THE ASYMMETRIC THICK DISK: A STAR-COUNT AND KINEMATIC ANALYSIS. II. THE KINEMATICS

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ABSTRACT

We report a kinematic signature associated with the observed asymmetry in the distribution of thick-disk/inner halo stars interior to the solar circle described in Paper I. In that paper, we found a statistically significant excess (20%–25%) of stars in quadrant I (l ~ 20°–55°) both above and below the plane (b ~ ±25° to ±45°) compared with the complementary region in quadrant IV. We have measured Doppler velocities for 741 stars, selected according to the same magnitude and color criteria, in the direction of the asymmetry and in the corresponding fields in quadrant IV. We have also determined spectral types and metallicities measured from the same spectra. We not only find an asymmetric distribution in the \( V_{LSR} \) velocities for the stars in the two regions, but the angular rate of rotation (\( \omega \)) for the stars in quadrant I reveals a slower effective rotation rate compared with the corresponding quadrant IV stars. The results for \( V_{LSR} \) and \( \omega \) also show an interesting dependence on Galactic longitude that is most pronounced in quadrant I. We use our [Fe/H] measurements to separate the stars into the three primary population groups, halo, thick disk, and disk, and conclude that it is primarily the thick-disk stars that show the slower rotation in quadrant I. These stars are also responsible for the observed variation of \( V_{LSR} \) and \( \omega \) with Galactic longitude. A solution for the radial, tangential, and vertical components of the \( V_{LSR} \) velocities reveals a significant lag of \( \approx 80 \) to \( 90 \) km s\(^{-1}\) in the direction of Galactic rotation for the thick-disk stars in quadrant I, while in quadrant IV, the same population has only a ~20 km s\(^{-1}\) lag confirming the kinematic asymmetry between the two directions. In Paper I, we concluded that the asymmetry in the star counts could be best explained by either a triaxial thick disk or an interaction between the bar in the disk and the thick-disk/inner halo stars. The results reported here support a rotational lag among the thick-disk stars due to a gravitational interaction with the bar as the most likely explanation for the asymmetry in both the star counts and the kinematics. The affected thick-disk stars, however, may be associated with the recently discovered Canis Major debris stream or a similar merger event.

Key words: Galaxy: halo — Galaxy: kinematics and dynamics — Galaxy: stellar content — Galaxy: structure

On-line material: machine-readable table

1. INTRODUCTION

In Parker, Humphreys, & Larsen (2003, hereafter Paper I), we reported evidence for an asymmetric excess of thick-disk/inner halo stars extending from approximately \( l ~ 20° \) to \( 55° \) and \( b ~ 25° \) to \( 45° \) both above and below the plane. In Paper I, we considered three possible explanations for the asymmetry, including a possible merger remnant, but concluded that either a triaxial thick disk (Blitz & Spergel 1991), with its major axis in quadrant I, or an interaction with the bar in the disk (Hernquist & Weinberg 1992; Debattista & Sellwood 1998) best explained the observations. Both of these would explain the star-count excess but with different kinematics. A triaxial thick disk/inner halo, for example, may have a distinct rotational velocity about the Galactic center different from the disk. Indeed, thick-disk stars are observed to have a lag of 30–50 km s\(^{-1}\) (Reid 1998; Chiba & Beers 2000) with respect to disk stars. However, a fast-rotating bar in the disk in quadrant I with corotation at 3–4 kpc from the Galactic center could induce a gravitational “wake” that would trap and pile up stars behind it (Hernquist & Weinberg 1992; Debattista & Sellwood 1998). In response to the bar, there would not only be an excess of stars, but some of the stars might show a measurable “lag” or slower rotation as a result. Thus in either case, if the asymmetry in the star counts is due to a structural feature, then it should be supported by an asymmetric pattern in the stars’ motions. To search for a kinematic signature associated with the asymmetry in the star counts that could also provide additional evidence for the cause of the asymmetry, we have obtained medium-resolution spectra for radial velocities, spectral classification, and metallicity estimates of stars selected from 12 fields, six each in the direction of the asymmetry and in the corresponding regions in quadrant IV.

In §§ 2 and 3, we briefly describe the observations and data reduction. In § 4, we discuss the velocities, spectral classification, metallicity estimates, and evidence for a population dependent asymmetry. In the final section, we summarize the results of our kinematics analysis and its implications for the origin of the observed asymmetry.

2. OBSERVATIONS AND FIELD AND OBJECT SELECTION

We used Hydra, a multiobject spectrometer on the 4 m Blanco Telescope at Cerro Tololo Inter-American Observatory
The WIYN Observatory is a joint facility of the University of Wisconsin–Madison, Indiana University, Yale University, and the National Optical Astronomy Observatory.

Further information regarding the specifics of the instruments can be found at http://www.noao.edu/ctio/ or http://www.noao.edu/kpno/wiyn/.

On the POSS I photometric system this color range, \((O-\text{E})\sim -0.8\) to \(-1.0\) mag, corresponds approximately to a \((B-V)\sim -0.0\) to \(-0.6\) and includes stars in the blue and intermediate color bins as defined in Paper I.

