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Probing the Canis Major stellar over-density as due to the Galactic warp

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Abstract. Proper-motion, star counts and photometric catalog simulations are used to explain the detected stellar over-density in the region of Canis Major, claimed to be the core of a disrupted dwarf galaxy (CMa, Martin et al. 2004, MNRAS, 348, 12; Bellazzini et al. 2004, [`arXiv:astro-ph/0311119`]), as due to the Galactic warp and flare in the external disk. We compare the kinematics of CMa M-giant selected sample with surrounding Galactic disk stars in the UCAC2 catalog and find *no* peculiar proper motion signature: CMa stars mimic thick disk kinematics. Moreover, when taking into account the Galactic warp and flare of the disk, 2MASS star count profiles *reproduce* the CMa stellar over-density. This star count analysis is confirmed by direct comparison with synthetic color−magnitude diagrams simulated with the Besançon models (Robin et al. 2003, A&A, 409, 523) that include the warp and flare of the disk. The presented evidence casts doubt on the identification of the CMa over-density as the core of a disrupted Milky Way satellite. This however does not make clear the origin of over-densities responsible for the *ring* structure in the anticenter direction of the Galactic halo (Newberg et al. 2002, ApJ, 569, 245; Yanny et al. 2003, ApJ, 588, 824).

Key words. astrometry – Galaxy: structure – Galaxy: formation – Galaxies: interactions

1. Introduction

Recent large scale surveys, in the optical and near-infrared, have been excellent tools to constrain the structure and the star formation history of the Milky Way and its satellite system. Growing evidence of satellite accretion, stellar streams, and sub-structures all point to inhomogeneities in both the Galactic disk and halo. The Sgr dwarf spheroidal (Ibata et al. 1997) is a strong evidence of the hierarchical formation in galaxies like the Milky Way. Ever since its discovery, the search for extra-Galactic satellite remnants has been most appealing. With the availability of the Sloan Digital Sky Survey, Newberg et al. (2002) showed evidence for at least 5 over-densities in the anticenter direction of the Galaxy. Four of these features, possibly part of a *ring*, were found close to the Galactic plane, suggesting two possible origins: (1) the remnant of a dwarf satellite galaxy in the process of disruption; or (2) a particular distribution of Galactic disk stars. The ring structure has been confirmed kinematically by Yanny et al. (2003) and using 2MASS data by Rocha-Pinto et al. (2003). Frinchaboy et al. (2004) and Crane et al. (2003) showed the existence of a structure of stellar clusters with coordinated radial velocities, further confirming the presence of a possible stellar ring at a distance of ≃18 kpc in the anti-center direction.

Martin et al. (2004, M04), investigating the ring structure with the 2MASS all-sky catalog, pointed to an elliptical-shaped stellar over-density centered at $l = 240°$, $b = -7°$. Accounting for simulations of (a) past mergers thick disk formation (Abadi et al. (2003), and (b) dwarf galaxies in-plane accretion (Helmi et al. 2003), M04 proposed this "feature" as the core of a satellite galaxy currently undergoing an in-plane accretion, namely the Canis Major dwarf spheroidal galaxy (CMa). In a companion paper, the same group (Bellazzini et al. 2004) searched for photometric signatures of CMa in color−magnitude diagrams (CMDs), and best identified the red clump and red giant branch of CMa in the CMDs of the Galactic open clusters NGC 2477 and Tom 1. Forbes et al. (2004) studying the age–metallicity relation for CMa probable cluster members pointed out a clearly distinct extragalactic origin of CMa debris. On the other hand, Kinman et al. (2004) did not find any over-density of RR Lyrae stars in an anti-center field of the Galaxy. This contrasts with the Zinn et al. (2003) study who possibly identified CMa stars in the so-called southern arc of the CMa ring.

Accreting Galactic satellites could be responsible for the creation of the observed Milky Way warp (Castro-Rodríguez et al. 2002). Evidence for the existence of a Galactic warp for the inter-stellar gas and dust are long dated since early HI observations (Oort et al. 1958), and more recent inter-stellar diffuse dust emission (Freudenreich et al. 1994; Freudenreich 1996) studies. The warp has been also detected in stellar star counts and can be seen as a systematic variation of the mean disk latitude with longitude (Djorgovski & Sosin 1989): observationally, the warp is an upward bending from the Galactic plane in the first and second galactic longitude quadrants ($0° \leq l \leq 180°$), and downward in the third and fourth ones ($180° \leq l \leq 360°$). *The warp feature is therefore important in the direction of CMa and has to be accounted for when asymmetries across the Galactic plane are investigated.*

A comprehensive formation scenario for the features found in CMa and their connection with other galactic structures seriously call for the determination of basic observational properties of CMa such as: metallicity, proper motion (pm), radial velocity etc. In the present paper we address the mean pm of stars in the direction of CMa in search for any kinematic signature. We also investigate a possible connection of the CMa over-density with the *warp* and *flare* of the Galaxy (Robin et al. 2003, and references therein) which manifest their maximum extent in the CMa region.

