THE LOCAL GALACTIC ESCAPE VELOCITY[1]

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ABSTRACT. From a new photometric and spectroscopic survey of high proper motion stars, combined with previously published work, we find that the local value of the escape velocity from the Galaxy exceeds 500 km s^{-1}. This gives direct dynamical evidence that the total Galactic mass exceeds the mass inside the solar orbit by a factor of at least five.

1. INTRODUCTION

Stars in the solar neighborhood moving on circular orbits about the Galactic center have Galactic rest-frame velocities, V_{RF}, of about 220 km s^{-1} (Gunn, Knapp, and Tremaine 1979, hereafter GKT). If the total mass of the Galaxy were contained within the solar Galactocentric distance, R_o, the Galactic mass would be 1.0 x 10^{11} $M_\odot$, assuming R_o = 8.5 kpc (GKT), and the local value of the escape velocity would be 311 km s^{-1}. The total mass of the Galaxy is, however, much larger, as has been shown by three different methods.

First, the Galaxy's observed rotation curve is flat or rising out to distances approaching $2R_o$ (Blitz, Fich, and Stark 1982), so that its dynamical mass is at least twice that inside R_o. The Galaxy thus resembles other disk galaxies with flat or rising rotation curves, as shown by optical data (Rubin <u>et al</u>. 1978, 1982; Burstein <u>et al</u>. 1982; Burstein and Rubin 1985) and suggested by radio data (Bosma 1981a,b).

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[1]Some of the observations reported here were obtained with the Multiple Mirror Telescope, a joint facility of the Smithsonian Institution and the University of Arizona.

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Second, radial velocities of distant globular clusters and of the Galaxy's retinue of dwarf spheroidal galaxies suggest a total mass approaching 10^{12} $M_{\odot}$ (Hartwick and Sargent 1978; Lynden-Bell et al. 1983; Peterson 1985). Here, unfortunately, the sample is small, and a relatively large uncertainty results from the unknown orbital eccentricities of the systems. The poor accuracy of the radial velocities has been a factor in the past, but is no longer the dominant source of uncertainty. In a similar context, Hawkins (1983,1984) has deduced a Galactic mass exceeding 10^{12} $M_{\odot}$, based on the (as yet) unconfirmed distance and velocity of his RR Lyrae candidate star R15.

Finally, the space velocities of nearby stars may be used to determine lower limits to the local escape velocity. For example, the wide co-moving pair HD 134439/40 has been known for over half a century to be such an extreme velocity system. The recent trigonometric parallax (Russell 1977), together with its very large proper motion and high radial velocity yield V_{RF} > 400 km s^{-1}. More recently, Sandage's (1969) very high radial velocity for the high latitude dwarf G64-12 yield V_{RF} > 400 km s^{-1}.

In this paper we use a sample of nearby stars with high space velocities to investigate the local velocity of escape from the Galaxy. Although this approach is vulnerable to errors in the distance determinations, the use of stars allows us to sample a larger number of high-velocity objects than the second method. In the sections below we discuss the data sources that have yielded extreme-velocity stars, the determinations of V_{RF}, and the limits that we can set on the local escape velocity and the total mass of the Galaxy.

2. DATA SOURCES

2.1 A New Survey of High-Velocity Stars

We have recently completed the first phases of a photometric and spectroscopic study of over 900 F, G, and K stars selected from the Lowell Proper Motion Catalog (Giclas et al. 1971, 1978). In brief, the stars all have proper motions exceeding 0.2 arc s yr^{-1}, and in most cases have two independent measures, the second being that of Luyten (1979 a,b; 1980 a,b). The V magnitudes range from 7.0 to 16.3 mag (the Lowell Catalog limit). UBV photometry exists for the entire sample, including our own 1225 measures for 867 stars. Digital spectrograms have been obtained for all the stars as well, using photon-counting Reticons to record 45 A of a single echelle order centered near 5200 A at high dispersion (2.2 A mm^{-1}) and high resolution (10 km s^{-1}) but at low to moderate signal-to-noise. Radial velocities with a typical accuracy of ± 0.7 km s^{-1} per observation were derived using digital cross-correlation techniques. As of July 1985 we had measured approximately 3400 velocities of the stars in our proper-motion sample.

