Moving Groups, Stellar Streams and Phase Space Substructure in the Galactic Halo

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Abstract. We have been exploring the phase space and metallicity distributions of stars in the North Galactic Pole field SA 57. The data are deep (B ≈ 22.5) proper motions and photometry, combined with Mayall 4-m spectroscopy using the HYDRA multifiber system to brighter (B ≈ 19.5) limits. Our early spectroscopic results confirmed the existence of a retrograde rotating, halo moving group in this field. We have since obtained many more spectra, and we find the halo stars in our survey to show a high degree of clumping in their $U - V - W - [\text{Fe/H}]$ distributions. From our data we conclude that (1) the halo is not a dynamically relaxed system, (2) phase space substructure could account for differences in halo kinematics derived from surveys along different lines of sight, and (3) the halo field star population may be derived predominantly from the accretion of stellar agglomerations, most likely dwarf galaxies. The latter conclusion agrees with that of Preston et al. (1994) from their work on blue, metal-poor stars.

1. Introduction

The idea of stellar moving groups has had a long tradition in Galactic studies, going back to Proctor's (1869) discovery of the two clearest examples of moving groups in the solar neighborhood – the Hyades and Ursa Major groups (see also Wilson & Raymond 1932, Roman 1949, Eggen 1960a, Soderblom & Mayor 1993). Much of the work on moving groups in the past four decades has been contributed by Olin Eggen, and good reviews of the early history of the subject can be found in Eggen (1965) and of more recent work in Eggen (1987). Among the solar neighborhood moving groups, three were recognized to consist of Population II stars – the Groombridge 1830, Kapteyn star and Ross 451 groups (Eggen & Sandage 1959, Eggen 1960b, 1977, 1978, Poveda et al. 1992).
On the basis of their kinematics, ultraviolet excesses, and the fact that these groups contained “cluster variables” (RR Lyrae stars), these particular groups were initially associated with globular clusters (Eggen 1965, Oort 1965).

Unfortunately, the history of the subject of moving groups has been somewhat checkered. Candidate moving groups identified in the solar neighborhood were often hard to define and to delineate from the general field of disk stars. The problem is compounded by the fact that nearby moving groups can be widely spread across the sky – as was recognized early by Hertzsprung (1909) for the Ursa Major group (which, for example, includes the star Sirius) and by Boss (1908) for the Hyades (and, for which circumstance, Boss developed the convergent point method of cluster analysis). As a consequence of this, the kinematics of individual member stars depend on differing contributions of proper motions and radial velocities, their respective observational errors, and errors in distance. Depending on how loosely one defines the kinematic boundaries of a particular group in $U - V - W$ space, one may find more or less candidate members, but also incur more or less contamination by unrelated stars. Because of these difficulties, the existence or definition of several groups proposed early on – e.g., the 61 Cygni, Vela and Corona Borealis ”moving clusters” – were questioned after further scrutiny (see Eggen 1965).

The early work on kinematical groups was of necessity confined to brighter, solar neighborhood stars. Modern instrumentation allows more distant parts of the halo to be surveyed, and it might be hoped that some of the difficulties in delineating moving groups that beset the earlier kinematical studies could be overcome. In the halo, the density of stars in occupied phase space is lower than the tightly concentrated phase space distribution of the disk. Thus, the contrast of any halo phase space clump could potentially be higher. Moving groups more removed from the Sun should also be more confined in the sky and member stars would be expected to share common radial and transverse velocities. Indeed, searches for distant moving groups usually rely on this latter assumption. Because proper motions for more distant stars are difficult to come by, most of the distant candidate moving groups of stars have been based on clusterings in radial velocity. Thus, faint surveys have resulted in a number of proposed moving groups based on radial velocity/distance features in surveys of distant, blue horizontal branch (BHB) stars (Sommer-Larsen & Christensen 1987, Arnold & Gilmore 1992) and somewhat closer, in situ dwarf stars (Doinidas & Beers 1989, Croswell et al. 1991, Cote et al. 1993). Unfortunately, as they are based on only one dimension of velocity, some proposed radial velocity groups may be only statistical fluctuations. For example, based on the proper motions from Spaenhauer (1989) and Majewski (1992; SM92 hereafter), we have been able to investigate the full space motions of Croswell et al.'s proposed moving group, and it appears to be a chance clustering of radial velocities. In addition, the dispersion of radial velocities in the Sommer-Larsen & Christensen group are apparently higher than first measured (Cote et al. 1993). However, while subject to this type of uncertainty, the radial velocity search technique can chalk up one very notable success, the discovery of the Sagittarius dwarf galaxy, which appeared as a radial velocity clump in a survey by Ibata et al. (1994).

