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DECIPHERING THE LAST MAJOR INVASION OF THE MILKY WAY

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ABSTRACT

We present first results from a spectroscopic survey of ∼2000 F/G stars 0.5–5 kpc from the Galactic plane, obtained with the Two Degree Field facility on the Anglo-Australian Telescope. These data show the mean rotation velocity of the thick disk about the Galactic center a few kiloparsecs from the plane is very different than expected, being ∼100 km s^{-1} rather than the predicted ∼180 km s^{-1}. We propose that our sample is dominated by stars from a disrupted satellite that merged with the disk of the Milky Way some 10–12 Gyr ago. We do not find evidence for the many substantial mergers expected in hierarchical clustering theories. We find yet more evidence that the stellar halo retains kinematic substructure, indicative of minor mergers.

Subject headings: Galaxy: evolution — Galaxy: formation — Galaxy: kinematics and dynamics — Galaxy: stellar content — Galaxy: structure — stars: kinematics

1. INTRODUCTION

Mergers and strong interactions between galaxies happen and may well be the dominant process in the determination of a galaxy's current Hubble type, particularly in the context of modern hierarchical clustering theories of structure formation (e.g., Silk & Wyse 1993). The recently discovered (Ibata, Gilmore, & Irwin 1994) Sagittarius dwarf spheroidal galaxy is inside the Milky Way and is losing a significant stellar mass through tidal effects (Ibata et al. 1997), forming star streams in the halo (Mateo, Olszewski, & Morrison 1998; Ibata et al. 2001; Yanny et al. 2000) but having little effect on the present structure of the bulk of the Galactic disk.

The outcome of a merger of two stellar systems depends on several factors, most importantly the mass ratio and density contrast. During a merger, energy, momentum, and angular momentum are redistributed so that the common aftermath of a merger between a large disk galaxy and a smaller, but still significant, satellite galaxy (more massive than the Sagittarius dwarf spheroidal galaxy) is a heated disk and a disrupted satellite (Quinn & Goodman 1986; Velazquez & White 1999). This is currently the most plausible model for the origin of the thick disk in our Galaxy (see reviews in Gilmore, Wyse, & Kuijken 1989; Majewski 1993) and those of other galaxies; the stochastic nature of the merger process allows for a wide variety of, and indeed nonexistence of, thick disks in external galaxies, as observed, provided only a small number of merger events are involved. Determination of the stellar populations in the Galactic thick disk tests this model and so constrains the merger history of the Milky Way (Gilmore & Wyse 1985; Wyse 2001).

All indications are that the Galactic thick disk is composed of only very old stars, ages $\gtrsim$10 Gyr, equivalent to forming at a redshift of $\gtrsim$1 (Wyse 2000). This implies that the event that formed it from the thin disk, which now contains stars of all ages, occurred a long time ago, with little subsequent extraordinary heating of the thin disk. If this model is valid, it may be possible to identify stars captured from the accreted galaxy and to distinguish them from those formed in the early thin disk of the Milky Way. This would allow tight constraints on what merged, and when it merged, and on the early star formation in an extended disk. These are important tests of hierarchical clustering theories of structure formation.

2. THE SURVEY

We are investigating the stellar populations of the Galactic thick disk and halo through a statistical study of the kinematics (radial velocities) and metallicity distributions of stars a few kiloparsecs from the midplane of the Galactic disk, down several lines of sight. Our survey uses the Two Degree Field (2dF) multiobject spectrograph (Lewis et al. 2002) on the Anglo-Australian Telescope, which provides 400 spectra simultaneously; we obtained data with spectral resolution of 2.5 Å, in the wavelength range of 3700–4700 Å. The velocity accuracy per star is ∼15 km s^{-1}, determined from repeat observations and from a globular cluster standard. Chemical abundance determinations are in progress. We here present our first kinematic results, for around 2000 stars.

