The Dynamics, Structure & History of Galaxies
ASP Conference Series, Vol. nnn, 2002
G. S. Da Costa & E. M. Sadler, eds

Star Streams in the Milky Way Halo

Heather Morrison

Dept of Astronomy, Case Western Reserve University
10900 Euclid Ave, Cleveland OH 44118 USA

Mario Mateo

Department of Astronomy, University of Michigan, 821 Dennison Bldg., Ann Arbor, MI 48109–1090
electronic mail: mateo@astro.lsa.umich.edu

Edward W. Olszewski

Steward Observatory, University of Arizona, Tucson, AZ 85721
electronic mail: edo@as.arizona.edu

R.C. Dohm-Palmer

Department of Astronomy, University of Michigan, 821 Dennison Bldg., Ann Arbor, MI 48109–1090
electronic mail: rdpalmer@astro.lsa.umich.edu

Paul Harding

Steward Observatory, University of Arizona, Tucson, Arizona 85726
electronic mail: harding@billabong.astr.cwru.edu

Amina Helmi

Max Planck Institut fur Astrophysic, Garching bei Munchen, Germany
electronic mail: ahelmi@mpi-garching.mpg.de

John Norris

Research School of Astronomy and Astrophysics, ANU, Private Bag, Weston Creek PO, 2611 Canberra, ACT, Australia
electronic mail: jen@mso.anu.edu.au

Kenneth C. Freeman

Research School of Astronomy and Astrophysics, ANU, Private Bag, Weston Creek PO, 2611 Canberra, ACT, Australia
electronic mail: kcf@mso.anu.edu.au

Stephen A. Shectman

Carnegie Observatories, 813 Santa Barbara St, Pasadena, CA, 91101
electronic mail: shec@ociw.edu

Abstract.

The last 10-20 years has seen a profound shift in views of how the Galaxy's halo formed. The idea of a monolithic early collapse of a single system (Eggen, Lynden-Bell and Sandage 1962) has been challenged by observations at high redshift and by cosmological models of structure formation. These findings imply that we should see clear evidence of hierarchical formation processes in nearby galaxies. Recent studies of our Galaxy, made possible by large-scale CCD surveys such as the Sloan Digital Sky Survey (SDSS), have begun to reveal tantalizing evidence of substructure in the outer halo. We review evidence for tidal streams associated with known Milky Way satellites and for star streams whose progenitors are still unknown. This includes results from the SDSS and our own ongoing pencil-beam halo survey, the Spaghetti survey.

1. Introduction

A revolution is underway in our understanding of how galaxies form: The idea of a monolithic collapse of a single system at earliest times (Eggen et al. 1962) has been challenged by observations at high redshift and by increasingly sophisticated models of the evolution of structures within the basic framework of the Hot Big Bang model (for example, Pearce et al. 1999, Steinmetz & Navarro 1999). These findings imply that we should see clear evidence of hierarchical formation processes within nearby galaxies. Indeed, some of the earliest work that suggested complex and possibly hierarchical evolutionary histories for galaxies such as ours came from studies of the stellar populations of the outer halo of the Milky Way (Searle and Zinn 1978). Studies of nearby and high-redshift systems represent complementary approaches.

We can learn much about accretion processes in galaxy formation using the Milky Way because we can view our halo in 3 dimensions. By adding the kinematics of halo stars to their 3-D positions, moving groups are given enhanced contrast (see, for example, Harding et al. 2001). This sort of study is impossible for any other spiral galaxy.

Recent studies of our Galaxy have begun to reveal tantalizing evidence of possible substructure in the halo, both locally (Majewski 1992, Côté et al. 1993, Arnold and Gilmore 1992, Helmi et al. 1999) and at larger distances (Ivezić et al. 2000, Yanny et al. 2000). And of course, the Sgr dwarf galaxy (Ibata et al. 1995) is injecting globulars and field stars that formed in a completely separate entity from the Milky Way into its halo. The question has now shifted from 'Did accretion play any role in the formation of the Galaxy?' to 'How much of the Galaxy formed from accretion of hierarchical fragments?' We will show below that the data that is needed to answer the second question definitively also has the potential to teach us about the dark matter halo of the Galaxy and may directly constrain cosmological formation models such as that of Klypin et al. (1999), Moore et al. (1999).