2.2 Previous Surveys

Although our new survey is large and unbiased in metallicity, we chose to enlarge the sample significantly by adding stars from several other studies of high-velocity stars. We have therefore included in our analyses all high-velocity F, G, and K dwarfs of which we are aware whose proper motions exceed 0.2 arc s yr^{-1}. The major sources are the studies of Sandage (1964, 1969, 1981), the compilation of Eggen (1964), Saio and Yoshii (1979), and a private file maintained by one of us (BWC). These additional samples contain about 300 stars, all with published UBV photometry and radial velocities.

Eggen (1976) obtained UBV photometry for stars near the South Galactic Pole, and Carney and Peterson (1985a) studied 27 of the fainter metal-poor stars. JHK photometry was obtained to confirm the photometric parallaxes, and low-resolution spectrograms were taken to eliminate white dwarfs and measure radial velocities. Eggen (1969 his Table 2) also published a list of possible extreme velocity stars, with V_{RF} ranging from 400 to 2000 km s^{-1}. Included in his list are 23 stars blue enough ($B-V < 1.0$ mag) for reliable photometric parallaxes (see section 3.1 below). Carney and Peterson (1985b) have studied 18 of these stars utilizing Vby and JHK photometry, and low-resolution spectroscopy. One star has $V_{RF} > 400$ km s^{-1}.

3. KINEMATICS

To determine space velocities, it is necessary to know the distance for each star in order to convert proper motions into tangential velocities. To correct each space velocity to the galactic rest frame we must remove the small contribution due to the solar peculiar motion and the large contribution due to Θ_O, the circular velocity of the Local Standard of Rest (LSR):

$$(V_{RF})^2 = U^2 + (V + \Theta_O)^2 + W^2. \tag{1}$$

Θ_O plays a second role in our work, because the ratio of the total Galactic mass, M_{TOT}, to the mass within the LSR orbit, M_{LSR}, will depend on V_{ESC}/Θ_O, where V_{ESC} is the local escape velocity measured in the Galactic rest frame. In the simple case of a flat rotation curve extending from R_O to some abrupt cut-off at R_{LIM}, we have

$$\begin{aligned}(V_{ESC}/\Theta_O)^2 &= 2 \ln (M_{TOT}/M_{LSR}) + 2 \\ &= 2 \ln (R_{LIM}/R_O) + 2\end{aligned} \tag{2}$$

3.1 Photometric Parallaxes

We have used UBV colors to derive photometric parallaxes for the dwarf stars in our survey. In the absence of interstellar reddening, the B-V color of a dwarf is determined primarily by its temperature and composition. In Figure 1a we show absolute magnitude, M_V, versus color, B-V, for members of the Hyades cluster, after removal of binaries and binary candidates (Carney 1982). The halo dwarfs with accurate trigonometric parallaxes are also shown (Carney 1979b). The large separation

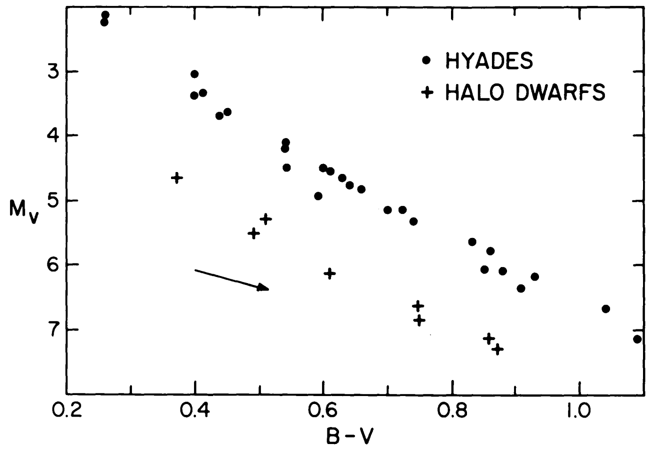

Fig. 1a. The main sequences for the Hyades and for the metal-poor halo dwarfs in the B-V versus M_V color-magnitude diagram.