2. CMa proper-motion

In the absence of specific pm studies of CMa, in this paper we make use of the recent USNO CCD Astrograph Catalog second release (UCAC2, Zacharias et al. 2004) to investigate a possible pm signature of the CMa. The first epoch data for the pm come from different catalogs including Hipparcos/Tycho, AC2002.2, as well as re-measured AGK2, NPM and SPM plates. In general, Zacharias et al. estimate pm errors to be 1 ÷ 3 mas/yr for 12th magnitude stars and about 4 ÷ 7 mas/yr around the 16th magnitude. The pm reference is absolute and it has been evaluated using external galaxies. A useful feature of the UCAC2 catalog is the inclusion of the J, H and K magnitudes from the 2MASS survey. We also made use of the online Milky Way photometric and kinematic simulations based on the Besançon Galaxy model (Robin et al. 2003): its main advantage is the reduction of a number of free parameters (e.g. the thin disk scale height at different ages) and, most interestingly, the inclusion of *warping* and *flaring* of the Galactic disk.

To estimate the pm of CMa we extract UCAC2 $\mu\alpha$, $\mu\delta$ (in this paper we assume $\mu\alpha = \mu\alpha\cos\delta$), J, and K data in 3 fields having a radius of 1°. The first centered on the Sgr to be used for testing the procedure, the second on CMa and the last on the open cluster NGC 2477. Adopting the selection criteria outlined in Bellazzini et al. and M04, we use the K, $(J-K)$ diagrams to extract M-giants *presumably* belonging to CMa and estimate the mean UCAC2 pm. Although simple, this approach is rather tricky. As it is well depicted by the study of Platais et al. (2003), the presence of residual color/magnitude terms in any pm analysis is almost unavoidable. This is specially true when one deals with an all-sky catalog, where the *pm is derived from different first epoch sources*. Aware of these facts, the minimal approach was to (i) assess the reliability of the UCAC2 measurements by a comparison with fields of known pm, and (ii) limit the UCAC2 pm data to *only one* first epoch catalog in order to limit internal inhomogeneities. Several tests were performed re-measuring the mean pm of globular clusters and comparing these with the values reported in Dinescu et al. (1999). The overall agreement has been very good for all measurable cases (16 clusters with distances ranging from 3 to 13 kpc), with an overall scatter of less than 2.5 mas. In conclusion, the best confidence level was found with the AC2002.2 dataset (see Zacharias et al. 2004): we restricted our analysis on it.

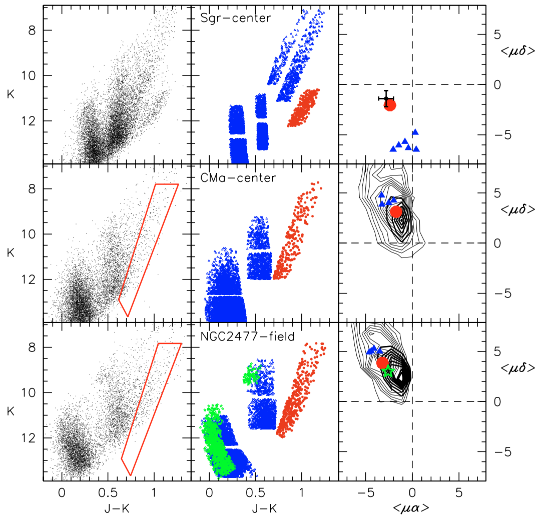

Fig. 1. 2MASS $K, (J-K)$ dereddend CMDs and corresponding UCAC2 proper-motion plots of the Sgr dwarf spheroidal, CMa and NGC 2477. For each row, from left to right: (1) a 1° K, $(J-K)$ 2MASS CMD limited to stars with UCAC2 pm data based on the AC2002.2 catalog; (2) the same CMD but showing only the selected stellar populations for which a mean pm is to be determined; and (3) the mean pm of the selected populations following a 2σ-clipping to eliminate outliers (see online colored version of the figure).