Our specific interest in the subject of moving groups came as a result of continued difficulties in describing the results of our kinematical survey of faint, in situ stars by means of conventional descriptions of the Galaxy that include a
well-mixed, prograde-rotating Population II. In this contribution, we recount our
finding and investigation of substructure, including candidate moving groups, in
the phase space distribution of non-local, halo stars through use of full space
velocity data derived for stars at faint magnitudes. We discuss our findings in
the context of the structure and origin of the Galactic halo, and point out their
implications for future studies of halo stars.

2. First Puzzling Results – The Retrograde Halo

In SM92, we presented the absolute proper motions of a complete sample of stars
to B = 22.5 in the North Galactic Pole (NGP) field SA57. These allowed us to
study the $U$ and $V$ components of stellar motion as a function of height above
the Galactic plane. The proper motions were derived from a 16 year baseline
of Mayall 4-m, prime focus plates on fine-grained, III-a emulsions. The good
scale and large field of these plates yielded proper motions with random errors
of 0.08 arcsec/century for the majority of the stars, and allowed a tie-in to an
absolute reference frame of compact galaxies and previously identified QSOs to
better than 0.01 arcsec/century. Stellar distances were derived for 250 stars
(about one third of the sample) with B–V ≤ 1.1 and U ≤ 21.5 from photometric
parallaxes incorporating U band plates to estimate metallic line-blanketing. All
photographic photometry was calibrated with photoelectric and CCD stellar
sequences (cf. Majewski et al. 1994).

These photometric and astrometric data led to several controversial conclu-
sions. Because of the magnitudes studied, the local volume explored by the F, G
and K dwarfs is relatively small, and the SM92 sample consists mainly of Inter-
mediate Population II (IPII, or thick/extended disk) and halo stars. However,
the distance at which the transition between dominance by IPII stars and halo
stars occurred appears to be relatively high, near 5.5 kpc. This was evident most
clearly in the distribution of ultraviolet excesses with distance, but there were
also signs of a kinematical signature at this distance. Throughout much of the
survey distance range, the asymmetric drift velocities of the stars as a function
of height appeared to be suitably described by two Gaussian distributions. The
IPII showed a gradient in mean rotational velocity, slowing from only a mod-
erate asymmetric drift locally to something like ~100 km/s near 5 kpc above
the Galactic plane (a result in contradiction to some previous studies that de-
scribed this population with a single rotational velocity), at which point a halo
population (visible in smaller numbers at closer distances) with more extreme
kinematics began to dominate. Unlike the IPII, the mean rotational velocity of
the halo appeared to be a constant at all surveyed distances. Most remark-
ably, the mean rotational velocity of the halo was measured to be $-275 \pm 16$ km/s,
or in retrograde motion if the rotational velocity of the Local Standard of Rest
(LSR) is adopted as 220 km/s. The implication of this surprising result is that
the majority of the halo stars in this sample could not have been formed as a re-
sult of the traditionally envisioned collapse of proto-Galactic matter as in Eggen
et al. (1962), since under such circumstances it is impossible to account for the
opposing mean angular momenta of the halo and disk. Rather, a retrograde
rotation for the halo suggests an origin through accretion processes.
Because of its bearing on collapse models, and, especially, because of its contradiction with almost all previous studies of halo kinematics (notable exceptions being Pier 1984, Reid 1990 and Allen et al. 1991), it is important to verify this retrograde halo result, to search for possible sources of systematic error or to reconcile the results with the other studies. A 25% error in either the proper motions or the distances, or both combined, are needed to make the apparent retrograde result a non-rotating one. Correcting any possible systematic zero-point error in the proper motions has the unfortunate and nonintuitive result of making the more distant halo stars rotate faster (in a prograde sense) than more nearby stars, and was regarded as unlikely in SM92. More likely is the possibility of distance errors. For example, Ryan (1992) concluded that systematic errors of as much as 16% might occur through use of UBV photometric parallaxes. It should be pointed out, however, that the SM92 distances were calculated under the assumption that all survey stars in the survey were on the (metallicity dependent) subdwarf main sequence, and ignored completely the possibility that some of the stars would be expected to be evolved main sequence, subgiant, or giant stars, and that perhaps as much as half of the stars could be unresolved binaries. Both of these effects exacerbate the distance problem by making the stars intrinsically more luminous than assumed.