2. The "Spaghetti" Survey

Several years ago we began a search designed to find halo streams if they are present. Since then, the Sloan Digital Sky Survey (SDSS) team has found one stream in their first few hundred degrees of equatorial test data (Ivezić et al. 2000, Yanny et al. 2000). Our group has found evidence that has strengthened the case that this substructure is associated with the Sgr dwarf using velocities of halo giants (Dohm-Palmer et al.2001). Our survey is unique in using a set of halo tracers (giants) that can be observed spectroscopically out to distances of hundreds of kpc where it is likely that only dwarf galaxies are found.

Our photometric survey consists of several hundred pencil beams at high Galactic latitude, which will comprise 100 square degrees of data in the Washington system. Our goal is to use this survey, the spectroscopic followup, and our extensive modelling, to quantify the amount of halo substructure associated with completely destroyed satellites, with partially destroyed satellites like the Sgr dwarf, and with intact objects such as ω Cen. More details of the survey are available in Morrison et al. (2000), Dohm-Palmer et al.(2000), Morrison et al. (2001) and at http://www.astro.lsa.umich.edu/users/rdpalmer/spag/. In this paper we focus on the part of the survey which identifies distant halo giants.

Local studies of halo stars passing through the solar neighborhood are limited in numbers of stars, do not well sample all regions of the halo, and often have biased kinematics. Chiba and Yoshii(1998) have shown that the 250 red giants and RR Lyrae stars with space motions determined from Hipparcos occupy a region extending to at most 35 kpc from the Galactic center. Carney et al. (1996) derive the apogalacticon distances of approximately 1200 local stars. There are only 23 stars in this sample with calculated apogalacticon distances larger than 30 kpc. These particular stars, by definition, are on extremely elongated orbits. There are vast parts of the Milky Way, and vast parts of phase space, therefore left unsampled. Figure 1 illustrates this clearly: halo globular clusters are plotted with open symbols, and it can be seen that they extend out to almost 100 kpc from the Galactic center. Known field stars (taken from the compilation of Beers & Sommer-Larsen 1995) are shown with closed circles. Most halo field stars known are within a few kpc of the Sun.

Figure 2 shows the spectrum of one of the most distant giants we have identified so far, star l304.49b+60.51, which lies at a distance of $\sim$80 kpc from the Sun. We expect to identify several hundred giants from the extreme outer halo when our 100 square degree survey is complete: an order of magnitude more than are currently known.

3. Searching for Substructure in the Outer Halo

Halo red giants are useful probes because of their high luminosity, which makes spectroscopic followup much easier. However, they are rare: we average $\sim$1 giant in each 0.25 square degree field. This means that we cannot use many of the techniques which were developed to search for substructure in the larger local samples. These techniques are often one- and two-dimensional variations on the use of velocity histograms, whether to search for a spike (Côté et al. 1993),

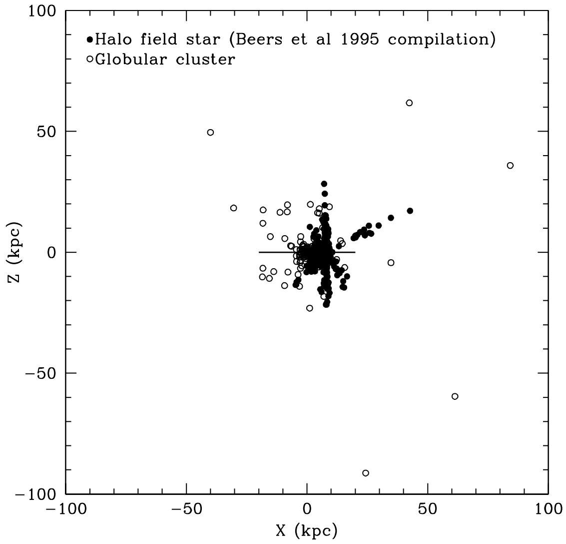

Figure 1. Halo field stars known in 1995, from the compilation of Beers & Sommer-Larsen (1995), plotted with closed circles. Comparison with the distribution of globular clusters (open circles) shows that even though halo field stars are likely to stretch out to ~100 kpc from the Sun, very few are known in the outer halo.

