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# MAPPING THE GALACTIC HALO. V. SAGITTARIUS DWARF SPHEROIDAL TIDAL DEBRIS 60° FROM THE MAIN BODY

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## ABSTRACT

As part of the Spaghetti Project Survey, we have detected a concentration of giant stars well above expectations for a smooth halo model. The position ($l \sim 350°$, $b \sim 50°$) and distance (∼50 kpc) of this concentration match those of the northern overdensity detected by the Sloan Digital Sky Survey. We find additional evidence for structure at ∼80 kpc in the same direction. We present radial velocities for many of these stars, including the first published results from the 6.5 m Magellan telescope. The radial velocities for stars in these structures are in excellent agreement with models of the dynamical evolution of the Sagittarius dwarf tidal debris, whose center is 60° away. The metallicity of stars in these streams is lower than that of the main body of the Sgr dwarf, which may indicate a radial metallicity gradient prior to disruption.

*Subject headings:* Galaxy: evolution — Galaxy: formation — Galaxy: halo — Galaxy: stellar content

## 1. INTRODUCTION

Decisive evidence is mounting in support of a Galactic halo predominately formed through mergers and accretion. High-redshift observations and modern simulations of structure evolution within the framework of cold dark matter (Pearce et al. 1999; Steinmetz & Navarro 1999) suggest that large galaxies formed hierarchically through the progressive merger of smaller pregalactic structures. Observational evidence of this process can be identified in fossil remains of past accretions or mergers in the Milky Way.

The remains of an accreted galaxy can be identified in the Galactic halo as coherent substructure in space (Johnston, Hernquist, & Bolte 1996), velocity, or both (Helmi & White 1999; Harding et al. 2001). There are several examples of such coherent groups (Majewski, Munn, & Hawley 1994; Côté et al. 1993; Arnold & Gilmore 1992; Helmi et al. 1999). One of the most dramatic is the Sagittarius dwarf (Ibata, Gilmore, & Irwin 1994) and its extension to at least 17 kpc to the southeast (Mateo, Olszewski, & Morrison 1998), which demonstrates that galaxy accretion is a process that continues even today.

More recently, Yanny et al. (2000) and Ivezic et al. (2000) found an overdensity of blue horizontal-branch (HB) stars and RR Lyrae–type stars, respectively, in the Sloan Digital Sky Survey (SDSS) commissioning data. The overdensity covers 35° on the sky and is located near $\alpha = 14^{\rm h}.7$, $\delta = 0°$ ($l = 351°$, $b = 52°$), 50 kpc from the Sun, and is 60° from the center of the Sgr dwarf. This structure has also been detected with carbon stars (Ibata et al. 2001) and a color-magnitude diagram analysis (Martínez-Delgado et al. 2001). Very recently, this feature was also found by Vivas et al. (2001) as part of the QUEST RR Lyrae–type variable star survey. They also found an overdensity of RR Lyrae stars at closer distances, partially associated with the globular cluster Pal 5 and partially without identification.

A comparison with models of the disruption of the Sgr galaxy (Johnston et al. 1999; Helmi & White 2001; Ibata et al. 2001) strongly suggests that this structure is tidally stripped material from the Sgr dwarf (Ivezic et al. 2000). However, none of the techniques to date have been able to confirm this with both distance and velocity data. As part of the Spaghetti Project Survey (SPS; Morrison et al. 2000), we have serendipitously identified giants associated with the SDSS overdensity and have measured their radial velocities and distances. The excellent agreement with model predictions leads us to conclude that this structure is, indeed, tidal debris from the Sgr dwarf. Furthermore, we have identified additional structures at different distances that may be multiple wraps of the Sgr dwarf tidal stream.

## 2. THE SPAGHETTI SURVEY

The SPS is a photometric and spectroscopic survey designed to identify structure in the Galactic halo (Morrison et al. 2000). For this study, we use the modified Washington photometric system (Canterna 1976; Geisler 1984) to identify candidate red giants. The $M-51$ color index is sensitive to surface gravity, while $C-M$ gives a photometric abundance. Candidate halo stars *must* be observed spectroscopically to confirm the photometric classification and metallicity and to obtain a radial velocity.