Meanwhile, it was shown (SM92, Majewski 1992, 1993) that if one accounts for the fact that the IPII contains stars of very poor metallicity, perhaps encompassing abundances as low as that of the halo (for example, as characterized recently by Norris 1994), that it has a large spread in kinematics (e.g., the low rotational velocities at larger distances from the plane seen in SM92), and that it dominates the halo to distances as high as $Z = 5.5$ kpc, there is accord between the previous surveys and SM92. Note that Reid (1990) had already found a slightly retrograde result, $-240 \pm 30$ km/s, for his most distant NGP dwarfs, while Pier (1984) also found $-272 \pm 41$ km/s for distant BHB stars, although the latter stars were not in fields particularly sensitive to this measurement (though a similar result was obtained by Doinidas & Beers 1991). Allen et al. (1991), investigating a sample of $[\text{Fe/H}] < -2.0$ sample of dwarfs, found an even more extreme retrograde result ($-317$ km/s) for nearby stars that attain maximal distances from the Galactic plane, $Z_{\text{max}}$, greater than 4 kpc. Similar constraints placed on the Carney et al. (1990) sample also produced slightly retrograde results. It is worth noting Kuijken & Tremaine’s (1994) recent study of the mean Galactic rotational velocity at $R_o$ and the velocity of the LSR (which is only identical in the case of a circularly symmetric disk). Their work indicates a $V_{\text{rot}}(R_o)$ more like 200 km/s and yields $V_{\text{rot}}(\text{LSR}) = 180$ km/s in the proposed situation that the solar neighborhood lies near the minor axis of the potential of an elliptical Galactic disk. This effectively increases the magnitude of the variously measured retrograde velocities of the halo.

Several newer analyses that have limited their study of halo stars to distances beyond which the IPII is thought to make a significant contribution have now obtained mean retrograde results: Carney et al. (1995) find $-265 \pm 22$ km/s, Wilhelm & Beers (1995) obtain $-312 \pm 35$ km/s, and Kinman et al. (1995) also see a retrograde halo. Such agreement is gratifying; yet, in light of our own more recent results, it is also a bit puzzling that retrograde halos are seen in some “all-sky” surveys since we (see below) are now inclined to attribute our retrograde results to features that may be more localized.
3. Evidence for Kinematical Substructure in Halo Field Stars

Additional evidence existed in the SM92 proper motion survey that supported the idea of accretion in the halo. A group of eight stars in the IPIT-dominated distance range $2.9 \leq Z \leq 4.7$ kpc (but predominantly within 300 pc of $Z = 4550$ pc) and with extreme, halo-like velocities were found to be distributed asymmetrically with $-414 \leq U \leq -116$ and $-480 \leq V \leq -254$ km/s. While there were only a relatively small number of stars in the survey, this group stands out because most stars at these distances have much less extreme velocities with respect to the Sun. Only a few stars at nearer distances showed halo kinematics, but several of these inhabit the same region of the $U - V$ plane as the group of eight. At larger distances, the intrinsic spread in the stellar $U - V$ velocities masked our ability to discern any additional stars which might be associated.

In SM92 it was suggested that the stars constituted a moving group of halo stars, which, unlike previous distant candidates, had been found via proper motions and identified as peculiar in two dimensions of velocity. The very large $U$ and $V$ spread made the group appear different from previously identified moving groups. However, much of this velocity spread may be due to observational error, since the mean random distance errors in these stars are something like 237 pc (comparable to the observed 300 pc spread for most of the stars). Much less relative spread is seen in the raw proper motions in the $l = 90^\circ$ direction.