3. DATA REDUCTION AND VELOCITY MEASUREMENT

Hydra has its own software reduction task DOHYDRA within the larger Image Reduction and Analysis Facility.
software package (IRAF). DOHYDRA is a specialized package with multiple tasks for scattered light subtraction, flat fielding, fiber throughput correction, wavelength calibration, extraction, and sky subtraction. There is a degree of automation and built-in record keeping that is necessary for the volume of data generated by this instrument. The task CCDPROC was used to correct each image for the overscan and bias. Each individual exposure was processed with DOHYDRA using the projector flats for the flat field, the comparison spectra for the dispersion correction, and a simple text table generated by the instrument to identify the apertures.

Fig. 1.—Map of the selected fields observed at CTIO and KPNO. The light gray identifies observations made on the Blanco 4 m at CTIO in 1999, dark gray for the 2000 observations, and black indicates those fields observed with the WIYN 3.5 m at KPNO in 2000.

| FIELD | \(l\) (deg) | \(b\) (deg) | STARS | SKY | EXPOSURE TIME (minutes) | NIGHTS OBSERVED |
|-------|-------------|-------------|-------|-----|-------------------------|-----------------|
| CTIO 1999 |
| P913       | 320.0       | 30.0        | 54    | 4   | 40 \(\times\) 4         | Apr 15          |
| P566       | 20.0        | 32.0        | 50    | 5   | 40 \(\times\) 3, 60      | Apr 15, 17      |
| CTIO 2000 |
| P913       | 320.0       | 30.0        | 56    | 5   | 40 \(\times\) 3          | May 28          |
| P566       | 330.0       | 33.0        | 49    | 4   | 40 \(\times\) 2          | May 27          |
| CTIO 2000 |
| P913       | 320.0       | 30.0        | 56    | 5   | 40 \(\times\) 3          | May 28          |
| P566       | 330.0       | 33.0        | 52    | 5   | 40 \(\times\) 3, 40      | May 28, 29      |
| WIYN 2000  |
| P387       | 40.0        | 41.0        | 80    | 5   | 40 \(\times\) 3          | Jun 2           |
| P448       | 40.0        | 30.0        | 77    | 5   | 40 \(\times\) 3          | Jun 2           |

\(^{6}\) IRAF is written and supported by the IRAF programming group at the National Optical Astronomy Observatory (NOAO) in Tucson, Arizona. NOAO is operated by AURA, Inc., under cooperative agreement with the NSF.
used. DOHYDRA first identifies the apertures, then flat fields the images by extracting and averaging the flat-field spectra over all fibers. Interactively, the average flat field is fitted by a high order function, spline3 order 100, that normalizes the images by extracting and averaging the flat-field spectra. The spectra were then dispersion corrected after identifying lines in the comparison spectra. The spectra were not continuum subtracted as this made no difference for measuring the velocities for stars observed on multiple observing runs. Minor differences exist but were within the errors expected for measurements at this resolution. The duplicate observations were combined by taking the weighted average radial velocity for each star. Accounting for duplicates, we have radial velocities for 741 stars, 418 stars in quadrant I and 323 stars in quadrant IV. The heliocentric velocities are given in Table 4.

4. VELOCITIES, SPECTRAL CLASSIFICATION, AND METALLICITIES

In this section, we review the measured velocities corrected to the local standard of rest (LSR) and the corresponding angular rotation rate ($\omega$) in the two quadrants, compare the stars’ kinematics with their spectral types and metallicities, and discuss the kinematics of the three primary population groups in the two quadrants.

4.1. Kinematics

In Figure 2, we show the normalized histograms of the measured velocities for the quadrant I and IV stars corrected to the LSR using the solar motion values from Hipparcos data reported in Ibata et al. (1997). Both quadrants show a very broad range in velocities with high-velocity tails to negative velocities in quadrant I and to positive velocities in quadrant IV as we would expect, but surprisingly both show net negative velocities. After removing the obviously high-velocity Population II stars with $V_{\text{LSR}}$ greater than $\pm200$ km s$^{-1}$, the mean LSR-corrected velocities are $-19.3 \pm 3.2$ and $-15.3 \pm 4.0$ km s$^{-1}$ for quadrants I and IV, respectively, with standard deviations ($\sigma$) or dispersions of 65.3 km s$^{-1}$ and 68.8 km s$^{-1}$, respectively.
respectively. If we assume a uniform, axisymmetric thick disk that is rotating with a circular velocity comparable to the thin disk, an observer at the LSR would expect to measure stars with positive LSR velocities in quadrant I, since these stars are moving away from us, and negative velocities in quadrant IV since the stars would be approaching. The velocities should be comparable for stars at similar distances and symmetric directions but of opposite sign. However, the thick disk is known to rotate slower or lag the thin disk by 30–50 km s\(^{-1}\) compared with quadrant IV. Of course, the stars in quadrant I have a slower circular rotation. However, the stars in quadrant I have a slower circular rotation. However, the stars in quadrant I have a slower circular rotation. However, the stars in quadrant I have a slower circular rotation. However, the stars in quadrant I have a slower circular rotation. However, the stars in quadrant I have a slower circular rotation. However, the stars in quadrant I have a slower circular rotation. However, the stars in quadrant I have a slower circular rotation. However, the stars in quadrant I have a slower circular rotation. However, the stars in quadrant I have a slower circular rotation. However, the stars in quadrant I have a slower circular rotation.