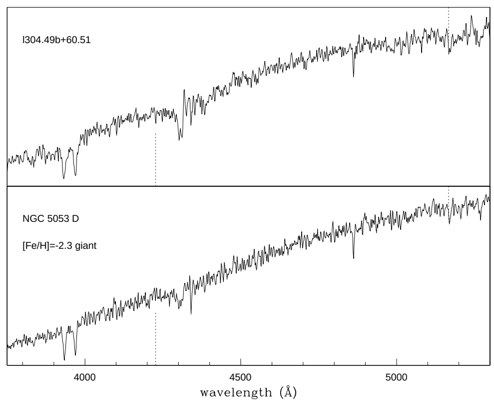

Figure 2. Spectrum of one of the most distant halo giants we have identified, star l304.49b+60.51, which has a metallicity of [Fe/H]$\simeq$−1.9 and a distance of ~80 kpc from the Sun. Shown for comparison is the spectrum of a giant of similar color in the most metal-poor globular cluster known, NGC 5053 D. The features that we use for luminosity discrimination, CaI 4227 and the Mgb/MgH feature, are marked.

unusual outliers (Majewski 1992) or simply a non-gaussian velocity distribution (Harding et al. 2001).

We have used the extensive simulations of Harding et al. (2001), re-normalized so that one particle corresponds to one halo giant, to help us identify and test techniques to search for substructure. Our method uses the fact that that there are strong correlations between position and velocity along a disrupting stream, illustrated in Figure 3. Our sparse sampling reduces the numbers of stars detected in a given stream, but preserves the position/velocity correlations, as can be seen in Figure 3.

Since we can measure the distances to our giants with reasonable accuracy, we are able to derive all three spatial coordinates, but because they are too distant for proper motions until space missions such as GAIA and SIM are operating, we only have one of the three velocity coordinates, the line-of-sight radial velocity V_{los}. We define a scaled metric in these four dimensions to measure the correlations between distance and velocity: two stars with similar distances and velocities will have a very small 4-D "distance" apart.

For two stars with galactic latitude, galactic longitude, distance and velocity l_1, b_1, d_1, V_1 and l_2, b_2, d_2, V_2, we write the metric as:

$$D_{lbdV} = \Big(w_1(l_1 - l_2)^2 + w_2(b_1 - b_2)^2 + w_3(d_1 - d_2)^2 + w_4(V_1 - V_2)^2\Big)^{1/2}$$

We choose the scalings w_i for the l, b, distance and velocity terms to account for the different measurement accuracy of each quantity, and for the fact that streams can spread spatially but have a tight relation between position and velocity at a given location. We know l and b very accurately, velocity to $\sim$10% (20 km/s) and distance to $\sim$25%, so two values that differ by less than their errors will be given less weight than values that differ significantly.

We use two different simulated datasets to test this technique, with sample sizes equal to our expected number of giants when we have completed our survey. The first contains 500 points from an accreted halo simulation constructed with 23 disrupting tidal streams from the library of Harding et al. (2001). These points were chosen from a dataset containing 320,000 points in 23 streams in a way that simulates our real observations. We used our real field centers for the 50 square degrees where observations have been taken, and planned field centers plus reflections about the galactic plane to make 400 pencil-beam field centers at high galactic latitude. If the stream particle was in the 0.25 square degrees surrounding a field center, we applied observational errors of 20 km/s for velocity and 25% for distance. The second dataset contained points from a smooth halo constructed with an isotropic velocity ellipsoid, as described in Harding et al. (2001), chosen to simulate our real observations in the same way.

We calculate the value of the scaled 4-d metric described above for every pair of points in the smooth and accreted halo simulations. As expected, the accreted halo shows significantly more points with small values of the metric, as can be seen in Figure 4. We are working with Jiayang Sun (CWRU statistics) to develop sensitive statistical tests for this accretion signature.