Figure 1 presents CMDs and pm diagrams for 3 selected fields, from top to bottom: *Sgr-center*, *CMa-center* ($l = 240°$, $b = -7°$) and *NGC 2477-field*. The stellar populations selected in the middle panels are mainly field stars chosen to span all possible color and magnitude ranges in order to check for any pm gradient. The bulk of the selected disk populations with $(J-K) < 0.8$ are expected to have a heliocentric distance of <2 kpc (open triangles), while objects with $(J-K) > 0.8$ and $8 \leq K \leq 14$ are found mainly at distances >2 kpc (filled circles). On the top row of Fig. 1 the identification of the Sgr M-giants (filled circles) is straightforward, showing the red giant tip at $K \simeq 11.0$. The right upper panel plots the estimated mean pm of the 6 presumably *field* populations (filled triangles) which show a clustering around $\langle\mu\alpha,\mu\delta\rangle \simeq (-1.0,-6.0)$ mas. The dispersion of the mean pm of the field stars is due to the different nature and distance of the selected objects. The dispersion of the 6 field samples (≃2.0 mas) can be used as a conservative error estimate of our mean pm determinations. Relatively speaking, the mean pm of the Sgr red giants clearly stands out at $\langle\mu\alpha,\mu\delta\rangle \simeq (-2.5,-2.0)$ mas, and is well separated from surrounding field stars. This is due to the almost polar orbit of Sgr. A filled square with error bars shows the mean value of the Sgr proper motion as derived by Irwin et al. (1996) from HST data: $\langle\mu\alpha,\mu\delta\rangle = (-2.80 \pm 0.80, -1.40 \pm 0.80)$ mas. The excellent agreement between the two values strengthens our confidence in measuring pm with UCAC2 up to a distance of ~25 kpc from the Sun.

Turning our attention to CMa, we extract M-giants within an oblique stripe, as done in Bellazzini et al. (2004) in the NGC 2477 field. CMa giants are plotted as filled circles in the

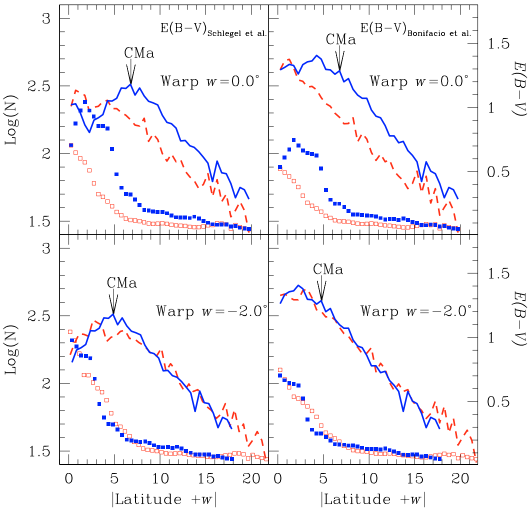

Fig. 2. Latitude profiles of a 2MASS M-giant star sample selected around CMa. Upper-left panel assumes a North/South symmetry around $b = 0^{\circ}$, lower-left panel assumes a warp amplitude of $2.^{\circ}0$ in the southern direction. Star counts in left panels are corrected for reddening using the Schlegel et al. maps. Right panels show the same plots, except for correcting the Schlegel et al. values with the formula given in Bonifacio et al.