By chance, a number of survey fields with existing photometry and spectroscopy lie near the direction of the SDSS overdensity. We will focus on 16 of these fields that lie in the region defined by $300° < l < 360°$, $0° < l < 30°$, and $30° < b < 70°$ and were imaged in 1999 April (Dohm-Palmer et al. 2000). A complete

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TABLE 1
Confirmed and Potential Giants Associated with Sgr Tidal Debris

| Star | $V_0$ | $(M-T2)_0$ | [Fe/H][a] | $M_V$ | Distance (kpc) | Heliocentric Velocity (km s$^{-1}$) |
|---|---|---|---|---|---|---|
| 003.06+61.30 ...... | 19.21 | 1.174 | −1.8 | 0.830 | 47.5 | 12 |
| 011.85+51.95 ...... | 17.57 | 1.192 | −1.3 | 0.720 | 23.4 | −143 |
| 017.04+46.40 ...... | 16.81 | 1.130 | −1.7 | 1.097 | 13.9 | 56 |
| 017.35+46.50 ...... | 16.53 | 1.237 | −1.5 | 0.200 | 18.3 | 112 |
| 301.78+45.46 ...... | 16.68 | 1.130 | −1.8 | 1.059 | 13.3 | ... |
| 302.36+49.04 ...... | 17.38 | 1.255 | −3.6 | −0.007 | 30.0 | ... |
| 302.43+48.83 ...... | 19.86 | 1.136 | −1.5 | 1.141 | 55.5 | ... |
| 304.49+60.51 ...... | 18.90 | 1.363 | −1.8 | −0.922 | 80.0 | 63 |
| 304.69+60.52 ...... | 16.86 | 1.197 | −1.8 | 0.276 | 20.7 | 278 |
| 305.22+61.24 ...... | 17.24 | 1.187 | −1.8 | 0.307 | 24.4 | 56 |
| 305.32+60.58 ...... | 16.91 | 1.177 | −1.7 | 0.484 | 19.2 | −62 |
| 305.44+61.34 ...... | 16.38 | 1.178 | −1.1 | 0.938 | 12.3 | ... |
| 305.50+60.65 ...... | 17.52 | 1.370 | −1.0 | −0.204 | 35.1 | 207 |
| 322.12+39.91 ...... | 16.18 | 1.180 | −1.4 | 0.772 | 12.1 | 329 |
| 322.18+40.02 ...... | 19.51 | 1.120 | −2.2 | 0.889 | 53.1 | ... |
| 326.26+49.00 ...... | 17.79 | 1.236 | −1.6 | 0.176 | 33.4 | −68 |
| 332.71+46.84 ...... | 17.64 | 1.144 | −1.5 | 1.050 | 20.8 | 142 |
| 333.34+46.51 ...... | 19.10 | 1.111 | −1.6 | 1.331 | 35.7 | ... |
| 333.50+46.75 ...... | 18.27 | 1.138 | −1.3 | 1.179 | 26.1 | 76 |
| 338.85+68.27 ...... | 16.66 | 1.218 | −2.4 | −0.037 | 21.9 | −28 |
| 340.15+68.30 ...... | 19.49 | 1.169 | −1.5 | 0.823 | 54.1 | ... |
| 347.28+53.30 ...... | 19.06 | 1.163 | −1.7 | 0.882 | 43.2 | 84 |
| 347.42+53.31 ...... | 16.50 | 1.208 | −1.5 | 0.437 | 16.3 | 169 |
| 347.68+53.06 ...... | 17.02 | 1.121 | −1.8 | 1.107 | 15.2 | −119 |
| 354.95+66.01 ...... | 19.86 | 1.149 | −1.6 | 0.992 | 59.3 | ... |
| 355.89+51.10 ...... | 19.86 | 1.232 | −1.4 | 0.346 | 80.0 | 33 |
| 355.99+51.16 ...... | 16.90 | 1.187 | −1.5 | 0.626 | 18.0 | −113 |
| 356.15+50.95 ...... | 18.26 | 1.304 | −1.5 | −0.290 | 51.1 | 47 |
| 356.54+51.18 ...... | 19.10 | 1.221 | −1.0 | 0.724 | 47.3 | ... |
| 356.70+51.23 ...... | 17.16 | 1.446 | −1.6 | −1.072 | 44.2 | 25 |
| 356.81+51.06 ...... | 19.28 | 1.146 | −1.4 | 1.088 | 43.5 | ... |
| 356.88+51.09 ...... | 19.14 | 1.138 | −1.3 | 1.200 | 38.8 | ... |