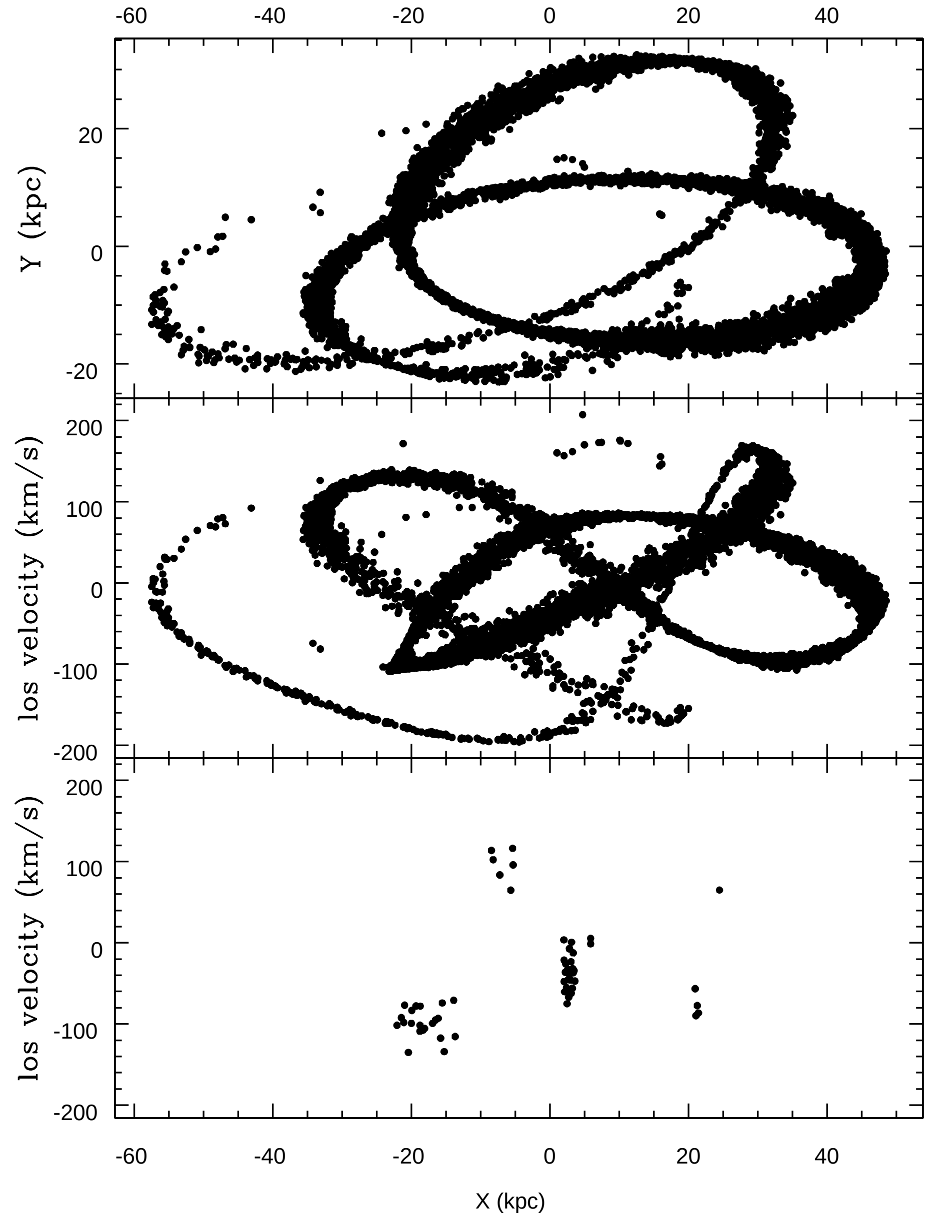

Figure 3. Disruption of a stream in position and velocity space. The top panel plots the X and Y galactic coordinates of points along several wraps of the stream. The middle panel shows the line-of-sight velocity plotted against X, illustrating the velocity gradients along the stream. The bottom panel shows the particles that would be observed in a 100 square degree survey such as ours, with realistic errors added in both distance and velocity. Although the picture is less clean, correlations between position and velocity still persist.

