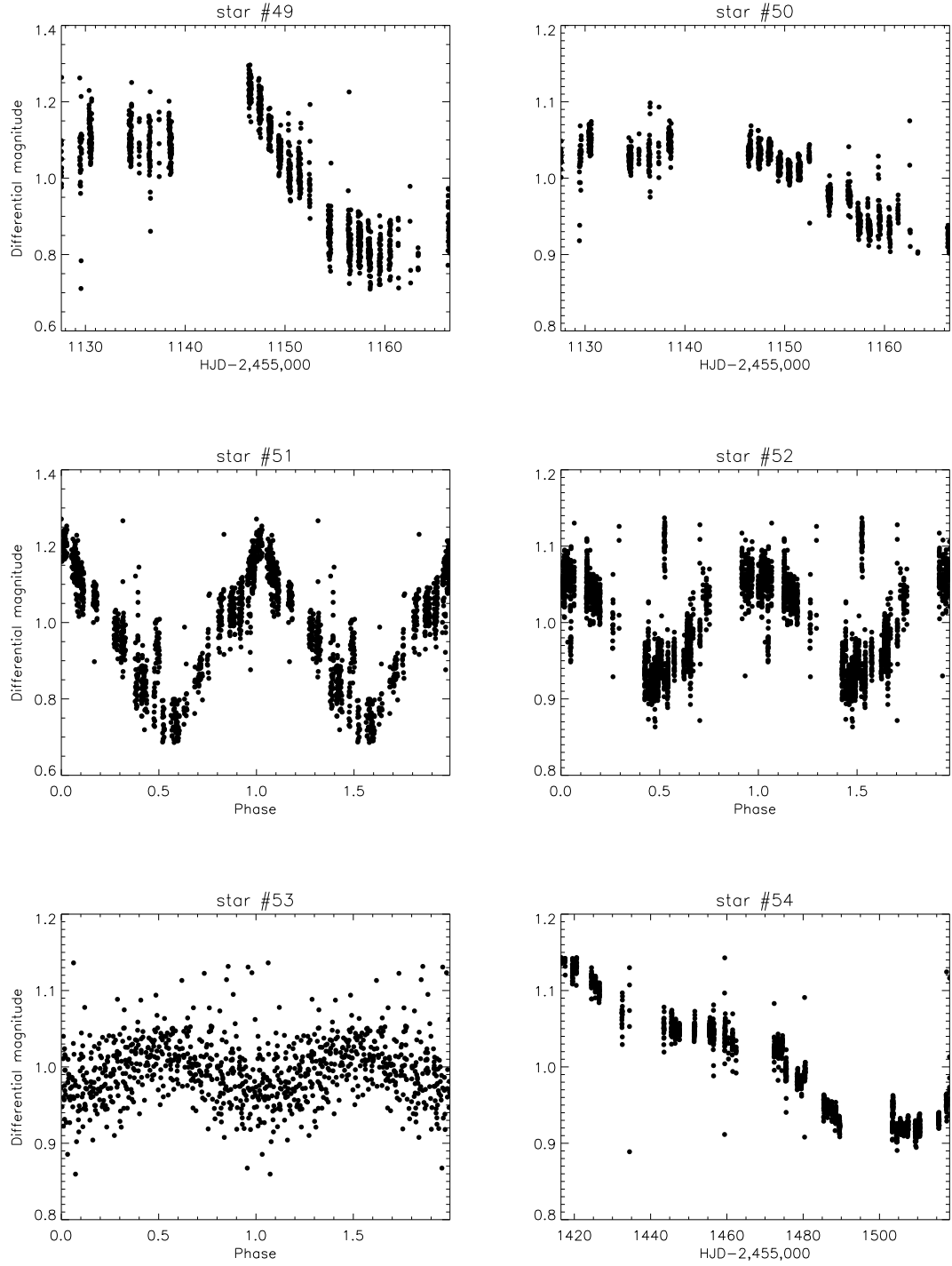


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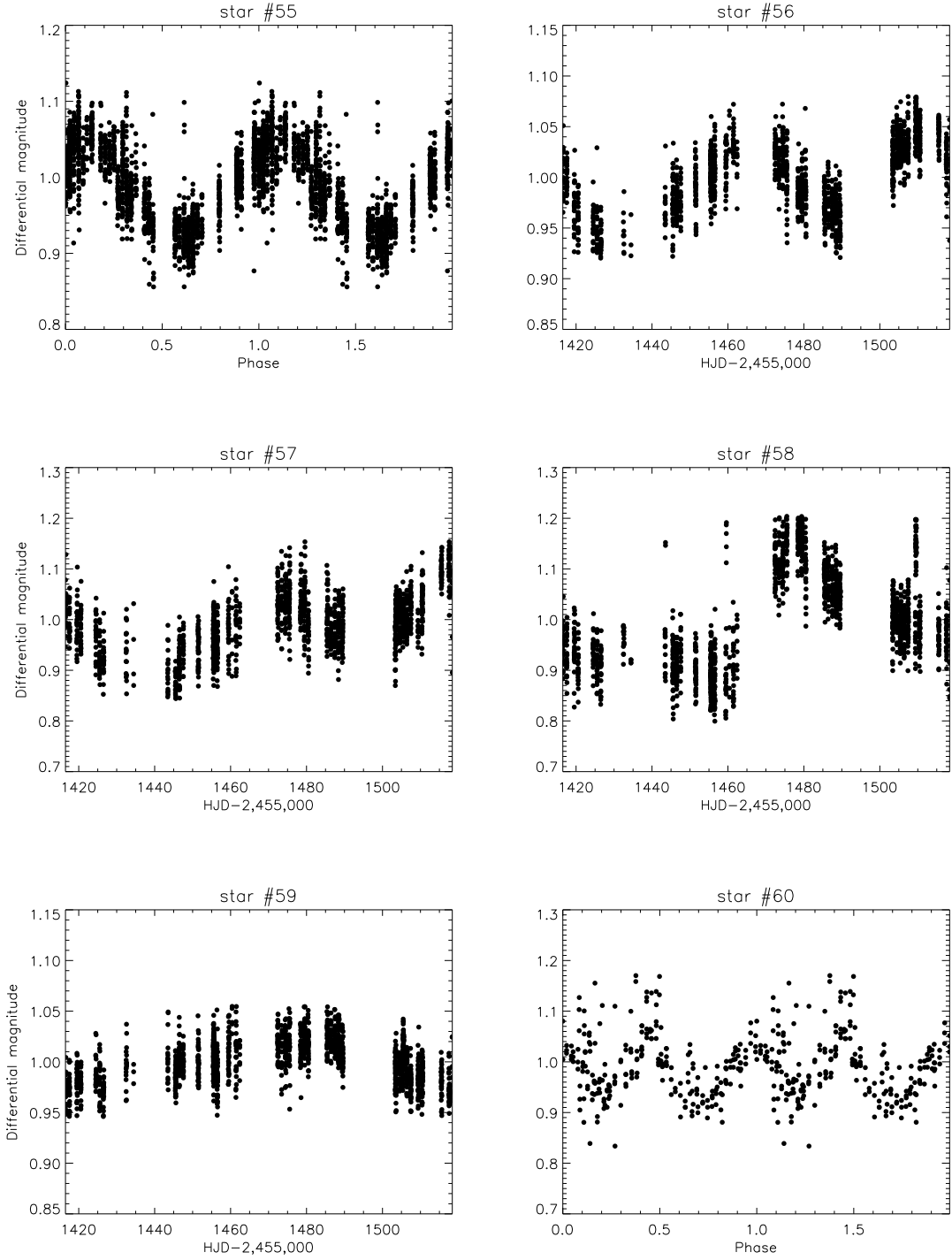


Fig. 1.—: *continued*

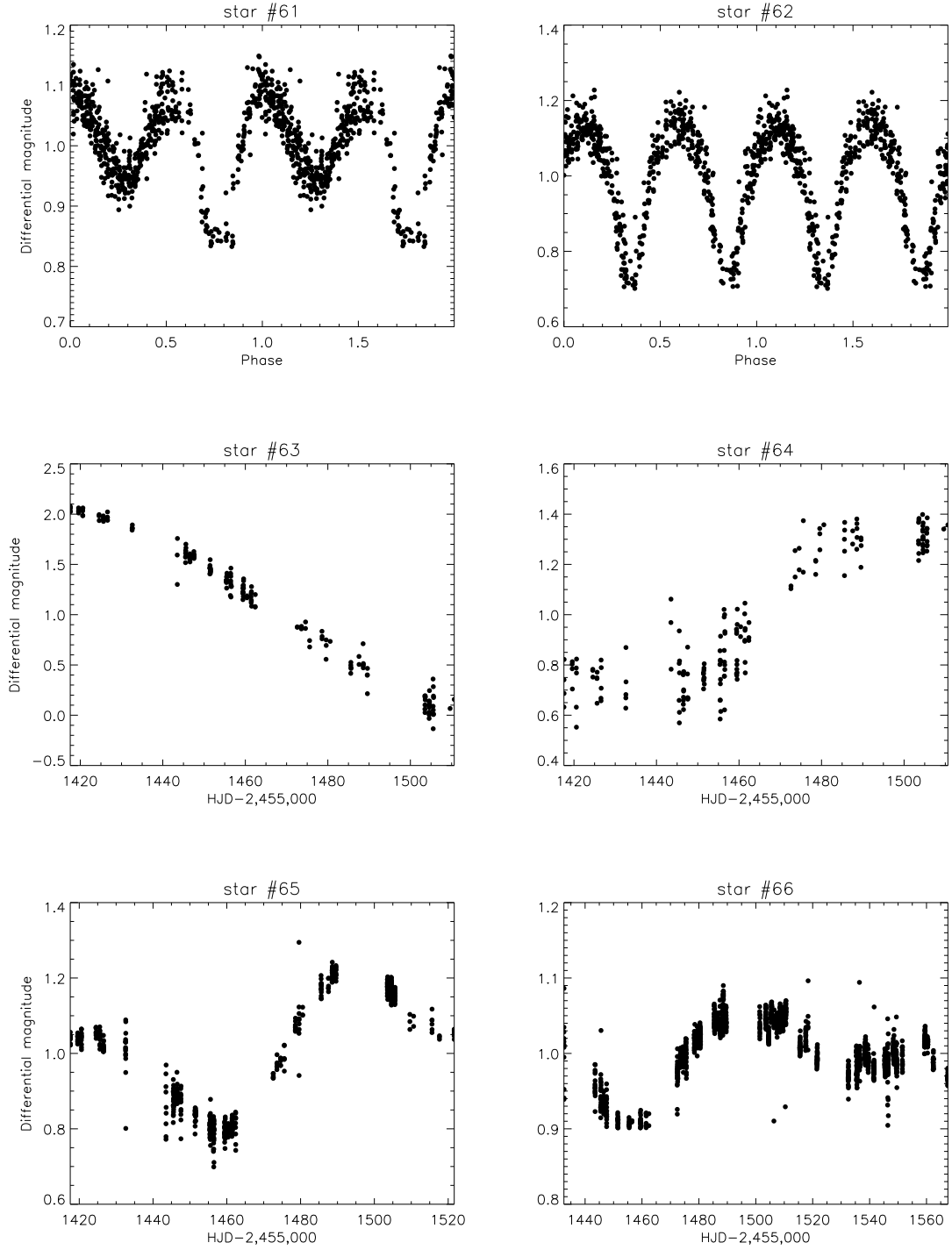


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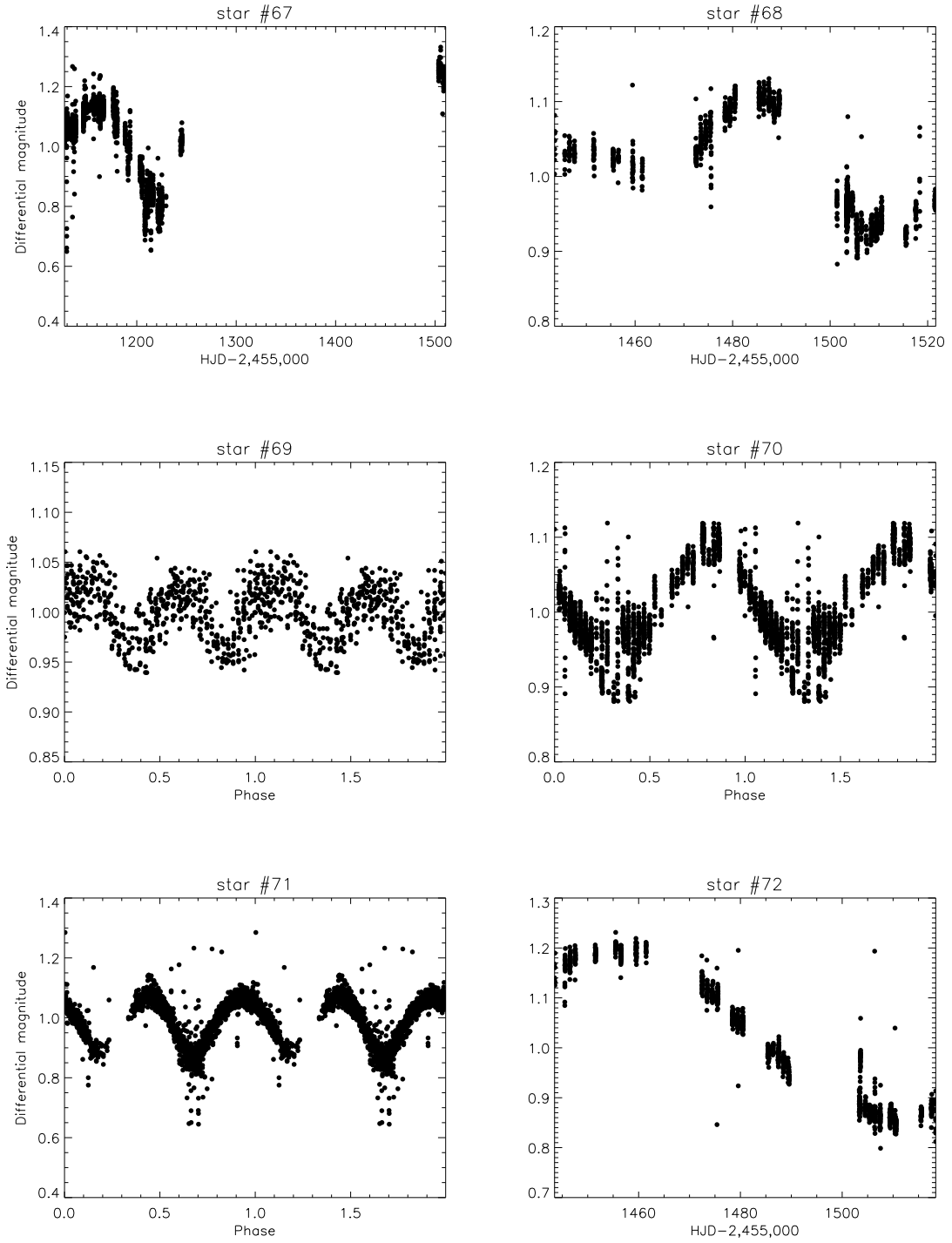