central panels of the middle and lower rows of Fig. 1. Stars belonging to the open cluster were selected within a radius of $0.^{\circ}2$ (light starred symbols), clearly showing the main sequence and red clump. As in the Sgr field, the mean pm of disk stellar populations (filled triangles) in the CMa-center and NGC 2477 fields show a dispersion of ±2.0 mas, with a rather lower dispersion around the NGC 2477 as expected for its low latitude. We estimate a mean pm of CMa-center M-giants to be $\langle\mu\alpha, \mu\delta\rangle \simeq (-1.7, 3.1)$ mas. This is in the same pm direction of disk stars, although slightly offsetted (∼1.5 mas in both $\mu\alpha$ and $\mu\delta$). To better understand this offset, on both right panels we overplot contour levels of simulated kinematic stellar catalogs using the Besançon Galactic model. The simulated catalogs were divided into two stellar subgroups (as done for the 2MASS J, K color selection) according to their heliocentric distance: thin line contours show stars within 2 kpc, i.e. $(J - K) < 0.8$, while thick line contours show stars with distance >2 kpc, i.e. $(J-K) > 0.8$. For each population, the counts have been divided in 9 linear contour levels. We note that the above stated value of CMa-center pm is in fair agreement with expected mean pm value of the latter group of disk objects, with a mean distance of ≃8 kpc. Thus, when accounting for a mean error of ±2.0 mas and an offset merely due to distance projections, the mean pm of CMa-center seems perfectly compatible with outer disk dynamics in circular prograde motion. This finding is in agreement with the Crane et al. (2003) solution for the kinematics of the "Monoceros" structure which appears compatible with a disk component rotating at 220 km s^{-1} at a distance of 18 kpc and showing a thick disk velocity dispersion. Radial velocity measurements and a detailed computation of the CMa orbit will be presented in a separate paper (Zaggia et al., in preparation).

3. CMa and the Galactic disk warp

López-Corredoira et al. (2002) recently studied the existence of the warp in the Galactic stellar populations using star counts of old-population red clump giants selected from 2MASS CMDs. Their Fig. 15, on the ratio of North and South Galactic caps star counts shows a clear sinusoidal behavior with longitude. Excess of star counts in the northern hemisphere latitudes was found for $l \leq 180^{\circ}$, and an opposite trend for $l \geq 180^{\circ}$. They basically concluded their analysis *confirming the existence of the warp in the old stellar population whose amplitude is coincident with that of warped gas and young disk stars*. They also identified a strong flare, i.e. a change in the scale-height, of the outer disk. Previously, Freudenreich et al. (1994) using COBE/DIRBE near-infrared data found that the absolute maximum amplitude of the latitude displacement is $1.^{\circ}5 \div 2.^{\circ}0$. Interestingly, the over-density in CMa and *"structure A"* in the symmetric quadrant ($0^{\circ} < l < 180^{\circ}$) (see Figs. 4 and 5 in M04) coincide respectively with the southern and northern regions where the warp amplitude is strongest. This clearly indicates that the warp and flare of the disk can heavily affect star counts analysis of low latitude, distant regions. To test the impact of Galactic warp and flare near the core of CMa we revisited the analysis performed by M04. A suitable CMa M-giants sample was extracted from the 2MASS catalog using the same oblique selection region depicted in the CMDs of Fig. 1, i.e. *sampling the region with CMa giants excess*. The sample was spatially limited along a latitude stripe between $-20^{\circ} \leq b \leq 20^{\circ}$, in the longitude range $235^{\circ} \leq l \leq 245^{\circ}$, i.e. corresponding to the CMa spatial FWHM, as derived in M04. J and K magnitudes were corrected for reddening in two different ways using: (1) *raw* Schlegel et al. (1998) values, and (2) *modified* Schlegel et al. values as suggested in Bonifacio et al. (2000). Star counts were computed in latitude bins of $0.^{\circ}5$ (the results don't change using the $4^{\circ} \times 2^{\circ}$ binning as in M04).

In Fig. 2 the upper-left panel shows the folded star count profiles for the northern (dashed line) and southern (solid line) galactic caps. In this panel the assumed North/South symmetry is at $b = 0^{\circ}$ without introducing any warping in the Galaxy, i.e. with a warping angle $w = 0.0$. Also plotted are the Schlegel et al. (1998) reddening mean values for the southern (filled rectangles) and northern (open rectangles) hemispheres along the same spatial region. The CMa location is identified with a vertical arrow. A glance at Fig. 2 shows that the southern part of the profile is clearly offsetted with respect to the northern part, i.e. the CMa over-density as identified in M04. In the lower-left panel of Fig. 2 the same star counts are presented assuming a warp amplitude of $w = 2.^{\circ}0$ in the southern direction, i.e. a North/South symmetry at $b = -2.^{\circ}0$. The curves plotted in the lower panel *show no* significant changes varying w by $\pm 0.^{\circ}3$ around $w = -2.^{\circ}0$. The clearest feature in this panel is the almost perfect symmetry around $b = -2.^{\circ}0$. Moreover, the North/South symmetry is also reflected in the two reddening curves which show a far better symmetry down to the mid plane. As a result of taking into account the disk warp, one notes that although the CMa over-density persists, it is *seriously weakened*.