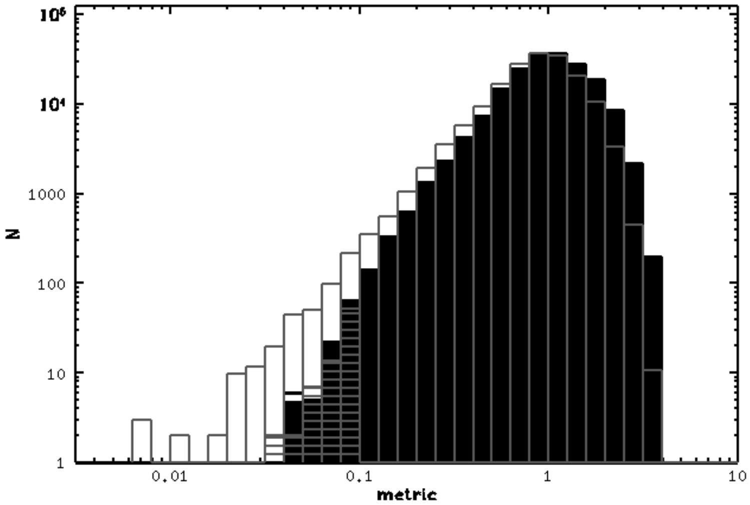

Figure 4. Comparison of 4-d metric values for a smooth halo (filled histogram) and for an accreted halo (open histogram). (Cross-hatched histogram shows particles matched with particles from another stream). It can be seen that the accreted halo has significantly more points with small 4-d distances, as expected.

4. First Results

Here we show some preliminary results for our sample of 58 halo giants with spectroscopic confirmation. The distances are calculated using the photometric metallicities only at this point, although we will soon have spectroscopic metallicities available, which will lead to more accurate distance measures. Figure 5 shows the histogram of metric values for this sample (calculated as described above) and the histogram of metric values for a smooth halo sample with the same size as our real halo giant sample, chosen from the simulated smooth halo described above. While the sample size is small, we are already seeing some of the signatures of an accreted halo.

Some of the smallest values of the 4-d metric in our giant sample come from a group of stars which are located in the same region of the sky as the SDSS overdensity (Ivezić et al. 2000, Yanny et al. 2000). This gives us the opportunity to test suggestions that this stream is associated with the Sgr dwarf by comparing the velocities of giant stars at similar distances to the SDSS BHB and RR Lyrae stars to the predictions of models of the disruption of Sgr. We have chosen to use the models of Helmi & White (2001), which, unlike earlier models of its disruption, can explain the fact that the galaxy was not completely disrupted on its first few passages without resort to unusual scenarios such as a very stiff and extended dark matter halo (Ibata & Lewis 1998) or a convenient recent collision with the Large Magellanic Cloud (Zhao 1998).

Figure 6 shows the predictions of the purely stellar model of Helmi & White (2001) for particles close to the minor axis of the Galaxy, compared with the actual positions and velocities of 21 confirmed metal-poor giants in this direction.

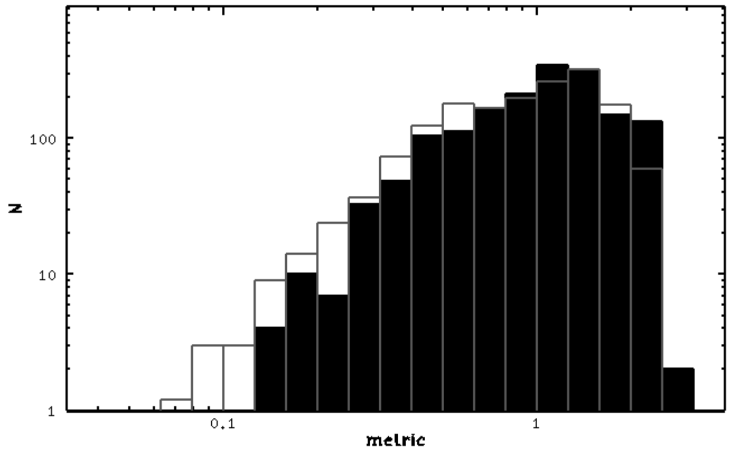

Figure 5. Comparison of 4-d metric values for a smooth halo (filled histogram) and for our preliminary halo giant sample (open histogram). The smooth halo was constructed to have the same sample size as our real sample. Although the sample size is small, we are already seeing indications of some clustering in the 4-d velocity/distance space.

