MAPPING THE ASYMMETRIC THICK DISK: THE HERCULES THICK-DISK CLOUD

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ABSTRACT

The stellar asymmetry of faint thick-disk/inner-halo stars in the first quadrant ($l = 20°–45°$) that was first reported by Larsen & Humphreys and investigated further by Parker et al. has recently been confirmed by the Sloan Digital Sky Survey (SDSS). Their interpretation of the excess in the star counts as a ringlike structure, however, is not supported by critical complementary data in the fourth quadrant, which is not covered by the SDSS. We present stellar density maps from the Minnesota Automated Plate Scanner Catalog of the POSS I showing that the overdensity does not extend into the fourth quadrant. The overdensity is most probably not a ring. It could be due to interaction with the disk bar, or it could be evidence of a triaxial thick disk or a merger remnant/stream. We call this feature the Hercules Thick-Disk Cloud.

Subject headings: Galaxy: kinematics and dynamics — Galaxy: structure

1. INTRODUCTION

Larsen & Humphreys (1996) initially reported a substantial asymmetry of faint blue stars in the first quadrant (Q1) of the inner Galaxy, $l = 20°–45°$, compared with complementary fields in the fourth quadrant (Q4) based on star counts from the Minnesota Automated Plate Scanner (MAPS)\(^1\) (Cabanela et al. 2003). Parker et al. (2003) made a more in-depth survey to map the extent of the asymmetry using 40 contiguous fields in each of three regions: Q1 above and below the plane and Q4 above the plane. Q4 below the plane is not covered in the first Palomar Observatory Sky Survey (POSS I). They found a 25% excess in the number of probable thick-disk stars in Q1 above and below the plane, when compared to the complementary Q4 fields. The region was irregular in shape and covered several hundred square degrees, but, with a completeness limit at $\sim 18$–$18.5$ mag, the stars showing the excess in Q1 were relatively nearby, $\sim 1$–$2$ kpc from the Sun. Parker et al. (2004) also found an associated kinematic signature, a significant lag of $80$–$90$ km s$^{-1}$ in the direction of Galactic rotation for the associated thick-disk stars in Q1.

The recent release of the Sloan Digital Sky Survey (SDSS) Data Release 5 photometry in the direction of the observed asymmetry in Q1 led to the discovery of a feature at much fainter magnitudes, the distant Hercules-Aquila cloud (Belokurov et al. 2007), and the photometric parallax study by Jurić et al. (2008) confirmed our nearer asymmetry in the inner Galaxy as an overdensity at a galactocentric radius of 6.5 kpc situated 1.5 kpc above the plane. The SDSS, however, is not well designed for a good study of the thick disk inside the solar orbit. It extends below $b = 30°$ in only a few directions in Q1 and has only limited coverage in Q4.

We are continuing our program of photometric and spectroscopic observations to map the size and extent of the asymmetry along our line of sight and to determine the degree of spatial and kinematic asymmetry above and below the plane. We are using the SMARTS Consortium Cerro Tololo Inter-American Observatory (CTIO) 1 m Y4KCam and the Steward Observatory 90” Bok telescope 90Prime Mosaic imager to obtain wide-field multicolor CCD imaging to fainter completeness limits than the POSS I. Spectra of the candidate thick-disk stars for radial velocities and metallicity estimates have been observed using the Hydra multiobject spectrometer on the CTIO Blanco 4 m telescopes and the Hectospec on the MMT Observatory 6.5 m telescope.

In this Letter, we present a stellar number density map that we created from the MAPS POSS-I scans, to provide a more global reference for our current deeper but more spatially restricted photometric and spectroscopic study of the thick disk in the inner Galaxy. Other works (Xu et al. 2007) have used plate data to supplement gaps in the SDSS at more southern declinations, with good success. Our map of the stellar density in Q1 and Q4 covers much of the sky unavailable to SDSS and demonstrates that the nearby asymmetry in Q1 does not represent a ring above the Galactic plane but, instead, is a significant substructure or cloud extending over many square degrees in Galactic longitude and latitude. We call this feature the Hercules Thick-Disk Cloud.

