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The stellar content of the open clusters Tombaugh 1 and Ruprecht 46

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ABSTRACT

V and I CCD photometry has been carried out for two poorly known open clusters: Tombaugh 1 and Ruprecht 46. Photometry has also been obtained for nearby fields to correct for the effects of field star contamination. Estimates of the cluster fundamental parameters (reddening, distance and age) are given for Tombaugh 1 from comparison with theoretical isochrones of the Padova group. We find that this is an intermediate-age open cluster about 1 Gyr old, and probably of solar abundance. The colour excess $E(B-V)$ and the apparent distance modulus $(m-M)$ are about 0.40 ± 0.05 and 13.60 ± 0.20 mag, respectively. These results improve on previous determinations of the distance, and put Tombaugh 1 at about 3.0 kpc from the Sun. The high degree of contamination from field stars prevents us from obtaining firmer results. We estimate the cluster radius to be about 4.0 arcmin. As for the luminosity function (LF), there is satisfactory agreement with that derived from the standard Salpeter ($x = 1.35$) initial mass function (IMF), allowing for the uncertainties in the subtraction of field stars.

Ruprecht 46 was poorly studied before. From our analysis it emerges that this object is not an open cluster, but simply a density fluctuation above the background level.

Key words: Hertzsprung–Russell (HR) diagram – stars: luminosity function, mass function – open clusters and associations: individual: Tombaugh 1 – open clusters and associations: individual: Ruprecht 46.

1 INTRODUCTION

In this series of papers (Carraro & Patat 1994; Patat & Carraro 1995) we are presenting new photometric data for poorly studied or unstudied old open clusters. Our aim is to obtain good-quality photometry which allows us not only to enlarge the sample of studied clusters, but also to estimate their fundamental parameters reliably.

We report here results for two southern open clusters: Tombaugh 1 and Ruprecht 46. Table 1 shows their equatorial and galactic coordinates for the 1950.0 equinox. We selected these clusters from a sample of potentially old but not yet well-studied objects (Phelps, Janes & Montgomery 1994, table 4).

The major difficulty one encounters with this class of clusters is related to their position. They are located at very low latitude in the Galactic plane, and consequently they usually suffer from strong absorption and contamination by field stars.

On the other hand, it is crucial to include these clusters in the group of well-studied old open clusters: the use of this family of objects to probe global properties of the Galactic disc requires a statistically complete sample, that is to say, all the clusters in a given Galactic disc volume have to be sampled. There is clear evidence (Phelps et al. 1994) of the presence of old clusters embedded in low galactic latitude regions of the disc, probably in the act of crossing the Galactic plane.

While the absorption is in some way predictable (see, for instance, the maps from Neckel & Klare 1980), the problem of contamination is more cumbersome. Usually the observation of nearby fields for any cluster is required in order to distinguish cluster members from non-members. This operation is a delicate one; the field in the Galactic plane is

Table 1. Equatorial and galactic coordinates of the clusters.

Name	R.A.(1950) h:m:s	DEC.(1950) (°)(′)	l (°)	b (°)
Tombaugh 1	06:58:12	-20:24	232.22	-7.32
Ruprecht 46	07:59:54	-19:20	238.37	+5.89

highly inhomogeneous, and the choice of a comparison field becomes troublesome and subjective. This fact causes errors in star counts, and the luminosity functions are difficult to handle.

At the same time, the presence of field stars along the line of sight to the clusters provides an explanation (together with other effects) for the broadness of the main sequence (MS), quite typical for these objects.

Great care has to be used to select fields away from void or lumpy regions in order to have a good representation of the disc population in the neighbourhood of the clusters.

In this paper we present colour–magnitude diagrams (CMDs) in the V, $V-I$ plane and the MS luminosity function for Tombaugh 1, and CMDs in the V, $V-I$ plane for Ruprecht 46, and compare them with stellar models. In Section 2 we present the observations, the data reduction, and a discussion of the photometric errors and completeness; in Section 3 we describe results for Tombaugh 1, while in Section 4 we present results for Ruprecht 46. Finally, Section 5 gives our conclusions.

2 OBSERVATIONS, DATA REDUCTION, PHOTOMETRIC ERRORS AND COMPLETENESS CORRECTION

Observations were conducted at La Silla on 1994 December 3 and 5, using the TK-coated 512 × 512 pixel CCD #33 mounted at the Cassegrain focus of the 0.92-m ESO–Dutch telescope. The nights were photometric, with an average seeing of 1.1 arcsec. The scale on the chip is 0.44 arcsec per pixel, and the array covers about 3.3 × 3.3 arcmin^2 on the sky. Five fields, four in the region of the cluster Tombaugh 1 (Fig. 1) and one about 15.0 arcmin northwards, were observed in the V and I passbands. For Ruprecht 46 we observed three fields, one centred on the cluster and two on the east and west sides, in the V and I passbands. Details of