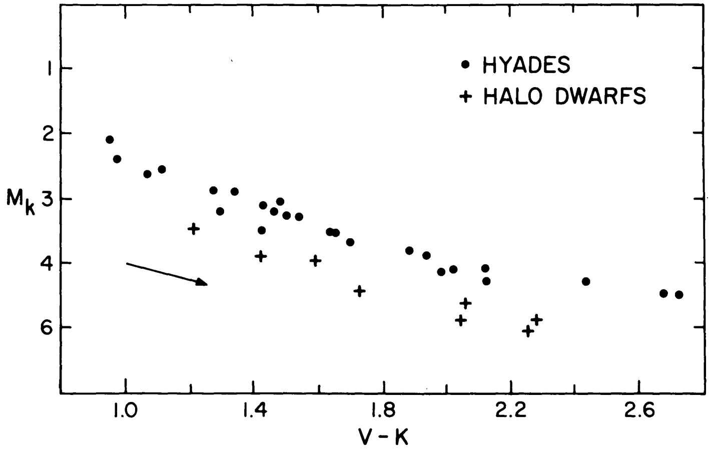

Fig. 1b. The main sequences for the Hyades and for the metal-poor halo dwarfs in the V-K versus M_K color-magnitude diagram.

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between the Hyads and the halo dwarfs illustrates one of the main difficulties in determining M_V for stars with various compositions. If we assume that the disk and halo populations have identical helium abundances, or that helium correlates (or anticorrelates) with metallicity in a well-behaved way, we can interpolate between the two sequences as a function of metallicity. With UBV photometry, metallicity affects both M_V (through opacity) and B-V (through blanketing). This last point is illustrated by Figure 1b, where we use metallicity-insensitive V-K (Carney 1983) instead of B-V. The gap between the Hyads and the halo dwarfs has been more than halved because the redder pass-bands are much less affected by blanketing. However, since we rely primarily on UBV data, we must establish a reliable metallicity-based interpolation scheme that does not require infrared K measurements. We have chosen to work with the normalized ultraviolet excess, $S(U-B)_{0.6}$ (hereafter S) as defined by Sandage (1969). Its relationship to [Fe/H] has been calibrated by Carney (1979a). Carney and Latham (1985a) discuss this procedure in some detail, and find that by interpolating B-V using S^2, a typical accuracy of ± 0.2 mag in M_V (corresponding to an accuracy of ± 10 percent in the distance) can be achieved.

3.2 Reddening

The first-order effects of reddening are shown for E(B-V) = 0.1 mag by the arrows in Figures 1a and 1b. On the U-B versus B-V color-color diagram the reddening vector is steeply inclined to the stellar locus; reddening increases a star's ultraviolet excess and thus lowers its estimated metallicity and luminosity. Thus if the effects of reddening are ignored, the values derived for the star's space velocity will be too low. We can ignore reddening and still set lower limits to V_{ESC}. However, since we are also interested in the upper limits, we have estimated E(B-V) for each star.

For stars lying above or below the Galactic plane by more than 10 degrees, we used the reddening maps of Burstein and Heiles (1982) and assumed the dust is distributed smoothly with a scale height of 150 pc. For lower-latitude nearby stars, we used the map of Paresce (1984); for those lower-latitude stars more distant than 150 pc, we determined E(B-V) versus distance using published spectral types and UBV photometry for early-type stars within 1 or 2 degrees of each program star, then the revised δ and M_V values were iterated a few times. We discuss our results with and without these reddening corrections in sections 4.1 and 4.2 below.