Fig. 1.—: *continued*

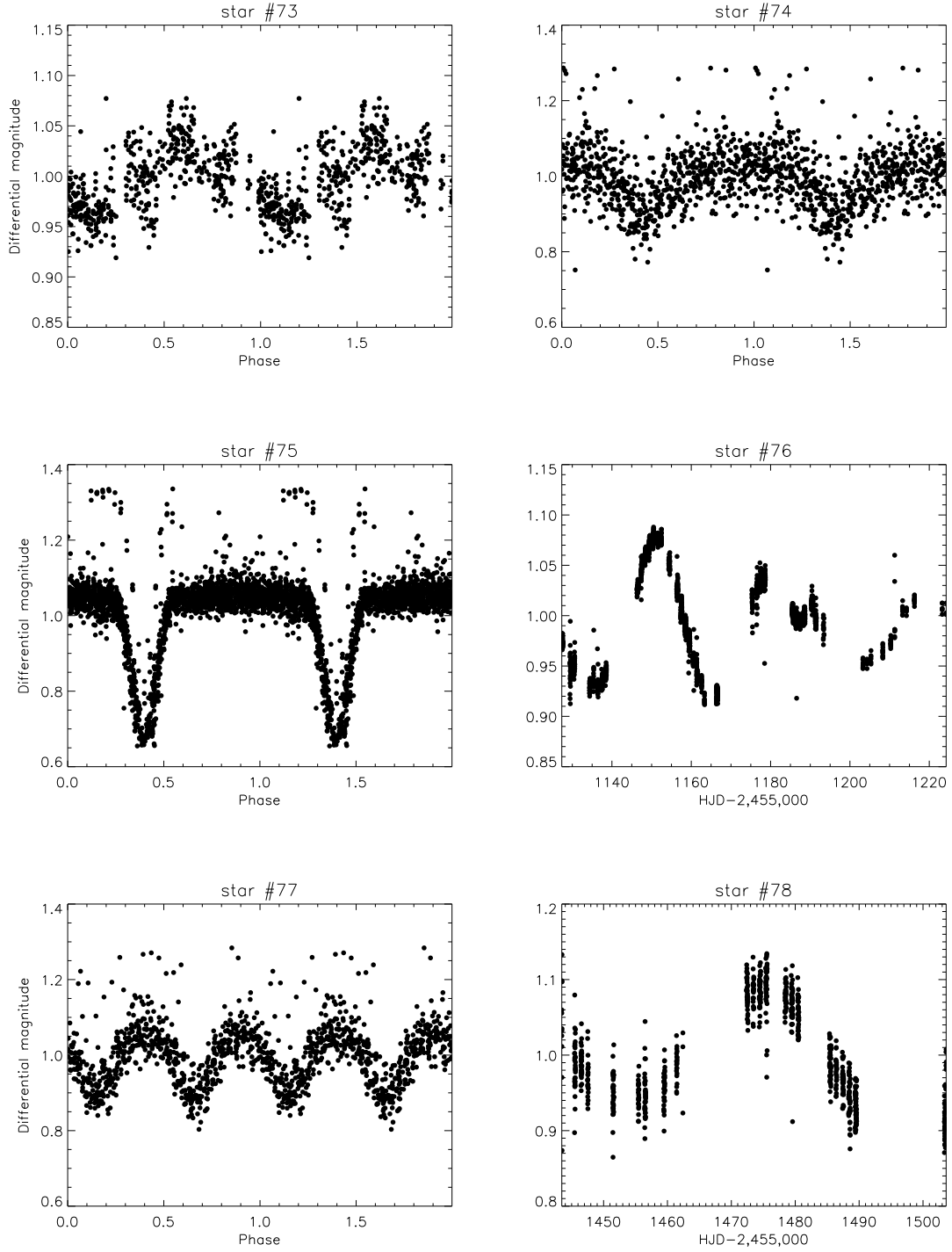


Fig. 1.—: *continued*

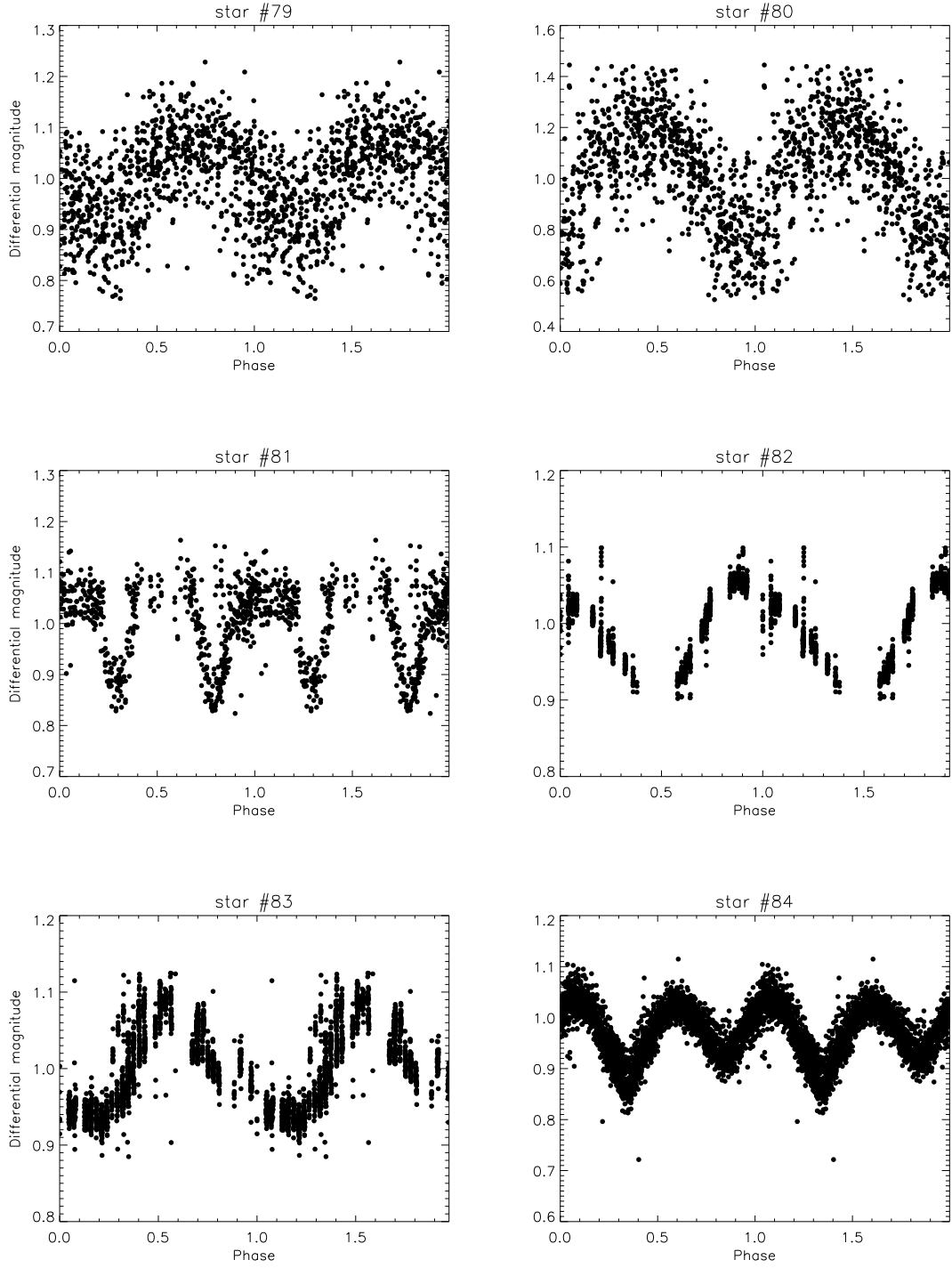


Fig. 1.—: *continued*

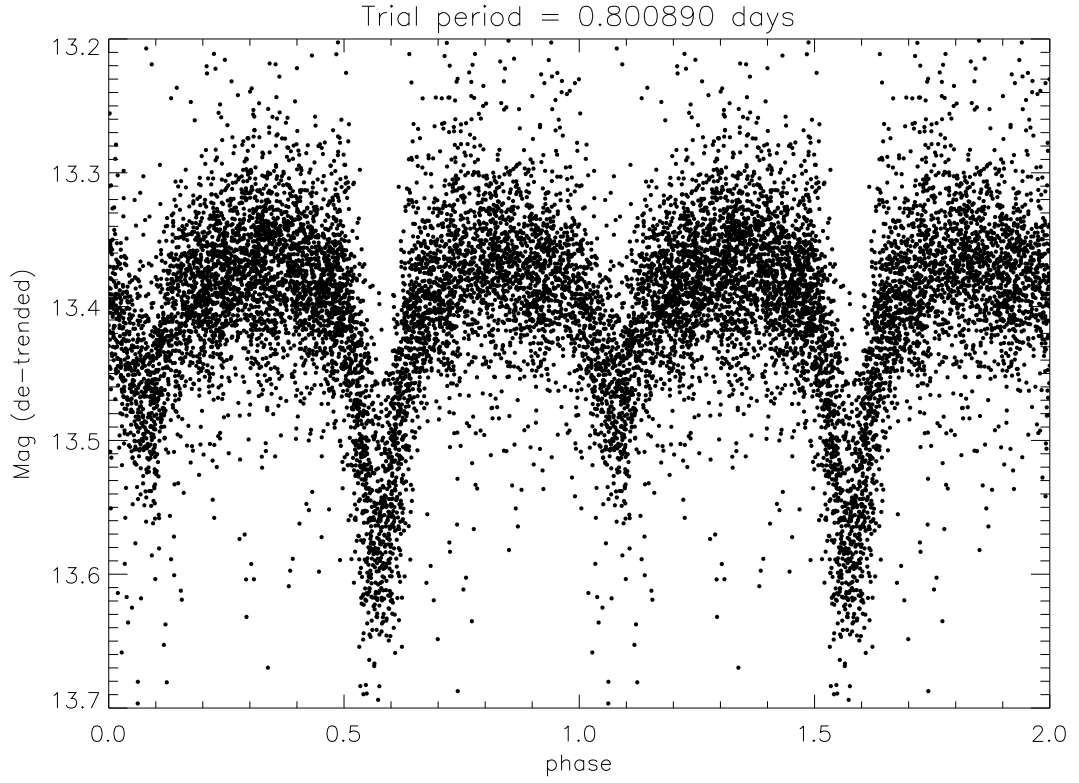


Fig. 2.—: Folded light curve of the star SWASP J052950.48+315439.8 (#10 in Tab. 1), obtained from data of the SuperWASP survey. By comparing this light curve to that obtained in a different band-pass by APACHE (Fig. 1) it can be noticed the different depth of the secondary minimum for this eclipsing binary system.

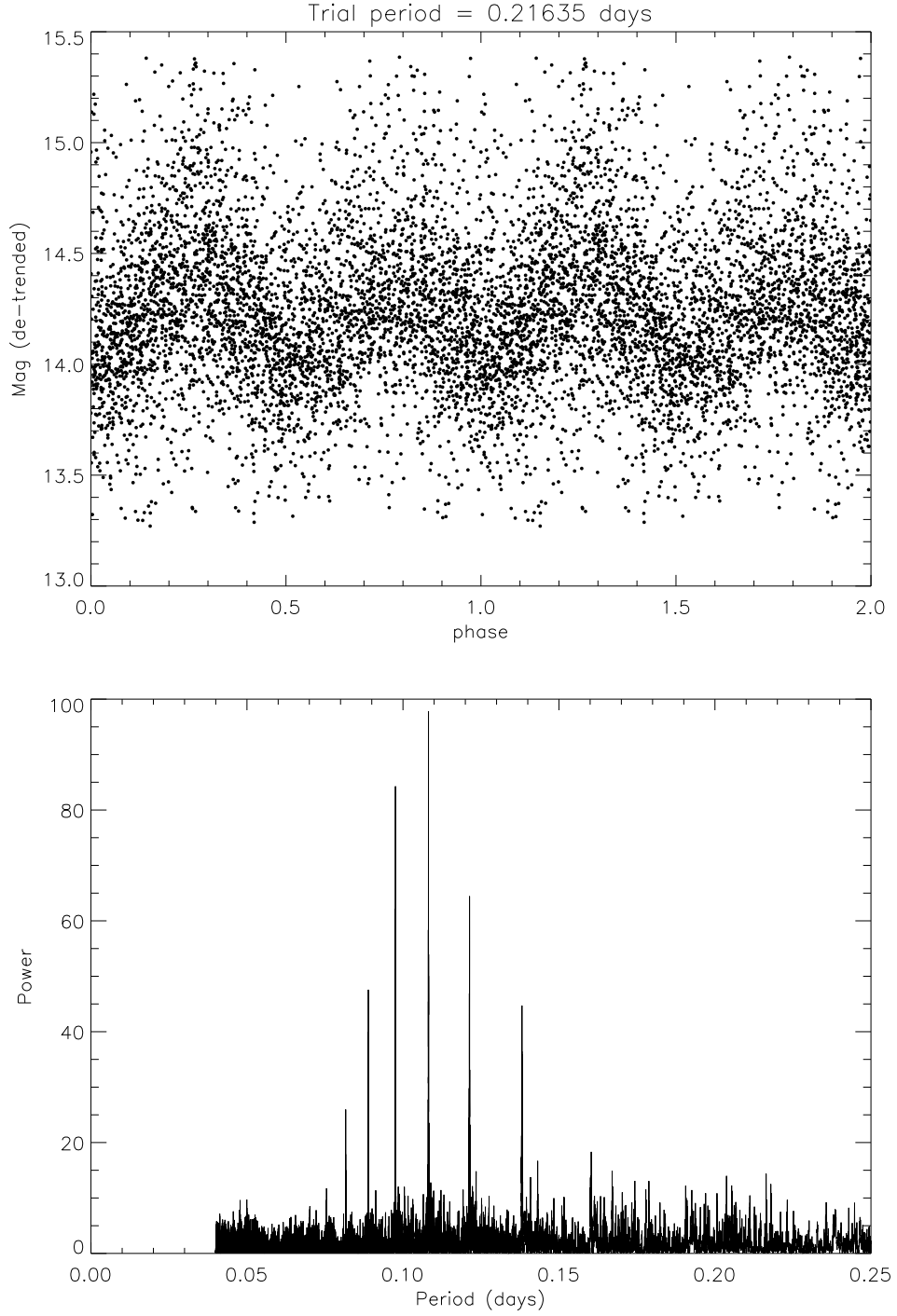


Fig. 3.—: *Top panel*: light curve of the star UCAC4 624-036803 (SWASP J070307.60+344203.60) (#13 in Tab. 1), obtained from data of the SuperWASP survey. Data are folded according to double the period with the highest peak in the Lomb-Scargle periodogram and rounded to the last significant digit. *Bottom panel*: the Lomb-Scargle periodogram in the range of periods of interest.