[a] All metallicity determinations are photometric, except those for stars 017.35+46.50, 304.49+60.51, 332.71+46.84, and 356.15+50.95, which are preliminary spectroscopic measurements.

list of these fields, and the stellar photometry, is available through the NASA Astronomical Data Center database.[9]

We applied our giant selection criteria (Morrison et al. 2001) to the photometry from this subset of fields. In order to include some fainter, potentially more distant giants in our first spectroscopic observations with Magellan, we relaxed the $M-51$ error selection limit, which is the most crucial (Morrison et al. 2001), from 0.02 to 0.032 mag, matching the largest error among all previously confirmed giants in these fields. There are 32 giant candidates, of which 21 have been confirmed spectroscopically using the criteria of Morrison et al. (2001). These are listed in Table 1.

The photometric metallicity (Morrison et al. 2000), coupled with globular cluster giant branches (Da Costa & Armandroff 1990), transformed to $M-T2$ (Morrison et al. 2001), allows us to determine the absolute magnitude of each star. The metallicity determined in this way is subject to errors of order 0.3 dex, which leads to distance errors of about 25%.

The spectra for the six most distant giants are shown in Figure 1, along with two standards for comparison. Star 355.89+51.10 was observed on 2001 February 20–22 with the newly commissioned 6.5 m Magellan I telescope at the Las Campanas Observatory, with the Boller and Chivens spectrograph. Details of the spectral reduction process will be available in M. Mateo, P. Harding, M. Morrision, E. Olszewski, R. C. Dohm-Palmer, K. C. Freeman, & J. Norris (2001, in preparation). Both velocities and preliminary metallicities (Morrison et al. 2001) were determined from the spectra. Velocities are accurate to within 20 km s$^{-1}$. In most cases, the agreement between the spectroscopic and photometric metallicities is better than 0.2 dex. The photometric value is listed in Table 1, with the exceptions of 017.35+46.50, 304.49+60.51, 332.71+46.84, and 356.15+50.95, whose preliminary spectroscopic metallicities differed significantly from the photometric values.

[9] Available at http://adc.gsfc.nasa.gov.

## 3. MODEL COMPARISON

Figure 2 is a histogram of the heliocentric distance for all giant candidates. The shaded histogram is the subset of candidates that have been confirmed to be giants spectroscopically. The solid curve is the predicted number of giants based on a model from Morrison (1993) for a smooth $R^{-3.5}$ halo. The model is normalized using the local halo giant density (Morrison 1993) and has an axial ratio variation prescribed by Preston, Shectman, & Beers (1991). A model was made for each of the 16 selected fields, including a bright cutoff limit that varied from field to field and a constant faint cutoff at $V = 20$.

There is a concentration of candidates between 40 and 60 kpc, matching the distance of the SDSS overdensity. Of these, four stars have radial velocities. Based on our success rate for stars at this magnitude, we expect that approximately half the remaining candidates at this distance will be confirmed to be giants and that the other half will be revealed to be subdwarfs (Morrison et al. 2001). Taking this into account, there remain three to four stars in each of the three bins near 50 kpc, where we only expect one to two stars.