3.3 Galactic Rotation

GKT determined Θ_0 = 220 km s^{-1} using 21 cm data, and Arp (1985) utilized Local Group radial velocities to estimate Θ_0 = 250 km s^{-1}. If we can select a halo population that has no net rotation in the galactic rest frame, then we can determine Θ_0 by measuring the mean motion of the sample with respect to the LSR. Several such studies have already been done. Woolley and Savage (1971) found a value of Θ_0 = 224 ± 25 km s^{-1} using 79 field RR Lyraes, while Pier (1984) obtained 272 ± 41 km s^{-1} using 150 field halo AB stars. With a much smaller sample (21) of blue horizontal branch stars, Sommer-Larsen and Christensen (1985) found Θ_0 = 172 ± 40 km s^{-1}. For a subsample of 46 metal-poor globular clusters, Frenk and White (1980) found a value of 190 ± 35 km s^{-1}, while Zinn's (1985) sample of 81 such clusters yielded Θ_0 = 170 ± 23 km s^{-1}, compared to 225 ± 52 km s^{-1} for the sample of 33 clusters more than 7 kpc from the Galactic center. Using a sample of 107 southern metal-poor ([Fe/H] < -1.4) dwarfs and giants, Norris et al. (1985) found Θ_0 = 182 ± 20 km s^{-1}. To these studies, we now add two more.

First, we have obtained over 300 radial velocities for 82 of the red giants with [Fe/H] < -1.5 in the studies of Norris et al. (1985) and Bond (1980). This all-sky kinematically unbiased (all stars were originally identified in objective prism surveys) sample of 175 metal-poor stars yields $\Theta_O = 205 \pm 23$ km s^{-1}.

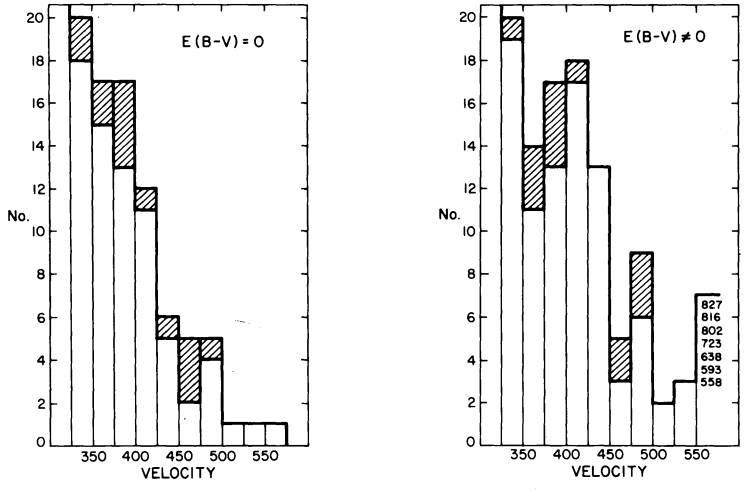
Second, we have used our own, kinematically biased, database. If we use only stars with absolute U or W velocities greater than Θ_O, we will have a kinematically-selected spheroidal population. The 205 such stars in our survey yield $\Theta_O = 231 \pm 8$ km s^{-1}.

The mean of the various determinations of Θ_O for stellar halo population is $\Theta_O = 227 \pm 7$ km s^{-1} (with our results superceding those of Norris et al. 1985). It appears that some of the globular clusters may belong to a slightly different population, that the local metal-poor halo population has no obvious net rotation, and that Θ_O lies between 220 and 230 km s^{-1}.

4. RESULTS

4.1 A Lower Limit to V_{ESC}

In Figure 2a we show a histogram of rest-frame velocities that exceed the Keplerian escape velocity, assuming no reddening (the shaded parts represent stars not contained in our new survey). From this plot we conclude that V_{ESC} must be at least 400 km s^{-1}, and may be as high as 550 km s^{-1}. When reddening corrections are included, the space velocities of several stars increase substantially, as can be seen by comparing Figures 2a and 2b. Unfortunately the stars with the largest space motions in Figure 2b are also the stars for which the reddening corrections are the largest and the most uncertain. If we restrict ourselves to stars with modest reddening, we get the sample plotted in Figure 3. For each star a line connects the velocities calculated with



Figs. 2a and 2b. Histograms of the numbers of stars versus Galactic rest-frame velocity. The left plot assumes no reddening, while the right plot includes reddening corrections. The stars in the shaded areas are from previous studies.