The results for \(V_{\text{LSR}}\) and \(\omega\) show a kinematic asymmetry between quadrants I and IV corresponding to the observed asymmetry in the star counts. However, these results alone do not allow us to distinguish between radial streaming along the major axis of a triaxial thick disk and a rotational lag due to interaction with the bar in the disk.

Furthermore, when we inspect the results for the individual fields (Table 5), we note that there is a very interesting gradient or dependence of the mean \(V_{\text{LSR}}\) values on longitude, especially in quadrant I. The mean \(V_{\text{LSR}}\) values become more negative at the greater longitudes in quadrant I and somewhat more positive in quadrant IV. This dependence may let us separate the radial and tangential components to determine if the kinematic asymmetry is due to streaming in the radial direction or a lag entirely in the direction of Galactic rotation.

In § 4.4 below, we use additional information on the stars’ metallicities to reexamine their kinematics as a function of

### Table 4: Velocities, Spectral Types, and Metallicities

| Field/OBS Run | APS Star Number | O Mag | O–E | \(l\) (deg) | \(b\) (deg) | \(V_{\text{helio}}\) (km s\(^{-1}\)) | \(\sigma_{\text{helio}}\) (km s\(^{-1}\)) | Number of Lines | [Fe/H] \(^{a}\) | Spec. Type |
|---------------|----------------|-------|-----|------------|--------|-----------------|----------------|----------------|--------------|------------|
| P332/3...     | 1931756        | 16.1  | 0.8 | 51.3       | 37.1   | -12.5           | 3.6            | 4              | -0.71        | 0.15        | G5–G8      |
| 2058237       | 16.5           | 0.6   | 50.9 | 37.5       | -80.3  | 11.5            | 4              | 0.30           | 0.22         | G0          |
| 2500783       | 16.0           | 0.6   | 50.3 | 36.8       | -31.8  | 3.7             | 6              | 0.30           | 0.15         | G5          |
| 2199563       | 16.1           | 0.9   | 50.5 | 37.5       | 108.6  | 11.1            | 6              | 0.99           | 0.31         | G5–G8      |
| 1922793       | 15.9           | 0.7   | 51.1 | 37.4       | -84.8  | 9.9             | 8              | -0.46          | 0.35         | G5–G8      |
| 2215458       | 16.3           | 0.6   | 50.7 | 36.9       | -153.4 | 8.8             | 4              | -1.01          | 0.15         | F5          |

\(^{a}\) 1, 2, and 3 refer to the three observing runs CTIO 1999, CTIO 2000, and WIYN 2000, respectively.

\(^{b}\) Positions for the stars can be obtained from the Minnesota Automated Plate Scanner (MAPS) Catalog of the POSS I using either the sql-based query for individual stars (http://aps.umn.edu/catalog/sql.html) or the skybox query (http://aps.umn.edu/catalog) for a region on the sky.

\(^{c}\) Stars with spectra considered too noisy to obtain reasonable abundance estimates have ellipses as their [Fe/H] value and are not used in the measurement of the mean. Stars with inferred \((\beta - V)_{\odot}\) colors outside the “optimum range” are labeled with a colon. Stars with a noisy spectrum, but have an abundance estimate are labeled with an “N.”

\(^{d}\) 1, 2, and 3 refer to the three observing runs CTIO 1999, CTIO 2000, and WIYN 2000, respectively.

\(^{e}\) Positions for the stars can be obtained from the Minnesota Automated Plate Scanner (MAPS) Catalog of the POSS I using either the sql-based query for individual stars (http://aps.umn.edu/catalog/sql.html) or the skybox query (http://aps.umn.edu/catalog) for a region on the sky.

\(^{f}\) Stars with spectra considered too noisy to obtain reasonable abundance estimates have ellipses as their [Fe/H] value and are not used in the measurement of the mean. Stars with inferred \((\beta - V)_{\odot}\) colors outside the “optimum range” are labeled with a colon. Stars with a noisy spectrum, but have an abundance estimate are labeled with an “N.”

\(^{g}\) 1, 2, and 3 refer to the three observing runs CTIO 1999, CTIO 2000, and WIYN 2000, respectively.

\(^{h}\) Positions for the stars can be obtained from the Minnesota Automated Plate Scanner (MAPS) Catalog of the POSS I using either the sql-based query for individual stars (http://aps.umn.edu/catalog/sql.html) or the skybox query (http://aps.umn.edu/catalog) for a region on the sky.

\(^{i}\) Stars with spectra considered too noisy to obtain reasonable abundance estimates have ellipses as their [Fe/H] value and are not used in the measurement of the mean. Stars with inferred \((\beta - V)_{\odot}\) colors outside the “optimum range” are labeled with a colon. Stars with a noisy spectrum, but have an abundance estimate are labeled with an “N.”

\(^{j}\) 1, 2, and 3 refer to the three observing runs CTIO 1999, CTIO 2000, and WIYN 2000, respectively.

