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

H. J. Rocha-Pinto,[1,2] S. R. Majewski,[2] M. F. Skrutskie,[2] R. J. Patterson,[2] H. Nakanishi,[3] R. R. Muñoz,[2] and Y. Sofue[4]

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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 3° 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 ($l \sim 240°$) is an artifact of a dust extinction window opening to the overall density rise to the more significant Argo structure centered at larger longitude ($l \sim 290° \pm 10°$, $b \sim -4° \pm 2°$).

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

Online material: color figures

1. INTRODUCTION

Newberg et al. (2002) identified a low-*b* excess of stars in the Sloan Digital Sky Survey (SDSS) at $[l, b] \sim [223°, +20°]$, 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, hereafter M03) identified the same structure in their study of Two Micron All Sky Survey (2MASS) M giants. Ibata et al. (2003) observed the structure with optical color-magnitude diagrams (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 analog of "shells" found around elliptical galaxies deriving from minor mergers several gigayears in the past.

More detailed study of the distribution of 2MASS M giants has shown that (1) this newly found structure is indeed ringlike, 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, hereafter Paper I; Martin et al. 2004a, hereafter M04a); (2) the structure contains stars enriched >10 times higher than the $[Fe/H] = -1.6$ previously reported by Yanny et al. (2003), belying a large metallicity spread (Paper I; Crane et al. 2003) like that seen in MW satellite galaxies; and (3) the stars in the structure follow a slightly noncircular 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 represents tidal debris from a Sagittarius (Sgr) dwarflike 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; $l \sim 240°$), 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, on the basis of comparisons 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; Martínez-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 $l \sim 290°$.

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 $0.85 < J - K_S < 1.5$, $K_S < 13.0$, photometric quality flag AAA,

[1] Observatório do Valongo, UFRJ, Rio de Janeiro, RJ 20080-090, Brazil; helio@ov.ufrj.br.

[2] Department of Astronomy, University of Virginia, Charlottesville, VA 22903; srm4n@virginia.edu, mfs4n@virginia.edu, rjp0i@virginia.edu, rrm8f@virginia.edu.

[3] Nobeyama Radio Observatory, Minamimaki, Minamisaku, Nagano 384-1305, Japan; hnakanis@nro.nao.ac.jp.

[4] Institute of Astronomy, University of Tokyo, 2-21-1 Osawa, Mitaka, Tokyo 181-0015, Japan.

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_S and $J - K_S$, 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 $(A_J,\ A_{K_S},\ E_{J-K_S}) = (0.90,\ 0.25,\ 0.65)\alpha E_{B-V}$, where E_{B-V} is from Schlegel et al. (1998) and $\alpha = \frac{2}{3}$ (Rocha-Pinto et al. 2004). As with previous, similar studies (Paper I; M04a), 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, $1° \times 1°$ (l, b) bins than the $4° \times 2°$ bins of M04a or the $4° \times 4°$ bins of Paper I. (2) M04a 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. H. J. Rocha-Pinto et al. (2006, in preparation) describe 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, although we start from a parameterization meant to produce a classical "star count 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 ($1° \times 1°$) 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 $\langle[\mathrm{Fe/H}]\rangle = -1.0$ and $\sigma_{[\mathrm{Fe/H}]} = 0.4$, 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 three-dimensional density distributions (Fig. 1), where stellar densities in the projected distance ranges $r \leq 6$ kpc and $20\ \mathrm{kpc} < r \leq 50$ kpc are essentially eliminated. In contrast, in the distance range dominated by the ring,

