STRUCTURE AND KINEMATICS AT THE NORTH GALACTIC POLE

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ABSTRACT. Results from a complete survey of proper motions to $B = 22.5$ at the North Galactic Pole are summarized. Evidence from this and other surveys indicates that (1) the thick disk may extend to as much as 5.5 kpc above the Galactic plane at the solar radius, and (2) the thick disk may contain stars with metallicities as low as [Fe/H] = -1.6 or lower. These two properties of the thick disk mean that surveys of halo stars risk serious contamination by thick disk stars unless very conservative selection criteria are used. Applying these conservative selection criteria to existing surveys of halo stars reveals a surprising result - namely, that the halo is in retrograde rotation.

1. The Mayall 4-m Proper Motion Survey

We are conducting a deep astrometric survey (Majewski 1990, 1992) which relies on KPNO 4-m photographic plates to obtain high quality ($\sigma_\mu < 0.10''$ cent^{-1} to $B = 22.0$) proper motions for magnitude limited ($B \leq 22.5$) samples of stars in key Galactic fields. We have now completed work on a 0.3 deg^2 field at the North Galactic Pole (NGP). Multicolor *UBV* photometry has been used to provide estimates of abundance (through uv-excess) and distance (through photometric parallaxes) for a subsample ($U < 21.5$) of blue ($0.3 \leq B - V \leq 1.1$) dwarf stars extending to distances of tens of kiloparsecs above the Galactic plane. The proper motions have been tied to an extragalactic reference frame of 139 galaxies and QSOs to better than 0.01" cent^{-1}. Most surveys of halo dwarfs have been limited to the solar neighborhood, with samples defined by high proper motions or low metallicity. However, it has become clear (Carney *et al.* 1990, Norris & Ryan 1989b, Morrison *et al.* 1990, Majewski 1990) that separation of the various stellar populations on the basis of kinematics and/or abundance is fraught with difficulties because the distributions of these properties for the thin disk, thick disk, and halo have significant overlap. Our deep survey allows study of the kinematical and chemical properties of the Galactic thick disk and halo from a complete sample of field dwarfs *in situ*.

2. Properties of the Thick Disk

An important result from this survey is that a relatively sharp break is seen in the distribution of ultraviolet excesses at a distance of about 5.5 kpc above the Galactic plane. A similar metallicity break is also seen in the K giant data of Ratnatunga & Freeman (1989). Furthermore, the distribution of u and v velocities (stellar motions parallel to the Galactic plane) in our survey also show a break at this same distance. Together, these data suggest a sudden change in the mix of stellar populations from thick disk to halo, and that the thick disk extends to a relatively large distance from the Galactic plane, $z \sim 5.5$ kpc. On the near side of this break, the thick disk stars are observed to have a linear variation in asymmetric

B. Barbuy and A. Renzini (eds.), The Stellar Populations of Galaxies, 61–64.

drift with z, but no metallicity gradient. Although it is beyond the scope of this discussion, we note that this is a strange result since it seems to imply a dissipational origin for the thick disk on the one hand, and a more chaotic origin on the other. A key point for the present discussion is that the thick disk is found to have a *broad* distribution in metallicity, with stars as metal-poor as $[Fe/H] \sim -1.6$, and possibly even more metal weak. The presence of these metal-weak thick disk stars was first demonstrated by Morrison *et al.* (1990). Recently, Rees & Cudworth (1991) have determined that the metal weak ($[Fe/H] < -1.3$) globular cluster M28 has thick-disk-like kinematics; if the globular cluster system has anything to do with the field star population, this might be further evidence of a metal-weak tail in the thick disk.

3. Properties of the Halo

In keeping with a number of other recent studies of the halo, our data show no metallicity gradient to distances tens of kiloparsecs above the Galactic plane. The dispersion in metallicity is quite large, and, as found by Carney *et al.* (1990), there exist in our sample halo stars with metallicities as high as $[Fe/H] \sim -0.5$. The most surprising result of our astrometric survey, however, is that the mean reflex velocity of the halo is measured to be approximately -275 $\mathrm{km\,s^{-1}}$, with no variation with z-distance. Best estimates of the rotational velocity of the Local Standard of Rest (LSR) yield values near 220 $\mathrm{km\,s^{-1}}$. The H I velocity work of Gunn *et al.* (1979) gives 220 ± 10 $\mathrm{km\,s^{-1}}$for this value and is generally regarded as definitive. Thus our measured reflex velocity implies that the halo is in *retrograde* rotation about the Galaxy (at least in the direction of the NGP).