Our survey is of F/G stars ($B-V \leq 0.7$) with V-band apparent magnitudes in the range 17.0–19.5. This preferentially selects main-sequence stars close to the turnoffs of the thick disk and halo populations, at distances of several kiloparsecs. Our primary fields are at $(l, b) = (270, -45)$ and $(270, +33)$, against Galactic rotation; thus, radial velocities, in combination with a distance, approximate Galactocentric orbital angular momentum, without the need for transverse velocities. Bulge stars do not contribute at this distance from the Galactic center, while the apparent magnitude/distance selection provides a strong bias against the thin disk.

Star count model predictions in one of our "rotation" fields for the relative contributions of F/G stars belonging to each of

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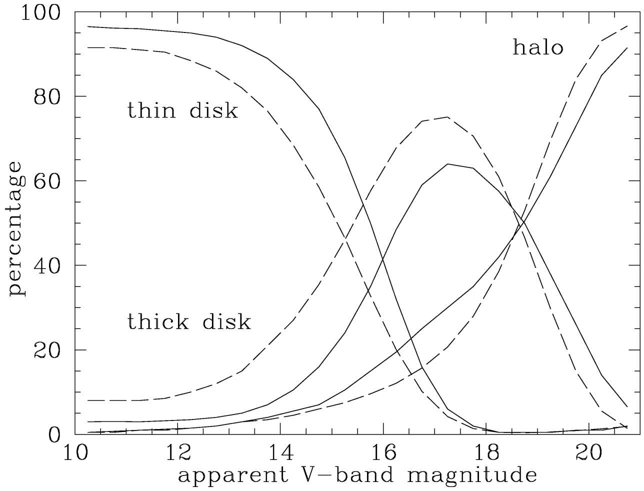

FIG. 1.—Star count predictions for the relative contributions of the thin disk, thick disk, and stellar halo to the counts of unevolved F/G stars in one of our fields (they do not differ substantially between our fields). The predictions with two different normalizations and scale heights for the thick disk are shown, to illustrate the current range of plausibility. The first model (*solid curves*) has local normalization of 2% and scale height of 1300 pc, and the second (*dashed curves*) has local normalization of 8% and scale height of 850 pc. Standard parameters for thin disk and stellar halo are assumed.

the three dominant populations of the Milky Way that contribute at the solar neighborhood, as a function of apparent magnitude, are shown in Figure 1, derived from a derivative of that star count model described by Gilmore (1984).

3. RESULTS

We detect a substantial population of stars on orbits that are intermediate between those of the canonical thick disk and the canonical stellar halo. As metallicities are not yet available, we sort on distance statistically, using apparent magnitude, since all stars observed have similar colors. Figure 2 shows the line-of-sight (radial) velocity histograms for stars that have spectra with signal-to-noise ratio greater than 20, in the lines of sight that probe orbital angular momentum. The top panel shows the distributions for the statistically nearer subsample, stars with $V <$ 18, while the bottom panel shows more distant stars, $18 \leq V <$ 19.5 (we have observed twice as many 2dF pointings of faint stars in the line of sight at $b = +33$, resulting in approximately twice as many radial velocities in this field, compared to the $b = -45$ field). These data are compared with the predictions of a model with a thin disk, thick disk, and halo with standard stellar kinematics, resulting from the median of 11 random samplings of three Gaussians with means and dispersions given in Table 1 (based on Dehnen & Binney 1998 and Chiba & Beers 2000). The model kinematics were fixed, independent of magnitude range, and the relative proportions of each component are chosen within the ranges in Figure 1, for the characteristic magnitude of each sample, namely, $V = 17.5$ for the top panel with the ratio of thin : thick : halo of 5 : 69 : 26 and $V = 18.5$ for the bottom panel with thin : thick : halo of 0.5 : 54.5 : 45. Using the Bergbusch & VandenBerg (2001) isochrones, at these magnitudes typical thick-disk stars with [Fe/H] ~ -0.5 dex and $B-V = 0.6$ ($M_V \sim +4.9$) would be at distances from the Sun of ∼3.3 and ∼5.3 kpc, while typical halo stars with metallicity of ~ -1.5 dex and $B-V = 0.5$ ($M_V \sim +5.4$) would be at distances of ∼2.6 and ∼4.2 kpc, respectively.