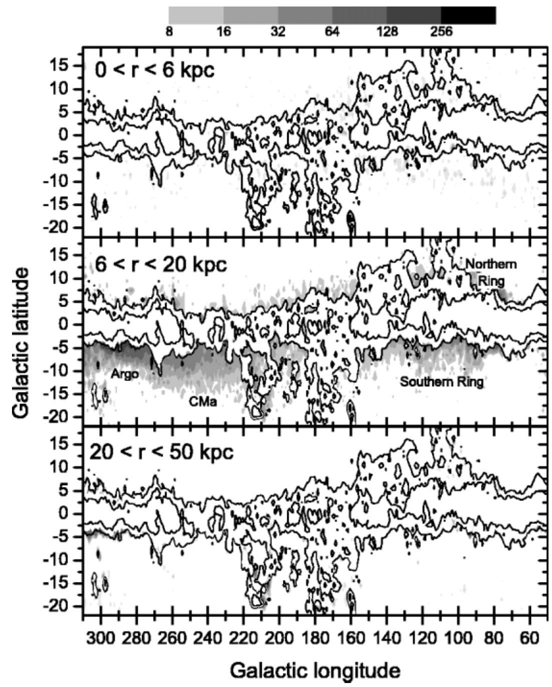

FIG. 1.—Residual 2MASS late-type giant star density with respect to our MW model projected onto the celestial sphere at different distance ranges. Contour levels represent geometrically increasing densities in number of stars deg^{-2}. The solid lines show E_{B-V} contour levels at 0.55 and 1.20 mag; regions having $E_{B-V} > 0.55$ have been discarded from the analysis. This figure supports our claim that the CMa overdensity is only an outlying part of the larger Argo overdensity seen in the 6 kpc $< r \leq 20$ kpc range. [*See the electronic edition of the Journal for a color version of this figure.*]

6 kpc $< r \leq 20$ kpc, significant residual densities—which we claim are true *overdensities*—can be seen.

3. THE ARGO OVERDENSITY

Most of the tilde-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 $l = 210°$ to at least the left edge ($l = 310°$) of our sample range and peaking at $[l, b] \sim [290°, -4°]$. From the overall rise in density toward 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 $-4° < b < +2°$ near $285° < l < 300°$, 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 4–8 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 $l \sim 290°$ 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 at $[l, b] = [285°, -5°]$ and $[l, b] = [285°, +5°]$. From this difference, a well-defined red giant branch (RGB) associated with Argo emerges from the "RGB smear" created by closer, fore-

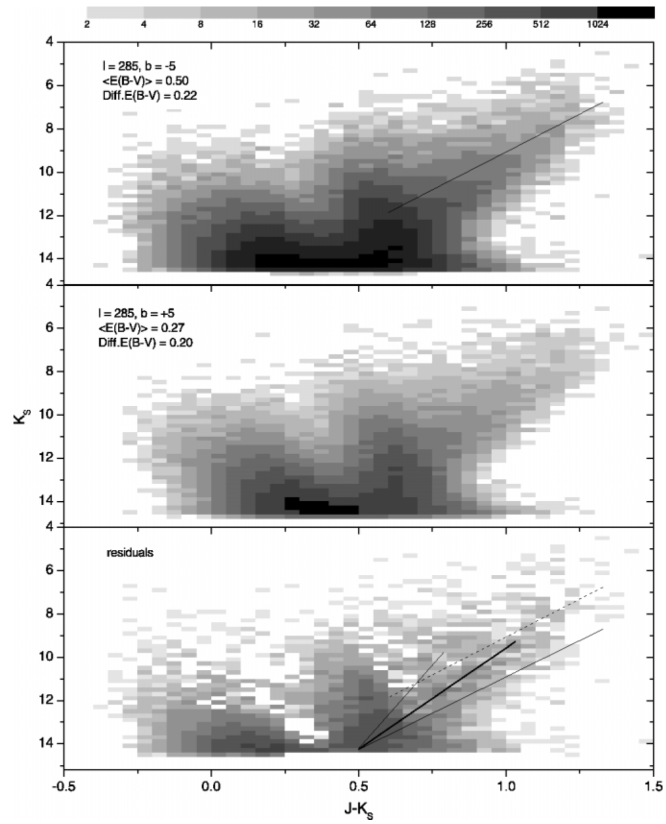

FIG. 2.—2MASS CMDs for (*top*) a field with an excess of stars associated with the Argo overdensity, (*middle*) a control field (same *l*, opposite *b*), and (*bottom*) their difference. The line in the top panel shows that the bulk of MW giants can be fitted by an [Fe/H] $= -0.1$ RGB isochrone having a median distance modulus of 14 mag (i.e., 6.3 kpc). This isochrone is reproduced in the lower panel as a dashed line to demonstrate that the residual RGB we associate with Argo is mostly fainter. The solid lines in the bottom panel show [Fe/H] $= -1.4$, -0.7, and 0.0 RGB isochrones placed 13.8 kpc from the Sun to match the distinct RGB from Argo as well as the previously suggested (see § 1) large [Fe/H] spread of the anticenter ring. Residue at $J - K_s \sim 0.5$ may represent Argo red clump stars.

ground 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 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 differencing is not inconsistent with the presence of an Argo red clump at the same general distance (Salaris & Girardi 2002).