4. Is the Halo in Retrograde Rotation?

Until recently, two types of surveys have been used to derive the value of the rotational velocity of the Galactic halo. The first type of survey selects halo stars from the solar neighborhood based on either kinematics or metallicity. Great care must be used in interpreting velocity data from kinematically-selected samples, as has been stressed by Norris & Ryan (1989b). Unless the selection bias is well understood, in general it is preferable to rely on non-kinematically biased samples. However, selection of halo stars on the basis of low metallicity must take into account the presence of the metal-weak thick disk stars. *Unless the selection threshold is extremely conservative, metallicity-selected samples risk severe contamination by the thick disk population.* Morrison *et al.* point out that in the solar neighborhood, thick disk stars with $-1.0 \leq [Fe/H] \leq -1.6$ outnumber halo stars in the same metallicity range by a factor of two. Thus, in order to select a local sample of stars with pure halo kinematics, a metallicity limit of at least $[Fe/H] \leq -1.6$ must be used.

The second type of halo survey makes use of luminous stars at great distances as tracers of the halo population. A number of such surveys have been conducted using RR Lyrae stars, blue horizontal branch (BHB) stars, carbon stars, and giant branch stars, and all have relied exclusively on radial velocity information. Based on a compilation of data from these surveys, Norris (1986) concluded that the halo is in prograde rotation with a speed of 37 ± 10 $\mathrm{km\,s^{-1}}$, in contradistinction to the retrograde result we have obtained. However, it should be pointed out that, in general, these tracer surveys have probed to distances only a few kiloparsecs from the sun, less than the $z \sim 5.5$ kpc extent of the thick disk. *Halo tracer studies which probe to within only 5 kpc or so from the Galactic plane may be severely contaminated by evolved thick disk stars.* Since the thick disk has a significant rotational velocity compared to the halo, the presence of even a small number of such stars in a halo star sample could greatly influence any derivation of the rotational velocity.

It is worthwhile to review the various halo surveys while remaining cognizant of these two important sources of contamination by thick disk stars. In Table 1 we summarize the derived halo reflex velocities from halo surveys, concentrating only on those stars in these surveys which lie beyond the $z \sim 5$ kpc spatial extent of the thick disk or, if drawn more locally, more metal poor than the metal-weak thick disk stars. The number of stars in each sample is given as N. The Pier (1984) results are listed with the caveat that the distribution of his stars are not ideal for measuring the rotational velocity of the halo. The value listed for Ratnatunga & Freeman (1989) is based on a naive trigonometric deprojection of the mean radial velocity, 168 ± 25 km s^{-1}, found for the most distant stars in their field at ($l = 272$, $b = +38$) with the assumption of no net motions other than pure cylindrical rotation. The resulting value of -213 km s^{-1}is an *upper* limit, since some of the rotational motion is transverse to the line of sight. The result for Majewski (1992) is based on an average of the three most distant halo bins in his Table 10. The Allen *et al.* (1991) stars are those for which they have determined a maximum z-distance greater than 4 kpc; the reflex velocity listed is obtained by converting their mean angular momenta with $v_{LSR} = 225$ km s^{-1}and $R_o = 8.0$ kpc. For the Norris & Ryan (1989b) data, we list three values for the halo reflex velocity: their result using both proper motions and radial velocities, their result after correction for selection biases (in particular the high proper motion selection bias), and their result using only radial velocity data (but based on the proper motion-selected sample). The Norris & Ryan correction makes the reflex velocity more positive, but we stress that this correction was formulated with the *a priori* assumption that the halo is in *prograde* rotation by 40 km s^{-1}.