In the past few years, we have begun a program to obtain radial velocities of stars in the SM92 field as well as several other fields (Majewski et al. 1994, 1995). We have been using the HYDRA multifiber system (Barden et al. 1993) on the Mayall 4-m telescope to obtain spectra with a velocity resolution of $\approx 10 - 20$ km/s. Our immediate concern has been to retrieve $W$ velocities for our NGP stars, but we intend to use the spectra to analyze the chemical abundances of our stars in the NGP and other fields, and to study the kinematics of stars of late spectral types. A priority was to obtain radial velocities for stars in the candidate proper motion moving group. Initially (Majewski et al. 1994) we obtained radial velocities for six stars in the group, and found them to span the range $-48 \leq W \leq -86$, where the 15 km/s dispersion in the group is again comparable to the random error in measurement. That the stars were not randomly distributed about $W = 0$ km/s highlights their kinematical peculiarity. Kolomogorov-Smirnov probabilities that their radial velocity distribution might be drawn from a conventional, well-mixed halo population with $\sigma_W \approx 85$ km/s are less than 1% and, from an IPIT population with $\sigma_W \approx 45$ km/s, less than 0.1%. Thus, the early radial velocity data provided independent support that the SM92 proper motion moving group represents kinematical substructure in the distribution of halo stars. The retrograde halo result suggested that the bulk of the halo may have derived from accretion. The apparent verification of the NGP moving group underscores the point that our halo has accreted stars in the form of distinct stellar agglomerations – globular clusters, Galactic satellites, Searle & Zinn (1978) ”fragments” – that have left fossils visible in the halo today.
4. Opening a Can of Worms

Our early radial velocity results gave some preface to our next peculiar finding. It happened that due to poor luck with weather early in the survey, our spectra were accumulated in more or less increasing magnitude order. Thus most of the first velocities obtained were of IP II stars. But the \( W \) velocities of the several other stars with halo kinematics, specifically, those at other distances but in the same region of the \( U - V \) diagram as the moving group above, also were negative. As more and more halo stars were observed, we became concerned that almost all of them had negative radial velocities. Systematic error was suspected, but, as the IP II stars did not show such an imbalance in their \( W \) velocities and, with the fiber system, their spectra were obtained simultaneously with the halo stars, we could not determine how such an error might be able preferentially to single out halo stars. In addition, our velocities agreed reasonably with the results of Croswell et al. (1991) for many stars in common. At one point in the survey, 16 of 17 stars for which the SM92 data indicated a retrograde velocity had \( W < 0 \) km/s and 22 of 25 stars with estimated \([Fe/H] < -0.8 \) had \( W < 0 \) km/s. Upon discussion of this track record with George Preston, he jokingly suggested that these results were so extraordinary that we ought to stop collecting data because any such high "batting average" was sure to diminish.

We ignored this sage advice and continued to collect data for fainter, more distant stars in the survey, so that, indeed, our "batting average" has lowered somewhat; nevertheless, the results are still rather peculiar for stars with \( Z < 8 \) kpc. Our spectroscopic data now include 280 stars of type F and later and extending to \( V \approx 19.5 \). We find that 21 of 24 retrograde stars and 26 of 34 stars with photometric \([Fe/H] \leq -0.8 \) for which we have spectra have \( W < 0 \) km/s. Based on these two means of delimiting halo stars, it appears that in the direction of the NGP, the halo is predominantly falling towards the Galactic plane. The \(< W >\) velocities for these two subsamples are \(-56\) and \(-29\) km/s, respectively. For six stars at \( Z > 8 \) kpc, the \( W \) are more randomly distributed, and this may indicate that the kinematical features to which we are calling attention here may be limited to distances closer than \( Z = 8 \) kpc.