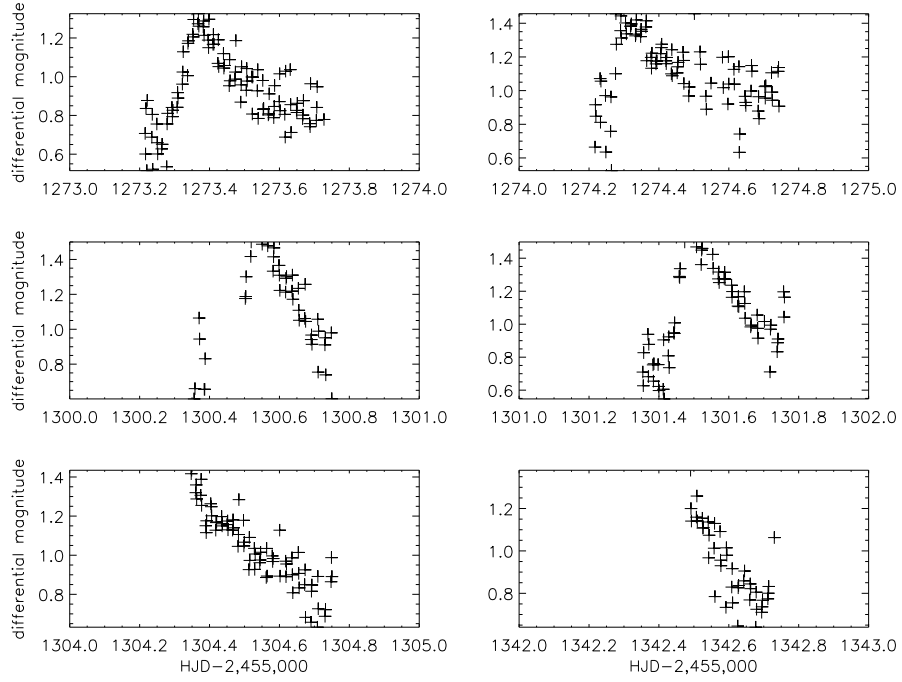


Fig. 4.—: Sample of APACHE light curves of the star UCAC4 872-000839 obtained during six observing nights. Looking at the characteristics of the flux variations, the star can be tentatively and generically classified as a pulsating variable, anyway lacking a reliable determination of the periodicity. No data from the SWASP archive are available.

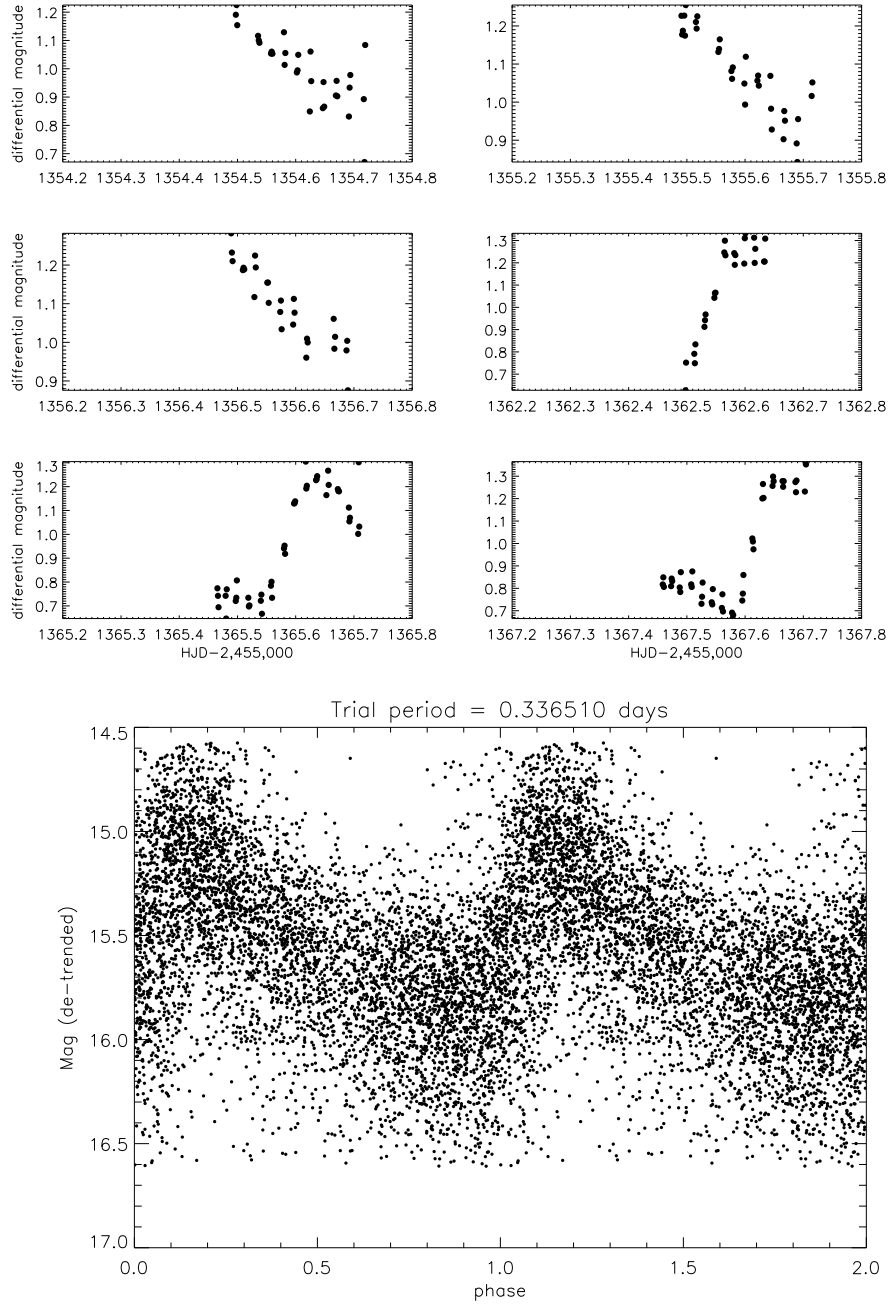


Fig. 5.—: *Top panel*: sample of APACHE light curves of the star UCAC4 664-056989 obtained during six observing nights. Looking at the characteristics of the flux variations, the star can be tentatively and generically classified as an RRab variable, anyway lacking a reliable determination of the periodicity. *Bottom panel*: the real nature of this variable is unveiled, and a reliable period estimation made possible, thanks to the data in the SWASP archive, showed here. The star indeed appears to be an RRab variable.

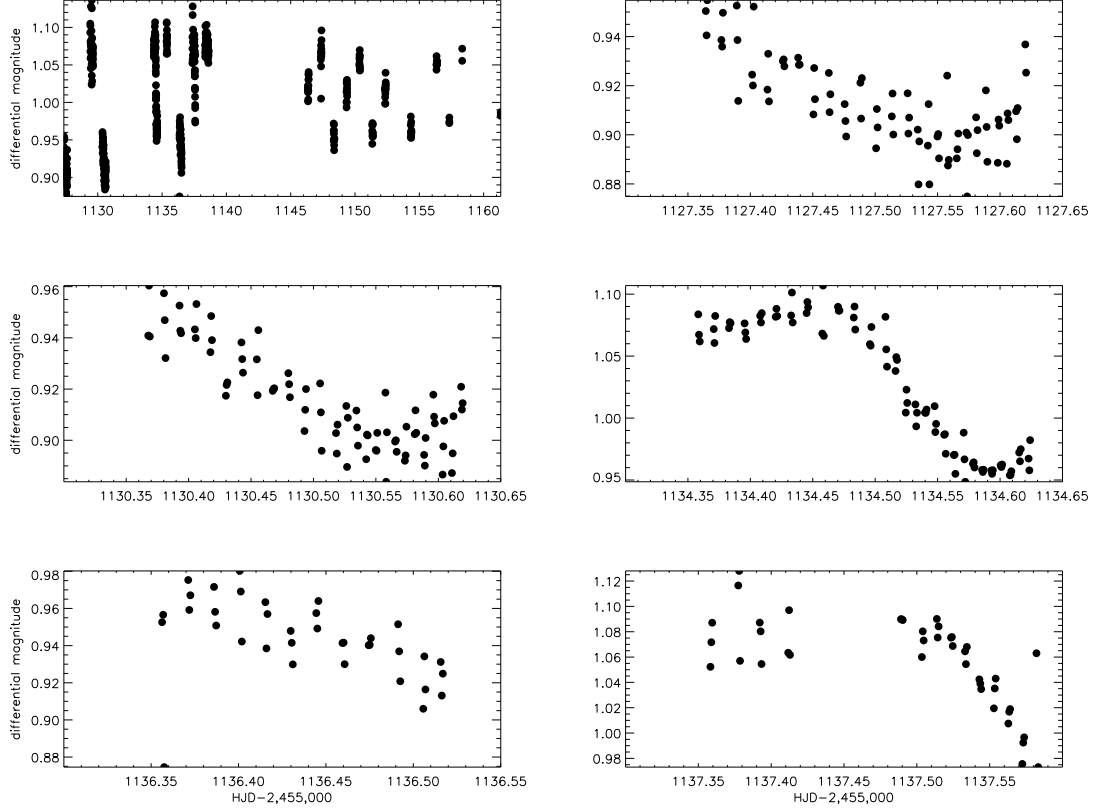


Fig. 6.—: *First panel*: sample of APACHE light curves of the star UCAC4 744-062741. The upper left plot shows the light curve during the whole timespan of observations. The other plots show the light curves obtained during five different nights. They correspond to the 1st, 3rd, 4th, 6th and 7th sub-intervals of the first plot. From our data alone we can not conclude anything about the variability type of this star. *Second panel*: light curve obtained from data of the SWASP survey and folded according to the best period $P=1.5174$ days found after a Lomb-Scargle analysis. *Third panel*: light curve from APACHE folded according to the best period $P=1.5$ days found after a Lomb-Scargle analysis.

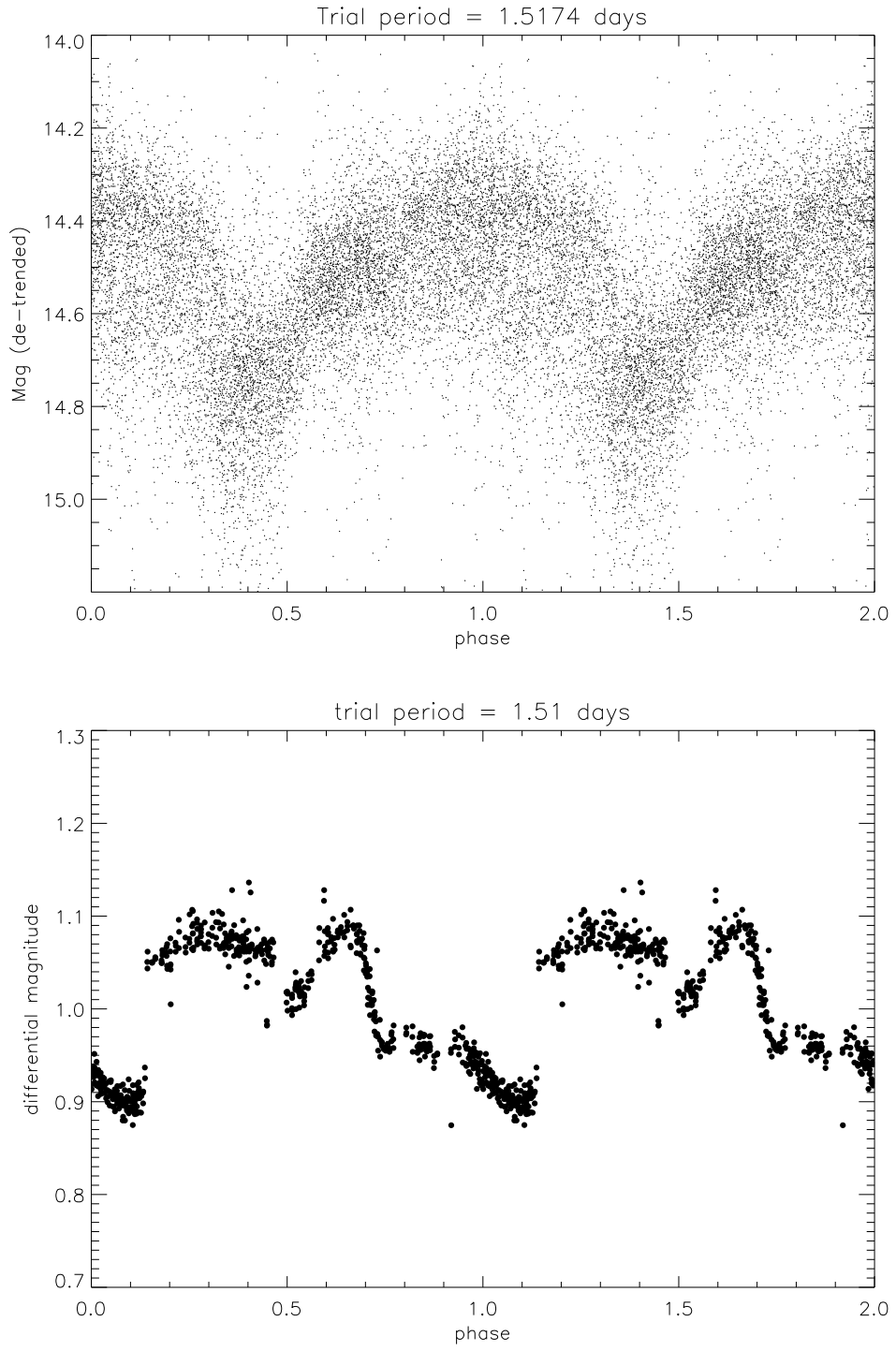


Fig. 6.—: *continued*

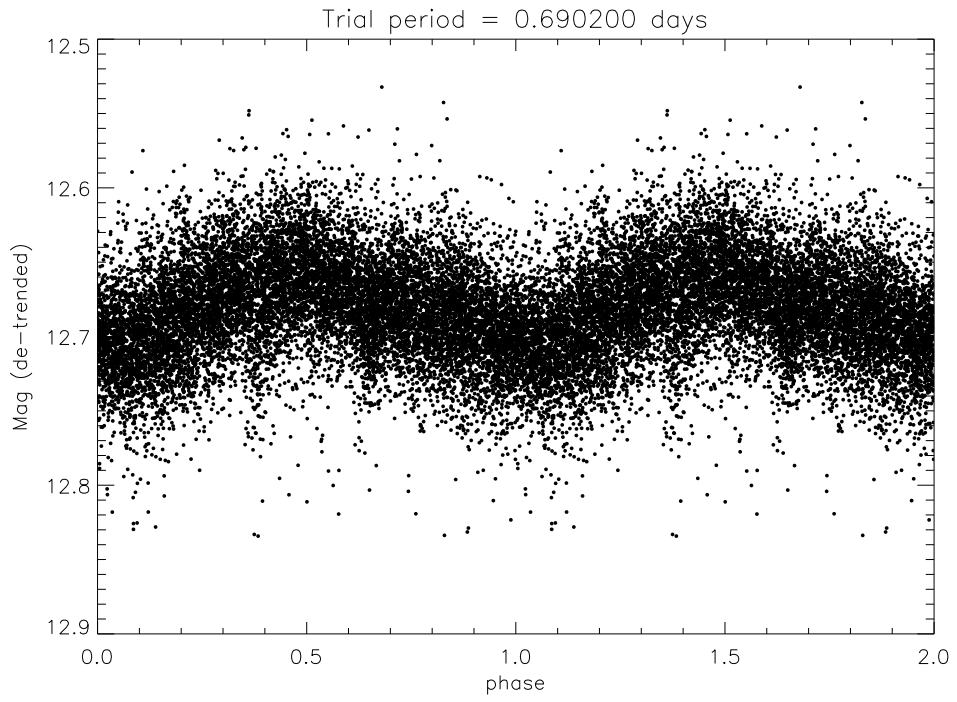


Fig. 7.—: Light curve of the star UCAC4 744-062741 obtained with data from the SWASP survey and folded according to the best period found $P=0.6902$ days.

