THE DOG ON THE SHIP: THE “CANIS MAJOR DWARF GALAXY”
AS AN OUTLYING PART OF THE ARGO STAR SYSTEM
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ABSTRACT

Overdensities in the distribution of low latitude, 2MASS giant stars are revealed by systematically peeling away from sky maps the bulk of the giant stars conforming to “isotropic” density laws generally accounting for known Milky Way components. This procedure, combined with a higher resolution treatment of the sky density of both giants and dust allows us to probe to lower Galactic latitudes than previous 2MASS giant star studies. While the results show the swath of excess giants previously associated with the Monoceros ring system in the second and third Galactic quadrants at distances of 6–20 kpc, we also find a several times larger overdensity of giants in the same distance range concentrated in the direction of the ancient constellation Argo. Isodensity contours of the large structure suggest that it is highly elongated and inclined by about 11° to the disk, although details of the structure — including the actual location of highest density, overall extent, true shape — and its origin, remain unknown because only a fraction of it lies outside highly dust-obscured, low latitude regions. Nevertheless, our results suggest that the 2MASS M giant overdensity previously claimed to represent the core of a dwarf galaxy in Canis Major (l ~ 240°) is an artifact of a dust extinction window opening to the overall density rise to the more significant Argo structure centered at larger longitude (l ~ 290° ± 10°, b ~ -4° ± 2°).

Subject headings: Galaxy: structure – Galaxy: disk – Local Group – galaxies: interactions

1. INTRODUCTION

Newberg et al. (2002) identified a low-b excess of stars in the Sloan Digital Sky Survey (SDSS) at [l, b] ~ [223, +20]°, with distances beyond, and with a larger apparent scale-height than, the nominal Milky Way (MW) disk. They attributed this excess to the presence of either a newly discovered dwarf galaxy or tidal stream lying just outside the Galactic disk. Majewski et al. (2003, M03 hereafter) identified the same structure in their study of 2MASS M giants. Ibata et al. (2003) observed the structure with optical CMDs for fields spanning over 100° of longitude, and proposed as a most likely explanation of this apparent “ring” around the MW disk that it is “a perturbation of the disk, possibly the result of ancient warps”. Meanwhile, Yanny et al. (2003) relied on SDSS spectra and imaging in other areas to argue the structure represents the remains of a tidally disrupted MW satellite, whereas Helmi et al. (2003) explored models of the structure as either a “transitory localized radial density enhancement” from particles stripped off a satellite on a recent peri-Galactic passage, or the analogue of “shells” found around elliptical galaxies deriving from minor mergers several Gyr in the past.

More detailed study of the distribution of 2MASS M giants has shown that (1) this newly-found structure is indeed ring-like, spanning >170° around the disk at a typical Galactocentric distance of ~16 kpc and broadened into both north and south Galactic hemispheres (Rocha-Pinto et al. 2003, Paper I hereafter; Martin et al. 2004a, M04a hereafter), (2) the structure contains stars enriched >10× higher than the [Fe/H]=–1.6 previously reported by Yanny et al. (2003) belying a large metallicity spread (Yanny & Crane et al. 2003) like that seen in MW satellite galaxies, and (3) the stars in the structure follow a slightly non-circular orbit with a relatively low (13–20 km s⁻¹) velocity dispersion (Crane et al. 2003; Martin et al. 2004b). Both globular and old open clusters spatially and kinematically correlated to the structure have been identified (Crane et al. 2003; Frinchaboy et al. 2004; Bellazzini et al. 2004); these clusters follow a well-defined age-metallicity relation. This combined evidence supports the view that the anticenter “ring’t’ represents tidal debris from a Sagittarius (Sgr) dwarf-like galaxy along an orbit with low inclination to, and orbital radius just larger than, the MW disk.

More recently, probing asymmetries in the 2MASS M giant distribution about the Galactic plane, M04a claim to have found the core of a satellite galaxy in Canis Major (“CMa”; l ~ 240°), which they argue to be the progenitor of the ring. However, Momany et al. (2004) have argued that CMa may be the MW disk stellar warp, based on comparison of observed to synthetic CMDs generated by models of a warped MW disk. This has prompted vigorous debate over the nature of CMa (Bellazzini et al. 2004; Martin et al. 2004b; Sbordone et al. 2005; Peñarrubia et al. 2005). Whatever its origin, that there is a “CMa overdensity” has apparently gained wide acceptance (e.g., Forbes et al. 2004; Tosi et al. 2004; Sbordone et al. 2005; Martinez-Delgado et al. 2005).