Two other surveys at the NGP give consistent radial velocity results for halo tracers. When our results were described to George Preston, he recalled very similar, unpublished results by Jeff Pier from ten years ago. During his survey of RR Lyrae stars in the SA 57 field, Pier found 25 of 38 to have \( W < 0 \) km/s with mean \( W = -48 \) km/s, results that naturally raised concerns about calibration problems. A recent survey of BHB stars in SA57 by Kinman et al. (1994) also finds a \( W \) imbalance: 14 of 21 have negative \( W \) and with \(< W > = -63 \) km/s.

Finally, we discuss the prograde rotating stars that have halo-like kinematics. Figure 1 shows the \( U - V - W-[Fe/H] \) distribution of F, G and K stars with \( Z < 8 \) kpc from our (Majewski et al. 1995) spectroscopic sample. In this figure, we have removed likely IP II stars, those with \( V > -80 \). These stars seem to show additional substructure in their velocity-metallicity distributions; we have highlighted three apparent clumps, selected on the basis of position in the \( V - W \) diagram, with different symbols. In addition to the retrograde, negative \( U \), negative \( W \), predominantly metal-poor moving group already discussed, there appears to be another group of stars (circles) centered near \((V,W) \approx (-150, +50) \) km/s that are skewed towards positive \( U \) and photomet-
Figure 1. The distribution of photometric abundance, $[\text{Fe/H}]$, and $U-V-W$ velocities for SM92 stars with $Z < 8$ kpc and $V < -80$ km/s. The dotted line in panel (c) indicates the approximate demarcation between prograde and retrograde orbits, assuming the $V_{rot}(LSR) = 220$ km/s. Three clumps of stars - indicated by separate symbols – large circles, triangles, and squares – have been defined on the basis of Figure 1(c).

A third possible group (triangles) near $(V, W) \approx (-100, -50)$ km/s has a $U$ distribution more symmetrically distributed about 0 km/s but a metallicity distribution that is also relatively high. It is possible that our NGP observing cone intercepts three intersecting fossil streams that are the remains of disrupted stellar agglomerations.

If real, the segregation of the majority of our halo stars into distinct groups points to accretion as the dominant process in the origin of halo field stars. This is reminiscent of models of structure formation in cold dark matter scenarios (cf. Frenk et al. 1988) which indicate that galaxies form through the coalescence of many subunits. These subunits are continuously accreted by enlarging galaxies (Navarro et al. 1994). Some signs that such processes might have occurred in our own halo is the existence of the Magellan Stream; various suggested alignments of the Galactic satellites with each other and with some halo globular clusters (Kunkel & Demers 1976, Kunkel 1979, Lynden-Bell 1982, Majewski 1994); and the growing evidence for moving groups of halo stars and even globular clusters (Da Costa & Armandroff 1995, Lynden-Bell & Lynden-Bell 1995).
The frequency with which candidate moving groups are reported hints at the possible prevalence of fossil streams in the Galactic halo. What might be the parent bodies of these fossils?

Oort (1965) discussed the existence of Population II moving groups in the context of "tubes" of stars strung out along the three-dimensional orbits of disintegrating parent bodies. He suggested that the parent bodies might be globular clusters and, from the frequency of Eggen's Population II groups in the solar neighborhood, estimated that $10^3$ clusters would need to have disintegrated over a Hubble time. In 10 Gyr, these clusters would produce tubes of cross-section 0.1 kpc$^2$ and length 60 kpc. More recent N-body simulations of the break-up of dwarf satellite galaxies (with velocity dispersions of typically 10 km/s) in a Milky Way-like potential (Kuhn 1993, Moore & Davis 1994, Johnston et al. 1995, Velazquez & White 1995) demonstrate that the stellar debris can maintain remarkable coherence along the orbital path of the satellite over a Hubble time, whereas the stellar debris from the accretion of larger satellites like the LMC, with dispersions more like 50 km/s, become more widely dispersed.