\(^{k}\) Positions for the stars can be obtained from the Minnesota Automated Plate Scanner (MAPS) Catalog of the POSS I using either the sql-based query for individual stars (http://aps.umn.edu/catalog/sql.html) or the skybox query (http://aps.umn.edu/catalog) for a region on the sky.

\(^{l}\) Stars with spectra considered too noisy to obtain reasonable abundance estimates have ellipses as their [Fe/H] value and are not used in the measurement of the mean. Stars with inferred \((\beta - V)_{\odot}\) colors outside the “optimum range” are labeled with a colon. Stars with a noisy spectrum, but have an abundance estimate are labeled with an “N.”
used the reference table and online spectral catalog by Jones standards exist for the metal-weak population. Instead, we served standards for each spectral subtype, and because few call our types “approximate” because we did not have ob-
of the stars for which we have a measured radial velocity. We effective rotation.

quadrant I thick-disk stars are participating in a slower stellar population and confirm that a significant fraction of the quadrant I thick-disk stars are participating in a slower effective rotation.

4.2. Spectral Types

We have also determined approximate spectral types for all of the stars for which we have a measured radial velocity. We call our types “approximate” because we did not have observed standards for each spectral subtype, and because few standards exist for the metal-weak population. Instead, we used the reference table and online spectral catalog by Jones (1996),\(^7\) plus spectra of our velocity standards in the classification process. Comparison of the spectral types for stars observed at both CTIO 1999 and WIYN 2000 demonstrates that our method is internally consistent. However, we note that the stars observed during the CTIO 2000 run were subject to a small light leak, which produced an offset in the flux level of each spectrum. This did not affect the velocity measurements, which were confirmed by comparing the results for the multiply observed stars. We classified these spectra according to the same criteria as the other stars, and comparison with the types for the stars with duplicate spectra show that the spectral types are consistent; although the classifications for these stars perhaps should be considered somewhat less reliable. All of the stars with spectra with sufficient S/N for the velocity measurements and spectral classification are listed in Table 4.

Figure 4 shows a histogram of the spectral types for stars in quadrant I compared with quadrant IV. There are approxi-mately the same relative numbers of the different spectral types in the two quadrants with slightly more early-type stars (A8–F5) classified in quadrant I than in quadrant IV. Comparing the spectral types with the LSR velocities in Figure 5, we note that more of the A8–G0 stars in quadrant I have larger, in this case, more negative LSR velocities, suggestive of thick-disk/inner halo star velocities, than observed for the same types of stars in quadrant IV.

4.3. Metallicities

We obtained metallicity estimates for our stars using the methodology and calibration of Beers et al. (1999), which is based on the relationship between a Ca II K line index, KP, and the \((B-V)_0\) colors. The line indices KP and HP2 were obtained using their procedures, but since we do not have measured \((B-V)_0\) colors for our program stars, we have followed the procedure described by them based on an estimate of the dereddened color, from the Balmer-line index, HP2. Previous experience suggests that this procedure works quite well for stars of “intermediate” color, e.g., stars with \(0.40 \leq (B-V)_0 \leq 0.80\), with an estimated scatter on the order of 0.05 mag but exhibits somewhat higher scatter for stars with colors outside this range. The great majority of our program stars fall within this optimal color range.

\(^7\) Available at ftp://ftp.noao.edu/catalogs/coudelib.