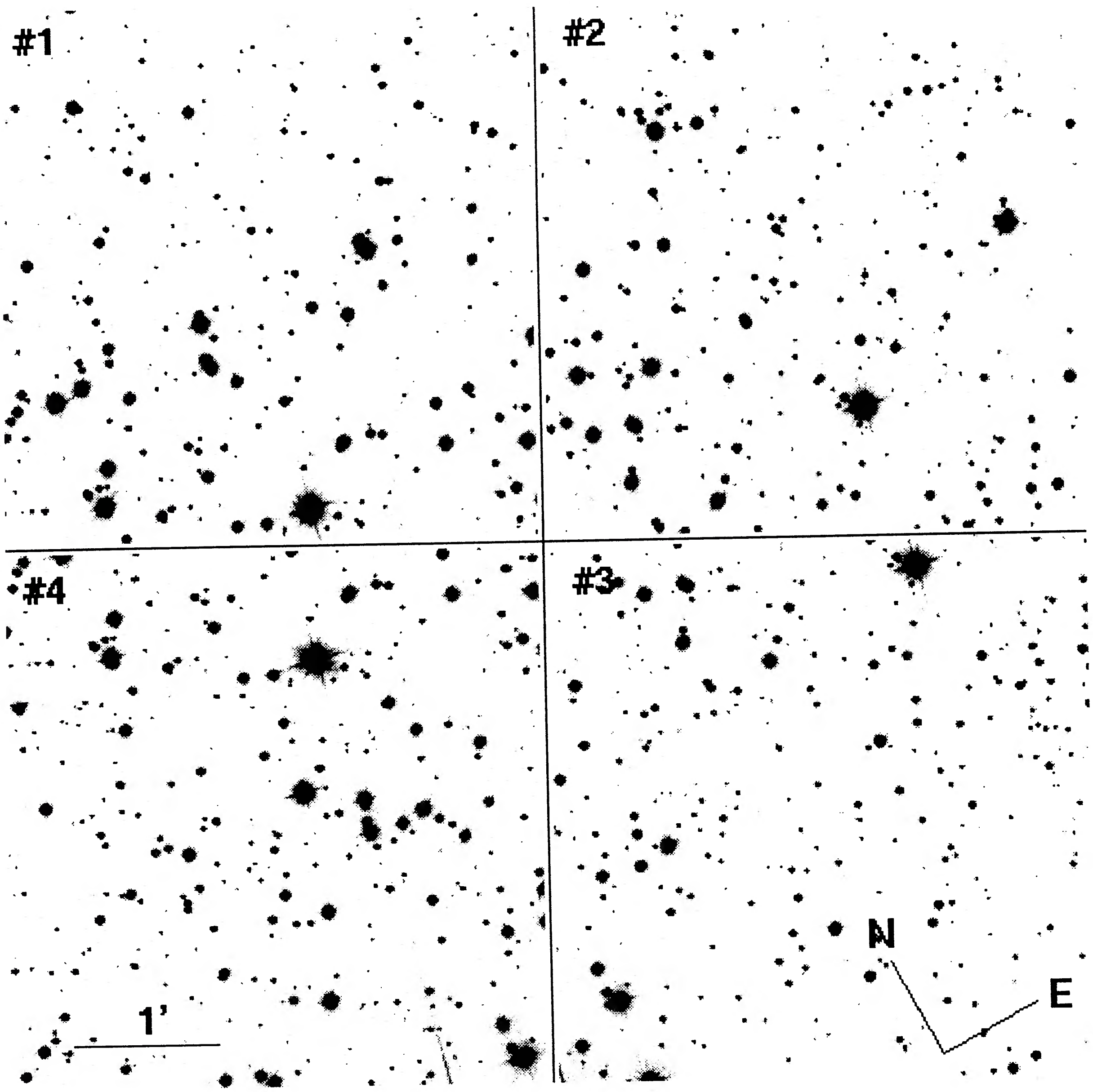

Figure 1. V frames of the four fields in the region of Tombaugh 1.

the observing run for Tombaugh 1 and Ruprecht 46 are given in Tables 2 and 3, respectively.

The standard fields PG 0231, SA 95-139 and GD50 (Landolt 1992) were monitored each night just before and Rubin 149 just after the clusters. Finally, a series of flat-field frames on the twilight sky were taken. The frames have been flat-fielded and bias-corrected by means of standard routines in the ESO MIDAS software package. Further reductions were performed at the Department of Astronomy in Padova (Italy) using the DAOPHOT package and the accompanying ALLSTAR program (Stetson 1991) for Tombaugh 1, and the ROMAFOT package (Buonanno et al. 1983) for Ruprecht 46, in the MIDAS environment. We decided to use ROMAFOT for Ruprecht 46 because of the presence of two bright stars in the centre of the field, which required a careful and interactive reduction in order to avoid spurious effects.

The instrumental v and i magnitudes have been transformed into standard Johnson V and I magnitudes using fitting coefficients (colour term and zero-point) derived from observations of the standard field stars from Landolt (1992), after including exposure time normalizations and airmass corrections. The transformations are given by the following equations:

$$(V-I)=1.050\times(v-i)+1.075, \quad (1)$$

$$V=v+0.027\times(V-I)-2.992. \quad (2)$$

The resulting magnitudes and colours for Tombaugh 1, Ruprecht 46 and the background fields are contained in a series of tables available upon request, together with the frame coordinates (X and Y) and the instrumental ALLSTAR or ROMAFOT rms errors σ. The errors affecting this calibration are expected to be of the order of 0.01 mag.

