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Structure and Kinematics of the Stellar Halos and Thick Disks of the Milky Way Based on Calibration Stars from SDSS DR7

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Abstract. The structure and kinematics of the recognized stellar components of the Milky Way are explored, based on well-determined atmospheric parameters and kinematic quantities for 32360 "calibration stars" from the Sloan Digital Sky Survey (SDSS) and its first extension, (SDSS-II), which included the sub-survey SEGUE: Sloan Extension for Galactic Understanding and Exploration. Full space motions for a sub-sample of 16920 stars, exploring a local volume within 4 kpc of the Sun, are used to derive velocity ellipsoids for the inner- and outer-halo components of the Galaxy, as well as for the canonical thick-disk and proposed metal-weak thick-disk populations. This new sample of calibration stars represents an increase of 60% relative to the numbers used in a previous analysis. A Maximum Likelihood analysis of a local sub-sample of 16920 calibration stars has been developed in order to extract kinematic information for the major Galactic components (thick disk, inner halo, and outer halo), as well as for the elusive metal-weak thick disk (MWTD). We measure velocity ellipsoids for the thick disk, the MWTD, the inner halo, and the outer halo, demonstrate that the MWTD may be a component that is kinematically and chemically independent of the canonical thick disk (and put limits on the metallicity range of the MWTD), and derive the inferred spatial density profiles of the inner/outer halo components. We also present evidence for tilts in the velocity ellipsoids for stars in our sample as a function of height above the plane, for several ranges in metallicity, and confirm the shift of the observed metallicity distribution function (MDF) from the inner-halo to the outer-halo dominated sample.

Keywords. astronomical data bases: surveys, Galaxy: halo, structure, methods: data analysis, stars: abundances

1. The New Analysis: Main Results

The new sample is 60% larger than the sample used in Carollo *et al.* 2007. Also, the addition of numerous low-latitude observations from SEGUE, and recent improvements in the SSPP (in particular for the determination of metallicities for metal-rich stars) have enabled much clearer distinctions to be drawn between the kinematic behavior of the various Galactic components we consider in our analysis. The first step of our analysis was to explore which quantities can best be used to constrain the mixtures of components present in the local calibration-star sample, concluding that the Galactocentric rotational velocity, V_ϕ, and Z_{max} (the maximum vertical distance of a stellar orbit above or below the Galactic plane) are superior to available alternatives. The subtle, but important, question of how many components are required to account for the observed kinematics of halo stars in the local sample was then considered. On the basis of an objective clustering approach, applied to the low-metallicity sub-sample of local stars with [Fe/H] < -2.0, we demonstrated that (a) a single-population halo is incompatible with the observed kinematics, that (b) a dual-component halo, comprising populations we associate with the inner and outer halo, is sufficient to accommodate the observed kinematics, and that (c) although additional components (of unspecified physical origin) can be added, they are not required (and in any case, provide no statistically significant improvement in the kinematic fits). We concluded that a dual-halo model is preferred on the grounds of its simplicity (see Carollo *et al.* 2009 for details).

We have developed a flexible Maximum Likelihood (ML) approach for further analysis of the kinematics of Galactic components. We used a low-metallicity sub-sample of local stars in order to obtain estimates of the mean rotational velocity and dispersion of the outer-halo population, obtaining values of $\langle V_\phi \rangle = -80 \pm 13$ km s^{-1}, slightly more retrograde than that obtained by Carollo *et al.* 2007 (~ -70 km s^{-1}) from the DR5 sample of local calibration stars. For the dispersion, we obtained $\sigma_{V_\phi} = 165 \pm 9$ km s^{-1}, a substantially larger value than reported by previous authors who considered only a single-component halo. The ML approach was then used in order to estimate the rotation and dispersion of the inner-halo component, based on an examination of cuts on Z_{max} for the low-metallicity sub-sample. We obtained, for stars with $Z_{max} < 10$ kpc (where the inner-halo component dominates) values of $\langle V_\phi \rangle = 3 \pm 4$ km s^{-1}, and $\sigma_{V_\phi} = 100 \pm 2$ km s^{-1} for the rotational velocity and dispersion, respectively. The existence of a gradient in the mean rotational velocity for the inner-halo component, as claimed previously by Chiba & Beers 2000, is confirmed. We obtained a value of $\triangle\langle V_\phi \rangle/\triangle|Z| = -28 \pm 9$ km s^{-1} kpc^{-1}, for stars located within 2 kpc of the Galactic plane. Such a gradient may represent the signature of a dissipatively-formed flattened inner halo. Clearly, in many aspects our inner-halo population is essentially kinematically identical to "the halo" population studied by Chiba & Beers 2000, and many others.