| TABLE 5 |
|------------------|------------------|------------------|------------------|------------------|
| **MEAN LSR VELOCITIES AND ROTATION RATES FOR QUADRANT I AND IV FIELDS** |
| Field | \(l\) | \(b\) | \(N_{\text{stars}}\) | \(\langle V_{\text{LSR}} \rangle\) (km s\(^{-1}\)) | \(\sigma_{V_{\text{LSR}}}\) (km s\(^{-1}\)) | \(\omega\) (km s\(^{-1}\) kpc\(^{-1}\)) | \(\sigma_\omega\) (km s\(^{-1}\) kpc\(^{-1}\)) |
| Q1 .......... | ... | ... | 405 | -19.2 ± 3.2 | 62.3 | 21.8 ± 1.2 | 23.2 |
| P332 .......... | 51.0 | 37.0 | 37 | -42.1 ± 8.4 | 51.2 | 19.0 ± 1.7 | 10.4 |
| P387 .......... | 40.0 | 41.0 | 57 | -35.0 ± 7.6 | 57.3 | 18.4 ± 2.0 | 14.9 |
| P448 .......... | 40.0 | 30.0 | 60 | -15.9 ± 8.1 | 62.8 | 23.9 ± 1.8 | 14.1 |
| P507 .......... | 31.0 | 32.0 | 65 | -20.7 ± 8.6 | 69.5 | 21.6 ± 2.5 | 20.0 |
| P505 .......... | 21.0 | 42.5 | 64 | -26.4 ± 8.3 | 66.2 | 14.9 ± 3.9 | 31.5 |
| P566 .......... | 20.0 | 32.0 | 122 | -1.0 ± 5.7 | 63.2 | 27.1 ± 2.5 | 27.1 |
| QIV .......... | ... | ... | 317 | -15.3 ± 3.9 | 68.8 | 33.4 ± 1.4 | 24.2 |
| P855 .......... | 309.0 | 37.0 | 31 | 14.9 ± 10.8 | 60.2 | 24.5 ± 2.2 | 12.2 |
| P799 .......... | 320.0 | 41.0 | 60 | -8.7 ± 8.5 | 66.1 | 29.7 ± 2.7 | 17.4 |
| P913 .......... | 320.0 | 30.0 | 54 | -16.1 ± 7.9 | 58.0 | 31.1 ± 1.8 | 13.1 |
| P858 .......... | 329.0 | 32.0 | 43 | -14.5 ± 13.1 | 86.3 | 31.7 ± 3.8 | 25.1 |
| P741 .......... | 339.0 | 41.0 | 63 | -33.3 ± 8.3 | 65.5 | 42.7 ± 3.9 | 30.7 |
| P802 .......... | 339.5 | 33.0 | 66 | -18.2 ± 8.8 | 71.8 | 35.1 ± 3.7 | 30.4 |
Using this method, we estimated the metallicities for 581 of the 741 stars in Table 4. Metallicities were not measured from those spectra with the small light leak mentioned in § 4.2. Some of the spectra were also too noisy to obtain a reliable measurement and are so designated in the table. The normalized histograms for the \([\text{Fe/H}]\) values are shown in Figure 6; the mean error in the individual \([\text{Fe/H}]\) values (\(\sigma_{[\text{Fe/H}]}\)) is 0.25 dex. The distribution of the metallicities confirm our selection criteria with a predominance of thick-disk and halo stars in this color range. Removing the extremely metal-poor stars with \([\text{Fe/H}] < -2.2\), the stars in quadrant I have a mean \([\text{Fe/H}] = -1.06 \pm 0.07\) and therefore appear to be slightly more metal-rich than those in quadrant IV with a mean \([\text{Fe/H}] = -1.27 \pm 0.12\). Quadrant IV’s mean \([\text{Fe/H}]\) is close to what we would expect for a mixed metal-poor population.

Assuming that the stars in both quadrants are a mixed population, quadrant I apparently has relatively more stars with a higher metallicity, perhaps more representative of the thick-disk population, which has a mean \([\text{Fe/H}]\) of approximately -0.7. This is consistent with the excess of presumed thick-disk stars (Paper I) in the quadrant I fields yielding a slightly higher metallicity.

### 4.4. Population Separation and the Kinematics

With this additional metallicity information, we use \([\text{Fe/H}]\) and \(V_{\text{LSR}}\) to separate our sample into the three primary population groups and repeat our calculations of the mean \(V_{\text{LSR}}\) and \(\omega\). As in §§ 4.1 and 4.3, we initially remove the extreme high-velocity stars with \(|V_{\text{LSR}}| \geq 200\ \text{km s}^{-1}\) and define the three groups according to metallicity: disk, \(-0.3 \leq [\text{Fe/H}] \leq 0.30\); thick disk, \(-1.2 \leq [\text{Fe/H}] \leq -0.30\); and halo, \(-2.2 \leq [\text{Fe/H}] \leq -1.2\). Admittedly, given the uncertainties with our method for determining the metallicities (due primarily to the need for estimated colors), the errors in the individual \([\text{Fe/H}]\) values, plus the natural spread and overlap in \([\text{Fe/H}]\) for these three groups, we do not expect a clean separation. There is undoubtedly some contamination and overlap, especially between the disk and thick-disk stars given our criteria. For that reason, we have used the \(V_{\text{LSR}}\) to further refine the separation. For example, a star with an \([\text{Fe/H}]\) indicative of the disk or thick disk, but with a \(|V_{\text{LSR}}| \geq 150\ \text{km s}^{-1}\), was reassigned to the halo population. Figures 7 and 8 show the resulting histograms for \(V_{\text{LSR}}\) and \(\omega\), respectively, for the halo, thick-disk, and disk populations in quadrants I and IV. The mean values with their errors and standard deviations are given in Table 6.

The results for the presumed halo population are much as we would expect for a population with a high velocity dispersion with respect to the LSR. With the large dispersion in their velocities, the results for the halo population in the two
quadrants do not appear to be significantly different. The quadrant I halo stars, however, do have a slightly lower mean rotational rate than for those in quadrant IV.

The differences in the mean velocities and rotation rates between the two quadrants for the thick-disk and disk stars confirm our previous conclusion that a significant population of quadrant I stars are rotating slower than those in quadrant IV. Recall that the expected $V_{\text{LSR}}$ velocities are positive and negative in quadrants I and IV, respectively, and at the distances and directions of these stars should be on the order of 10 to 25 km s$^{-1}$. The mean $V_{\text{LSR}}$ values for the presumed disk and thick-disk stars in quadrant IV are consistent with this expectation, but the thick-disk stars do not show a significant positive shift in $V_{\text{LSR}}$ or the slower effective rotation expected for this population. In quadrant I, the shift to more negative velocities and the rotational lag is quite apparent confirming the kinematic asymmetry affecting the thick-disk stars, and to some extent the disk stars, between quadrants I and IV. We also note that the velocity dispersions for the thick-disk stars in both quadrants and for the disk stars in quadrant I are noticeably higher than the nominal dispersions for the thick disk ($\approx 45$ km s$^{-1}$) and for main-sequence disk G stars ($\approx 30$ km s$^{-1}$), which may be due to a mixture from other high-velocity populations in each case.