Even more striking is the correlation of radial velocities for stars in this structure. The velocities of the four stars with spectra are remarkably similar ($\sigma = 31.5$ km s$^{-1}$) compared

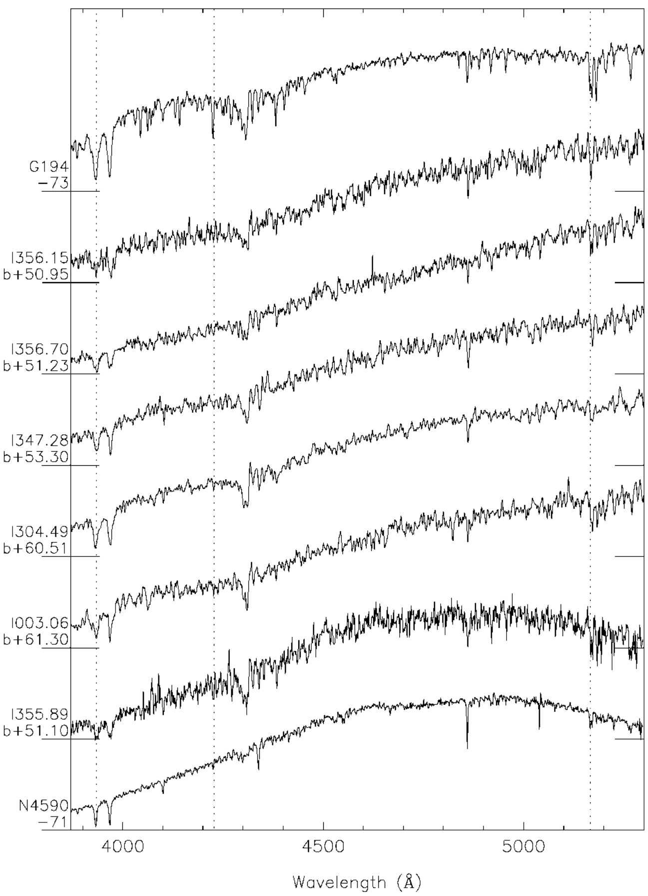


FIG. 1.—Spectra of the six stars beyond 40 kpc and two standard stars. G194−37 is a known subdwarf with [Fe/H] = −2.0, and N4590−71 is a globular cluster giant with [Fe/H] = −2.1. The tick marks indicate the zero flux level for each successive star. The dotted lines mark three spectral indicators used to distinguish dwarfs from giants: Ca II K λ3934, Ca I λ4227, and Mg *b* λ5167. Note that the subdwarf has a much stronger Ca I line than any of the distant giants.

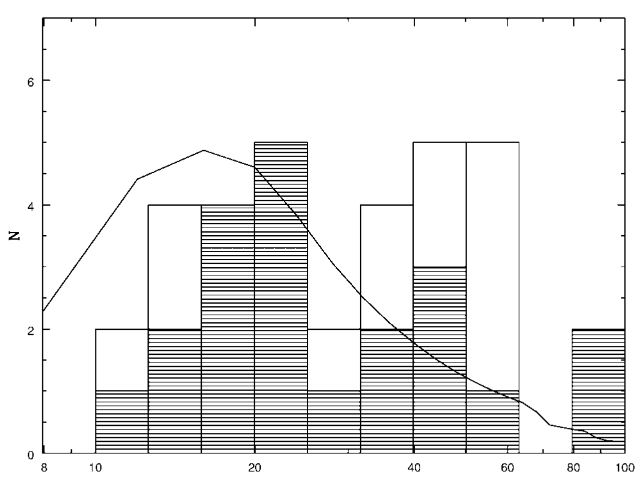


FIG. 2.—Histogram of the heliocentric distance for all giant candidates. The giant stars come from 16 selected fields with Galactic coordinates $300° < l < 360°$, $0° < l < 30°$, and $30° < b < 70°$. The shaded histogram shows all spectroscopically confirmed giants. To match the largest error of a confirmed giant, we have included all candidates with an $M-51$ error less than 0.032. Given this error limit, we expect that approximately half the unconfirmed stars near 50 kpc are actually metal-poor subdwarfs. The solid curve is a model prediction from a smooth $R^{-3.5}$ density profile, based on the selected fields observed. Note the overdensities at 50 and 80 kpc, and possibly near 20 kpc.