In this contribution we call into question a “core” overdensity in CMa, and find an apparently more significant giant star overdensity at l ~ 290°.

2. DATA AND COMPARISON MODEL

We extract a giant star candidate sample from the 2MASS all-sky point source release as all stars having dereddened 0.85 < J – K < 1.5, K < 13.0, photometric quality flag A and that meet the M giant color locus restriction used by M03. For each star we derive a distance probability distribution function (DPDF) based on its dereddened, PSF-fitted K and J – K, the variation of the color-absolute magnitude relation with [Fe/H] Ivanov & Borissova 2002, and an assumed
[Fe/H] distribution for giants typical of the ring (a Gaussian with mean [Fe/H] = -1 and spread 0.4 dex). Calculation of the DPDF is described in more detail in Paper I. We adopt as a single distance estimate, \( r \), for each star the mode of its DPDF.

Extinctions were calculated as \((A_J, A_K, E_J - K) = (0.90, 0.25, 0.65) \times E_{B-V}\), where \( E_{B-V} \) is from Schlegel, Finkbeiner, & Davis 1998 and \( \alpha = \frac{1}{4} \) (Rocha-Pinto et al. 2004). As with previous, similar studies (Paper I, M04) our analysis is limited to \( E_{B-V} \leq 0.55 \) to avoid false overdensity signals from small-scale differential reddening or errors in its estimation. However, we make several improvements over previous work: (1) To more closely follow the \( E_{B-V} = 0.55 \) “border” our maps are binned into finer, \( 1^\circ \times 1^\circ \) \((l,b)\) bins than the \( 4^\circ \times 2^\circ \) bins of M04 or the \( 4^\circ \times 4^\circ \) bins of Paper I. (2) M04 depended on direct comparisons of one region of the sky to another presumed to be “symmetric” — a procedure that requires both regions to have \( E_{B-V} \leq 0.55 \) and that ultimately removes large regions of “good” sky from consideration because comparison fields are too reddened. Here we rely on a Galactic model of the number of stars from canonical Galactic populations as a function of distance and \((l,b)\) as a reference for all \( E_{B-V} \leq 0.55 \) fields, which allows us to probe areas of the sky previously ignored.

The densities of the asymmetries sought are small compared to the MW foreground density. The goal of creating a Galactic model is to “fairly” remove the majority of this foreground to highlight the residual. Rocha-Pinto et al. (2006; in preparation) describes the Galaxy model in detail; here we outline the general procedures used to construct it. The key to such a model is that it be smooth, have a cylindrically symmetric density distribution about the Galactic center, and be constrained globally by the observed density distribution in available, low \( E_{B-V} \) lines of sight, so that, in the mean, most of the 2MASS giants are removed when the model is subtracted from the “observed” \((l,b,r)\) distribution to leave behind a high contrast picture of “overdensities”. To this end, the model does not need to be exact, nor should it necessarily be interpreted as a true description of the MW giant star distribution, though we start from a parameterization meant to produce a classical “starcount model” from thin disk, thick disk and halo density laws (those of Siegel et al. 2002). These density laws are multiplied by adopted luminosity functions for the corresponding stellar populations and integrated from the brightest to faintest absolute magnitudes of stars that can be in our observed sample. After integration over solid angle \((1^\circ \times 1^\circ)\) and normalization of the results to the observed stellar density at longitudes not contaminated by known stellar streams or the Magellanic Clouds, we have the expected number of stars coming from each contributing MW population within a given \( r \) range.

Because the 2MASS stars have distances calculated as if they have come from a hypothetical stellar population with \( \langle\text{[Fe/H]}\rangle = -1.0 \) and \( \sigma_{\text{[Fe/H]}} = 0.4 \), stars from the simulated MW have their distances recalculated with a DPDF in the same way — i.e. as if their simulated metallicity were unknown. That our model MW succeeds in removing the bulk of the canonical MW populations of giants is shown in the difference between the observed and model 3D density distributions (Fig. 1), where stellar densities in the projected distance ranges \( 6 \leq r \leq 20 \) kpc and \( 20 < r < 50 \) kpc are essentially eliminated. In contrast, in the distance range dominated by the ring, \( 6 < r \leq 20 \) kpc, significant residual densities — which we claim are true overdensities — can be seen.