In order to obtain more realistic error estimates, we have performed some experiments with artificial stars (see Patat & Carraro 1995 for more details) in Tombaugh 1 by means of the ADDSTAR routine of DAOPHOT. We found errors of 0.03, 0.10 and 0.17 mag at I magnitudes 15, 17 and 19, respectively, and errors of 0.02, 0.09 and 0.16 mag at the same V-magnitude levels. These values are consistent with the outputs from DAOPHOT, and in reasonable agreement with the observed width of the MS at the same magnitude levels, which turns out to be 0.15, 0.20 and 0.35 mag, respectively. We found basically the same errors for the field frames. The broadening of the MS is due to various causes: photometric errors, unresolved binary stars, internal reddening and/or spread in metallicity.

The completeness analysis has been performed in the usual way (see Patat & Carraro 1995 for details), and only for Tombaugh 1. We selected as template frame for Tombaugh 1 the field #1 (see below). It turns out that the completeness degree is greater than 50 per cent up to V and $I \simeq 19.0$ mag, both for the cluster and the field.

Table 2. Observational log of Tombaugh 1, ESO-Dutch 0.92-m telescope, La Silla (Chile). FWHM is indicated under the seeing column.

Region	Date	Time (UT)	Filter	Exposure (secs)	seeing (″)
#1	Dec. 5, 1994	4^h35^m	I	10	1.1
#1	Dec. 5, 1994	4^h37^m	I	300	1.1
#1	Dec. 5, 1994	4^h45^m	V	10	1.1
#1	Dec. 5, 1994	4^h47^m	V	300	1.2
#2	Dec. 5, 1994	5^h04^m	V	10	1.1
#2	Dec. 5, 1994	5^h05^m	V	300	1.2
#2	Dec. 5, 1994	5^h15^m	I	10	1.0
#2	Dec. 5, 1994	5^h18^m	I	300	1.1
#3	Dec. 5, 1994	5^h35^m	I	10	1.0
#3	Dec. 5, 1994	5^h39^m	I	300	1.1
#3	Dec. 5, 1994	5^h48^m	V	10	1.1
#3	Dec. 5, 1994	5^h50^m	V	300	1.1
#4	Dec. 5, 1994	6^h05^m	V	10	1.0
#4	Dec. 5, 1994	6^h07^m	V	300	1.1
#4	Dec. 5, 1994	6^h18^m	I	10	0.9
#4	Dec. 5, 1994	6^h20^m	I	300	1.0
Field	Dec. 5, 1994	6^h31^m	I	300	1.0
Field	Dec. 5, 1994	6^h41^m	V	900	1.2

Table 3. Observational log of Ruprecht 46, ESO-Dutch 0.92-m telescope, La Silla (Chile). FWHM is indicated under the seeing column.

Region	Date	Time (UT)	Filter	Exposure (secs)	seeing (″)
#1	Dec. 5, 1994	7^h17^m	V	300	1.2
#1	Dec. 5, 1994	7^h25^m	I	300	1.2
#2	Dec. 3, 1994	5^h45^m	V	10	1.2
#2	Dec. 3, 1994	5^h46^m	V	600	1.2
#2	Dec. 3, 1994	6^h01^m	I	10	1.1
#2	Dec. 3, 1994	6^h03^m	I	600	1.1
#3	Dec. 5, 1994	7^h40^m	I	300	1.2
#3	Dec. 5, 1994	7^h49^m	V	300	1.2

3 TOMBAUGH 1

The cluster Tombaugh 1 was discovered by Tombaugh (1938), together with Tombaugh 2, during his search for trans-Neptunian planets. Tombaugh (1941) presented for the first time photographic plates of both the clusters, together with three other objects discovered in the meantime. He remarks that Tombaugh 1 has an angular radius of 5.0 arcmin, and that it is probably obscured by the presence of numerous field stars. He measured about 30 stars of 14th and 15th magnitude. The same kind of remarks were made by Haffner (1957), who independently rediscovered the cluster and named it Haffner 1. Finally, Tifft (1959) discovered Tombaugh 1 in his search for classical Cepheids near galactic clusters. Tombaugh 1 is also designated as OCL 603 and C0658 − 202, and classified as a cluster of the Trumpler class III 2 m.

A more recent and detailed work on Tombaugh 1 has been carried out by Turner (1982), who obtained photoelectric photometry for 25 stars in the region of the cluster with the aim of checking the membership of the Cepheid star XZ Canis Minoris. As a by-product, he obtained a colour excess $E(B-V)=0.27\pm0.01$ mag, a distance of about 1300 pc from the Sun, and an age around 8×10^8 yr on the scale of the old Geneva isochrones (Maeder & Mermilliod 1981). Moreover, Turner (1982) stressed the presence of several subgiant and giant stars and some possible blue stragglers as additional distinctive features of the cluster.