The data for the brighter stars and the model are in tolerable agreement, showing the well-established canonical thick-disk

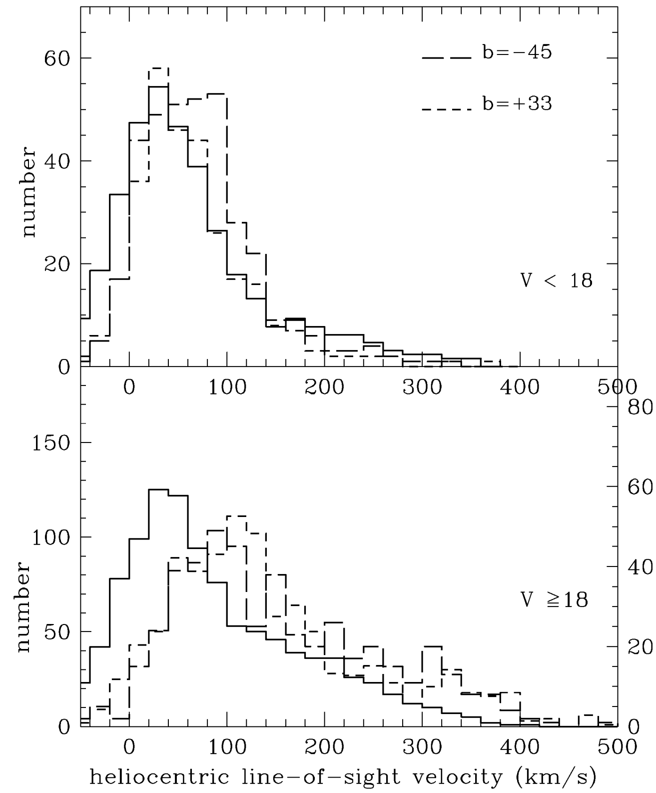

FIG. 2.—Radial velocity histograms for F/G stars in two lines of sight, compared to model predictions. The kinematics of the brighter stars, with apparent magnitude less than 18 in the *V* band, are shown in the top panel, and the kinematics of the fainter stars are shown in the bottom panel. The solid histograms result from random sampling Gaussians with "standard" kinematics, as described in the text. The short-dashed histograms are the data for the field at $b = +33$, in which at these distances the heliocentric line-of-sight velocity corresponds to ∼80% of rotation velocity, while the long-dashed histograms are the data for the field at $b = -45$, in which it corresponds to ∼70%. In the bottom panel, the *y*-axis scale on the right-hand side refers to the long-dashed histogram.

lag of less than 50 km s^{-1}, although there is a noticeable difference between the radial velocity distributions in the two fields. However, there is an obvious disagreement in the bottom panel, for the fainter stars, in that the typical star shows a mean lag behind the Sun of ∼100 km s^{-1}. The peak of the observed distribution is significantly displaced from the model predictions. This disagreement is not sensitive to the adopted normalizations or scale heights for the thick disk and halo but indicates the need for a substantial revision in the standard kinematical model of the Milky Way.

We emphasize that the number-magnitude-color distribution of stars seen in our fields is similar in both fields (many kiloparsecs apart at these apparent magnitudes) and is consistent with the predictions of standard star count models. We have

TABLE 1
STELLAR KINEMATICS

Component	σ_W	$\langle V_{lag} \rangle$	σ_V	Z_{max} for $W = \sigma_W$ (pc)
Old thin disk	20	20	25	300
Local thick disk	35	35	50	600
Stellar halo	95	220	105	3000
Satellite debris?	60	100	70	1200

NOTE.—Z_{max} is calculated using the vertical potential at the solar circle derived by Kuijken & Gilmore 1989.

detected not a small perturbation superposed on a smooth well-understood background, but rather intrinsic complexity in the kinematic distribution function of stars ascribed in standard models to the thick disk. We also note that the predictions of the Gaussian halo fail to reproduce the local peak in the data at around 300 km s^{-1}, which is suggestive of a retrograde halo stream (velocities above ~180 km s^{-1} in these lines of sight are retrograde), as may be produced by accretion of a small satellite (e.g., Helmi et al. 1999). This feature will be discussed elsewhere.

