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THE FIELD OF STREAMS: SAGITTARIUS AND ITS SIBLINGS

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ABSTRACT

We use Sloan Digital Sky Survey (SDSS) Data Release 5 (DR5) u, g, r, i, z photometry to study Milky Way halo substructure in the area around the North Galactic Cap. A simple color cut ($g - r < 0.4$) reveals the tidal stream of the Sagittarius dwarf spheroidal, as well as a number of other stellar structures in the field. Two branches (A and B) of the Sagittarius stream are clearly visible in an RGB-composite image created from 3 magnitude slices, and there is also evidence for a still more distant wrap behind the A branch. A comparison of these data with numerical models suggests that the shape of the Galactic dark halo is close to spherical.

Subject headings: galaxies: kinematics and dynamics — galaxies: structure — Local Group — Sagittarius dSph – Milky Way: halo

1. INTRODUCTION

Stellar streams in the Milky Way halo produced by the accretion of smaller galaxies are a standard prediction of hierarchical merging cosmogonies (e.g., Lynden-Bell & Lynden-Bell 1995, and references therein). The most spectacular example is the disrupting Sagittarius dwarf spheroidal (Sgr dSph), originally discovered by Ibata, Gilmore & Irwin (1995). It has a heliocentric distance of $\sim$ 25 kpc and is centered at Galactic coordinates of $\ell = 5.6°$ and $b = -14.0°$ (Ibata et al. 1997). It is dominated by an intermediate age population (between 6 and 9 Gyrs, Bellazzini et al. 2006), but there is evidence for a much older population (> 10 Gyrs) as well (Monaco et al. 2003). The metallicity [Fe/H] ranges from very metal-poor (as low as -2 based on the globular clusters) up to approximately solar, with probably a mean of ~ -0.5 (Monaco et al. 2005, and references therein). It was realised early on that there was some tidal debris in the neighbourhood of the Sgr dSph (Ibata et al. 1997; Majewski et al. 1999) and that the distribution of this material traced the Sgr dSph orbit. Subsequently, Yanny et al. (2000) used Sloan Digital Sky Survey (SDSS) first-year commissioning data to identify an over-density of blue A-type stars in two strips located at (ℓ, b, R) = (350°, 50°, 46 kpc) and (157°, −58°, 33 kpc), which were then matched with the Sgr stream (Ibata et al. 2001). Likewise, Ivezić et al. (2000) noticed that clumps of RR Lyrae stars in SDSS commissioning data lay along the Sgr stream's orbit.

The best panorama of the Sgr stream to date was obtained by Majewski et al. (2003) using M giants selected from the Two Micron All-Sky Survey (2MASS). They saw the trailing tidal tail very clearly in the Southern Galactic hemisphere, as well as part of the leading arm reaching towards the North Galactic Cap. Here, we use SDSS Data Release 5 (DR5) to provide a picture of the leading arm of the Sgr stream in the vicinity of the North Galactic Cap with remarkable clarity, together with a number of other notable stellar structures in the field.

2. THE DATA AND A SIMPLE COLOR CUT

SDSS (York et al. 2000) is an imaging and spectroscopic survey that has mapped $\sim$ 1/4 of the sky. Imaging data are produced simultaneously in five photometric bands, namely u, g, r, i, and z (Fukugita et al. 1996; Gunn et al. 1998; Hogg et al. 2001; Adelman-McCarthy et al. 2006; Gunn et al. 2006). The data are processed through pipelines to measure photometric and astrometric properties (Lupton, Gunn, & Szalay 1999; Stoughton et al. 2002; Smith et al. 2002; Pier et al. 2003; Ivezić et al. 2004) and to select targets for spectroscopic follow-up. For de-reddening, we use the maps of Schlegel, Finkbeiner, & Davis (1998). DR5 covers $\sim$ 8000 square degrees around the Galactic North Pole, together with 3 strips in the Galactic southern hemisphere. We use the catalogue of objects classified as stars with artifacts removed [11], together with magnitude limits $r < 22$ and $g < 23$. At low right ascension and declination, we are limited by the boundary of DR5. We choose to cut our sample at $\alpha = 230°$ and $\delta = 60°$. This gives us a total of $\approx 2 \times 10^7$ stars.