3.1 Cluster structure

Looking at the POSS, or at Turner (1982; see his fig. 1), it appears that Tombaugh 1 is a faint cluster weakly emerging from the field background. This is also confirmed by an isodensity map that we produced in order to analyse in more detail the structure of this object. Basically, we counted the stars in a sampling box running on a grid covering the whole cluster, and then we performed a contour plot of the regions with constant stellar density, as shown in Fig. 2. To prevent strong contamination by field stars we included in the analysis only stars brighter than $V=18.0$, which probably belong to the MS of Tombaugh 1 (see the next section). It turns out that Tombaugh 1 has an irregular structure and does not show a clear density peak that can be identified with the cluster centre. Several narrow peaks emerge on an almost constant background and define the cluster *core*. The barycentre of this system, computed using only the stars with $V<18.0$, appears to be somewhat off-centre with respect to the region covered by our CCD frames (see Fig. 2). This suggests that during the observations we lose a small fraction of the cluster region. This is due to the presence of several bright stars in the zone, clearly visible in Turner (1982, fig. 1), that would have prevented us from obtaining deep exposures.

Looking at Figs 1 and 2, it appears that Tombaugh 1 is roughly symmetric with respect to this centre definition, allowing us to derive some information on the cluster radial profile. This is shown in Fig. 3, and was constructed by counting stars in circular coronae of constant areas, after selecting stars in a magnitude interval weakly affected by incompleteness problems ($11.0<V<18.0$). We have also subtracted the field contribution, which turns out to be 3.12 arcmin^{-2}. We find that the density of stars is roughly constant within a circle of about 2.5 arcmin around the adopted centre. Then it drops rapidly, reaching the field level at about 4.0 arcmin. This suggests that the cluster radius is around 3–4 arcmin, which is smaller than previous estimates.

3.2 The colour–magnitude diagram

The global CMD of Tombaugh 1 is shown in Fig. 4. The main features of this CMD can be described as follows.

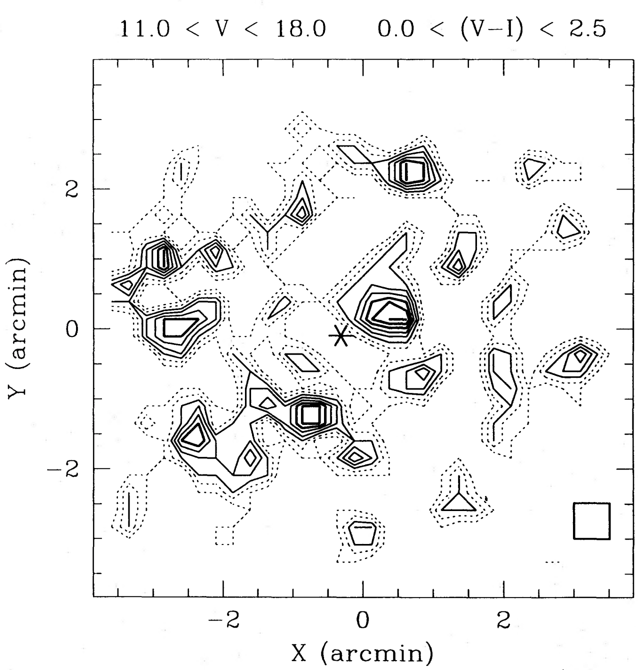

Figure 2. Isodensity map showing the local star counts in the region of Tombaugh 1. The contours are displayed at intervals of 10 per cent, starting from 20 per cent of the maximum density, with the dotted ones corresponding to counts below 50 per cent. The origin of the coordinate system corresponds to the geometrical centre of the area covered by the four CCD frames. The asterisk is located at the barycentre of stars with $V<18.0$. The square in the lower right corner is the sampling box used to compute the local star density.

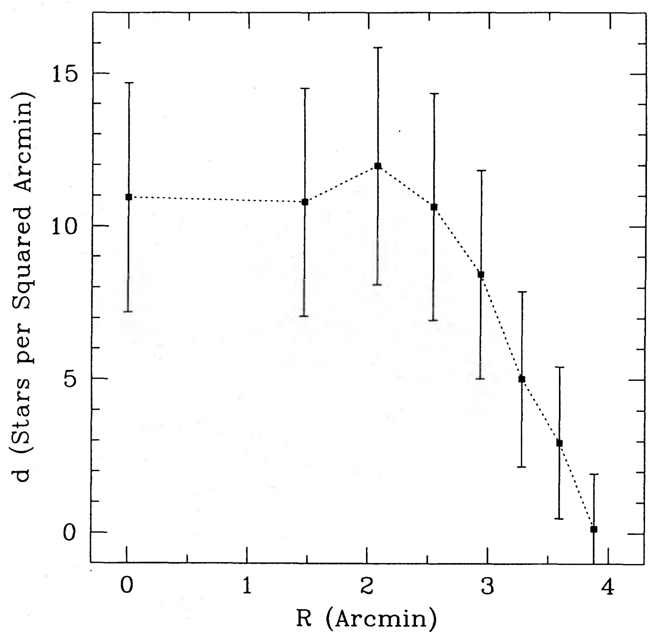

Figure 3. Radial star counts in Tombaugh 1.