2. THE STELLAR DENSITY MAPS

The figures presented in this Letter were originally created to provide a reference frame for the interpretation of our ongoing observations of the thick disk using narrower yet deep multicolor CCD imaging. They were made using the same set of POSS-I fields selected by Parker et al. (2003) above the Galactic plane, and the fields are fully described in that publication. The 80 POSS-I plates cover 2900 deg$^2$ on the sky, and all are complete to fainter than 18th magnitude in the O band (blue) and have colors ($O - E$) available from the paired observation in the red (E band). Their placement on the sky is shown in Figure 1 for Q1 and in Figure 2 for Q4. The $B - V$ extinction in each field is plotted from Schlegel et al. (1998) and is substantially less than $E(B - V) < 0.2$ in all fields. We defer a discussion of the Q1 data below the plane to a later paper, because it is not relevant to the present Letter.

\(^1\) The MAPS Catalog of the POSS I is available online at http://aps.umn.edu.
The MAPS Catalog has superior stellar photometry when compared with most other digitized plate catalogs of the POSS, because each plate has its own independent photometric calibration derived from our own CCD observations, as described in Larsen & Humphreys (2003), or from photoelectric photometry (Lasker et al. 1988) and uses an isophotal diameter-to-magnitude relation for the stars.

The individual plate catalogs were merged, duplicates in the plate overlap regions removed, and interstellar extinction from Schlegel et al. (1998) was applied on a star-by-star basis using the standard interstellar extinction law. We assume that the bulk of the extinction comes from relatively near the Sun and that our objects of interest are much farther away, so that the extinction is a zero-point correction. A global geometric vignetting correction was applied to all of the plates in the MAPS Catalog. However, we found that some plates had larger vignetting problems (probably due to moonlight). As a result, we applied an additional radial magnitude correction to the MAPS magnitudes for five of the 80 plates, to bring the number densities at the plate edges into line with the well-behaved and well-calibrated plate center. Star-galaxy classification uses a neural network and is described in Odewahn et al. (1992, 1993) and Cabanela et al. (2003). Any uncertainty in object classification is not a significant factor in the creation of these maps.

We then selected stars in the magnitude range $14 < O < 18$ (or approximately $13.5 < V < 17.5$) above the completeness limits. Since the plates still have some magnitude zero-point differences and cosmic scatter, we used the “blue ridgeline” at $O - E \approx 1.0$ or $B - V \approx 0.6$ as a fiducial reference, to select a sample of stars with blue and intermediate colors (see Parker et al. 2003; Fig. 5). Stars bluer than the ridgeline are representative of the stars that show the asymmetry (Parker et al. 2003). Although the exact location of the blue ridge in $O - E$ color varies somewhat from plate to plate and with Galactic longitude and latitude, due to the relative contributions of stars from the halo, disk, and thick disk, it provides a strongly identifiable feature on each color-magnitude diagram (see Fig. 3). The color variations between adjacent plates will thus be small compared to the variations across the full 180° of sky covered. Our magnitude and color search limits are illustrated on one of our color-magnitude diagrams shown in Figure 3.

3. DISCUSSION AND CONCLUSIONS

After the reduction steps outlined above, we then binned the stars $0.25^\circ \times 0.25^\circ$ in $l$ and $b$, to create maps of the stellar density distribution of the faint blue and intermediate color stars shown in Figures 4 and 5. The figures are color-coded with respect to number density per 0.0625 deg$^2$.

Juric et al. (2008) described the excess in Q1 as due to a “ringlike” structure, because the overdensity appeared to be radially constant and circular in cross section in their Figure 27. The center of the overdensity region ranges from $(X, Y, Z) = (6.5, -2.2, 1.5 \text{ kpc})$ to $(6.5, 0.3, 1.5 \text{ kpc})$ and can easily be converted into Galactic coordinates. This is shown as the purple line in Figure 4. If the feature were symmetric about $l = 0^\circ$, it would project into Q4 to $(6.5, 2.2, 1.5 \text{ kpc})$. This projection is also shown as a purple line in Figure 5. Comparison of Figures
from above the plane as they entered Q4, the opposite should be
coherent population of stars were moving together toward the disk
of velocity was less negative for Q1 than it was for Q4. If a
Q4, and found, in a somewhat weak result, that the
from overdensity regions in Q1, compared with a control sample
Parker et al. (2004) studied the velocities of samples of stars taken
pening if the overdensity were falling into the plane in Q4. Finally,

![Image](61x621 to 293x721)

Fig. 4.—Density image created for the stars in Q1 with the POSS-I plate
boundaries from Fig. 1 overlaid in green. Notice how there is a distinct
overdensity on the order of about 30% between $l = 25^\circ$–$45^\circ$ and $b = 30^\circ$–$35^\circ$
when compared with the corresponding Q4 stars in Fig. 5. Comparison with
Fig. 1 shows that extinction cannot be causing the feature that we see. The
location of the Jurić et al. (2008) overdensity is shown by the purple line.