In § 4.1, we commented on the evidence for a gradient in the mean $V_{\text{LSR}}$ velocities with Galactic longitude (see Table 4). Using the additional information from the metallicities, we have investigated the results for $V_{\text{LSR}}$ and $\omega$ as a function of population type in the different fields; summarized in Table 7. The thick-disk stars, and to a somewhat lesser extent, the halo stars in quadrant I,8 show a dependence of their mean $V_{\text{LSR}}$ values on longitude, while the quadrant IV stars do not show a similar dependence. The observed $V_{\text{LSR}}$ is a combination of the stars’ motions in the radial ($v_r$), tangential ($v_\phi$), and...
Fig. 8.—Distribution of $\omega$ with population type in quadrants I and IV: (a, b) halo, (c, d) thick disk, and (e, f) disk.

| Table 6 | Mean LSR Velocities and Rotation Rates for the Three Populations |
|---------|---------------------------------------------------------------|
|         | Population         | $N_{\text{stars}}$ | $\langle v_{\text{LSR}} \rangle$ (km s$^{-1}$) | $\sigma_{v_{\text{LSR}}}$ (km s$^{-1}$) | $(\omega)$ (km s$^{-1}$kpc$^{-1}$) | $\sigma_{\omega}$ (km s$^{-1}$kpc$^{-1}$) |
|         | QI                  |                   |                                             |                          |                                |                                        |
| Disk...... | 24                 | $-6.9 \pm 9.8$    | 47.8                                        | $26.4 \pm 3.3$           | 16.2                             |
| Thick disk | 195                | $-12.9 \pm 4.1$   | 57.6                                        | $24.5 \pm 1.4$           | 19.4                             |
| Halo......  | 152                | $-34.4 \pm 5.7$   | 70.5                                        | $16.2 \pm 2.1$           | 25.9                             |
| QIV       | Disk......         | 8                 | $-16.1 \pm 12.6$                           | 35.9                      | $30.7 \pm 3.7$                   | 10.4                                  |
| Thick disk | 55                 | $-24.1 \pm 8.4$   | 62.3                                        | $36.4 \pm 2.9$           | 21.5                             |
| Halo......  | 99                 | $-27.8 \pm 7.2$   | 71.4                                        | $38.2 \pm 2.7$           | 27.0                             |
vertical \(v_z\) directions (see eq. [2]), and the contribution of each to the total velocity will depend on the star’s direction and distance. For example, looking toward the Galactic center, P566 and P505 \((l \approx 20^\circ)\), \(v_r\) will be the primary component, while toward \(l\) of \(40^\circ\) to \(50^\circ\) the radial and tangential contributions should be more nearly equal. Assuming that we have a uniform population of stars in these different fields with a common or shared motion, the observed dependence on longitude for the quadrant I stars should allow us to estimate the three components and determine if the quadrant I thick-disk kinematics are due primarily to radial streaming or rotational lag. We have used the method of least squares applied to

\[
V_{\text{LSR}} = [v_r \cos \theta + (v_\phi - V_\odot \sin \theta) \cos b + v_z \sin b, \quad (2)
\]

where \(\theta\) is the angle between the line of sight from the Sun to the star and the Galactic center to the star, \(\sin \theta = R_\odot \sin l/R_*,\) and \(R_*\) is the distance of the star from the Galactic center. Assuming the stars are 1 and 2 kpc from the Sun, we solved for \(v_r\), \(v_\phi\), and \(v_z\). The results are summarized in Table 8. Not surprisingly, the uncertainty in the solutions is large given the small number of stars and the intrinsic dispersions of the thick-disk stars in these three directions. Nevertheless, the three-parameter solution for the quadrant I stars shows that the slower effective rotation for these stars is due to slower motion in the direction of Galactic rotation \(v_\phi\) with a lag of \(\sim 80\) km s\(^{-1}\) with respect to circular rotation in the disk and slower than the \(40–50\) km s\(^{-1}\) normally assumed for the thick disk. The radial component shows a net motion toward the Galactic center, but it is small and probably not significant. We repeated the same solutions for the quadrant IV stars. Although there are only 55 stars in this set, the results are distinctly different than those for quadrant I. The results for \(v_z\) are sufficiently anomalous, implying a large motion toward the plane with a large error, that it is probably meaningless. We