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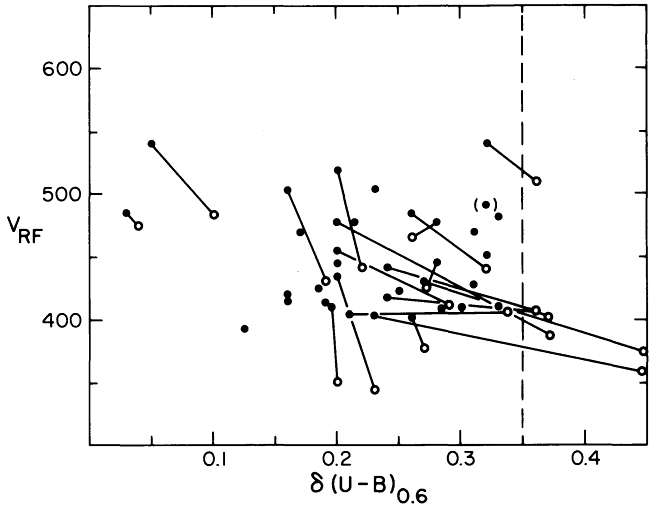

Fig. 3. V_{RF} versus metallicity for stars with modest reddening. For each star a line connects the velocities calculated with and without reddening corrections.

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and without reddening. The dashed line at δ = 0.35 mag represents the limit expected for extremely metal-deficient stars. Stars to the right of this limit may have a blue companion or may not have been sufficiently dereddened. Note that none of these stars have space velocities greater than 550 km s^{-1}, but a few exceed 500 km s^{-1}. We now consider whether any of these stars have had their velocities inflated by uncertainties in their photometric parallaxes and proper motions.

For the uncertainty in the photometric parallax we adopt ± 0.3 mag, and for the proper motion errors we use the difference between the Lowell and Luyten values. If we convolve the uncertainties due to reddening, photometric parallax, and proper motion, and eliminate stars with velocity uncertainties larger than ± 70 km s^{-1}, we are left with the 15 stars plotted in Figure 4. We conclude that the lower limit to V_{RF} is about 525 km s^{-1}.

4.2 An Upper Limit to V_{ESC}?

Two questions arise when we try to estimate the upper limit to V_{ESC}. First, have we determined V_{RF} reliably for all our extreme-velocity stars? Regrettably, the answer is yes for only 15 of the 55 stars likely to have V_{RF} > 400 km s^{-1}. More work must be done on the remaining 40 stars to see if stars with V_{RF} much larger than 500 km s^{-1} can be confirmed.

Second, how complete is our sample? Have we worked to faint enough limits to reach the highest-velocity stars? When we began the observational work, we chose a V magnitude limit of approximately 14.0 mag. At this limit we expected a significant fraction of the faintest

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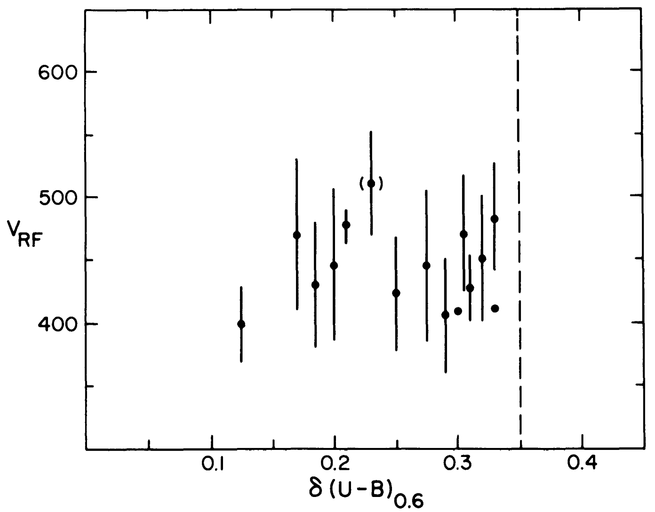