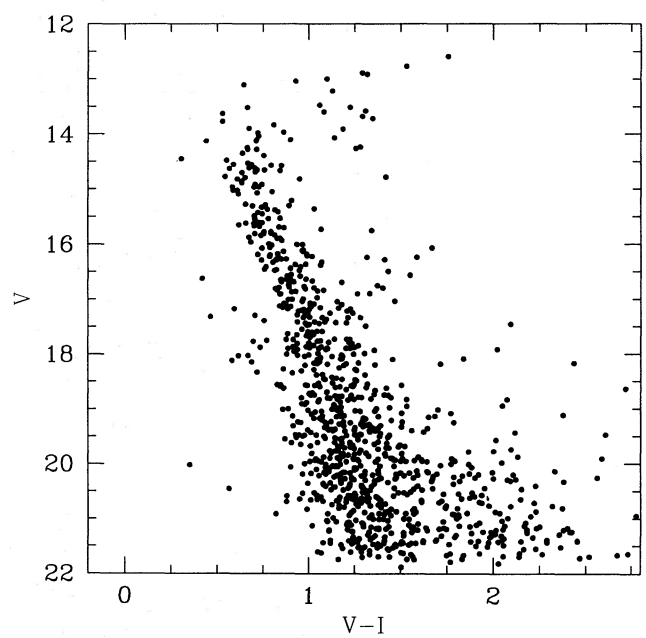

Figure 4. CMD for all the studied stars in Tombaugh 1.

There is a clear MS down to $V \simeq 20.0$ mag, with the turn-off point (TO) located at $V \simeq 14.5$ mag, $(V-I) \simeq 0.6$ mag. Down to $V \simeq 20.0$ mag, the photometric errors and the field star contamination dramatically broaden the sequence. Stars outside the MS, both toward the red and blue sides are likely to be disc field stars between us and the cluster. In Fig. 5 we show the single CMDs, which help us to understand where different populations come from. In particular, the better definition of frames #1 and #4 indicates that they are in the inner region of the cluster, and this confirms the results of Section 2. In fact, the field population on the red side of the MS comes mostly from frames #2 and #3, which cover the outskirts of the cluster.

A small group of stars (17) defines the evolved population of Tombaugh 1. A clump of He-burners can be recognized at $V \simeq 13.5$ mag, $(V-I) \simeq 1.25$ mag, although it appears sparse both in magnitude and in colour. It is worth stressing that we did not miss bright stars, because none of them was saturated in the short-exposure frames. The TO morphology is not very clear, probably because of the presence of unresolved binary stars. The evolved region of the CMD is also not clear, and it is hard to say if a giant branch exists or not.

The global morphology of Tombaugh 1 CMD resembles that of NGC 5822 (Twarog, Anthony-Twarog & McClure 1993), NGC 2477 (Hartwick, Hesser & McClure 1972) and NGC 6603 (Bica, Ortolani & Barbuy 1993), suggesting that this is an intermediate-age open cluster of the Hyades generation.

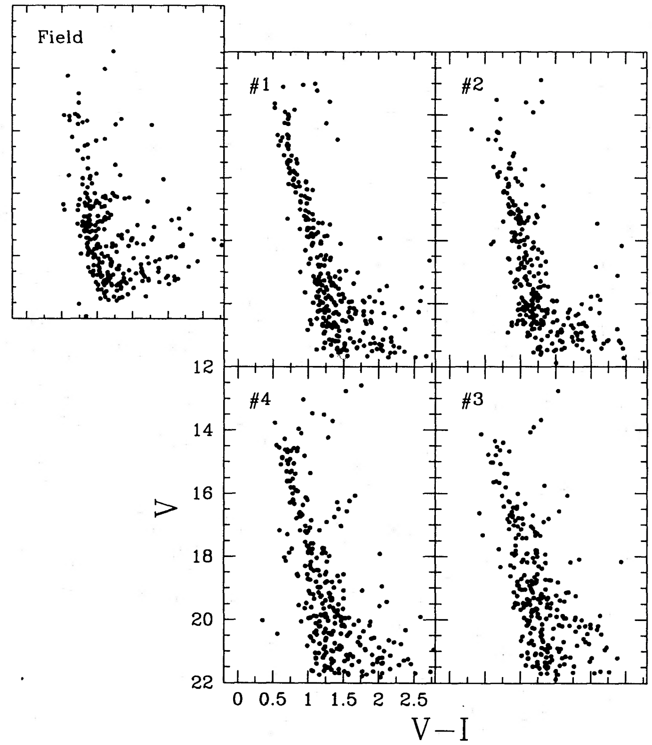

Figure 5. CMDs for the different CCD frames in the field of Tombaugh 1.

3.3 Evolved stars in Tombaugh 1

We have investigated the spatial distribution of the evolved stars in Tombaugh 1 in order to get some information on the dynamical status of the cluster. This is shown in Fig. 6, where we have plotted the stars with $11.0 < V < 14.5$ and $1.0 < (V-I) < 2.5$ to study the presence of possible peaks in the distribution. No firm conclusions can be drawn, given the small number of stars involved. Anyway, it emerges that the evolved stars are distributed randomly within the cluster, with the barycentre very close to that of the system defined by stars with $V < 18.0$. This probably means that Tombaugh 1 is not yet relaxed and that no mass segregation has occurred. Moreover, intermediate-age and old open clusters are known to host bright stars in their outskirts (Hawarden 1975), and Tombaugh 1 seems to follow this trend.