Figure 3 compares our results for the more distant stars with the predictions of a revised model, where the adopted kinematics of the "thick-disk" stars are instead those of the "satellite debris" as given in Table 1, all other quantities being held fixed. The agreement with the velocity distribution is much improved, except (as expected) for the local maximum at $V \gtrsim 300$ km s^{-1}.

Our results demonstrate that far from the Galactic plane the "thick disk" is a population that has significantly lower mean rotational velocity, and most probably higher values of velocity dispersion, than it has close to the midplane. Previous investigations have seen indications of this "vertical shear" at lower Z-distances (Wyse & Gilmore 1986; Majewski 1993; Chiba & Beers 2000; and indeed one can see indications in the top panel of Fig. 2, especially the field at $b = -45$), but the observations had been interpreted in terms of a smooth gradient with Z-height within a population characterized by one vertical velocity dispersion. Thus, to explain the large change in mean azimuthal streaming seen in the observations would require a disk distribution function such that the angular velocity of stars on the orbits sampled by observing 2–3 kpc vertically from the disk, at approximately fixed radial distance, differs by a factor of 2 from those samples at lower Z-heights. An effect of this large an amplitude is hard to envisage. A more straightforward interpretation is that the "thick disk" has a distribution function that has a composite functional form. Whether this is actually a continuum or superposition of discrete components remains to be determined.

4. IMPLICATIONS

This new appreciation that a significant fraction of "thick-disk stars" are on orbits with angular momentum around half that of the Sun's orbital angular momentum resolves a recently discovered puzzle in the white dwarf population of the Galaxy. Two recent surveys (Oppenheimer et al. 2001; Nelson et al. 2002) have detected candidate white dwarfs, based on their high transverse motion across the sky, in numbers that are significantly higher than expected on the basis of normal thin- and thick-disk kinematics. This has led to speculations of a baryonic dark halo (Oppenheimer et al. 2001; Nelson et al. 2002). However, our result that typical stars on orbits that take them far from the plane have higher than expected mean velocities increases the expected detections in any proper-motion–selected sample and resolves the discrepancies. Indeed one expects "shredded-satellite" stars to be found in local, proper-motion–selected samples. Just such a population, with a mean azimuthal streaming velocity of ~100 km s^{-1}, was identified by Fuchs, Jahreiss, & Wielen (1999), based on the subset of the Carney et al. (1994) sample with *Hipparcos* distances and proper motions (resulting in only a handful of stars in the "excess" population).

What do our results mean for the evolution of our Galaxy, presumably a typical disk galaxy? In the standard hierarchical clustering and merging picture of galaxy formation, a thick disk is an expected outcome of a significant merger. Depending

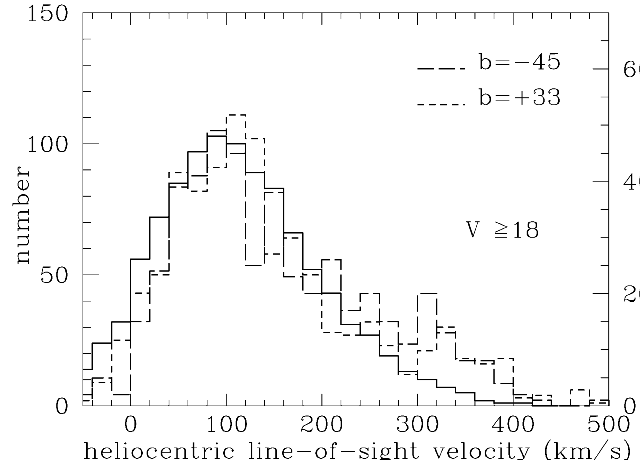

FIG. 3.—Same as the bottom panel of Fig. 2, but now with the model modified such that the kinematics of the "satellite debris" from Table 1 has been adopted for the "thick-disk" stars. Much improved agreement is seen, except for $V \gtrsim 300$ km s^{-1}.