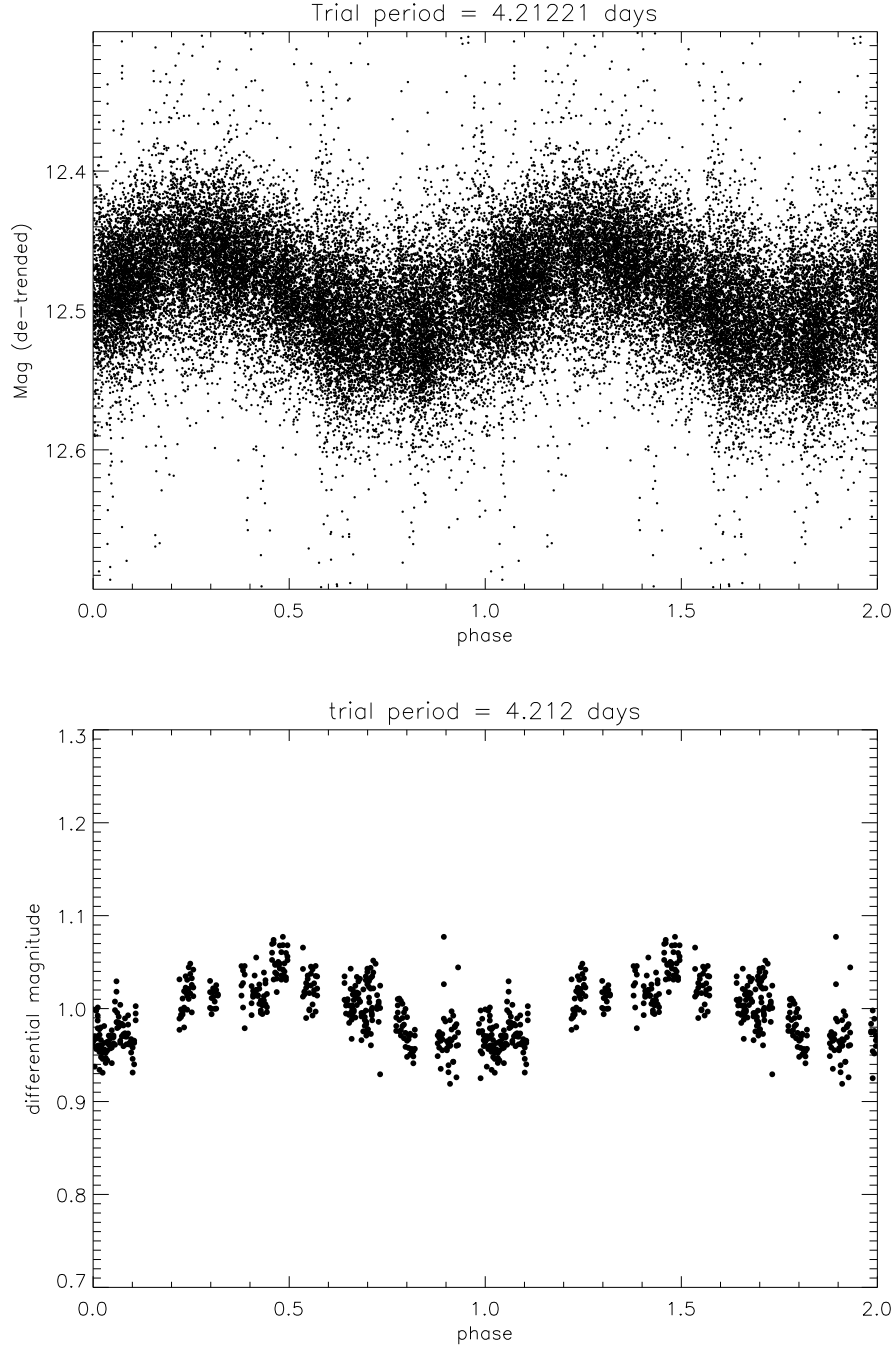


Fig. 8.—: Photometry of the star UCAC4 588-128603. (*1st and 2nd panels*): light curves of SWASP and APACHE survey respectively, folded according to the best period $P=4.21221$ days found by applying the Lomb-Scargle algorithm to the SWASP time-series. (*3rd and 4th panels*): light curves of SWASP and APACHE survey respectively, folded according to the second, significant period $P=0.80635$ days found by applying the Lomb-Scargle algorithm to the SWASP time-series.

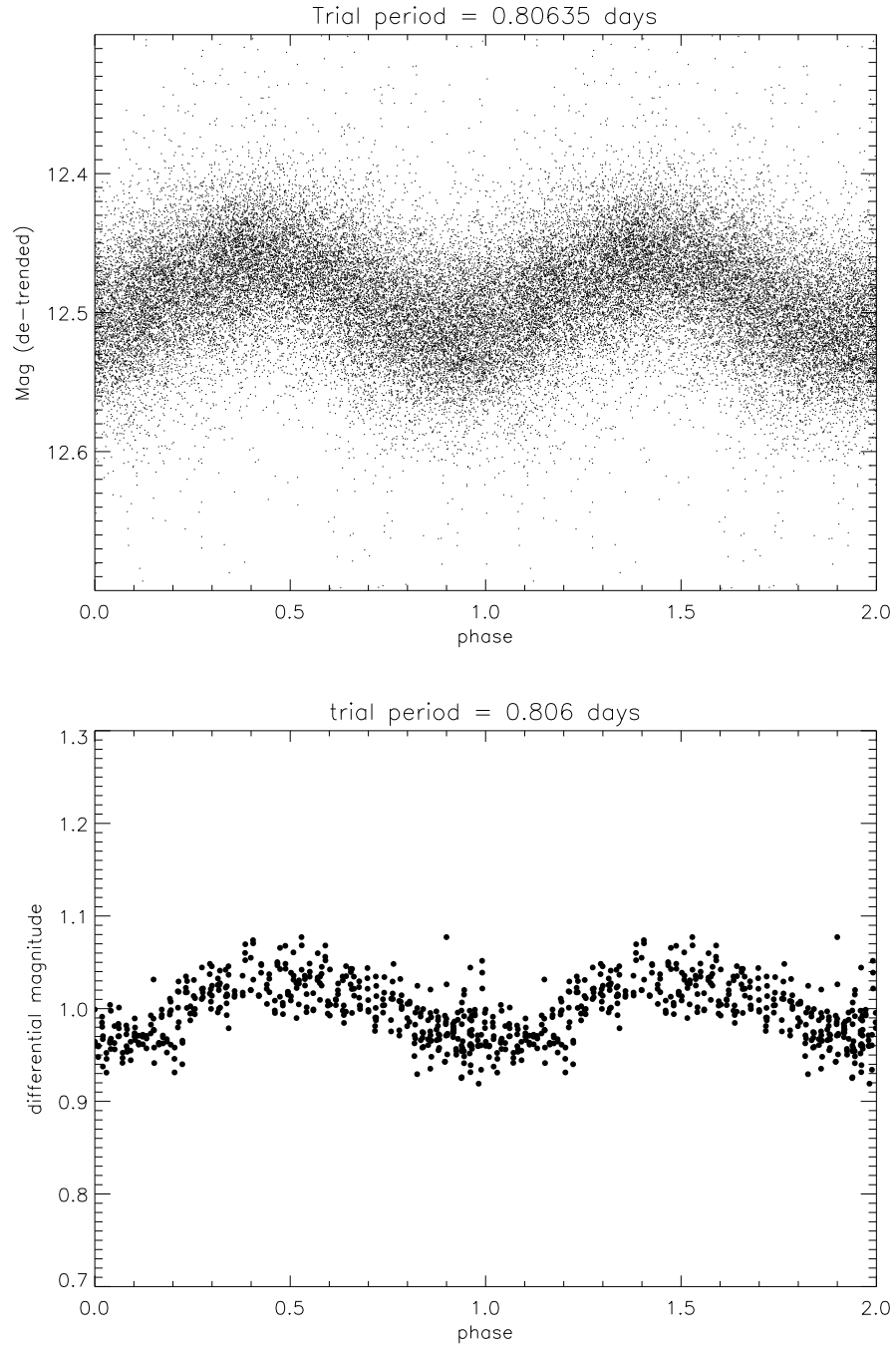


Fig. 8.—: *continued*

Table 1. Variable stars discovered by APACHE during the first observing season. For stars with two periods indicated, that in parenthesis is the one determined from the APACHE data, while the other is estimated from SuperWASP archive data. The amplitudes of the light curves are measured from APACHE data. Time T_0 correspond to phase=0 in the folded light curves.

ID	Name	RA (J2000)	DEC (J2000)	Mag V	Period (days)	Amplitude (mag)	T_0 (HJD-2,455,000)	Variability type	Note
1	UCAC4 744-001518	002.6931077	+58.6863575	14.86	7.55 (7.518)	~ 0.25	1146.3523197	ROT?	(1)
2	UCAC4 743-001636	002.7103159	+58.5618373	10.21	0.10625 (0.09603)	~ 0.02	1146.3523197	DSCT	(2)
3	UCAC4 758-009639	015.1541895	+61.5753528	14.27	1.20557	~ 0.6	1146.4105864	E	(3)
4	UCAC4 752-014548	018.8161518	+60.3735250	13.14	1.087	~ 0.3	1146.3866004	EB	
5	UCAC4 870-000885	018.9877518	+83.9571120	16.77	0.40861	~ 0.3	1273.2157609	EW	
-	UCAC4 872-000839	021.2561924	+84.2626639	16.17	?	—	—	RR?	(4)
6	UCAC4 728-026837	044.2308518	+55.5203950	16.38(GSC2.3)	?	~ 0.4	1146.4709166	L	
7	UCAC4 618-013561	062.4040074	+33.4937250	12.83	?	~ 0.25	1162.5960791	L	
8	UCAC4 713-031969	063.5650233	+52.5300092	14.4	6.22	~ 0.4	1208.3673785	E	(5)
9	UCAC4 709-034533	074.7646086	+51.7157109	10.77	?	~ 0.05	1328.2561929	L	
10	UCAC4 610-021265	082.4603353	+31.9110003	13.59	0.80089 (0.80086)	~ 0.3	1210.5113093	EW	(6)
11	UCAC4 619-030850	092.0415889	+33.6711831	13.01	2.008 (2.009)	~ 0.27	1205.5239017	EB	(7)
12	UCAC4 521-023140	094.9127039	+14.0543662	12.47	$\sim 77?$	~ 0.16	1270.3904921	L	(8)
13	UCAC4 624-036803	105.7816774	+34.7009262	15.90	0.21635 (WASP)	~ 0.25	1246.5895718	EW	(9)
14	UCAC4 715-044844	105.9254200	+52.8823920	13.22	0.3281 (0.32811)	~ 0.33	1205.4926955	EW	(10)
15	UCAC4 664-056989	179.4896992	+42.6626264	14.19	0.33651	~ 0.5	1353.4968403	RRab	(11)
16	UCAC4 609-049172	208.1377689	+31.6871487	13.47	0.35471 (0.35470)	~ 0.16	1301.7535576	EW	(12)
17	UCAC4 666-060394	232.1916465	+43.0916548	12.79	1.9756 (1.9788)	~ 0.1	1127.3672611	ROT	(13)
18	UCAC4 633-053996	250.3480433	+36.5047900	12.26	?	~ 0.1	1367.4885131	L	
19	UCAC4 633-054311	250.4026556	+36.4431934	15.06	?	~ 0.3	1367.4885131	L	(14)
20	UCAC4 633-054908	250.4621462	+36.4817620	11.82	?	~ 0.2	1367.4885131	L	(15)
21	UCAC4 652-057450	253.3608262	+40.3033556	14.83	1.47	~ 0.45	1420.4785809	EB	