| Field & Population | \(N_{\text{star}}\) | \(\langle V_{\text{LSR}} \rangle\) (km s\(^{-1}\)) | \(\sigma_{V_{\text{LSR}}}\) (km s\(^{-1}\)) | \(\langle \omega \rangle\) (km s\(^{-1}\) kpc\(^{-1}\)) | \(\sigma_\omega\) (km s\(^{-1}\) kpc\(^{-1}\)) |
|-------------------|-----------------|----------------|----------------|----------------|----------------|
| P332 (51\(^{\circ}\), 37\(^{\circ}\)) | | | | | |
| Thick disk ......... | 23 | –35.6 ± 9.2 | 44.1 | 20.3 ± 1.9 | 9.0 |
| Halo ................ | 6 | –105.0 ± 22.4 | 54.9 | 6.2 ± 4.5 | 11.1 |
| P387 (40\(^{\circ}\), 41\(^{\circ}\)) | | | | | |
| Thick disk ......... | 22 | –22.4 ± 8.0 | 37.5 | 21.7 ± 2.1 | 9.7 |
| Halo ................ | 31 | –48.7 ± 10.8 | 60.2 | 14.9 ± 2.8 | 15.6 |
| P448 (40\(^{\circ}\), 30\(^{\circ}\)) | | | | | |
| Thick disk ......... | 37 | –18.7 ± 8.4 | 51.1 | 23.3 ± 1.9 | 11.5 |
| Halo ................ | 15 | –33.0 ± 20.0 | 77.5 | 20.0 ± 4.5 | 17.4 |
| P507 (31\(^{\circ}\), 32\(^{\circ}\)) | | | | | |
| Thick disk ......... | 44 | –14.3 ± 10.4 | 69.0 | 23.4 ± 3.0 | 19.8 |
| Halo ................ | 15 | –36.0 ± 20.8 | 80.5 | 17.2 ± 6.0 | 23.1 |
| P505 (21\(^{\circ}\), 42\(^{\circ}\)) | | | | | |
| Thick disk ......... | 21 | –5.6 ± 10.6 | 48.4 | 24.8 ± 5.0 | 23.0 |
| Halo ................ | 38 | –31.0 ± 11.3 | 69.5 | 12.8 ± 5.3 | 32.9 |
| P566 (20\(^{\circ}\), 32\(^{\circ}\)) | | | | | |
| Thick disk ......... | 48 | +5.1 ± 8.9 | 61.9 | 29.7 ± 3.8 | 26.6 |
| Halo ................ | 47 | –18.7 ± 9.6 | 66.0 | 19.5 ± 4.1 | 28.4 |

\(^a\) No [Fe/H] measurements for population separation.
therefore repeated the solutions for both quadrants with only two parameters, setting \( \mu = 0 \). These solutions for quadrant IV for the two assumed distances from the Sun yielded more uniform results with smaller errors and show only a small rotational lag and a marginal radial outflow, which is probably not significant. Interestingly, the quadrant I solutions for \( v_r \) and \( v_\theta \) are compatible with the three-parameter results with smaller errors. We conclude that the quadrant I thick-disk stars have a lag of 80–90 km s\(^{-1}\) in the direction of Galactic rotation, while a similar population in quadrant IV has a probable lag of only \( \sim 20 \) km s\(^{-1}\), confirming the kinematic asymmetry between the two directions.

5. DISCUSSION—POSSIBLE CAUSES OF THE ASYMMETRY

In Paper I, we considered three possible explanations for the observed asymmetry in the stars counts, a fossil remnant from an ancient merger, a triaxial thick disk, and an interaction with the bar in the old or thin disk in quadrant I, and concluded that either the triaxial thick disk or a bar/thick-disk interaction could best explain the excess in the star counts, but that the merger remnant was less likely. Hernquist & Weinberg (1992) and Debattista & Sellwood (1998) showed that a rotating bar in the disk could induce a gravitational “wake” that would trap and pile up stars behind it, and these stars may thus show a measurable lag in their rotational velocities. Likewise, a triaxial thick disk could also yield different effective rotation rates because of noncircular streaming motions along the major axis.

Numerical simulations suggest that triaxial dark halos are a natural consequence of cold dark matter scenarios (Dubinski & Carlberg 1991). Based on studies of rotating triaxial spheroids, Blitz & Spergel (1991) suggested that there may be both a rounder outer halo and a triaxial (flattened) inner halo. This model is supported by observations that show both a round outer halo (Hartwick 1987; Chiba & Beers 2000) and evidence for a large flattened distribution in the inner halo (Wyse & Gilmore 1989; Larsen & Humphreys 1994; Chiba & Beers 2000). Curir & Mazzei (1999) also find a high probability that a rotationally supported disk and a nonaxisymmetric halo can trigger instabilities leading to the formation of a long-lived bar. Their simulations also suggest that these instabilities are similar in character to spiral-density waves and can affect stars at higher Galactic latitudes in a similar way.

For some time now, there has been substantial evidence for a bar within the bulge of the Milky Way, but numerous more recent studies in the Galactic plane \((b \pm 3^\circ)\); Blitz & Spergel 1991; Weinberg 1992; López-Corredoira et al. 1999; Feast & Whitelock 2000; Hammersley et al. 2000) have revealed the presence of a stellar bar extending beyond the bulge with a 3–5 kpc radius. Weinberg (1994) demonstrated that a structure with a rotating pattern speed in a disk system, assuming nearly circular orbits, generates three resonances: the inner Lindblad, the outer Lindblad (OLR), and another at the corotation location, which can lead to significant kinematic signatures in the line-of-sight velocities and velocity distributions. In his model, a triaxial rotating spheroid will produce an increased velocity dispersion near the OLR at approximately 4–5 kpc from the Galactic center. The high overall velocity dispersion measured for the stars in our study may be explained by the OLR of a triaxial thick disk or inner halo. However, it is just as likely that losses in angular momentum of a moderate stellar bar may reduce the bar’s pattern speed and inflate the velocity dispersions in the thick disk. Weinberg (1994) finds that the latter explanation supports his predictions of a stellar bar at 5 kpc with a position angle of 36° (see Fig. 3 in Weinberg 1992).