Figure 1 shows the density of stars satisfying the color cut $g - r < 0.4$ in SDSS DR5. As we show shortly, these are upper main sequence and turn-off stars belonging to the Sgr stream. This is a RGB-composite im-

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[11] See http://cas.sdss.org/astro/en/help/docs/realquery.asp#flags

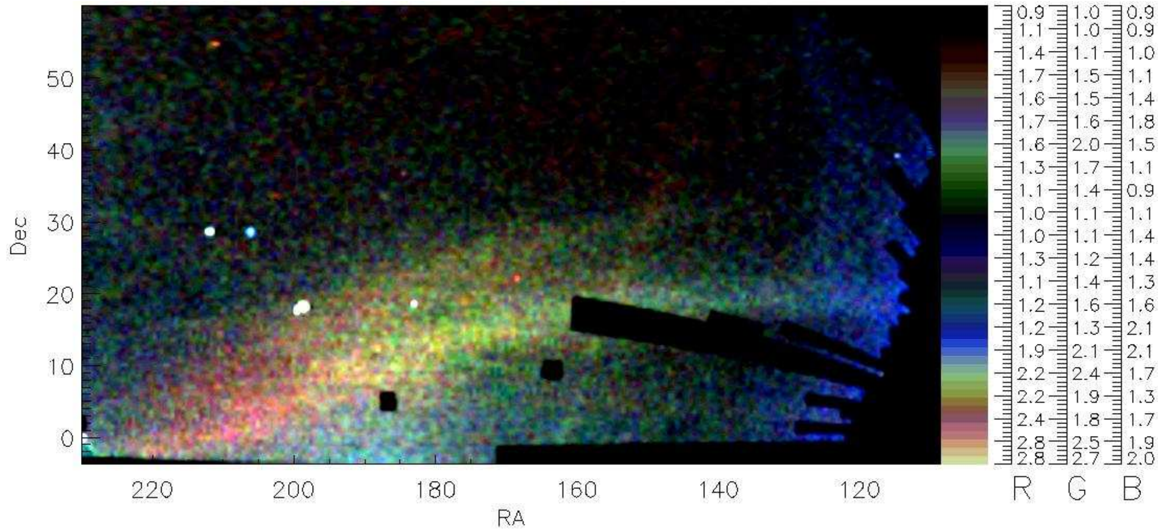

FIG. 1.— The spatial density of SDSS stars with $g - r < 0.4$ around the North Galactic Cap in equatorial coordinates, binned 0.5×0.5 arcdegrees. The color plot is an RGB composite with blue for the most nearby stars with $20.0 < r \leq 20.66$, green for stars with $20.66 < r \leq 21.33$ and red for the most distant stars with $21.33 < r \leq 22.0$. Note the bifurcation in the stream starting at $\alpha \approx 180°$. Further structure that is visible includes the Monoceros Ring at $\alpha \approx 120°$, and a new thin stream at $150° \lesssim \alpha \lesssim 160°$ and $0° \lesssim \delta \lesssim 30°$. The color bar shows a palette of 50 representative colors labeled according to the stellar density (in units of 100 stars per square degree) in each of red, green and blue components. The displayed density ranges are 102 to 330 (red), 107 to 304 (green) and 98 to 267 (blue).