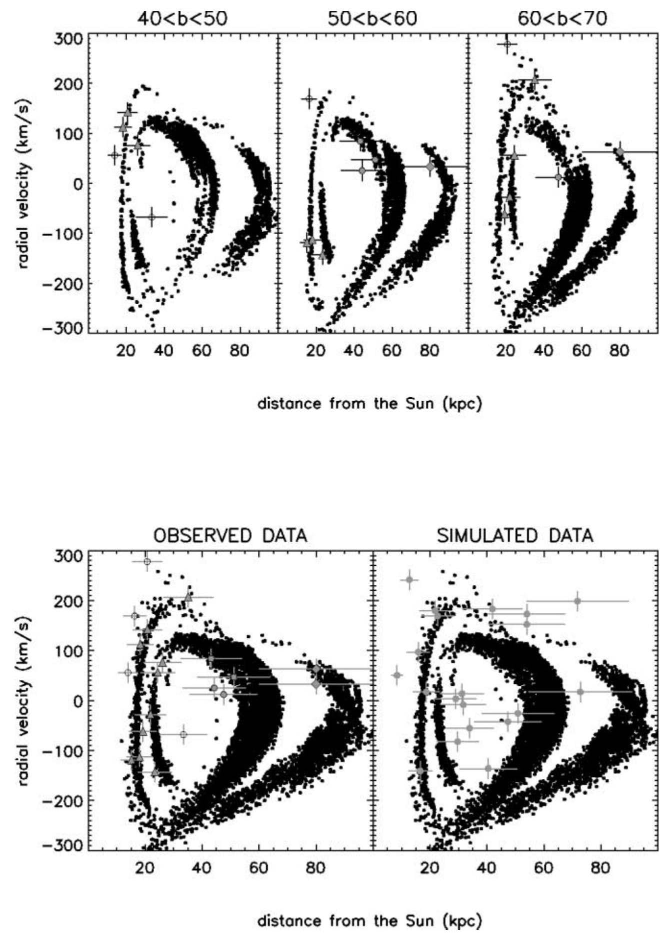


FIG. 3.—Distance vs. radial velocity for the Sgr dwarf stellar models of Helmi & White (2001). The model points come from the ranges $300° < l < 360°$ and $0° < l < 30°$. In the top panels, they have been divided into three latitude bins, while all latitudes are included in the bottom panels. Also plotted in the top panels are the giants with measured radial velocity. The gray diamonds mark the two most distant giants at 80 kpc, the filled circles mark the four giants near 50 kpc, the gray triangles mark stars matching the model near 20 kpc, and the open and gray circles mark stars that do not match the model within their error box. The bottom left plot shows the same data as the top panels, except not split into latitude bins. For comparison, we plot in the bottom right one of the 10,000 Monte Carlo simulations of 21 stars drawn from a smooth halo population.

with the velocity dispersion of all confirmed giants ($\sigma_{\rm obs}$ = 150.2 km s$^{-1}$). This association is certainly indicative of a coherent structure.

The models developed by Helmi & White (2001) predict that the Sgr dwarf corresponds to only the central region of a much larger, at least a few times $10^8\ M_\odot$, progenitor. These models predict that a large amount of mass would be expected in streams and that this mass can be either stellar or dark matter–dominated. In Figure 3, we plot the heliocentric distance and radial velocity for the particles in their stellar model that fall within our selected region of the sky. We have also plotted the locations of all candidate giants with measured radial velocities. The four stars near 50 kpc are shown with filled circles and match very well both the distance and the radial velocity found in the models.