Thus it would seem that dwarf spheroidals represent the largest possible parent body to leave coherent stellar streams. The Kinman et al. (1994) data may shed additional light on the nature of the progenitor of at least our retrograde stream. In their search for BHB stars among blue field stars, Kinman et al. uncover a contaminating population of relatively distant A stars, and these too show a $W$ imbalance: $< W > = -32 \pm 7$ km/s, and with 10 out of 14 having a negative $W$ velocity. These A stars are presumably related to the "high velocity A stars" of Rodgers et al. (1981) and Lance (1988). If the A stars, the RR Lyrae stars, the BHBs and our field stars all represent downfalling NGP debris from the same progenitor, then it must have been more like a dwarf galaxy with a mix of population ages, including relatively recent star formation, rather than a globular cluster. This conclusion is based on the assumption that the A stars are young (< 1 Gyr) main sequence stars and not blue stragglers. If so, then they also place a 1 Gyr upper limit on the time since disruption of the progenitor. A short time since disruption is also implied by the mean orbit of this stream, which brings it within 2 kpc of the Galactic center, close enough for significant bulge shocking on a single passage. Moreover, if the large velocity spread along the direction of rotation of our group is real, it could also argue for a more recent disruption based on the arguments of Woolley (1965). In any case, these A stars at the NGP provide potentially interesting link between our NGP retrograde stream and the population of "blue metal poor" stars described by Preston et al. (1994), and which these authors also attribute to the recent break-up of a Galactic satellite.

Of course, the strongest support for the idea that halo stellar streams may be derived from the disruption of dwarf spheroidals is the example provided by the Sagittarius dwarf galaxy discovered by Ibata et al. (1994). This galaxy is in the process of tidal disruption and the resultant tidal streams have apparently now been mapped over 20° of the sky. The interaction between Sagittarius and the Milky Way may be an appropriate paradigm for the formation of star streams of the type that we see towards the NGP.
5. Discussion

The finding of a mean retrograde rotation for the halo suggests the bulk of the halo was formed from accretion processes rather than from a general collapse that may have formed the disk. The moving group identified at the NGP (Majewski et al. 1994) may represent fossil remains of one such accretion event. That the halo in the direction of the NGP appears to be dominated by stars that are clumped in phase space indicates that perhaps all of the halo may have formed in a lumpy process of accretion, probably more or less continuously over the lifetime of the Galaxy. Under such circumstances, i.e., if the halo were made up entirely from the disruption of matter contained in discrete lumps a Hubble time ago, Tremaine (1993) has calculated the overfilling factor of tidal streams in any particular volume. In a well-mixed system, this overfilling factor would be $>> 1$, but at the solar radius one obtains (setting his $\Omega t = 450$) an overfilling factor consistent with our results at the NGP, namely a factor of several. It appears as if the Galactic halo may not be a dynamically relaxed system.

If the halo is dynamically young, then understanding its structure is much more complicated. As Eggen (1965) points out “It is usual in applying the various statistical procedures used in the study of stellar motions to assume that these motions are randomly distributed with, at most, only minor variations. If in fact the observed motions are dominated by those of a relatively few stellar groups, then many of these procedures may be invalid.” It may be risky to draw conclusions about global properties of the halo, particularly from studies along only a few lines of sight, if the halo has the structure of a “can of worms”. Such structure might explain discrepancies between various surveys of halo structure, kinematics and chemistry along different lines of sight. In this context, it is worth mentioning Guo’s (1995) very comparable survey to SM92 at the South Galactic Pole (SGP). His study uses prime focus plates from the Blanco 4-m telescope. Guo does not see a retrograde halo towards the SGP, which suggests that this property may be confined to the northern hemisphere. This is consistent with the fact that the retrograde stars in our survey seem to be participating in a large scale stream moving down towards the Galactic plane. But clearly more work is needed to understand in detail how these retrograde stars are distributed, since recent surveys (Carney et al. 1995, Wilhelm & Beers 1986) that probe both hemispheres are now also finding a net retrograde halo rotation. In order to understand the correlation scale of streaming motions such as those in the NGP field, we hope to expand our survey to a number of other fields aligned along the $l = 180^\circ$ meridional section, and to include fields in the general direction from which the NGP retrograde stream is coming.

Studies of the halo will now require much more systematic and dedicated efforts to untangle the inhomogeneity of this dynamically young system. But the payoff to opening this can of worms is that we will be able to reconstruct the history of the Milky Way in much greater detail by reading the tales told by the fossil stellar streams.

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