4 and 5, however, show that the density of these stars is not
symmetric with respect to the Sun-center line. There is a clear
excess of stars in Q1 over Q4 in the range $l = 25^\circ$–$45^\circ$ and $b = 30^\circ$–$40^\circ$. Furthermore, we emphasize that the excess would
not have been initially discovered if it had been a symmetric
ring, since we (Larsen & Humphreys 1996) were comparing star
counts for complementary fields in Q1 and Q4.

Could the “ringlike” structure be inclined to the plane and there-
fore not be visible in Q4? Most probably not. The full height of the
overdensity in $Z$ over an azimuthal distance of 2500 pc is only
500 pc (Jurić et al. 2008). Even for the pathological case of a
paper-thin–inclined distribution in $Z$, the maximum inclination
could only be $11^\circ$, and, given its width in $X$, it should have been
visible in Figure 5. Additionally, there is strong evidence from
Jurić et al. (2008; see their Fig. 27, left panel) that, for $X = 7250$–
7750 pc, the overdensity is exclusively above $Z = 1500$ pc. Ex-
amination of the same figure’s middle panel shows that all sig-
nificant contributors to the overdensity in this same $X$ range have
$Y < 1000$ pc. This would be the opposite of what should be hap-
pening if the overdensity were falling into the plane in Q4. Finally,
Parker et al. (2004) studied the velocities of samples of stars taken
from overdensity regions in Q1, compared with a control sample
Q4, and found, in a somewhat weak result, that the $Z$-component
of velocity was less negative for Q1 than it was for Q4. If a
coherent population of stars were moving together toward the disk
from above the plane as they entered Q4, the opposite should be
true.

The cloud of stars detected by Jurić et al. (2008) is not symmetric
about the $l = 0^\circ$ line and almost certainly is not a ring. This does
not change their other possible explanation for the feature, how-
ever. Given the broad extent of the cloud (Figs. 4 and 5), together
with its apparent small ranges in radial distance from the Sun and
its distance above the Galactic plane (their Fig. 27), the Hercules
Thick-Disk Cloud may be a debris stream consistent with the disk-
formation scenario described by Abadi et al. (2003). Although the
Hercules thick-disk cloud is relatively nearby on the sky, it is not
related to the more distant (10–20 kpc) Hercules-Aquila cloud
described in Belokurov et al. (2007). The northern extent of the
Hercules-Aquila cloud (Fig. 2 in Belokurov et al. 2007) is confined
to Galactic latitudes less than $30^\circ$, and, even in those regions, the
bulk of the stars are much fainter than our magnitude limit. The
contamination of our sample by Hercules-Aquila cloud stars would
be less than five objects per square degree (0.5 stars per bin) in
any case, given our relatively bright magnitude limits.

Other explanations are still possible, such as a triaxial thick
disk and an overdensity due to an interaction with the disk bar.
Analysis of our CCD photometry and spectroscopy for fainter
stars in Q1 and Q4 will be used to address this question.

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REFERENCES

Abadi, M. G., Navarro, J. F., Steinmetz, M., & Eke, V. R. 2003, ApJ, 597, 21
Belokurov, V., et al. 2007, ApJ, 657, L89
Cabanela, J. E., Humphreys, R. M., Aldering, G., Larsen, J. A., Odewahn,
S. C., Thurmes, P. M., & Cornuelle, C. S. 2003, PASP, 115, 837
Jurić, M., et al. 2008, ApJ, 673, 864
Larsen, J. A., & Humphreys, R. M. 1996, ApJ, 468, L99
———. 2003, AJ, 125, 1958
Lasker, B. M., et al. 1988, ApJS, 68, 1

Odewahn, S. C., Humphreys, R. M., Aldering, G., & Thurmes, P. 1993, PASP,
105, 1354
Odewahn, S. C., Stockwell, E. B., Pennington, R. L., Humphreys, R. M., &
Zumach, W. A. 1992, AJ, 103, 318
Parker, J. E., Humphreys, R. M., & Beers, T. C. 2004, AJ, 127, 1567
Parker, J. E., Humphreys, R. M., & Larsen, J. A. 2003, AJ, 126, 1346
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Xu, Y., Deng, L. C., & Hu, J. Y. 2007, MNRAS, 379, 1373