In addition to the concentration of giant candidates near 50 kpc, there is one near 20 kpc and one near 80 kpc (Fig. 2). The radial velocities of most of the stars near 20 kpc (Fig. 3) match the predictions for the Sgr dwarf streams; however, the range of predicted velocities at this distance is so large that this cannot be considered strong support for these being associated with the Sgr dwarf tidal debris. It is interesting to note that if most of these 20 kpc stars are indeed Sgr debris, then the smooth halo density at this distance must be much lower than simple models predict. This would suggest that a large fraction of the halo may be composed of streamlike structures, even as close as $R \sim 20$ kpc.

In contrast to the ∼20 kpc concentration, the two stars at 80 kpc show a spatial density and a velocity correlation above that expected from a smooth halo. Their position and velocity match model predictions for an earlier "wrap" of the Sgr dwarf tidal stream.

We compared the distance and velocity distribution of the 21 candidates with that of a smooth halo model. The smooth halo has an $R^{-3.5}$ density profile and a radially anisotropic velocity ellipsoid with $\sigma = 135$ km s$^{-1}$. We performed 10,000 Monte Carlo simulations of 21 stars drawn from the smooth halo, including observational errors. The fraction of simulations that give the observed distribution of four stars near 50 kpc with a velocity dispersion of 32 km s$^{-1}$ *and* of two stars near 80 kpc with a velocity dispersion 21 km s$^{-1}$ was 11 in 10,000. We also performed this same exercise by drawing the samples from the model of the Sgr dwarf (Helmi & White 2001). Nearly 70% of these 10,000 samples result in the observed distribution. Thus, the likelihood that these stars belong to a smooth halo is negligible.

The present data cannot be used to make a full comparison with the spatial density of the model stream. In particular, the spatial sampling of our fields, at this point, is too sparse to determine the width or direction of the stream, and numerous selection effects must be addressed. We can only note that the confirmed members at 50 kpc are spread over 16° in longitude. If the two stars at 80 kpc are included, the spread is over 50° in longitude. Furthermore, a detailed density comparison, for example, to determine if the 20 kpc stars are part of a stream or part of a smooth halo, must await a larger area to be studied, preferentially located far away from the expected sky position of the Sgr streams (A. Helmi, H. L. Morrison, E. W. Olszewski, P. Harding, M. Mateo, R. C. Dohm-Palmer, K. C. Freeman, & J. E. Norris 2001, in preparation).

Finally, we note that the mean metallicity of the six stars that we claim to be part of the Sgr stream ([Fe/H] $\sim -1.5$) is about 0.5 dex lower than the mean for field stars in the main body of the Sgr galaxy (Layden & Sarajedini 2000; Mateo et al. 1998). Many dwarf spheroidal galaxies show radial gradients in their HB morphologies such that the outer HB stars are bluer (Caldwell et al. 1998; Hurley-Keller, Mateo, & Grebel 1999; Da Costa et al. 2000; Harbeck et al. 2001). Since the outermost stars are preferentially stripped during tidal disruption (Piatek & Pryor 1995; Oh, Lin, & Aarseth 1995), the streams could exhibit a different HB population than the more tightly bound core. This could explain why the SDSS overdensity consists of large numbers of blue HB stars, while such stars are mostly absent in the core of Sgr. This is also consistent with the lower metallicity of the stream stars if the HB morphology gradient reflects an underlying metallicity variation in Sgr.

The destruction of dwarf galaxies is probably a crucial element in building up the stellar halo of our Galaxy. With further observations, the age information that we can recover from the different wrappings, combined with the metal abundances of the stream stars, will give a detailed observational picture of the progressive destruction of this galaxy. Deriving the chemical enrichment and star formation as a function of time and position in the Galaxy, for example, will help us understand the effect of tides on the internal evolution of such apparently fragile systems. Mapping the streams of Sgr will also provide some strong constraints on the large-scale evolution of the shape and structure of the Galactic potential on gigayear timescales and on the amount of dark matter substructure.

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