The mean rotational velocity and dispersion of the thick disk were then considered, based on inspection of a metal-rich ($-0.8 <$ [Fe/H] < -0.6) sub-sample of stars close to the Galactic plane. We obtained values $\langle V_\phi \rangle = 182 \pm 2$ km s^{-1} and $\sigma_{V_\phi} = 51 \pm 2$ km s^{-1} for stars in the range $1 < |Z| < 2$ kpc, where the thick disk is espected to dominate, and contamination from thin-disk stars should be negligible. The gradient in the asymmetric drift of the thick-disk component as a function of height above the plane, noted by previous authors, is very clear in our data as well; we derived $\triangle\langle V_\phi \rangle/\triangle|Z| = -36 \pm 1$ km s^{-1} kpc^{-1}, in excellent agreement with the rotational velocity gradients for disk stars obtained by Chiba & Beers 2000, Girard *et al.* 2006, and Ivezić *et al.* 2008. The ML approach was then applied to the full range of metallicities in our sample of local calibration stars, in order to determine the fractional contribution of the three primary components in our model as a function of Z_{max} (fixing as inputs the values of mean rotational velocities and dispersions derived previously for each component). This exercise indicated that, within 5 kpc from the plane, the thick-disk and inner-halo components contribute roughly equally (Figure 1). Beyond 5 kpc, the thick-disk component is absent, as expected. The inner-halo population dominates between 5 and 10 kpc. Beyond 10 kpc, the outer halo increases in importance, is present in equal proportion to the inner halo between 15 and 20 kpc, and dominates beyond 20 kpc. The inversion point in the dominance of the inner/outer halo is located in the range $Z_{max} = 15$–20 kpc.

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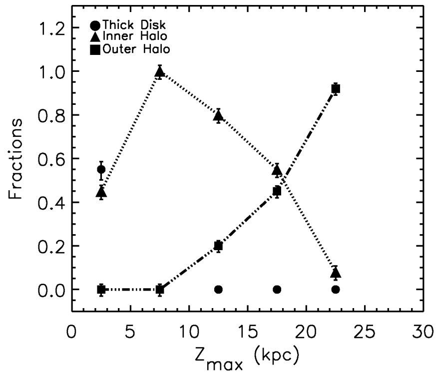

Figure 1. Derived stellar fractions, as a function of Z_{max}, for the thick disk (circle), inner-halo (triangle), and outer-halo (square) components.

We then used our extensive local dataset to examine the question of whether an independent MWTD component may be required in order to account for the rotational properties of stars close to the Galactic plane. The clustering analysis approach was applied to sub-samples of stars selected in metallicity and vertical distance |Z| (Carollo *et al.* 2009). We have demonstrated that, in the region closer to the Galactic plane, an independent MWTD component with $\langle V_\phi \rangle$ = 100–150 km s^{-1} and σ_{V_ϕ} = 35–45 km s^{-1} may be required in order to account for the rotational behavior of the stars in our local sample. We were also able to demonstrate that the metallicity range covered by the MWTD is $-1.8 <$ [Fe/H] < -0.8, and possibly up to [Fe/H] ~ -0.7. Finally, we found that the "as observed" MDF of stars in our sample changes with distance from the Galactic plane, exhibiting the anticipated shift from dominance by thick-disk and metal-weak thick-disk populations, with peaks at [Fe/H] = -0.6 and -1.3, respectively, to dominance by the inner-halo ([Fe/H] = -1.6) and outer-halo ([Fe/H] = -2.2) populations (see Beers's article, this volume, for more details).