Table 1—Continued

ID	Name	RA (J2000)	DEC (J2000)	Mag V	Period (days)	Amplitude (mag)	T ₀ (HJD-2,455,000)	Variability type	Note
22	UCAC4 592-063874	275.7670439	+28.3080614	14.01(GSC2.3)	~60?	~0.2	1127.3682196	L	
23	UCAC4 533-077928	279.6991892	+16.4103631	15.12	?	~0.5	1166.3294430	L	
24	UCAC4 533-078069	279.8361324	+16.5350567	14.97(GSC2.3)	?	~0.2	1166.3294430	L	
25	UCAC4 532-076755	279.8824256	+16.3173617	15.15	0.3199	~0.25	1166.3294430	EW	
26	UCAC4 533-078283	280.0367009	+16.5274503	14.58	?	~0.11	1166.3294430	L	
27	UCAC4 723-061541	283.8471103	+54.4308875	14.33	0.38399 (0.38399)	~0.7	1385.4985908	EW	(16)
28	UCAC4 723-061622	284.1744556	+54.5157323	13.34(GSC2.3)	?	~0.35	1385.4876350	L	
29	UCAC4 479-089263	284.6627689	+05.7352287	11.68	0.744	~0.1	1473.4154161	RRc	(17)
30	UCAC4 491-099556	284.8352648	+08.1355764	N.A.	?	~0.15	1432.4879724	L	(18)
31	2MASS 18592325+0810247	284.846896	+08.173555	N.A.	?	~0.25	1432.4879724	L	(19)
32	UCAC4 491-099593	284.8855603	+08.0666542	16.48(GSC2.3)	1.251	~0.35	1432.4879724	EW	
33	2MASS 19000738+0805125	285.030765	+08.086826	19.00(GSC2.3)	?	~0.25	1432.4879724	L	
34	UCAC4 490-094834	285.0720153	+07.9374948	16.58(GSC2.3)	?	~0.12	1432.4879724	L	
35	UCAC4 729-060138	290.8229630	+55.6600275	12.76	0.6902 (0.688)	~0.08	1434.3738137	ROT	(20)
36	UCAC4 728-061629	290.9937003	+55.5546067	14.81	0.36689 (0.3669)	~0.2	1434.3728183	EW	(21)
37	UCAC4 728-061766	291.4820559	+55.5007378	15.27(GSC2.3)	0.189029 (0.1890)	~0.1	1434.3738137	DSCT	(22)
38	UCAC4 811-027074	294.4105074	+72.0363334	13.63	?	~0.2	1424.3380554	L	
39	UCAC4 610-092144	297.3880989	+31.8705942	14.72(NOMAD)	?	~0.1	1127.5857519	L	
40	UCAC4 609-091131	297.4135403	+31.6445878	14.79(NOMAD)	?	~0.15	1127.5857519	L	
41	UCAC4 609-091297	297.4814474	+31.7204662	17.27(NOMAD)	?	~0.9	1127.5857519	L	
42	2MASS 19500382+3149132	297.515956	+31.820337	N.A.	?	~0.15	1127.5857519	L	
43	2MASS 19500885+3135499	297.536909	+31.597216	N.A.	?	~0.4	1127.5857519	L	

Table 1—Continued

ID	Name	RA (J2000)	DEC (J2000)	Mag V	Period (days)	Amplitude (mag)	T ₀ (HJD-2,455,000)	Variability type	Note
44	UCAC4 610-092592	297.5731206	+31.9941723	15.53(NOMAD)	?	~0.2	1127.5857519	L	
45	2MASS 19502059+3152091	297.585806	+31.869217	17.38(NOMAD)	?	~0.2	1127.5857519	L	
46	2MASS 19502935+3158417	297.622323	+31.978273	N.A.	?	~0.17	1127.5857519	L	
47	UCAC4 610-092815	297.6690953	+31.9639217	15.41(NOMAD)	0.427	~0.5	1127.5857519	EW	
48	UCAC4 609-091797	297.7097806	+31.6965225	12.70	~40?	~0.13	1127.5857519	L	
49	UCAC4 608-095594	297.7998224	+31.5728037	15.22(NOMAD)	?	~0.45	1127.5857519	L	
50	2MASS 19511471+3143128	297.811294	+31.720238	17.47	?	~0.14	1127.5857519	L	
51	UCAC4 623-096266	302.9632515	+34.4131084	15.28(NOMAD)	9.8	~0.45	1416.5074270	PULS	(23)
52	UCAC4 623-096337	303.0224745	+34.4758434	15.87(NOMAD)	~61?	~0.16	1416.5074270	L	
53	UCAC4 621-098928	303.0456662	+34.0879998	13.90	0.1365	~0.07	1416.5076083	DSCT?	
54	UCAC4 622-095023	303.0508565	+34.2564675	14.06(NOMAD)	?	~0.22	1416.5074270	L	(24)
55	UCAC4 622-095081	303.0868139	+34.3034262	17.07(NOMAD)	~44?	~0.15	1416.5074270	L	
56	UCAC4 622-095314	303.2126174	+34.2968739	16.19(NOMAD)	?	~0.12	1416.5074270	L	
57	UCAC4 623-096673	303.2543371	+34.4226409	14.72(NOMAD)	?	~0.25	1416.5074270	L	
58	UCAC4 622-095521	303.3453327	+34.3789689	13.58	?	~0.3	1416.5074270	L	
59	UCAC4 622-095554	303.3731539	+34.3134381	14.99(NOMAD)	?	~0.05	1416.5074270	L	
60	UCAC4 516-127264	303.6096042	+13.1699259	12.40	0.575	~0.2	1445.5441597	EW	
-	UCAC4 744-062741	306.3905642	+58.6538473	14.09	1.51?	~0.2	1127.3642954	ROT?	(25)
61	UCAC4 744-062753	306.4085277	+58.7603659	14.17(GSC2.3)	0.4406 (0.4405)	~0.25	1127.3642954	EW	(26)
62	UCAC4 744-062788	306.5188756	+58.7358845	15.2(GSC2.3)	0.3495	~0.45	1127.3642954	EW	
63	2MASS 20305052+5547074	307.710540	+55.785416	18.64(GSC2.3)	?	~2.0	1417.5662968	L	
64	UCAC4 729-067019	307.8310009	+55.7983139	15.56(GSC2.3)	?	~0.6	1417.5664087	L	

Table 1—Continued

ID	Name	RA (J2000)	DEC (J2000)	Mag V	Period (days)	Amplitude (mag)	T ₀ (HJD-2,455,000)	Variability type	Note
65	UCAC4 731-068791	308.1278424	+56.1299364	14.44	?	~0.4	1417.5664087	L	
66	UCAC4 621-112859	314.4579859	+34.1641767	13.84(NOMAD)	?	~0.15	1432.5597351	L	(27)
67	UCAC4 617-116284	315.4994471	+33.3210739	14.90(NOMAD)	?	~0.5	1127.3687558	L	
68	UCAC4 598-126361	317.6277274	+29.4905828	12.48	?	~0.2	1443.4864670	L	
69	UCAC4 621-122572	321.8936342	+34.0494003	12.09	0.43635 (0.438)	~0.1	1445.5736404	EW	(28)
70	UCAC4 590-130214	326.9765700	+27.9013675	12.71	~36	~0.2	1135.4185368	L	(29)
71	UCAC4 590-130270	327.0770353	+27.8228681	12.49	1.02500 (1.025)	~0.25	1127.3844791	EW	(30)
72	UCAC4 652-105561	327.4152459	+40.3802687	14.33	?	~0.35	1443.4839005	L	
73	UCAC4 588-128603	330.1270789	+27.4577517	12.72	4.21221 (1.29)	~0.08	1459.5047071	ROT?	(31)
74	UCAC4 789-036290	330.5805324	+67.6531512	16.00(GSC2.3)	0.17 (0.34)	~0.15	1127.3607291	DSCT (EW)	(32)
75	UCAC4 788-037466	330.9508409	+67.4961639	14.29(GSC2.3)	0.47	~0.4	1127.3602622	EA	
76	UCAC4 788-037537	331.1173995	+67.4969889	13.66(GSC2.3)	?	~0.16	1127.3602622	L	
77	UCAC4 788-037577	331.2463553	+67.5745589	15.62(GSC2.3)	0.36	~0.25	1127.3607291	EW	
78	UCAC4 726-083454	333.0765986	+55.1851717	14.67	?	~0.18	1127.3607291	L	
79	UCAC4 725-086173	333.2373680	+54.9382473	13.34	0.192835	~0.2	1127.3607291	DSCT?	
80	UCAC4 725-086241	333.2829348	+54.8638348	14.33	0.17234	~0.5	1443.4626241	DSCT?	
81	UCAC4 781-040386	333.4526621	+66.1133137	15.43	1.13	~0.2	1127.3604366	EB	
82	UCAC4 726-084171	333.5242624	+55.0744792	12.13	~50	~0.15	1127.3604366	L	
83	UCAC4 859-013147	343.6693409	+81.7063873	12.72	37	~0.17	1385.653719	L	
84	UCAC4 749-082493	352.8942900	+59.7192198	10.64	0.861	~0.2	1146.4200537	EW	

Note. — (1) Star 1SWASPJ001046.35+584111.0, 1837 points analyzed. APACHE data are less scattered than those of SWASP. (2) Star 1SWASPJ001050.47+583342.6, SWASP data with high scatter, 1969 over 2015 data analyzed (applying a 1-sigma clipping to the original data). (3) Eclipsing binary already known in VSX (Mis V1368) but the orbital period was not reported. (4) The light curve is discussed separately in Fig. 4. No SWASP data available for this star. (5) Only the primary minimum detected. (6) Star 1SWASPJ052950.48+315439.8, 7033 over 7110 data points from SWASP analyzed (applying a 3-sigma clipping to the original data). The secondary minimum appears deeper in the light curve from the APACHE survey. Refere to Fig. 2 for a comparison between SWASP and APACHE light curves. (7) Star 1SWASPJ060809.97+334016.5, 6223 over 6282 data points from SWASP analyzed (applying a 3-sigma clipping to the original data). The existence of a secondary minimum can be guessed from the APACHE light curve, while is not visible in SWASP data (not showed here). (8) Tentative period, but the phase coverage does not make possible a reliable estimation. (9) Star 1SWASPJ070307.60+344203.60, 4066 over 4305 data points analyzed (applying a 2-sigma clipping to the original data). Even with few data points, this faint star appears to be an eclipsing binary system in the APACHE photometry. From data of the SWASP public archive we derive the best period $P=0.21635$ days, that in this case we adopted for folding our data because is a far better estimate than that from APACHE data. This star is discussed separately in §4. (10) Star 1SWASPJ070342.10+525256.8, noisy light curve, 1094 over 1258 data points from SWASP analyzed (applying a 1-sigma clipping to the original data). (11) Star 1SWASPJ115757.51+423945.5, 5509 data point analyzed. From APACHE photometry alone, because the data are few, we could only guess that the star has a short period (<1 day), but a reliable determination was not possible. SWASP photometry helped us in classifying the star variability and estimating a reliable period. We show part of the APACHE light curve and the SWASP data in Fig. 5. (12) Star 1SWASPJ135233.09+314113.8, 7348 over 7425 data analyzed (applying a 3-sigma clipping to the original data). (13) Star 1SWASPJ152845.99+430530.1, 5387 over 5428 data analyzed (applying a 3-sigma clipping to the original data). Spotted star. Color indexes $B-V=0.98$, $V-J=1.78$, $V-K=2.39$. Tentative spectral classification: dK3/dK4. (14) Appears in Kopacki et al. (2003). V from Sandquist et al. (2010). (15) Appears in Kopacki et al. (2003). (16) Star 1SWASPJ185523.32+542551.4, 11972 over 12016 data analyzed (applying a 3-sigma clipping to the original data). (17) Observations in V band. Color indexes: $B-V=0.95$, $V-J=1.7$, $V-K=2.33$ (18) In on-line archive images it appears as a blended object. Faint, no V available. (19) Faint object in on-line archive images. (20) Star 1SWASP192317.5+553936.2, 12861 over 12919 data analyzed (applying a 3-sigma clipping to the original data). Results for this star are discussed separately in §4. (21) Star 1SWASPJ192358.37+553316.9, 12469 over 12596 data analyzed (applying a 3-sigma clipping to the original data). (22) Star 1SWASPJ192555.70+5530002.9, 12934 photometric points used in the analysis. (23) Undefined type of pulsating star. Modulation possibly due to rotation. We provide a more conservative uncertainty than that calculated as $1/\text{timespan}$. (24) Star listed in the International Variable Star Index (NSVS J2012124+341522) and classified as L. The reported periodicity of 88 days is not found in our data, that clearly show that the possible period should be longer. (25) Star 1SWASPJ202533.73+583913.9, 10637 over 10721 data points analyzed (applying a 3-sigma clipping to the original data). Because of its uncertain classification, this star is discussed separately in §4. (26) Star 1SWASPJ202538.05+584537.4, 10485 over 10550 data analyzed (applying a 3-sigma clipping to the original data). The primary minimum is not well sampled in the APACHE light curve. (27) Star listed in the International Variable Star Index (NSV 25408) and classified as an eclipsing binary, but without an estimate of the orbital period. No evidence for eclipses is present in the APACHE data. Rather, the star appears as an irregular variable. Thus we propose a change of variability status for this star. (28) Star 1SWASPJ212734.47+340257.9, 14781 over 14872 data analyzed (applying a 3-sigma clipping to the original data). (29) Long periodicity, assumed

tentatively nearly equal to 36 days by looking at the light curve. (30) Star 1SWASPJ214818.48+274922.0, 14086 over 14151 data analyzed (applying a 3-sigma clipping to the original data). (31) Star 1SWASPJ220030.52+272728.8, 21352 over 21499 data analyzed (applying a 3-sigma clipping to the original data). This star is discussed in detail in §4. Even if the classification remains uncertain, based on SWASP data we suggest this could be a rotating star. (32) Difficult classification, faint star/noisy light curve. We propose two possibilities, with corresponding periodicities.

Table 2. Most significant periods found for the star UCAC4 588-128603 by applying the Lomb-Scargle algorithm to the SWASP and APACHE data. The periods are listed in order of decreasing spectral power. Despite the different number of data points from the two surveys, similar periods are retrieved in both datasets, but not in the same order. Values are rounded to the last, significant digit.