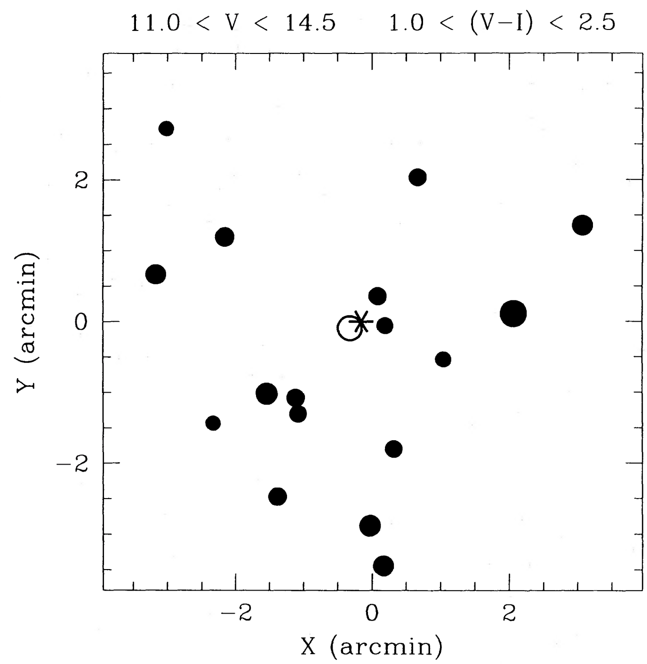

Figure 6. Finding chart for evolved stars in Tombaugh 1. The asterisk indicates the barycentre of all objects with $V < 18.0$, while the open circle is the barycentre of the more evolved stars.

3.4 Cluster parameters and MS luminosity function

A hint as to the cluster reddening can be obtained from the absorption map by Neckel & Klare (1980). In Table 4 we list the values of A_V for Tombaugh 1 and Ruprecht 46 as derived from their absorption maps. We took care to select regions as close to the clusters as possible. In fact, the maps of Neckel & Klare do not cover all the Galactic disc regions. In the case of Tombaugh 1 we found a region very close to the cluster (see their fig. 6d, 79), whereas for Ruprecht 46 the best available region is given in their fig. 6e, 87, in which it is significantly far away from the cluster. We computed the colour excesses $E(B-V)$ and $E(V-I)$, adopting for $R_V = A_V/E(B-V)$ the value of 3.0. In addition, the ratio $E(V-I)/E(B-V)$ was chosen to be 1.60, following Savage & Mathis (1979). In the case of Tombaugh 1, the $E(B-V)$ colour

Table 4. Total and selective absorption for the clusters.

Name	A_V mag	E_{B-V} mag	E_{V-I} mag
Tombaugh 1	0.30	0.10	0.16
Ruprecht 46	1.00	0.33	0.53

excess (see Table 4) is different from that of Turner (1982), who found $E(B-V)=0.27$ using five stars probably of A and F spectral types, and suggested that this value has to be considered as an upper limit.

The next step is to fit the cluster sequence with theoretical isochrones (Bertelli et al. 1994), and to look for a consistent reddening value. Using the available photometry and the well-defined CMD, we are in a position to obtain firmer estimates not only for the reddening, but also for the distance and the age of the cluster.

The main problem with that is the lack of any knowledge about the metal abundance of Tombaugh 1. Thus we are forced to use isochrones of different metallicity, and to try to find out which provides the best global fit. Several trials led us to conclude that the cluster has near-solar metal abundance ($Z=0.020$ in our system) and is about 1.0 Gyr old (see Fig. 7). This is confirmed by the value of the ΔV index (Carraro & Chiosi 1994) around 1.0. As a by-product we obtain a colour excess $E(V-I)\simeq 0.65$ and an apparent distance modulus $(m-M)\simeq 13.60\pm 0.20$. The derived colour excess $E(B-V)$ turns out to be 0.40 ± 0.05, in poor agreement with the estimate of Turner (1982), and larger than the value quoted by Neckel & Klare (1980).

The fit is not very good in the TO region: no traces can be found of the *blue hook* expected from the theoretical isochrone. In this context, it is important to stress the role played by the high level of contamination by field stars, which, together with the presence of some unresolved binary stars, blur out this region.

The distance to the cluster is estimated to be 3.0 kpc, significantly higher than that reported by Turner (1982). Using the galactic coordinates from Table 1, we have computed the galactocentric rectangular coordinates of Tombaugh 1, adopting $R_{\mathrm{GC},\odot}=8.50$ kpc. We obtain $X=10.3$, kpc, $Y=-2.3$ kpc and $Z=-0.4$ kpc. The resulting distance to the Galactic centre is about 10.5 kpc. Errors affecting these values depend mainly on the uncertainty in the derived distance modulus, and can be estimated to be around 20 per cent.