1.1. *Velocity Ellipsoids*

We derived estimates of the velocity ellipsoids for the thick disk, inner halo, and outer halo; an approximate ellipsoid for the MWTD was also derived. In the case of the thick-disk and outer-halo components, we examined the same sub-samples of stars used for determination of the rotational properties of these components. For the inner-halo, in the radial and vertical directions (where the strong overlap with multiple additional components complicates a mixture-model analysis), the velocities and dispersions were obtained by adopting the mean velocity and dispersion of a sub-sample of stars in a more restricted range of metallicity ($-2.0 <$ [Fe/H] < -1.5), where the inner halo is expected to be dominant. The velocity ellipsoid for the canonical thick disk, the inner- and outer-halo, as well as for the MWTD, are summarized in Table 1. The values obtained for the canonical thick disk match those of Chiba & Beers 2000. The inner halo is essentially non-rotating; its velocity differs from that reported by Chiba & Beers 2000, $\langle V_\phi \rangle \sim$ 30–50 kms^{-1}. Our velocity ellipsoid values are consistent, within the reported errors. This agreement has been obtained even though the Chiba & Beers 2000 analysis adopted a one-component halo, from which we conclude that their sample (and others) did not include significant numbers of outer-halo stars. For the outer halo, which exhibits a large net retrograde rotation, we have obtained a more tangentially anisotropic velocity ellipsoid, which was previously advocated by Sommer-Larsen 1997 from an analysis of radial velocities of distant horizontal-branch stars. Finally, the velocity ellipsoid for the

MWTD is (σ_{V_R}, σ_{V_ϕ}, σ_{V_Z}) = (59 ± 5, 40 ± 3, 44 ± 2 km s^{-1}). We also demonstrated that all three components of the velocity dispersions increase with decreasing metallicity, in a manner suggesting discontinuous transitions from the thick disk to the MWTD, and from the inner to the outer halo. This is a fundamental new result which can be used to place constraints on possible formation scenarios for the stellar components of the Milky Way by comparison with new-generation numerical simulations.

Table 1. Velocity Ellipsoids

Component	$\langle \mathbf{V}_R \rangle$ km s^{-1}	$\langle \mathbf{V}_\phi \rangle$ km s^{-1}	$\langle \mathbf{V}_Z \rangle$ km s^{-1}	σ_{V_R} km s^{-1}	σ_{V_ϕ} km s^{-1}	σ_{V_Z} km s^{-1}
Thick Disk	3 ± 2	182 ± 2	0 ±1	53 ± 2	51 ± 1	35 ± 1
MWTD	-13 ± 5	125 ± 4	-14 ± 5	59 ± 3	40 ± 3	44 ± 3
Inner Halo	3 ± 2	3 ±4	3 ± 1	150 ± 2	100 ± 2	85 ± 1
Outer Halo	-9 ± 6	-80 ± 13	2 ± 4	159 ± 4	165 ± 9	116 ± 3

1.2. *Inner-and Outer Halo Density Profile*

The kinematics for our local sample of calibration stars were used to infer density profiles for the inner-halo and outer-halo components. We obtained $\rho_{in} \sim r^{-3.12\pm0.20}$ for the inner halo, consistent with the derived density profile of "the halo" found by many previous authors (see Carollo *et al.* 2009, and reference therein). In contrast, the density profile obtained for the outer halo, $\rho_{out} \sim r^{-1.79\pm0.29}$, is substantially shallower than that of the inner halo, as expected from the higher values of the velocity dispersions for this component.

1.3. *Tilts of the Velocity Ellipsoids*

The kinematic parameters derived for stars in our local sample have been used to examine tilts of the velocity ellipsoids, as a function of height above the Galactic plane, over several intervals in metallicity. Misalignment of the velocity ellipsoids with the adopted cylindrical coordinate system has been found for all the selected sub-samples. At high metallicity, the tilt angle is 7°.1 ± 1°.5, when 1 < |Z| < 2 kpc, and 5°.5 ± 1°.2 at 2 < |Z| < 4 kpc. A similar value was reported by Siebert *et al.* 2008 for a sample of RAVE-survey stars at |Z| < 1 kpc (7°.3 ± 1°.8). At intermediate metallicity, the tilt angle is 10°.3 ± 0°.4, and 15°.1 ± 0°.3, while for low-metallicity stars we found 8°.6 ± 0°.5, and 13°.1 ± 0°.4, at 1 < |Z| < 2 kpc and 2 < |Z| < 4 kpc, respectively. The velocity ellipsoids point in the direction close to the Galactic center. The existence of these tilts indicates that kinematics of stars in our local sample are aligned with respect to a spherical, rather than cylindrical, coordinate system.

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