Lomb-Scargle periods (SWASP)	Lomb-Scargle periods (APACHE)
(days)	(days)
4.21221	1.29
0.80635	4.01
4.16551	0.81
1.30667	0.44
4.26001	-
0.44585	-

Chapter 5

Photometric analysis of stellar activity in support of spectroscopy: the synergy between APACHE and the GAPS programme

5.1 Introduction

When talking about the different ways used by astronomers to detect extrasolar planets, the two most successful indirect techniques -the radial velocity method and the search for photometric transits- have been typically used independently from each other. The discoveries made by photometric transit surveys have been necessarily confirmed by follow-up measurements of the stellar radial velocity variations to measure the mass of the planetary companion, and initial detections of stellar companions made via spectroscopy have driven follow-up photometric observations to search for transits for measuring the planetary radius. Collecting photometric and spectroscopic time series for the same sample of stars during the same observing season represents a strategic opportunity to search for and characterize new worlds orbiting other stars for several reasons. If a periodic signal probably due to a planetary companion is found in spectroscopic or photometric data of a star, the discovery made by the survey which uses one of the two techniques will immediately influence the priorities -thus the observing schedule- of the other survey. Thanks to a synergy like this, a successful detection of a transit will have as an immediate

result the measurement of the physical and orbital parameters of the planet, in particular its bulk density. Generally speaking, the photometric time series which are obtained at the same epochs of spectroscopic measurements represent a relevant support for characterizing the levels of stellar activity, which might be an important source of noise in stellar radial velocity measurements. This is a very relevant issue which can be responsible for false detections, especially in case of Earth-mass planets that produce small-amplitude RV variations. The contents of this Chapter are mainly related to this topic, which is particularly important when dealing with M dwarfs, because in general these stars are expected to show quite high levels of activity and a clear picture about their variability (intrinsic jitter), both photometric and spectroscopic, is still not well understood. [Queloz et al. \[2001\]](#), to cite an example of such kind of problematics related to Sun like stars, have showed that the surface magnetic activity on the star HD 166435 mimics the kind of radial velocity variations observed in stars with true planetary reflex motions, and from the analysis of time series of the spectroscopic line profiles, photometric data, and of a chromospheric activity index they demonstrated that stellar activity is actually the source of the radial velocity variations. Going back to red dwarfs, in the works of [Bonfils et al. \[2007\]](#) and [Forveille et al. \[2009\]](#), about a planetary companion around the M dwarfs GJ 674 and Gl 176 respectively, the photometric variability of the hosting stars was studied, after the detection of the companions in the RV, to look for evidence of rotational modulation induced by active regions/stellar spots. They could measure stellar rotation periods of ~ 35 and ~ 38 days, well distinct from the orbital periods of the planets (~ 4.7 and ~ 8.8 days respectively), and this evidence served for confirming their existence. These studies, together with several others, firmly demonstrate that a deep understanding and characterization of the effects of the stellar activity on photometry and spectroscopic parameters is necessarily required to differentiate them from those imputable to planets. It is worth mentioning here the interesting works of [Oshagh et al. \[2013\]](#) and [Boisse et al. \[2012\]](#), which could be an useful tool to consider in future to support the study described in this Chapter. They developed and made available to the community the software SOAP (Spot Oscillation And Planet), a package that simulates the effect of stellar spots and plagues on radial velocity and photometric time-series. They applied their model to real data, characterizing the variations of the radial velocity, line bisector, and photometric amplitude as a function of several variables (projected stellar rotational velocity, filling factor of the spot, resolution of the spectrograph, linear limb-darkening coefficient, latitude of the spot, and inclination of the star). The aim of SOAP is precisely that of distinguishing the reflex-motion due to a planetary companion from stellar activity-induced radial velocity variations.

Since the summer of 2012, almost in coincidence with the beginning of the APACHE observations, a strategic synergy between a photometric and spectroscopic survey materialized with the start of the GAPS programme (Characterizing the Global Architectures of Planetary Systems) at the Telescopio Nazionale Galileo (TNG), which is still ongoing (see [Covino et al. \[2013\]](#), [Desidera et al. \[2013\]](#) for the first results of GAPS). GAPS is an ambitious, challenging, long-term, manifold observational program that makes use of the exquisite capabilities provided by the spectrograph HARPS-N, which are unrivalled in the Northern Hemisphere. This project represents a milestone for the ground-based exoplanet science and it aims to characterize the global architectural properties of exoplanetary systems through several objectives: 1) determining the frequency of potentially habitable low-mass companions to northern low-mass stars; 2) testing planet formation and migration theories by searching for additional (low-mass) companions in known single- and multiple-planet systems; 3) deriving the first quantitative estimate of the frequency of Neptune-mass planets around northern low-metallicity stars; 4) undertaking a novel study to measure the occurrence rates of giant planets in dense stellar environments; 5) investigating the outcome of planet-disk and planet-planet interaction scenarios in exoplanet systems through innovative measurements of the Rossiter-McLaughlin effect; 6) providing novel measurements for the characterization of tidal dissipation effects due to the interaction between the planets and their host stars, for the understanding of the impact of star-planet interactions on stellar activity, and for the improvement of relevant physical parameters (masses, radii) of selected planet hosts. What is of interest here is stated in the first point. A sub-sample of more than 100 targets observed with HARPS-N is represented by bright M dwarfs, around which it should be possible to detect rocky planets thanks to the favorable mass ratio between the planet and the star. In fact, the resulting moderately large RV amplitudes of few m s^{-1} (e.g. [Charbonneau et al. \[2009\]](#)) are detectable with present-day precision measurements guaranteed by HARPS-N. Since GAPS was conceived, because some members of the APACHE Team are actively involved in the project it was obvious to foresee the inclusion in the list of the GAPS M dwarfs of a conspicuous number of targets inserted in the AIC. These have been included in the APACHE observing schedule by giving them the highest priority, and securing them with an observing timespan as long as the GAPS survey. I am collaborating to the GAPS programme as an observer and by performing a combined analysis of the photometric (APACHE) and spectroscopic (HARPS-N) data of the shared targets, which have been defined also with my contribution. The main goal of my study (which is the subject of this Chapter) was helping the GAPS team in searching for evidence of photometric variability in the observed M dwarfs and its characterization, which could be useful for a correct interpretation of the signals found in the

RV that are potentially ascribable to a planetary companion. The analysis of the APACHE light curves represents indeed the added value to this study, especially for their usefulness in measuring the rotation period of the observed M dwarfs, that can appear also as a signal in the RV data. However, after one single observing season this study must be necessarily considered as preliminary and only indicative of the potential represented by the synergy between APACHE and GAPS. Anyway, what is important to underline here is that the results obtained from APACHE have an immediate effect to the GAPS schedule, and viceversa, and this represents a great difference with the mentioned past studies, which used photometry as a follow-up study of those targets showing interesting signals in the RV. Evidence of stellar activity (e.g. flares) and of rotational modulation in the light curve of a target (accompanied by a measurement of the stellar rotation period) are immediately communicated to the GAPS team for considering the rejection of the M dwarf from the schedule. Conversely, spectroscopic measurements can reveal immediately that a target is actually not an M dwarf (e.g. a giant star or a early type ZAMS star), or that it is actually a binary system or a fast rotator. All these informations are shared immediately with the APACHE team, and they are used to remove the target from the observing list. What I have just stated actually has already happened in some occasions (for instance, the targets apache 2874 and apache 2961 showed to be an active star and a fast rotator respectively from the analysis of the photometric data, as discussed in Chapter ??), with an evident benefit for both the surveys.

In perspective, it is important to consider an effect that can be studied only after collecting data over a timespan of years: the change in the density of spots along the stellar magnetic cycle. This effect can also induce variations in RV and spectroscopic indices that can be erroneously attributed to a planetary companion. A very interesting work about this topic is that of [da Silva et al. \[2012\]](#). They have monitored the magnetic activity of a sample of 27 red dwarfs with the HARPS spectrograph with the purpose of revealing any correlations between the long-term activity variations and the observed RVs. As a proxy of the stellar activity the authors used the NaI index, which is then compared to simultaneous measurements of radial velocities and other relevant parameters of the spectral cross correlation function (CCF), as the bisector inverse slope (BIS) and the FWHM, which are good diagnostics of stellar activity. Their sample has been observed for a median timespan of 5.9 years, much longer than the single observing season of the GAPS programme considered in this Thesis. Among the conclusions to their work, [da Silva et al. \[2012\]](#) invite the planet hunters "to carefully check for long-term activity variations when analysing long timespans of RV data since activity cycles could be adding noise to the data or even mimicking the low-amplitude ($<5 \text{ ms}^{-1}$) signals

of planetary companions”. After the nominal five years of survey, it should then appear evident what can be the unvaluable contribution of the APACHE database to the analysis of the long-term photometric behaviour of the M dwarfs which will be spectroscopically monitored by GAPS and forthcoming surveys.

5.2 Preliminary results for a sample of APACHE M dwarfs observed with HARPS-N

After more than one year since the beginning of the observations for the GAPS programme, a good number of spectra have been collected for several targets. For almost all of them we have collected many photometric data points, which in some cases already give an insight into the level of activity of the stars. Here I show some preliminary results of the spectro-photometric combined study which I have performed for 25 targets, by analysing the behaviour of some spectroscopic parameters and the APACHE time-series in order to characterize their activity (intrinsic jitter). I summarize the results in Tables 5.1 and 5.2. The analyzed spectra are those collected by the end of November 2013, and the stars considered are only those with photometric measurements already secured by APACHE, with their general photometric results discussed in Section §4.3. I have included in the analysis also those targets with still few observations with HARPS-N but with a good photometric coverage guaranteed by APACHE. I refer to [Desidera et al. \[2013\]](#) for a general description of the HARPS-N spectrograph. In my analysis I have focused the attention on those spectroscopic parameters which are related to the activity of the stars, in particular on the bisector velocity span, as defined by [Queloz et al. \[2001\]](#), and the FWHM of the CCF, by looking for correlations with the radial velocity variations. Moreover, I have analyzed the behaviour of some chromospheric activity indicators based on the CaII H and K, H α , HeI D3, and NaI D1 lines, by looking for correlations among them and for periodicity in their time-series. These indicators have been calculated as explained in [da Silva et al. \[2011\]](#). Spectra acquired from the end of September until middle of November 2012 have not been considered for the analysis because of a failure of the HARPS-N CCD. Observations have been carried out during that period with only half chip working, but the data can not be considered fully reliable. Concerning the photometric results presented in Table 5.2, the values of the RMS measured for the seasonal light curves are the lowest between those determined by the two different photometric methods used by the TEEPEE pipeline, as described in §3.6. Some considerations about single targets are reported as notes at the bottom of Table 5.2. For a couple of targets, we have also analyzed

the light curves collected by the SuperWASP survey and publicly available at the SuperWASP on-line archive¹.

¹<http://exoplanetarchive.ipac.caltech.edu/applications/ExoTables/search.html?dataset=superwasptimeseries>

TABLE 5.1: Summary of the spectroscopic measurements for a sample of M dwarfs observed jointly by the surveys GAPS and APACHE.

ID	ID	# data	Mean photon noise	RV RMS	RV period	Corr. coeff.	Corr. coeff.	Activity index
(GAPS)	(APACHE)		(m s ⁻¹)	(m s ⁻¹)	(days)	(BIS vs RV)	[CaII(H&K) vs H _α]	period (days)
M2	6	28	1.11	4.32	-	-0.35	0.97	CaII(H&K): 0.338 (FAP=0.003) H _α : 0.338 (FAP=0.023)
M7	3122	29	9.35	293.23	100 (FAP=0.007)	+0.02	+0.02	-
M8	419	9	1.42	3.68	-	-0.06	0.75	-
M9	160	8	1.29	3.23	-	-0.23	+0.88	-
M10	418	2	1.49	1.1	-	-	-	-
M12	301	1	-	-	-	-	-	-
M17	3126	17	1.74	2.75	-	+0.04	0.6	-
M27	3083	10	3.12	236.55	-	-0.79	+0.98	H _α : 1.77 (FAP=0.46)
M28	2995	9	3.00	3.55	-	-0.02	+0.45	CaII(H&K): 0.39 (FAP=0.08)
M30	647	21	1.43	4.08	-	-0.53	+0.81	-
M31	822	25	13.14	72.41	~150?	+0.08	-0.09	-
M34	611	11	2.04	5.96	-	+0.22	+0.71	CaII(H&K): 0.42 (FAP=0.13)
M36	833	9	2.42	3.25	-	-0.41	+0.29	-
M40	467	1	-	-	-	-	-	-
M52	2864	1	-	-	-	-	-	-

Continued

M53	932	7	2.18	2.94	-	+0.18	-0.23	-
M56	1436	31	3.22	18.97	-	-0.12	+0.15	-
M59	2650	10	2.44	5.26	-	-0.33	+0.85	-
M62	1040	8	6.69	14.75	-	-0.17	+0.99	-
M76	3300	10	1.38	9.81	-	-0.41	+0.76	-
M86	3301	4	2.54	7.15	-	+0.73	-0.2	-
M98	2459	4	2.73	4.84	-	-0.66	+0.81	-
M99	2433	3	1.57	-	-	-	-	-
M100	2174	4	1.99	2.43	-	+0.27	+0.6	-
M101	2173	4	1.82	4.09	-	-0.97	+0.97	-

TABLE 5.2: Summary of the photometric measurements for a sample of M dwarfs observed jointly by the surveys GAPS and APACHE.

ID (GAPS)	ID (APACHE)	Expected median noise (mag)	Observed seasonal RMS (mag)	Photometric period (days)	Note
M2	6	0.006	0.014	12.9 (FAP=0.0001)	(1)
M7	3122	0.006	0.02	-	(2)
M8	419	0.007	0.004	-	(3)
M9	160	0.005	0.0088	-	
M10	418	0.0074	0.004	-	(3)
M12	301	0.0068	0.0127	-	(4)
M17	3126	0.0054	0.0068	-	
M27	3083	0.0056	0.0075	-	(5)
M28	2995	0.0053	0.006	-	(6)
M30	647	0.0051	0.0142	-	
M31	822	0.0066	0.0078	-	
M34	611	0.0064	0.0063	-	
M36	833	0.0052	0.024	-	
M40	467	0.005	0.005	-	
M52	2864	0.0067	0.0072	-	(7)
M53	932	0.0056	0.0124	-	(8)
M56	1436	0.003	0.009	-	(9)
M59	2650	0.0062	0.009	-	

Continued

M62	1040	0.0058	0.0105	-	
M76	3300	0.0062	0.0103	-	(10, 11)
M86	3301	0.0154	0.0048	~12? (FAP=0.0001)	(10, 12)
M98	2459	0.0057	0.0076	-	
M99	2433	-	-	-	
M100	2174	0.005	0.005	-	
M101	2173	0.006	0.015	-	(13)

(1) The periodicity observed in the activity indicators CaII(H&K) and H α could be due to the window function. In Fig. 5.1 we show the APACHE light curve (*top*), folded according to the tentative period $P \sim 12.9$ days, and (*last panel*) the light curve of the same star collected by the WASP survey. A Lomb-Scargle analysis of the WASP data results in the most prominent peak in the periodogram at $P \sim 15.5$ days, with the second most significant periodicity at $P \sim 10.7$ days. Then, from the APACHE and WASP photometry it seems that a periodic modulation with P of the order of 10 days is present for apache 6, possibly related to the rotation period of the star. (2) For this target there are 5 epochs with both spectroscopic and photometric measurements. (3) Very stable light curve. (4) More than 5000 photometric data points collected by APACHE. (5) Evidence for anti-correlation between the bisector velocity span and RV. Evidence for flux increase in the APACHE light curve after a gap of more than ~ 200 days (see Fig. 5.2). (6) The periodicity found for the CaII(H&K) index is not present as a peak in the spectral window. APACHE photometric data show that this star is particularly quiet over a timespan of nearly 100 days, with a low average intra-night RMS (below 0.002 mag). (7) APACHE observed this star flaring, as discussed in §4.6. (8) As already showed in Fig. 4.3, APACHE photometric data show that this star has decreased its magnitude of 0.02 mag (on average) -thus becoming brighter- over a timespan of nearly 100 days. Fig. 5.3 presents again the light curves of this star. Spectroscopic measurements by GAPS are subsequent those of APACHE discussed in this Thesis. (9) Photometric data collected with the 81 cm telescope in OAVdA. The star is monitored by one of the APACHE telescopes since November 2013. (10) Star initially not in the Apache Input Catalogue because too bright. It has been subsequently scheduled after it was included in the GAPS target list. Photometric observations are carried out with the V filter. (11) For this target there are 5 epochs

with both spectroscopic and photometric measurements. No clear correlations are seen between the spectroscopic parameters RV, bisector and FWHM and the differential magnitude. **(12)** The significance of the tentative rotation period found using the APACHE photometric data has been investigated through a bootstrap analysis. The folded light curve and the CLEAN periodogram are showed in Fig. 5.4. This star is also in the on-line SuperWASP database and named 1SWASPJ174533.55+465119.4. The WASP light curve is composed of more than 33,000 points, but it appears very noisy, probably with complications due to saturation. For this reason we could not use it to strengthen the significance of the signal found in the APACHE dataset. **(13)** Even though four spectra have been taken, an interesting anticorrelation is observed between the bisector velocity span and RV which could explain the observed RV jitter in terms of stellar activity. This target has been observed for a long period by APACHE during two main temporal segments separated by ~ 300 days, and the photometric time-series were showed in Fig. 4.3. The seasonal light curves, which we show again in Fig. 5.5, clearly show that after nearly one year this star changed its activity level, with the mean differential magnitude and the point scatter increased in the second temporal block. We did not find evidence for rotational modulation in the light curve.