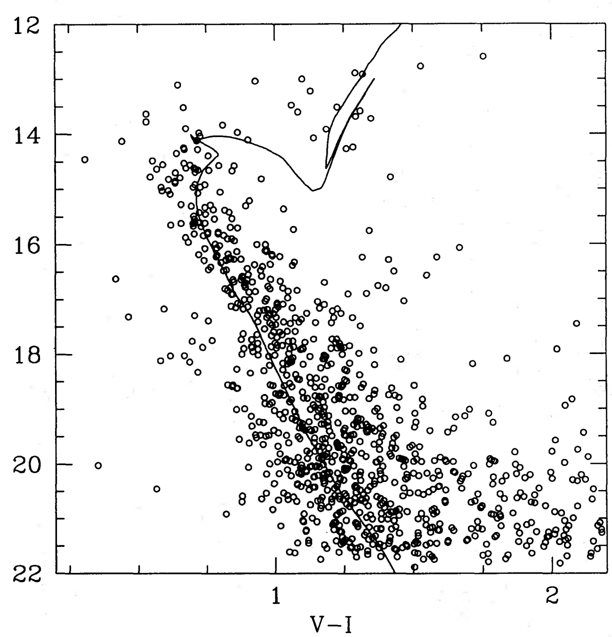

Figure 7. CMD of Tombaugh 1 as in Fig. 4. Superposed is an isochrone with $Z=0.020$ for an age of 1.0 Gyr. See text for more details.

Finally, we have constructed the integrated luminosity function (ILF) for the MS of Tombaugh 1, and compared it with a theoretical LF derived from an isochrone with solar metal abundance and for the previously derived age. For the IMF coefficient in the Salpeter law we chose the standard $x=1.35$ value. The result is shown in Fig. 8, where the theoretical LF has been shifted to the observed one adopting our apparent distance modulus (13.60 mag). The observed ILF has been obtained as follows. First, we corrected the cluster and field for incompleteness effects, as discussed in Section 2. Then we subtracted the field contribution from the cluster in each magnitude bin (see Patat & Carraro 1995). The error bars take into account both the uncertainties in the star counts (squared root of the counts), and those in the completeness correction procedure. The adopted standard Salpeter law provides only a partial reproduction of the MS of Tombaugh 1. Once more we stress that the main difficulty in this operation is the field star subtraction, which depends dramatically on the choice of the field in the Galactic plane.

4 RUPRECHT 46

Ruprecht 46 (OCL 637, C07589−192) was discovered by Ruprecht (1960), who described it as a poor cluster of Trumpler class II 3 p. He indicated an angular diameter of about 2.0 arcmin. He was also able to count 24 possible members, and suggested that the brightest stars have $V\simeq 12.0$. Afterwards Ruprecht 46 has been studied by Vogt & Moffat (1972). They performed a photoelectric survey for nine bright stars, suggesting that this object has to be a real old open cluster. They report a reddening $E(B-V)=0.07$ mag and a distance modulus $(m-M)=9.60$ mag according to the most probable fitting solution. In this section we present *VI* photometry for the stars in the region of Ruprecht 46 and address the question of the real nature of this object.

4.1 Is Ruprecht 46 a real open cluster?

Fig. 9 shows a mosaic of the three CCD frames taken in the region of Ruprecht 46. This object appears as a small stellar density enhancement with a diameter of about 2 arcmin. Following Ruprecht (1960), the open cluster *candidate* is contained in our field #2, and for this reason short exposures (10 s) have been taken both in V and I to prevent saturation and non-linearity problems for the brightest stars. The presence of two bright foreground stars, which were already saturated in the 10-s exposures, forced us to use the interactive path of ROMAFOT (Buonanno et al. 1983) to analyse the photometry of each single star, in order to avoid spurious effects due to the strong haloes present, especially in the field #2.

The CMDs of the single frames are shown in Fig. 10. The CMD of field #2, which should contain the core of the cluster, is the most dispersed, with an overabundance of bright stars ($12.5<V<14.5$) with respect to the other two frames. With the exception of this fact, the three CMDs are quite similar: they show no clear evidence of an MS or the presence of evolved stars. Moreover, they are rather similar

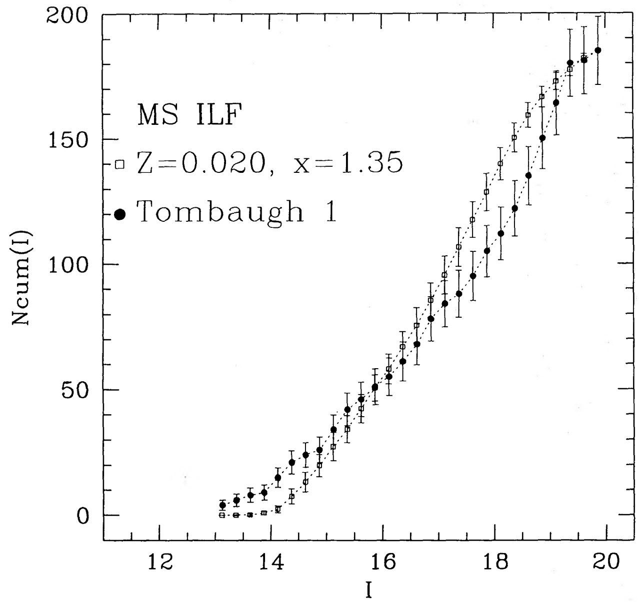

Figure 8. ILF for the MS of Tombaugh 1. Superposed is a theoretical LF computed adopting the standard Salpeter IMF.

to the CMD of the field population close to Tombaugh 1 (see Fig. 5). All these facts suggest that Ruprecht 46 is a simple density enhancement of bright stars ($V<14.5$), and not an open cluster. This clump of stars might have been responsible for Ruprecht's identification. In addition, the results by Vogt & Moffat (1972) rest on very poor statistics, and suffer from the well-known problems of photoelectric aperture photometry in crowded regions.