Various authors have noted that the Schlegel et al. maps overestimate reddening for $E(B - V) > 0.2$, in particular, Bonifacio et al. (2000) proposed a linear correction (their

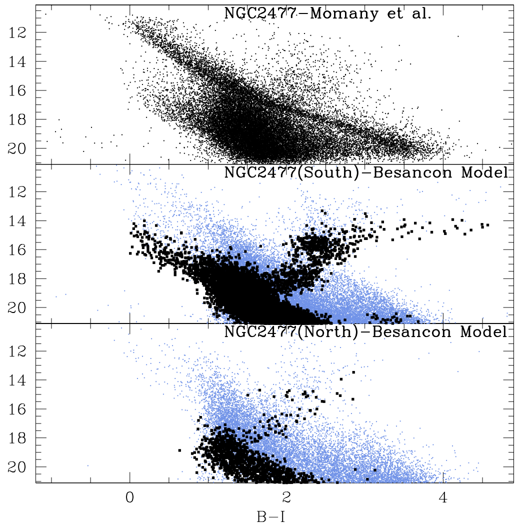

Fig. 3. V, $(B-I)$ diagrams of NGC 2477. Upper panel is from Momany et al. (2001), middle panel is a Besançon simulated CMD in an equivalent area along the same line of sight ($b = -5.^{\circ}8$). Lower panel is a Besançon simulated CMD at positive latitude ($b = +5.^{\circ}8$).

formula (1)) which lowers asintotically $E(B-V)$ of $\simeq$35%. The correction becomes quite important at low latitude with a difference of as much as $\simeq$0.2 mag in $(J-K)$ for an $E(B-V) = 1.0$. The previous analysis is repeated applying the Bonifacio et al. correction (right panels in Fig. 2). Assuming a $w = -2.^{\circ}0$ and correcting the reddening values it is quite evident that *both* star counts and reddening profiles show an excellent symmetry. This time however, the CMa over-density has almost disappeared. The assumed value of w is in good agreement with that found by Freudenreich et al. (1994, their Fig. 3) and Freudenreich (1996) for this particular zone. These studies suggest that the layers of dust and neutral hydrogen are similarly displaced from the Galactic plane. As regarding to stellar warp, evidence of a similar w value has been suggested in the 2MASS analysis of López-Corredoira et al. (2002). Indeed, for the line of sight at $l = 240°$ and galactocentric distances in the range $10 \div 14$ kpc they predict the height of the mid plane (due to the warp) to range between 300–450 pc. This translates into a warping angle of $w = 1.^{\circ}8 \div 2.^{\circ}4$ in the South direction. In conclusion, *an appropriate consideration for the warp and flare completely erases any over-density in CMa*.

Further support of the importance of the warp comes from the comparison of observed and synthetic CMDs. In Fig. 3 we compare a V, $(B-I)$ CMD of NGC 2477 (upper panel, Momany et al. 2001) with a Besançon synthetic catalog (middle panel). There is an excellent agreement between all observed features and simulated ones, except of course for the absence of the open cluster component and differential reddening effects in the simulated CMD. Clearly, sequences previously attributed to CMa (blue plume, young main sequence, red giants and red clump) are fully reproduced by the Galactic warped model. Plotted as heavy symbols are stars with a heliocentric distance between $7 \div 9$ kpc, a mean metallicity of $[\mathrm{Fe/H}] = -0.45 \pm 0.25$ and a mean age of 5.0 ± 1.5 Gyr. Curiously, similar parameters have been derived in Bellazzini et al. (2004) for the CMa stellar populations: a mean heliocentric distance of 8.3 ± 1.2 kpc, a mean metallicity in the range $-0.7 \leq [\mathrm{M/H}] \leq 0.0$ and a mean age between $2 \sim 7$ Gyr. On the other hand, the Galactic warped model shows a considerable decrease (a $\sim$10 factor) of the stellar component between $7 \div 9$ kpc in the NGC 2477-North field (Fig. 3, lower panel), i.e. it reproduces quite well the CMa South/North over-density. Similarly, Besançon simulated diagrams reproduce CMDs of the background populations of the open clusters having $-18° \leq b \leq -14°$ (see Sect. 4.3 in Bellazzini et al. 2003), showing a substantial decrease of the warp background contribution.

In conclusion, accounting for the Galactic warp and flare explains the detection of both the CMa over-density and related stellar populations. As a consequence, the CMa feature can not be the progenitor of the *ring* found by Newberg et al.

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