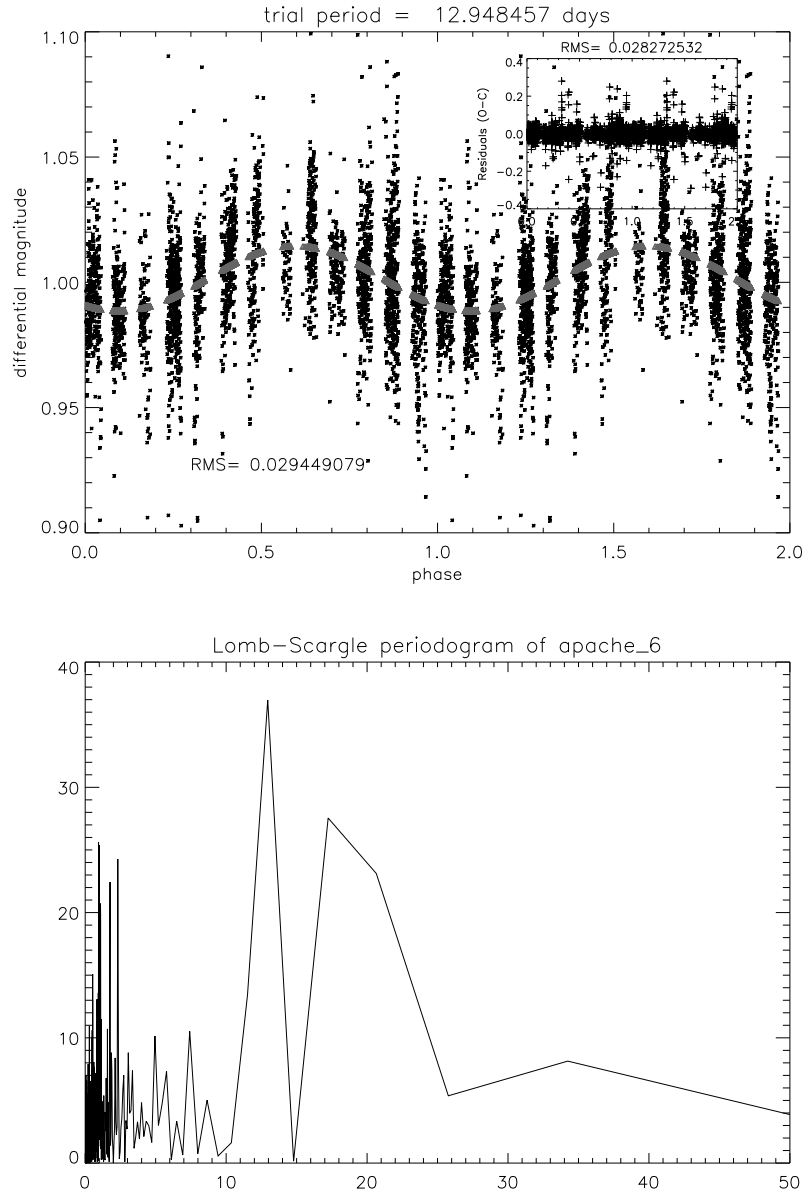
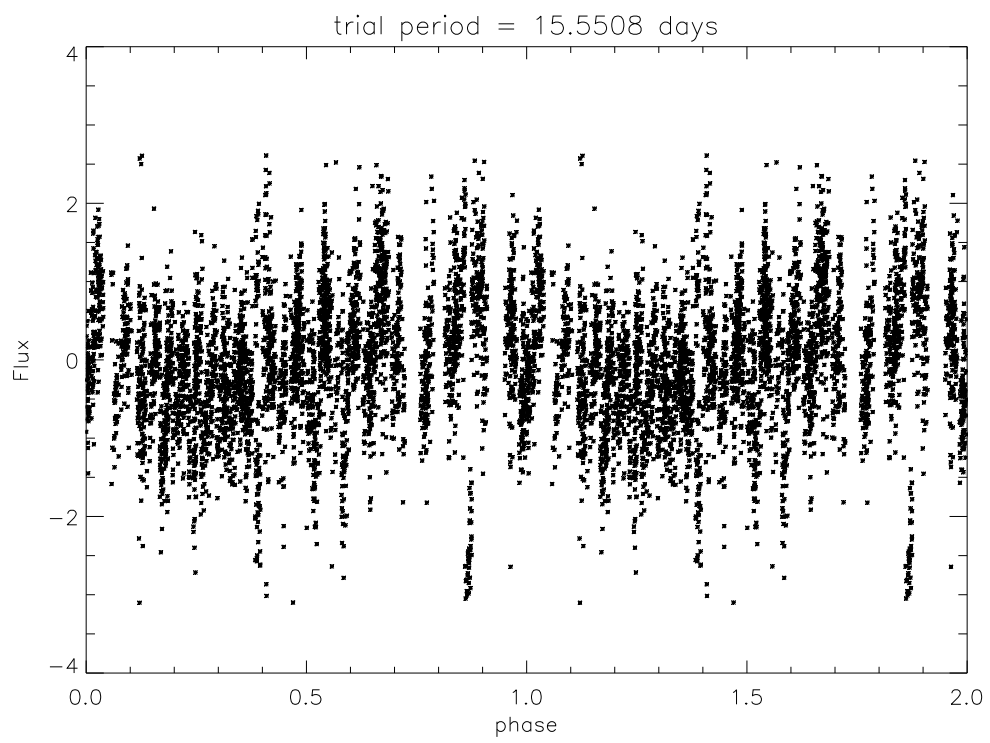


FIGURE 5.1: APACHE light curve of the target APACHE 6 (*top*), folded according to the most significant period found by using the Lomb-Scargle algorithm applied to the complete series of data (i.e. without binning). The points in gray represent the best-fit sinusoidal function of period $P=12.948457$ days applied to the data. The small nested plot shows the sinusoidal fit residuals. The L-S periodogram for the APACHE data is showed in the second plot. The last panel shows the WASP light curve folded at the best period found in this dataset.

FIGURE 5.1: *continued*

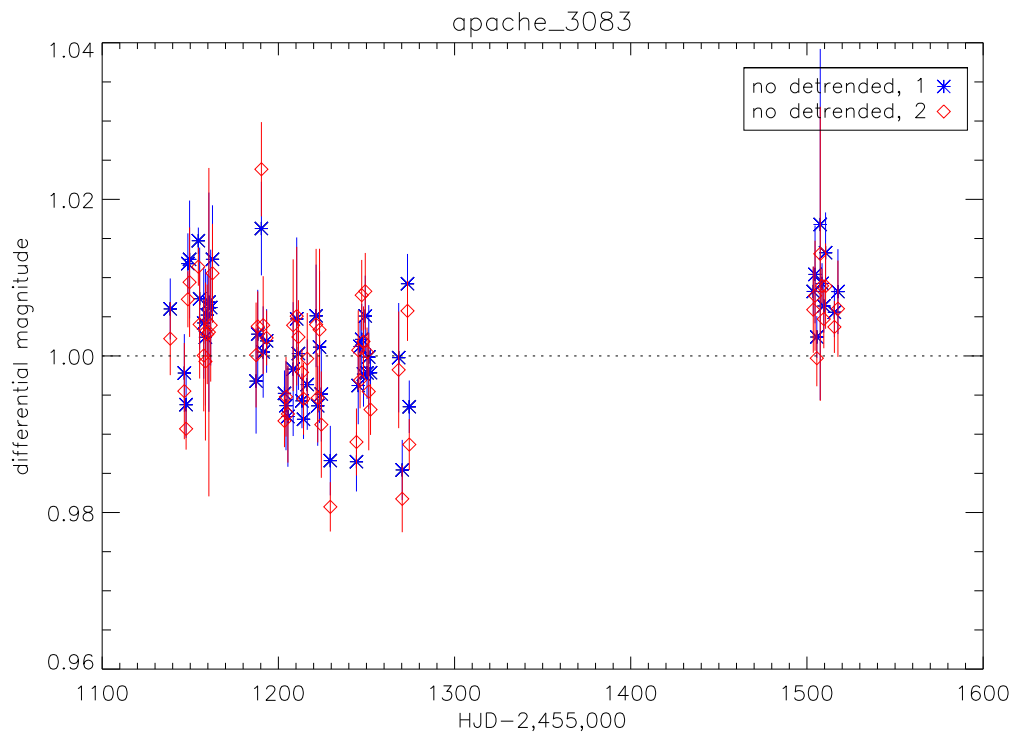


FIGURE 5.2: APACHE seasonal, no detrended light curves of the target APACHE 3083, obtained with the two photometric methods applied by the TEEPEE pipeline to select the best aperture radius and set of comparison stars. Both light curves show that the star has increased its mean brightness from December 2012 (first segment of data) to July 2013 (second group of data).

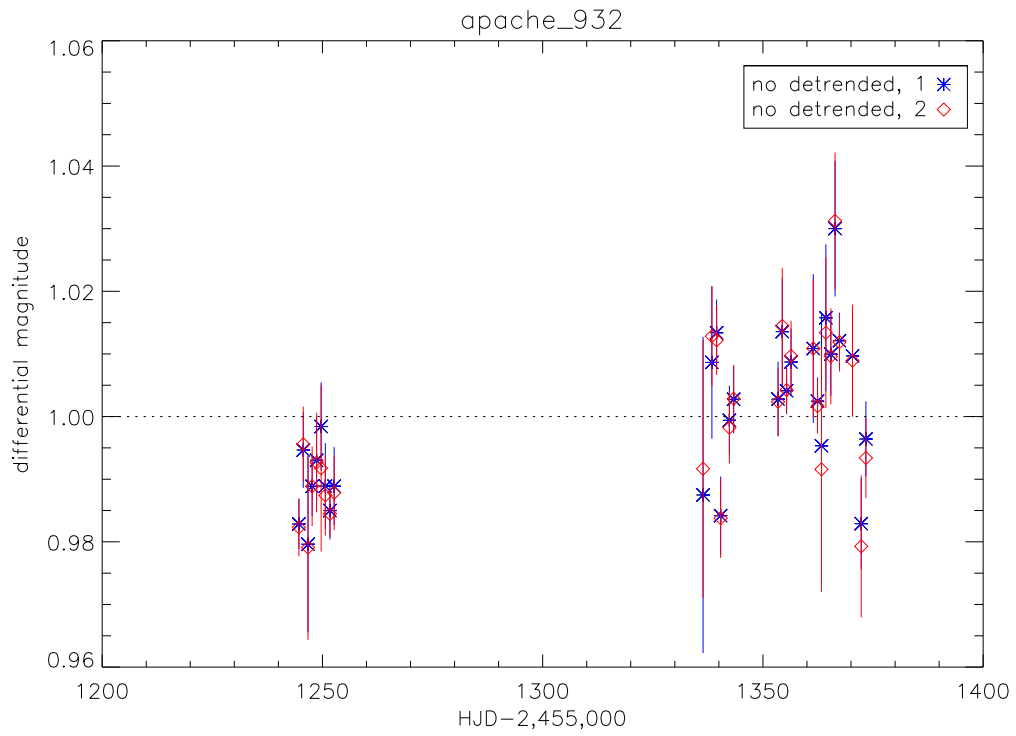


FIGURE 5.3: APACHE seasonal, no detrended light curves of the target apache 932, obtained with the two photometric methods applied by the TEEPEE pipeline to select the set of best aperture and comparison stars. Both light curves show that the star increased its mean brightness passing by the first observing segment to the second, separated by a gap of ~ 100 days.