![Fig. 1 — Residual 2MASS late type giant star density with respect to our MW model projected onto the celestial sphere at different distance ranges.](image)

3. THE ARGO OVERDENSITY

Most of the “w”-shaped arc of overdensity sweeping all of the way across the middle panel of Figure 1 can be attributed to the “anticenter ring/warp/Monoceros stellar structure,” discussed by the various studies referenced in §1. Here we focus specifically on the very obvious, large overdensity in the third and fourth quadrants from about \( l \approx 210^\circ \) to at least the left edge \((l \approx 310^\circ)\) of our sample range and peaking at \([l,b] \sim [290,-4]^\circ\). From the overall rise in density towards this specific point in Figure 1, we surmise that the trend continues and an even higher overdensity peak may lie somewhere in the obscured region with \(-4^\circ < b < +2^\circ \) near \(285^\circ < l < 300^\circ\), which spans the constellations Carina, Vela and Puppis. Because the peak of this large overdensity remains uncertain and possibly obscured, we call the structure “Argo,” after the large, ancient constellation later dismembered into Carina, Vela and Puppis by the IAU. As may be seen, the density of this region is significantly higher than any other visible giant star excesses — e.g., it is 4 to 8 times more dense than the densest, visible parts of the Northern and Southern Ring in the second quadrant.

The overall impression is that this large excess of giant stars constitutes one coherent structure with a “core” at \( l \sim 290^\circ \) but spreading well beyond. This core appears to be localized in distance. Figure 2 shows a 2MASS Hess diagram of the Argo core, created as the difference in Hess diagrams for fields \([l,b] = [285, -5]^\circ\) and \([l,b] = [285, +5]^\circ\). From this difference a well-defined red giant branch (RGB) associated with Argo emerges from the “RGB-smear” created by closer, foreground MW disk stars. The RGB residue has a highest Hess diagram density that is fit by an [Fe/H]= -0.7 population (Ivanov & Borissova 2002) at \( r \sim 13.8 \) kpc, but isochrones with a spread of metallicity not unlike that previously sug-
suggested for stars in the ring (see §1) and at this same distance seem to reasonably account for the triangular spread of residual red stars. That a red clump predominantly at fainter magnitudes remains after Hess diagram differentiating is not inconsistent with the presence of an Argo red clump at the same general distance (Salas & Girard 2002).

Another aspect of interest is that the isodensity contours tend to have ellipsoidal – *not* warp-like — character, with the major axes of the isopleths “jutting” out obliquely from the MW disk. In this respect, Argo resembles a large, distorted dSph galaxy, similar to the Sgr system. If, like Sgr, Argo is a coherent, symmetrical structure, we can “fit” ellipses to the visible isopleths to hypothesize its overall appearance (Fig. 3). The “eyeball’’ fit ellipses are centered at one point in the $E_{B-V} > 0.55$ region, but have variable axis ratio and inclination angle. The suggestion of a “twisting isophote” character resembles the M giant distribution of the Sgr core (see, e.g., M03’s Figs. 7e and 7f), which, with *its own* “ring” of tidal debris wrapping around the MW, may serve as a useful paradigm for Argo. The apparent inclination of Argo to the Monoceros ring (which seems to have a closer alignment to the MW disk) recalls the fact that the major axis of the Sgr core is canted (by 6°) with respect to its tidal stream (M03). These structural properties of the Argo system are certainly tantalizing support for the notion that it may be a tidally disrupting dSph-system — perhaps the progenitor of the Monoceros ring.

In their 2MASS M giant study, M04a also identified an apparently ellipsoidal overdensity, but with a geometrical center at $[l, b] \sim [240, -8]^\circ$. From this core-like feature, at an apparent distance of $10.0 \lesssim R_{GC} \lesssim 15.8$, M04a concluded that the center of the Monoceros system is in CMa. In contrast, our map shows nothing particularly special about this region, except that it lies within the overall density rise towards the Argo core, which in our map is $2-4 \times$ more dense than the excess at the position of the CMa “core.” Since the M04a analysis is using ostensibly the same database as ours, it is critical to understand the source of the discrepancy in results. Clues may lie in differences in how reddening affects each analysis:

- M04a used both a coarser $E_{B-V}$ map resolution and were forced to discard regions with highly extinguished Galactic plane-mirrored counterparts that we preserve through use of our model. The decreased area available to the M04a analysis is demonstrated by the difference between their and our $E_{B-V} = 0.55$ boundaries (Fig. 3). Much of Argo, including the highest density patch, has been removed from their analysis. In addition, with the M04a boundary it becomes less obvious that the overdensity at $l \sim 240^\circ$ is related to the one at $l \sim 290^\circ$ because of the intrusion of the elongated dust feature at $l \approx 265^\circ$ extending south to $b \sim -12^\circ$. The “approximately ellipsoidal” shape of CMa observed by these authors may be an artifact caused by the neighboring very reddened map cells — the $265^\circ$ reddening “fingert’’ and another at $l \approx 220^\circ$; the likely coordinates for the Monoceros structure core as given by M04a look to be the geometrical center of the outer Argo overdensity seen through this reddening window in their map.

Since the same arguments might be made about the nature and likely center of the Argo overdensity derived from our maps, it is important to stress both the provisional nature of our assessment of Argo and that most important clues about this star system still remain hidden.

4. CONCLUDING REMARKS

Our analysis of the 2MASS giant star distribution in the outer Galaxy, gives strong evidence for the presence of an excess of stars, in the distance range of the Monoceros ring, stretching across at least $210^\circ \leq l \leq 310^\circ$ with a concentration in the Argo region ($l \sim 290^\circ$), and suggests the CMa “core” is a reddening artifact sitting on the stern of Argo. At minimum, our results from an improved analysis of 2MASS M giants in high $E_{B-V}$ regions show a different structure to the stellar density enhancements in the MW third and fourth quadrants than...
It is also useful to compare the HI Galactic warp with the stellar asymmetries to see whether these coincide. Investigations of the gas warp show strong deviations from the Galactic plane both near \( l \sim 245^\circ \) and \( l \sim 290^\circ \) (see Fig. 5 by Sodroski et al. 1987). Figure 4 compares the stellar asymmetries found by this work with the asymmetries in the gas warp, according to the 3D data by Nakanishi & Sofue (2003). Although the southern gas warp asymmetry is similar in shape to that coming from the stars in the third and fourth Galactic quadrants, the gas warp is 2 and 5 kpc farther from the Sun than the stellar overdensity at the longitudes of CMa and Argo, respectively. Moreover, quite contrary to what is seen in the stellar overdensity, the HI warp shows a symmetrical deviation to the Northern hemisphere across the \( l = 0^\circ - 180^\circ \) Galactic meridian and, moreover, it is densest in this northern hemisphere. Since there is no counterpart to the northern hemisphere gas warp in the stellar data, we conclude that Argo is not likely to be simply a stellar counterpart to the gas warp. On the other hand, it is possible that the presence of this putative satellite galaxy could be the cause of the HI warp, given that interactions with satellite dwarf galaxies is the leading explanation for disk warps. (Shang et al. 1998, Schwarzkopf & Dettmar 2001; Reshetnikov et al. 2002).

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Fig. 4. — Comparison between the gas warp and the stellar overdensities found in this paper. The dark and light contour lines (blue and red lines, in the electronic version) in this plot refers to southern and northern hemisphere asymmetries, respectively, projected onto the Galactic plane. Contour levels indicate 0.2, 0.4, 0.6 and 0.85 of the maximum gas (5.36 M\(_\odot\) pc\(^{-2}\)) or stellar (4554 M giants kpc\(^{-1}\) rad\(^{-1}\)) cell density in this plot. The position of the Sgr dSph, as well as CMa and Argo, is shown.

previously reported. Figure 3 further explores our discovered peak overdensity in Argo as if it (not CMa) were the core of an elongated, possibly disrupting dwarf satellite galaxy, perhaps the source of the Monoceros ring. But further work is necessary to verify this and alternative explanations. For example, based on the distribution of 2MASS K giant candidates, López-Corredoira et al. (2002) report the discovery of a stellar warp in the outer disk. They base this conclusion on an apparently sinusoidal excess of stars with respect to \( l \), under equatorially symmetry. The south-north asymmetry in their data is strongest at \( l \sim 245^\circ \), coinciding with CMa, but the model proposed by the authors to reproduce these data peak around \( l \sim 290^\circ \), where Argo is found. While this may give the impression that Argo is the stellar component of the MW warp, their analysis relies on the same symmetry comparison methodology that affected other previous (e.g., Paper I, M04a) results. The Galactocentric coordinates of Argo, respectively, coincide with CMa, but (not CMa) were the core of a dSph, as well as CMa and Argo, is shown.

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