It can be seen that all of the halo giants with distances greater than 30 kpc agree well with the predictions of the Sgr disruption model, confirming the suggestions of Ivezić et al. (2000) and Ibata et al. (2001a) that the SDSS stream is associated with Sgr. The right-hand panel of the plot shows, for comparison, one simulation taken from a smooth halo: it can be seen that the arrangement of distances and velocities that we observe is very unlikely to have occurred by chance. More details of these observations can be found in Dohm-Palmer et al. (2001).

The wrap at distances near 50 kpc is the one detected by the SDSS. It is interesting to note that we may also have detected stars from the wraps near 20 kpc (although the large velocity range predicted for these wraps makes this harder to test) and from the wrap at 80 kpc, which contains debris lost from the Sgr dwarf on one of its earliest passages. Such debris, if confirmed with a larger sample, will give us the opportunity to measure the M/L ratio of the progenitor to the Sgr dwarf, as the outer regions are the first to be lost to tidal disruption, and the presence of a massive dark matter halo in the outer regions will help retain more stars than in a galaxy with little or no dark matter (Helmi 2000).

Our sample of giants from 100 square degrees of imaging will be large enough to assign membership to different streams in the outer halo. This will allow their use in ways that were almost inconceivable ten years ago. For example, we can learn about the structure of the progenitor satellites: the red giants that are Sgr stream members have a mean metallicity of [Fe/H]=–1.5, significantly more metal-poor than the main body of Sgr (Layden and Sarajedini 2000). This suggests that the Sgr progenitor had a radial abundance gradient. As mentioned above, identification of stars lost on early passages of Sgr will allow us to constrain the mass-to-light ratio of its progenitor. The spread in longitude of the Sgr debris will constrain the flattening of the Galaxy's dark matter halo

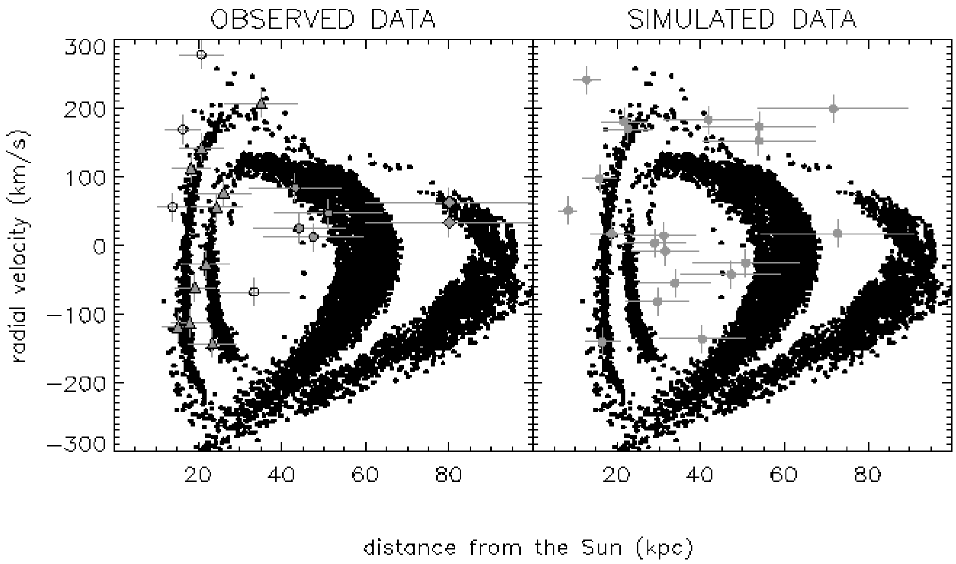

Figure 6. (Left panel) Comparison of the purely stellar model of the Sgr dwarf and its disruption from Helmi & White (2001) (closed black symbols) with the 21 halo giants we have found in this direction (grey symbols with error bars). The right panel shows the comparison of the model predictions with a typical simulation of a smooth halo. It is very unlikely that our data came from a smooth halo.