5 CONCLUSIONS

A comparison between the photometric data of Tombaugh 1 and the theoretical isochrones of Bertelli et al. (1994) has shown that this object is an intermediate-age open cluster ($t\sim1$ Gyr) with a near-solar metal abundance. The derived colour excess is $E(B-V)=0.40$, and the apparent distance modulus $(m-M)=13.60$, putting Tombaugh 1 at 3.0 kpc from the Sun. While our reddening and age estimates are in marginal agreement with those obtained by Turner (1982), his distance is 1.7 kpc smaller than ours. This is likely to be due to the small number of stars ($N=25$) used by this author, which makes it difficult to recognize the fundamental

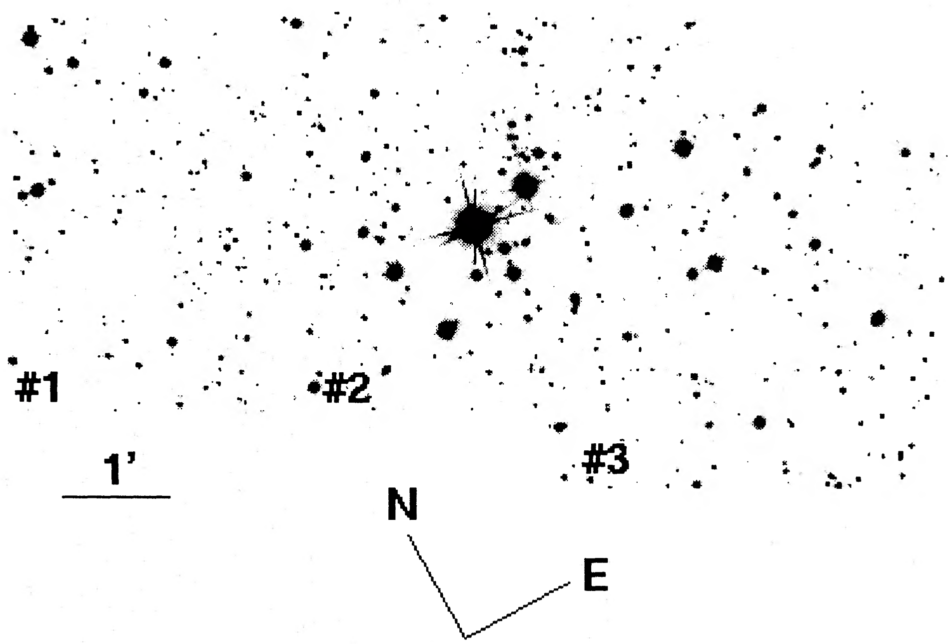

Figure 9. A mosaic of the three V images in the region of Ruprecht 46.

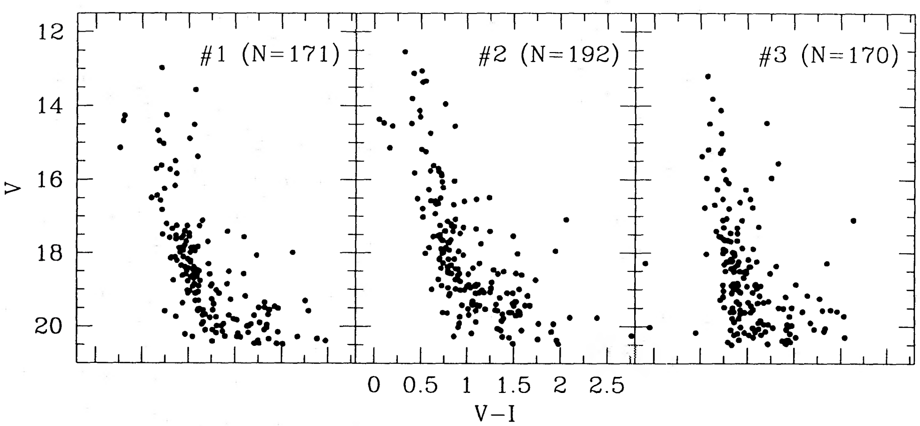

Figure 10. CMDs of the single fields for Ruprecht 46.

features in the CMD required for a meaningful fitting of theoretical isochrones. Since the photometry presented in this paper includes about 900 stars, with a clear appearance of an MS down to $V \simeq 20$ and a well-defined clump of subgiants, our results are more reliable.

The radius of the cluster is about 4 arcmin, and the structure is rather irregular without a clear central peak. The analysis of the distribution of the evolved stars shows no indication of mass segregation.

Finally, the photometric study of three fields in the region of Ruprecht 46 has revealed that this object is not an open cluster, since no clear MS or other meaningful features could be seen. Ruprecht 46 is just a random enhancement of stars brighter than $V = 14.5$.

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