Another aspect of interest is that the isodensity contours tend to have ellipsoidal—*not* warplike—character, with the major axes of the isopleths "jutting" out obliquely from the MW disk. In this respect, Argo resembles a large, distorted dwarf spheroidal (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., Figs. 7*e* and 7*f* in M03), 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.

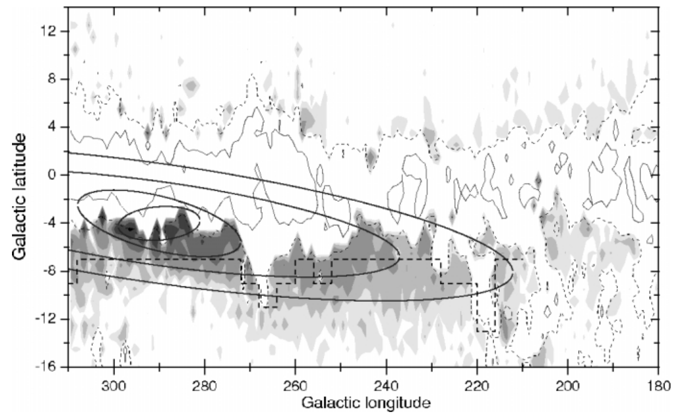

FIG. 3.—Same as the middle panel of Fig. 1, but with gray scales fit by the ellipses shown. The dashed line indicates the $E_{B-V} = 0.55$ reddening boundary adopted in the M04a study. The dotted and solid lines show the $E_{B-V} =$ 0.55 and 1.20 boundaries, respectively, from a finer extinction map resolution than used by M04a.

In their 2MASS M giant study, M04a also identified an apparently ellipsoidal overdensity but with a geometrical center at $[l, b] \sim [240°, -8°]$. From this corelike feature, at an apparent distance of $10.0 \lesssim R_{\rm GC} \lesssim 15.8$, 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 toward 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 $l \sim 240°$ is related to the one at $l \sim 290°$ because of the intrusion of the elongated dust feature at $l \simeq 265°$ extending south to $b \simeq -12°$. The "approximately ellipsoidal" shape of CMa observed by these authors may be an artifact caused by the neighboring very reddened map cells—the 265° reddening "finger" and another at $l \simeq 220°$; 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 $210° \leq l \leq 310°$ with a concentration in the Argo region ($l \sim 290°$) 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 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 equatorial symmetry. The south-north asymmetry in their data is strongest at $l \sim 245°$, coinciding with CMa, but *the model* proposed by the authors to reproduce these data peaks around $l \sim 290°$, 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) low-latitude 2MASS studies and, as such, cannot properly account for the presence of any satellite near and/or spanning across the MW midplane.

It is also useful to compare the H I 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 $l \sim 245°$ and $l \sim 290°$ (see Fig. 5 in Sodroski et al. 1987). Figure 4 compares the stellar asymmetries found by this work with the asymmetries in the gas warp, according to the three-dimensional 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 H I warp shows a symmetrical deviation to the northern hemisphere across the $l = 0°–180°$ 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 H I 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).

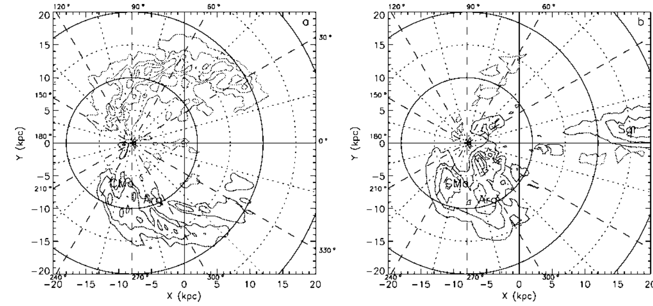

FIG. 4.—Comparison between the gas warp and the stellar overdensities found in this Letter. The dark and light contour lines in this plot refer to southern and northern hemisphere asymmetries, respectively, projected onto the Galactic plane. Contour levels indicate 0.2, 0.4, 0.6, and 0.85 of the maximum gas ($5.36\ M_\odot\ \mathrm{pc}^{-2}$) or stellar (4554 M giants $\mathrm{kpc}^{-1}\ \mathrm{rad}^{-1}$) cell density in this plot. The position of the Sgr dSph, as well as CMa and Argo, is shown. [*See the electronic edition of the Journal for a color version of this figure.*]

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