(Helmi 2000, Ibata et al. 2001b). We can even use the stream velocity dispersion to constrain the lumpiness of the Galaxy's dark halo, which will allow us to *directly* test the predictions of simulations of structure formation (eg Klypin et al. 1999, Moore et al. 1999).

Acknowledgments. The Galaxy's halo and its formation is a subject which is close to Ken's heart: he supervised two dissertations on the topic (Ratnatunga's and Morrison's). The technology available at the time (photographic plates) wasn't equal to the challenge of studying the outer halo, so it's a particular pleasure to be able to talk about a successful survey (and one that he is involved in) for his 60th year celebration. It looks like his early interest in accreted halos was spot on: the instrumentation just had to catch up!

HLM, EWO and MLM acknowledge support from the NSF on grants AST 96-19490, AST 00-98435, AST 96-19524, AST- 00-98518, AST 95-28367, AST 96-19632 and AST 00-98661.

References

Arnold, R. and Gilmore, G. 1992, MNRAS, 257, 225

Beers, T. C. & Sommer-Larsen, J. 1995, VizieR On-line Data Catalog: J/ApJS/96/175. Originally published in: ApJS, 96, 175

Carney, B. W., Laird, J. B., Latham, D. W. and Aguilar, L. A. 1996, AJ, 112, 668

Chiba, M. and Yoshii, Y. 1998, AJ, 115, 168

Côté, P., Welch, D.L., Fischer, P. and Irwin, M.J. 1993, ApJ, 406, L59

Dohm-Palmer, R. C., Mateo, M., Olszewski, E., Morrison, H., Harding, P., Freeman, K. C., & Norris, J. 2000, AJ, 120, 2496

Dohm-Palmer, R. C. et al. 2001, ApJ, 555, L37

Eggen, O. J., Lynden-Bell, D., & Sandage, A. R. 1962, ApJ, 136, 748

Harding, P., Morrison, H. L., Olszewski, E. W., Arabadjis, J., Mateo, M., Dohm-Palmer, R. C., Freeman, K. C., & Norris, J. E. 2001, AJ, 122, 1397

Helmi, A. 2000, doctoral dissertation, Leiden University

Helmi, A., White, S. D. M., de Zeeuw, P. T. and Zhao, H. 1999, Nature, 402, 53

Helmi, A. & White, S. D. M. 2001, MNRAS, 323, 529

Ibata, R. A., Gilmore, G. and Irwin, M. J. 1995, MNRAS, 277, 781

Ibata, R. A. & Lewis, G. F. 1998, ApJ, 500, 575

Ibata, R., Irwin, M., Lewis, G. F., & Stolte, A. 2001a, ApJ, 547, L133

Ibata, R., Lewis, G. F., Irwin, M., Totten, E., & Quinn, T. 2001b, ApJ, 551, 294

Ivezić, Željko et al. 2000, AJ, 120, 963

Klypin, A., Kravtsov, A. V., Valenzuela, O. and Prada, F. 1999, ApJ, 522, 82

Layden, A. C. & Sarajedini, A. 2000, AJ, 119, 1760

Majewski, S. R. 1992, ApJS, 78, 87

Moore, B., Ghigna, S., Governato, F., Lake, G., Quinn, T., Stadel, J. and Tozzi, P. 1999, ApJ, 524, L19

Morrison, H. L., Mateo, M., Olszewski, E. W., Harding, P., Dohm-Palmer, R. C., Freeman, K. C., Norris, J. E., & Morita, M. 2000, AJ, 119, 2254

Morrison, H. L., Olszewski, E. W., Mateo, M., Norris, J. E., Harding, P., Dohm-Palmer, R. C., & Freeman, K. C. 2001, AJ, 121, 283

Pearce F.R., Jenkins A., Frenk C.S., Colberg J.M., White S.D.M., Thomas P.A., Couchman H.M.P., Peacock J.A., Efstathiou G. 1999, ApJ, 521, 99

Searle, L. & Zinn, R. 1978, ApJ, 225, 357

Steinmetz M. & Navarro J.F. 1999, ApJ, 513, 555

Yanny, B., Newberg, H. et al. 2000, ApJ, 540, 825

Zhao, H. 1998, ApJ, 500, L149