Fig. 4. V_{RF} versus metallicity for stars with modest reddening. The error bars include uncertainties in reddening, photometric parallax, and proper motion. Only the 15 stars with velocities uncertain by less than $\pm$ 70 km s^{-1} are shown.

stars would prove to be cool white dwarfs. When this expectation was not borne out, we extended the survey to the limit of the Lowell Catalog. In the deeper sample the fraction of white dwarfs does rise dramatically as the faint limit is approached; all five stars with V > 15.5 are white dwarfs. Thus we doubt that extending the survey to a fainter limit using the NLTT Catalog is likely to uncover very many extreme velocity stars.

Our survey does not extend much south of declination -10 deg, except for the South Galactic Pole work and results from previous studies mentioned above in section 2.2. Eggen's list of candidates for extreme-velocity stars consists mostly of southern stars, but only one has proven to actually have an extreme velocity. We conclude that our future work should focus on improving the velocity determinations for our 40 stars with uncertain but potentially extreme velocities.

4.3 Implications for the Total Mass of the Galaxy

If we adopt V_{ESC} = 525 km s^{-1}, equation (2) suggests that M_{TOTAL}/M_{LSR} = 5.0 for Θ = 230 km s^{-1} (or 6.4 for 220 km s^{-1}). The total Galactic mass is thus likely to be in excess of 5 x 10^{11} $M_\odot$. This mass is similar to the result derived from the radial velocities of distant Galactic satellite systems (Peterson 1985). Thus these results give direct dynamical evidence for a large total mass of the Galaxy.

5. FUTURE WORK

We plan to refine the space velocity determinations for our highest-velocity stars in four ways. First, we will obtain more radial velocities to eliminate the possible error introduced by a large-amplitude binary and to indicate which stars are spectroscopic binaries and therefore may have their photometry contaminated by a companion. Second, we will obtain JHK (and possibly uvby) photometric data to confirm the metallicities (via Δm_1^* - Carney 1983) and especially the photometric parallaxes. Third, we hope to determine metallicities by comparing our observed spectra with theoretical spectra recently calculated covering the wavelength range 5150 - 5250 A for a grid of model atmospheres with T_{eff} = 4750, 5000 ..., 6500 K, [M/H] = 0.0, -0.5, ..., -3.0, and gravities appropriate for old main sequence stars. This effort should provide us with better metallicities, especially for the extremely metal-deficient stars, where the photometric metallicities have so little leverage. Finally, we will obtain moderate-resolution spectrograms at high signal-to-noise to measure the strengths of the narrower diffuse interstellar features at 5780, 5797, and 6195 A. Since these features correlate well with E(B-V) (Herbig 1975), we should be able to reduce significantly the uncertainties due to reddening.

We have identified many stars whose origins lie in the outermost Galactic halo, yet are momentarily near enough and bright enough for detailed study. Just as comets are used to study the primordial record of the outermost parts of the Solar System, so we plan to use our new high-velocity stars to probe the chemical history of the Galaxy's outer halo.

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DISCUSSION

MATHIEU: (1) What galactic mass model did you use for your total mass determination? How does the galactic mass implied by your high-velocity stars compare to that determined from the Blitz rotation curve? (2) To what extent can your results be affected by undetected photometric binaries?