The effect of a bar on its parent galaxy is dependent on the amount and distribution of dark matter in the galaxy. It has not yet been determined if a stellar bar is created by the interaction between a thin disk and an outer (potentially dark matter) halo, which then creates an asymmetric, triaxial thick-disk/inner halo, or whether, alternatively, the presence of a triaxial thick-disk/inner halo contributes to bar formation. In either case, the kinematics would be similar and the bar and major axis of the thick disk would be nearly aligned. If the leading edge of the triaxial thick disk is in quadrant I, as implied by the star-count excess, the differences between the rotational kinematics would lead to a more negative lag in the velocities in quadrant I as would a gravitational interaction with the disk bar also in quadrant I. Thus our results for a kinematic asymmetry between quadrants I and IV and slower effective rotation in quadrant I could be due to either cause.

The mean \( V_{\text{LSR}} \) velocities and rotation rates \((\omega)\) for the separate fields in quadrant I also show a dependence on Galactic longitude for the thick stars not shown by the stars in quadrant IV. Least-squares solutions for the three velocity components of the \( V_{\text{LSR}} \) show that the thick-disk stars in quadrant I have a major lag in their velocities in the direction of Galactic rotation much slower than for the quadrant IV stars and slower than the nominal thick-disk lag, with no significant radial component. This result supports a gravitational interaction with the bar as the more probable explanation for the observed asymmetries. This does not necessarily mean that the thick disk is not triaxial. As discussed above, bar/thick-disk interactions may be independent of a triaxial thick disk, or it might be the case that triaxial thick disks are a dynamical result of bar formation or vice versa and the two may be nearly aligned.
To further investigate the possibility that the asymmetry feature is a consequence of a gravitational wake induced by a stellar bar, V. P. Debattista & J. A. Sellwood (2003, private communication) have added a thick-disk component to their models and followed the evolution as a bar forms and rotates in the thin disk. Their preliminary results show that the non-axisymmetric response in the thick disk induced by the interaction with the stellar bar can give better agreement with the observed asymmetries in the star counts and kinematics. These models and a detailed comparison with the observations will be presented in a later paper (Debattista & Sellwood 2004).

In Paper I, we found a significant excess of thick-disk/inner halo stars in quadrant I above and below the Galactic plane extending from $l \sim 20^\circ$ to $55^\circ$ and from $|b| \sim 20^\circ$ to $45^\circ$, covering more than 600 ($\times$ 2) deg$^2$. Doppler velocities, spectral types, and metallicities reported here from spectra of 741 stars in quadrants I and IV reveal a kinematic asymmetry as well, which shows most strongly among the thick-disk stars. The stars in quadrant I have a negative mean LSR velocity with a significant net shift in the expected LSR velocity, a slower effective rotation rate, and a slightly higher mean metallicity than the stars in quadrant IV. We also demonstrate that the thick-disk stars in quadrant I have a significant lag in their velocities in the direction of Galactic rotation, much slower than that found for the quadrant IV stars and slower than normally assumed. These results tend to support a gravitational interaction between the thick-disk stars and the rotating stellar bar in the disk as the best explanation for the asymmetry in the star counts and the kinematics. Combined with the evidence reported by Larsen & Humphreys (2003) that some parameters such as the scale height and the normalization may vary with direction, the characteristics of the thick-disk population, including its kinematics, may depend on where one is looking.

After this paper was submitted, the discovery of the Canis Major merger remnant was announced by Martin et al. (2004). Their detection of an extensive remnant relatively nearby close to the Galactic plane suggests that such events may be the origin of the thick disk. In Paper I we rejected a merger remnant as an explanation for the star-count excess in quadrant I for several reasons, including the shape and extent of the asymmetry region on the sky, its presence above and below the plane, and a comparison with the debris field of the Sagittarius dwarf merger. However, the debris left by Canis Major or other mergers could contribute to our observed asymmetry in the star counts and kinematics and to the varying characteristics of the thick disk with direction (Larsen & Humphreys 2003). The region of our observed asymmetry is not reproduced in the simulations for Canis Major (Martin et al. 2004), although this does not necessarily eliminate the role of this or another merger. Indeed, the star-count excess and much slower rate of rotation for the thick-disk stars in the asymmetry feature could be due to interaction of a merger remnant with the bar in the disk. An important question to be decided with additional observations and modelling is whether the thick-disk/inner halo populations sampled in quadrants I and IV are a single population with asymmetric spatial and kinematic properties or are two different populations.

Future work will include additional velocity measurements at higher longitudes and in fields below the Galactic plane plus the addition of proper motions from the APS catalog and other all-sky surveys. These additional observations will help to further clarify the origin of the asymmetry.

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