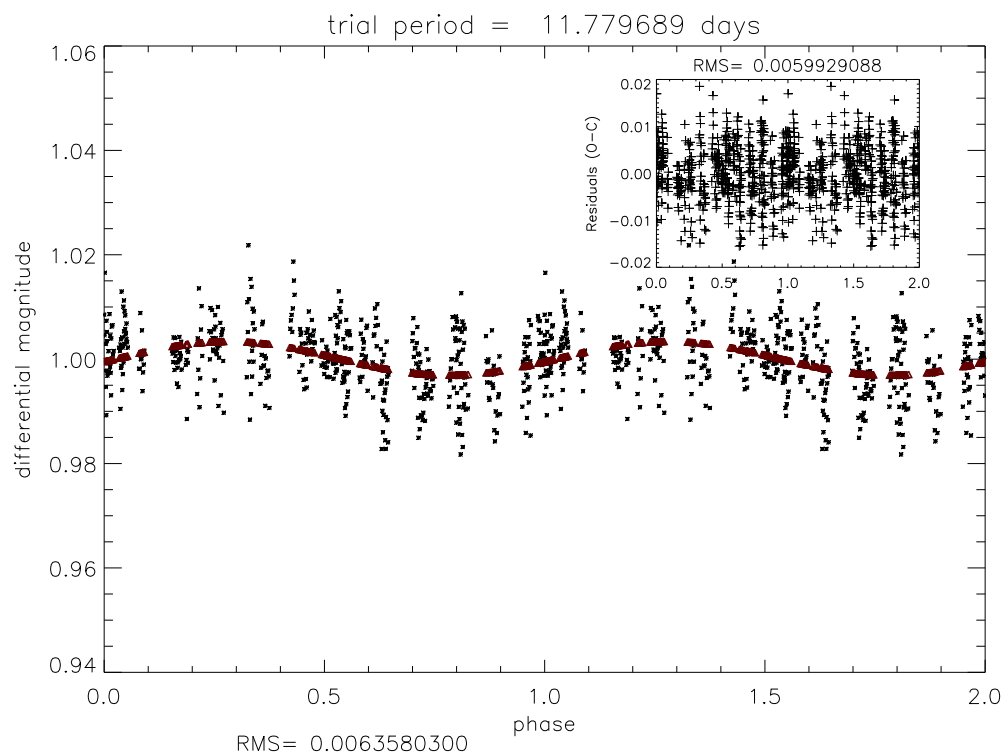
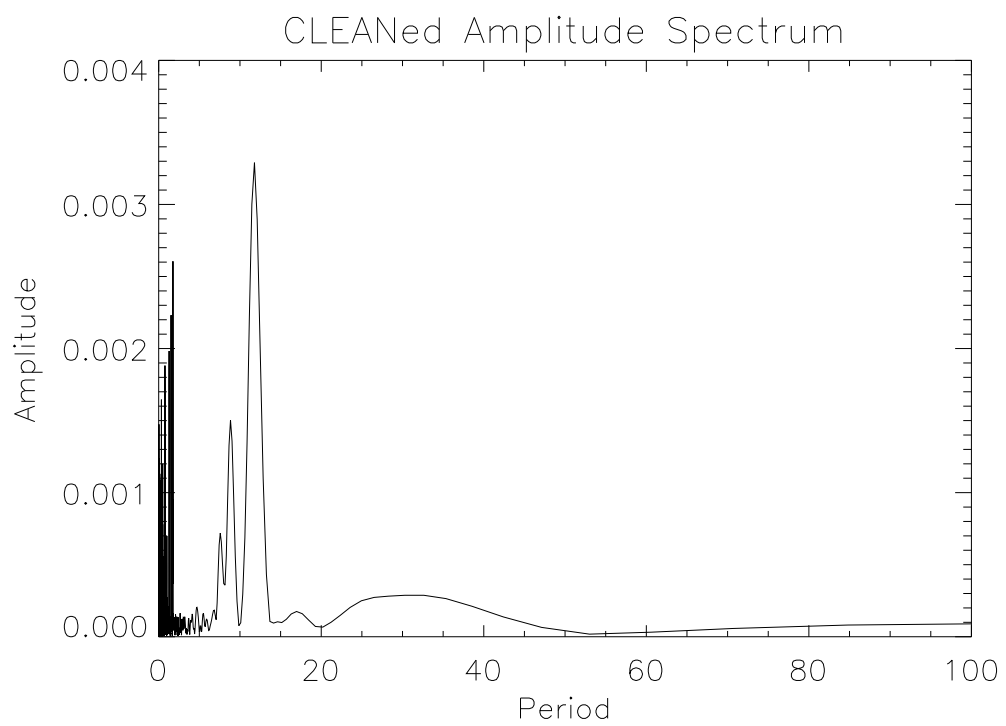


FIGURE 5.4: APACHE light curve of the target APACHE 3301 (*top*) folded according to the most significant period found by the CLEAN algorithm. The points in red represent the best-fit sinusoidal function of period $P=11.779689$ days applied to the data. The CLEAN periodogram is showed in the second plot. A similar periodicity has been found with the Lomb-Scargle algorithm, but with the RMS of the residuals slightly higher than that corresponding to the CLEAN solution. No significant peak appears in correspondence of this period in the window function (not showed here). This signal could be related to the rotation of the star, but more data will be collected to improve the sampling and verify this detection.

FIGURE 5.4: *continued*

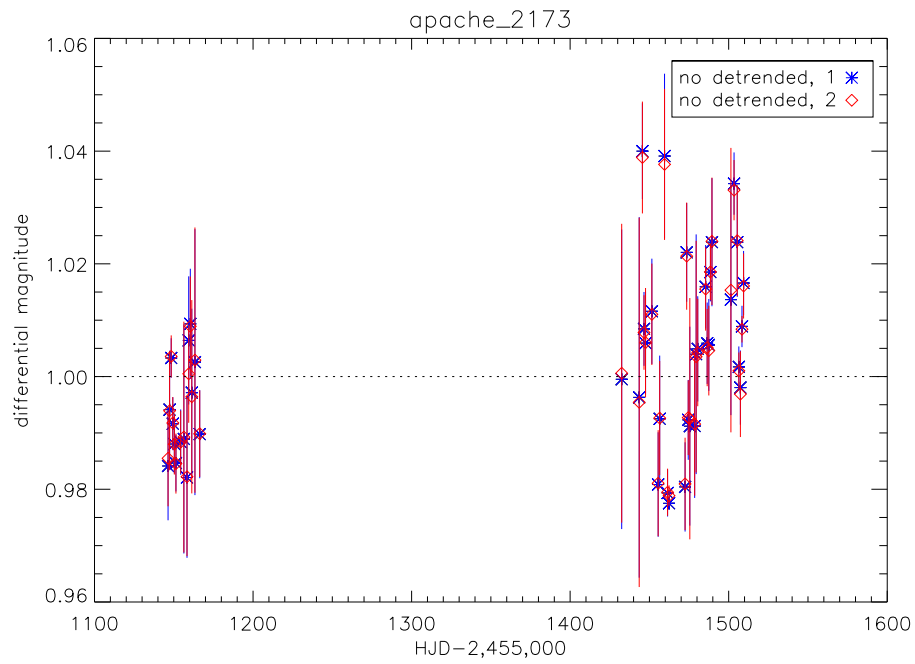


FIGURE 5.5: APACHE seasonal light curve of the target APACHE 2173 (GAPS M101), obtained with both the photometric methods used by the TEEPEE pipeline and without any detrending applied (the light curves detrended with the SysRem algorithm show a similar behaviour). This star shows evidence of long-term photometric variability, and this information can be useful for interpreting the spectroscopic data collected by HARPS-N.

Chapter 6

Conclusions and future prospects

In this Thesis I have described much of the history of the APACHE Project which encompasses five years of work in which I have been involved since the beginning. At present, APACHE is the only European operational survey completely designed for detecting small-size planets transiting early-to-mid type M dwarfs, by using an array of five automatic 40 cm telescopes. I have discussed the major steps undertaken to make the survey operational, and I have presented the most significant results after the first season of routine observations, demonstrating that the state of the Project is already well advanced. All the telescopes are properly working and we are capable of processing in an homogeneous way the great amount of photometric data already collected. Thus we can react quickly in case of detection of a promising transit signal, at first by organizing a follow-up campaign with the 81 cm telescope hosted in OAVdA, the same observing site where APACHE is carried out. However, after the first year APACHE has not yet found a strong transit candidate, and this is not surprising taking into account that the observations are carried out from a single location. We need to be patient and keep trying. Despite this, one major point I hope I have presented and discussed clearly in this Thesis is the great potential of the APACHE survey not only in discovering new worlds but also for improving our knowledge about the astrophysics of M dwarfs. As a point of great relevance, I have discussed the very strategic synergy between APACHE and the GAPS programme, underlying the importance for a challenging spectroscopic survey as GAPS to be supported by photometric observations collected during the same epochs (Chapter 5). This synergy could help in characterizing the stellar activity and in correctly interpreting possible periodic signals found in the radial velocity time series. Being part also of the GAPS team has been a great opportunity for me to be involved for

the first time in the analysis and interpretation of spectroscopic data applied to the search for new worlds. Surely, considering its importance, I plan to continue my work about the characterization of the M dwarfs atmospheric activity exploiting the potential of both the APACHE and GAPS surveys.

The data collected by the APACHE telescopes during the first season are particularly precious because they represent the first test bench for our team for identifying the weak points of the survey. The global results about the sample of M dwarfs monitored so far by APACHE will be discussed in detail in the near future for correcting and improving the observing strategy, in order to increase the chances of a planetary transit detection. For instance, we noticed that, as expected, the SNR of some targets can be improved by increasing the exposure times of the images, so we need to revise the algorithm for an automatic assignment of the exposures discussed in Chapter 3. Moreover, we need to define an appropriate strategy for identifying automatically the most significant transit candidates, while progressively new data are collected, and this not only a-posteriori but, preferably, while observations are ongoing, so that an immediate follow-up can be promptly set up.

A point not discussed here and that I plan to explore in the future is the impact of the correlated noise on the detection of periodic signals due to the stellar rotation. The results discussed in Chapter 4 have been obtained by applying the bootstrap analysis over the full timespan of observation, thus assuming that the data are only affected by white noise: each photometric point can be permuted and associated to each time stamp in the time series. As a preliminary approach to be investigated, the effects of red noise could be assessed by considering permutations of data blocks in a short time intervals, for instance initially by assuming a single night. The data points of such an interval stay anchored to it, but new time stamps are built from those of a different night. This way of applying the bootstrap analysis should "destroy" the contribution of the correlated noise over a time scale of a single night, thus making a detection of a periodic signal more robust.

About the determination of stellar rotation periods, considering that during the first season we have found evidence in the light curves of a rotational modulation for at five M dwarfs in the Apache Input Catalogue, we are confident to concretely increase the number of targets for which such an estimate will be possible. The modelling of the folded light curves can be an interesting outcome of this analysis, and for the work of this Thesis I have continued to apply a simple single-spot model to reproduce the observed changes in the stellar flux. Modelling the light curve of rotating stars in terms of stellar atmospheric inhomogeneities can be very helpful for characterizing the variations of the radial velocity and other spectroscopic

parameters as a function of variables like the projected stellar rotational velocity, filling factor of the spot, latitude of the spot, and inclination of the star. Interesting results have been obtained for example with the SOAP tool [Boisse et al., 2012] [Oshagh et al., 2013]. For future studies, the APACHE team is planning to improve the modelling of the M dwarfs light curves, whose results can be very useful mostly for the GAPS community.

The APACHE long-term photometric database could be very useful in the coming years for measuring the trigonometric parallaxes of the nearby, target M dwarfs, in many cases improving old existing estimates. Very recently this by-product of a targeted, long cadence survey as APACHE has been demonstrated to be handy by the MEarth team [Dittmann et al., 2013]. Using the photometric data collected by the MEarth telescopes over a multi-month baseline, they have measured the trigonometric parallaxes for 1507 stars, demonstrating that the scientific yield from the MEarth survey extends far beyond the goal of finding planets: in the same way, APACHE could yield a precious contribution into a better understanding of the astrophysics of M dwarfs. In fact, following the promising results of Dittmann et al. [2013], the potential of the APACHE photometry for astrometric measurements of nearby cool stars will be investigated by our team almost for free, with just a simple revision of the observing strategy. Once the parallax of some APACHE targets could be measured with good precision, this allows a good estimate of the true size of the stars and hence of a planetary companion possibly found in transit, taking into consideration that the uncertainty in radius measurements of the hosting stars represents a great concern for the characterization of the orbiting planets.

As a final prospect for the APACHE survey, it will be interesting and also useful for testing the survey performances looking for new variable stars in the very rich database. I have described in Chapter 4 the results of my independent search for variable stars in the data collected during the first observing season, leading to the identification of nearly 100 new variables. The additional work done for identifying and characterizing these stellar objects has been not only pleasant and very useful for improving my skills in understanding the nature of variables from the analysis of their more or less complex photometric time series, it also served for correcting and improving the software tools I have built primarily for producing the best quality light curves of M dwarfs. With the always renewed excitement of finding one morning on my monitor the very first evidence of the first APACHE alien world.

Appendix A

The Astronomical Observatory of the Autonomous Region of Aosta Valley

The Astronomical Observatory of the Autonomous Region of the Aosta Valley (OAVdA) in the Alps at the border with France and Switzerland, is located in the Saint-Barthélemy Valley at 1675 m a.s.l. and 16 km from the town of Nus. Managed by the Fondazione Clément Fillietroz-ONLUS, with funding from local administrations, the OAVdA opened in 2003. For the first years its initiatives were focused on public outreach education. Since 2006 the main activity has been scientific research thanks to an official agreement of cooperation established with the Italian National Institute for Astrophysics (INAF). The OAVdA researchers are involved in several research projects related to:

- Active Galactic Nuclei (AGNs) as part of the international Whole Earth Blazar Telescope (WEBT) organization;
- Minor bodies of the Solar System, in collaboration with the Minor Planet Center (MPC) in Cambridge (MA, USA) and the DLR-German Aerospace Center in Berlin (Germany);
- Solar corona (K-corona) with an innovative polarimeter designed for future space coronagraphic missions;
- Photometric detection of transits of small-size extrasolar planets orbiting M dwarf stars in the solar neighborhood;
- Asteroseismology of delta Scuti stars in the Kepler field, in collaboration with the Department of Physics, University of Johannesburg (South Africa);

With the exception of the latter, all projects are carried on in collaboration with the INAF-Astrophysical Observatory of Torino (INAF-OATo). The big efforts undertaken by the small number of people of the research staff have led to the authorship and co-authorship of several papers on international journals as *Astronomy Astrophysics*, *Icarus*, *Monthly Notices of the Royal Astronomical Society*, and *The Astrophysical Journal*. The complete list of publications related to the projects carried out at the OAVdA can be found on the Web site .

Scientific instrumentation

Here the most important research telescopes installed at the OAVdA site are shortly described:

- Five 40 cm telescopes RC Pro 400 LT f/8.4, used for the APACHE project, aimed at discovering small-size terrestrial planets around M dwarfs. Each telescope is equipped with a CCD camera Fli PROLINE KAF-1001 (Array Size: 1024 x 1024; Pixel size: 24 μ m; Pixel scale 1.5 arcsec/pixel; Field of view: 26.3' x 26.3');
- A 81 cm f/7.8 Bowen-Vaughan reflector telescope, equipped with a CCD camera FLI PL3041 back illuminated (2048 x 2048 array size, 15 μ m pixel size). This telescope is used for many projects and it will be used for the first follow-up of interesting objects monitored by the APACHE survey.

Education & Outreach

Besides scientific research, the Fondazione is institutionally committed to organise public outreach education activities. The OAVdA is designed to offer tours for students from kindergarten to high school, teachers and public at large. During daytime visits, in the Heliophysics Laboratory Sun's observation are allowed by a 250 mm Heliostat mirror. Light from our star is projected on a screen in visible light, and a solar spectrum is observed using a diffraction grating. During night-time visits people can observe the sky with seven identical 25 cm f/10 Cassegrain telescopes. In July 2009 the Planetarium of Lignan (diameter 10 m, 67 seats) joined the OAVdA. During the International Year of Astronomy 2009 the OAVdA and the Planetarium, both managed by the Fondazione Clément Fillietroz-ONLUS, gathered together an attendance of 15,246 people. The scientific research made at the OAVdA contributes greatly to the development of high quality public outreach, with the members of the research staff devoting 30% of their time to these initiatives.

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