CARNEY: (1) Our model is very simple. We assume a flat rotation curve beyond the solar circle to some limiting radius, R_{lim}, in which case M_{tot}/M_{LSR} is equal to R_{lim}/R_{LSR}. Thus if V_0 = 220 km s^{-1} and V_{esc} = 500 km s^{-1}, R_{lim} ~ 5 R_{LSR} or ~ 40 kpc. This extends further than Blitz's rotation curve, which is also essentially flat, and so implies even more mass. (2) Regarding binaries, our spectra rule out single- and double-lined binaries with periods shorter than a few years. Also, ubvy and JHK photometry can rule out pairs whose components differ by one magnitude or more in M_V. We cannot yet rule out equal components with moderately wide separations, but with Hal McAlister and others we've begun speckle interferometry observations of the brighter stars. In any event, should one star later prove to be two, the correction would increase the distance, hence the tangential velocity, hence the inferred escape velocity.

OSTRIKER: While your lower limits have got to be right, because you see the stars, I wonder about the upper limits. First, a statistical point. For example, suppose you wanted to determine the tallest possible person by measuring the height of everyone in this room. You'd probably not get it right. But you would get a better estimate by measuring everyone in Princeton. And your estimate would keep going up as the sample size increases. In your present sample you may just run out of stars. There is also a physical point. Imagine that the dark halo extends half way to M31, i.e., has a radius of 250 kpc, but suppose that the Galaxy has a hard edge with no stars beyond 40 kpc. Then all of the stars you see will have fallen at most from 40 kpc to us. You would only be measuring that much difference in the potential, which you would think gives the escape velocity. So there is always going to be a question about the distribution of stars you can sample compared with the distribution of matter.

CARNEY: I agree, although some stars may come from further out than 40 kpc. Even if the Galaxy has a hard edge, it has companions which have been stripped, and some of their stars have fallen from distances greater than 40 kpc.

OSTRIKER: Statistically you would expect very few of them to be picked up in your survey.

CARNEY: Very few, at least, of the stars coming from the systems we now see.

TREMAINE: I'd like to emphasize the point you're making. It seems to me that since you've selected the stars so heavily, it's possible that they include a population of stars wandering through the Local Group that could even have been stripped from M31. When I do the estimates very roughly, I find that there's a reasonable chance that a sample of your size might contain a few such stars. So, if I might make the opposite argument to Jerry, it's conceivable that these stars are not telling us much about the escape speed from the Galaxy but are telling us something about the kinematics of the Local Group.

CARNEY: That's perhaps why some of the metal-rich stars with high velocities are interesting.

LYNDEN-BELL: If Scott is correct, there should be a velocity bias, or anisotropy, of ~100 km s^{-1} toward M31.

AARONSON: What percentage of your distant halo giants are turning out to be binaries?

CARNEY: Of the halo dwarfs and giants in our programs with three or more radial velocities obtained over one- to three-year baselines, 15% are velocity variables. The true halo binary fraction is, of course, somewhat higher.

FABER: Can you redo the analysis using only the radial velocities?

CARNEY: Yes, and some of the stars, those with small error bars, are dominated by the radial velocity signature. For the star with V = -585 km s^{-1}, in particular, you can use the radial velocity alone to get a rest-frame velocity of ~410 km s^{-1}. There are also some stars which are leading the LSR - pulling away from it at substantial velocities. The halo red giants themselves don't unfortunately give particularly interesting numbers, but there are a few stars which suggest values of ~400 km s^{-1}.

WHITMORE: You commented that the Mg lines fell outside your wavelength coverage for the high velocity stars. At what velocity does this occur? Could it cause a selection bias, since it may be easier to measure the velocity when the Mg line is present than when it is outside your wavelength range?

CARNEY: The cutoff is at about 500 km s^{-1}. The correlation technique used to measure the velocities can still measure the velocity fairly well even when the Mg lines are not present.

RICHSTONE: In principle, your sample also gives you information on the velocity ellipsoid for the stars in the halo - for example, you know that for stars within 30 kpc, it's not very tangential.

CARNEY: We have chosen not to estimate the velocity ellipsoid for the proper-motion-selected sample just because the kinematic bias is so extreme. We have computed it for the halo red giants and find the normal proportions of 2:1:1 between the radial, tangential and axial velocity dispersions.