Table 1. "Pure" Halo Samples

Sample	Reference	N	v_{reflex} $(km\,s^{-1})$
Blue Horizontal Branch	Pier (1984)	150	(-272 ± 41)
K giants SA127, $<z>= 12.8$ kpc	Ratnatunga & Freeman (1989)	14	$< -213 \pm 32$
NGP dwarfs ($<z>\sim 13$ kpc)	Reid (1990)	~ 200	-240 ± 30
NGP dwarfs	Majewski (1990, 1992)	111	-267 ± 9
[Fe/H]≤ -2.0, $z_{max} > 4$ kpc	Allen *et al.* (1991)	13	-317
[Fe/H]≤ -1.8, uncorrected	Norris & Ryan (1989b)	254	-254 ± 6
[Fe/H]≤ -1.8, corrected	Norris & Ryan (1989b)	254	-236 ± 6
[Fe/H]≤ -1.8, V_{radial} only	Norris & Ryan (1989b)	254	-214 ± 14

If v_{LSR} is taken to be 220 $km\,s^{-1}$, then the results listed in Table 1 are relatively consistent in predicting a halo in retrograde rotation. Only the v_{reflex} values from the Ratnatunga & Freeman K giants and the radial velocity solution of Norris & Ryan are prograde results, and only barely. The former is an *upper* limit, and allows for a retrograde halo. The latter result is based on a sample of stars selected by high proper motion; this bias can select against stars with high *radial* velocities for some halo phase space distributions, and this bias, in turn, will yield a more positively rotating solution. The remaining entries in Table 1 are more extreme by many tens of kilometers per second, and give evidence for a retrograde halo, *if* our assumed value of v_{LSR} is correct (in light of the present discussion, however, it may be timely to "re-open the case" on v_{LSR}).

This rather surprising result may find a natural explanation by way of the satellite accretion models of Quinn & Goodman (1986). Retrograde moving satellites are more stable against tidal effects than prograde satellites, which are found to rapidly sink towards the Galactic center. If the halo field stars have come from disrupted satellites (as suggested earlier by Searle & Zinn 1978), then we might expect a preponderance of retrograde orbiting halo stars. Norris & Ryan (1989a) have found such an asymmetry towards retrograde orbits and have appealed to the Quinn & Goodman picture as an explanation. This satellite accretion picture can also explain the net retrograde motion of the 30 globular clusters with $-1.3 \geq$ [Fe/H]

≥ -1.7 (Rodgers & Paltoglou 1984), the presence of halo moving groups (cf. Doinidas & Beers 1989, and references therein), the high velocity A stars (Rodgers *et al.* 1981), and the existence of halo stars with high metal abundances (Carney *et al.* 1990, Majewski 1990).

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Discussion

Nemec: You have chosen to fit the stars with $z > 1$ kpc with a two-component 'halo plus thick disk' model. Based on this model you find for the 'thick disk' component a gradient [in asymmetric drift], which you interpret as due to dissipational collapse. Can you be sure that contamination from the high-z tail of the thin disk component, and contamination from the low-z side of the halo component, are not causing the apparent gradient?

Majewski: For $1 \leq z \leq 5.5$ kpc, the distributions for the metallicity and asymmetric drift appeared double-peaked and a two-Gaussian model seemed most appropriate for fitting. In this distance range, the tail of the halo distribution does overlap the distribution of thick disk points. However, if the halo velocity distribution is Gaussian for $z < 5$ kpc, as it is beyond this, then our technique should be robust against halo contamination. Contamination by thin disk stars could contribute to a gradient, but only within a few thin disk scale heights. Of course, an important question which remains to be answered is whether in fact the thin and thick disks are discrete components at all, or whether, as Norris suggests, the thick disk is simply a continuous and extended tail of the thin disk.

Corbally: How do you select for F and G dwarfs rather than giants? How might giant contamination affect your results?

Majewski: We assume *a priori* that all stars are dwarfs. At the faint magnitudes of the survey we would expect to find practically no giant contamination and subgiant contamination at a level of less than 10%. Note that assuming every star is a dwarf results in the *most conservative* kinematics. Converting proper motions to velocities for subgiant stars, which are at greater distances than dwarfs of the same apparent magnitude and color, results in a halo rotation even more extreme in the retrograde sense!

Corbally: Note that Corbally & Garrison (cf. poster contribution at this conference) find that about 7% of late F and G stars in the inner halo are in fact giants or subgiants rather than dwarfs, and this is in the region of the Hertsprung gap and so a lower bound.