on the mass, density profile, and orbit of the merging satellite, "shredded-satellite stars" may retain a kinematic signature distinct from that part of the thick disk that results from the heated thin disk. Satellites on prograde (rather than retrograde) orbits couple to the rotating thin disk more efficiently, and thus a merger with such a system is favored as the mechanism to form the thick disk (Quinn & Goodman 1986; Velazquez & White 1999). If any kinematic trace of the now-destroyed satellite galaxy is visible, it will be seen in the mean orbital rotational velocity of stars. The actual lag expected from the shredded satellite depends predominantly on the initial orbit and the amount of angular momentum transport in the merger process and is not ab initio predictable in a specific case.

In general, however, excluding special initial conditions, such as a circular orbit at large distance (see Walker, Mihos, & Hernquist 1996), satellite debris stars will be on orbits characterized by lower net rotational streaming about the Galactic center than that of the typical scattered former thin-disk star at a given distance from the Galactic center. In order to support themselves against the Galactic potential with less angular momentum support, the shredded-satellite debris must then have larger random motions (equivalent to pressure) than do the typical thick-disk stars: this is seen in numerical simulations of this process (Walker et al. 1996). It is these kinematics that allow their detection: stars with the highest amplitude of vertical motions (the satellite debris?) will be preferentially found farther from the plane than are most thick-disk stars (the heated thin disk?). If a population of former satellite stars exists, and the satellite was on an initial noncircular orbit consistent with cosmological simulations (van den Bosch et al. 1999), the apparent mean rotational velocity of stars far from the plane (the debris) will be less than it is for stars near the Sun, in the "classical" thick disk. This situation is easily distinguished from the possibility that all stars form a single, coherent, thick disk, in which case the rotational velocities of the most distant thick-disk stars, far from the plane, will not differ significantly from those nearby. This second model is inconsistent with our observations.

Our observations favor the interpretation that we have detected the shredded satellite. This is then evidence for a significant past merger experienced by the Milky Way, in the form of the direct detection of the intruder stars, stars that were formed in another galaxy, long ago. Decomposition of the star counts into a "heated thin disk" and a "shredded satellite," on the basis of the kinematics, suggests that a galaxy with perhaps one-quarter of the stellar mass of the early thin disk was the cause of the formation of the thick disk. The satellite debris may account for some of the distant structures seen by Newberg et al. (2002), but more data are needed to establish this. We do not see several distinct "extra" peaks in the velocity histograms, implying, in this interpretation, only one major past merger.

Alternative explanations remain viable. We may have found the remnant of an early merger event that occurred prior to a later merger that formed the bulk of the present thick disk. Outside the standard hierarchical merger-based cosmology, models without mergers exist: a vertically extended disk could have formed during the initial cooling and contraction of protodisk gas to reach equilibrium in a thin configuration (Norris & Ryan 1991; Burkert, Truran, & Hensler 1992). In this case, one then expects smooth vertical gradients in kinematics and metallicity within the continuous disk, now envisaged to encompass all of what we have identified as the thin disk, the thick disk, and the shredded satellite.

The bivariate distribution function of kinematics and chemical abundances provides more information than just kinematics: abundance determinations for our sample are underway. Smooth settling scenarios make specific predictions, but early merger models depend on the a priori unknown properties, at high redshift, of a now-destroyed galaxy. It is unlikely, however, that the chemical abundance distribution of the shredded satellite will be similar to that of the heated thin disk. Future chemical element ratio studies will be able to limit the star formation histories of thick-disk stars as a function of vertical velocity dispersion and quantify many of these general statements.

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