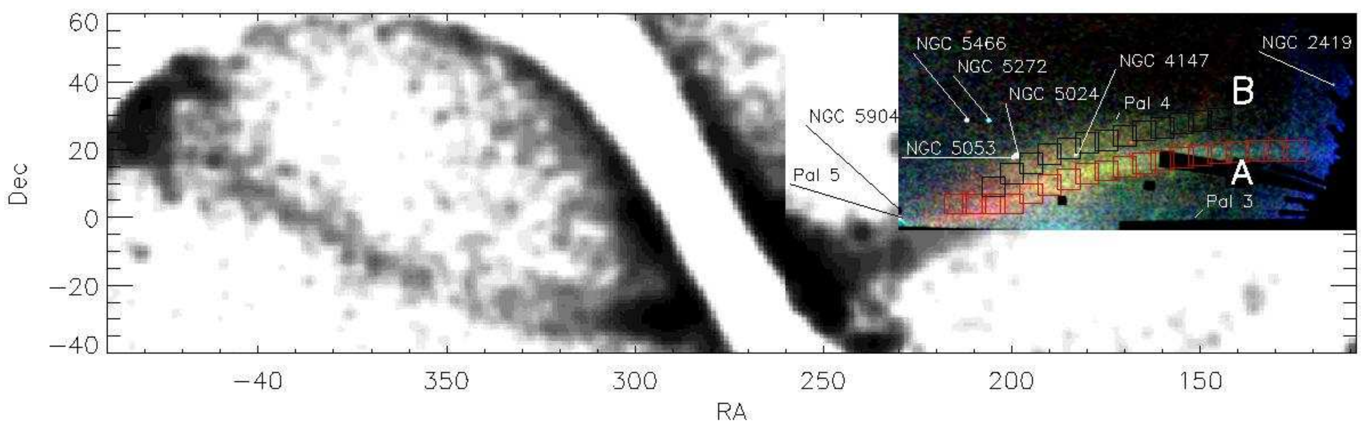

FIG. 2.— A panoramic view of the Sgr stream, obtained by combining the 2MASS M giants of Majewski et al. (2003) with the SDSS stars. Marked on the figure are branches A and B of the stream, together with some of the (possibly associated) globular clusters. Shown in red and black are the on-stream fields used in the analysis of Section 3 (see main text).

age assembled from three grayscale images colored red, green and blue corresponding to the density of the selected stars in the following three magnitude bins: red is $21.33 < r \leq 22.0$, green is $20.66 < r \leq 21.33$, and blue is $20.0 < r \leq 20.66$. For a given stellar population, these magnitude bins are distance bins, with red being the most distant and blue the nearest. There is a clear distance gradient along the stream, from the nearer parts at right ascensions $\alpha \approx 120°$ to the more distant parts at $\alpha \approx 210°$. There is also a bifurcation visible in the stream starting at about the North Galactic Pole; in what follows, we will refer to the lower declination branch as branch A, and the higher declination as branch B.

Majewski et al. (2003) traced the Northern stream of the Sgr for right ascensions α between 270° and 190°. For $\alpha < 190°$, Majewski et al. (2003) did not see a clear continuation of the stream. The combination of Majewski et al.'s (2003) M giants together with the SDSS stars in Figure 2 shows for the first time the entirety of the stream, including its continuation through the Galactic Cap and into the Galactic Plane. Figure 2 also shows the locations of a number of globular clusters, some of which are known to be associated with the Sgr stream. For example, Bellazzini et al. (2003) used 2MASS data to conclude that NGC 4147 was physically immersed in the stream.

Figure 1 displays such a remarkable wealth of Galactic substructure that it might appropriately be called the "Field of Streams". Among the most visible of these is the whitish-blue colored, and hence relatively nearby, stellar overdensity centered at $(\alpha \approx 185°, \delta \approx 0°)$, found by Jurić et al. (2005) and named the Virgo Overdensity; this is perhaps the same structure as the nearby 2MASS Northern Fluff (Majewski et al. 2003). Parts

TABLE 1

Locations of the on-stream fields along branch A (α, δ_A) and branch B (α, δ_B). The companion off-stream fields for branch A have the same right ascension but are offset in declination by $+20^\circ$ for $\alpha > 150^\circ$ and by -12° otherwise. For branch B, the off-stream fields are offset by $+13^\circ$ in declination.

Field No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
α	215°	210°	205°	200°	195°	190°	185°	180°	175°	170°	165°	160°	155°	150°	145°	140°	135°	130°	125°
δ_A	4°	4°	4°	4°	7°	9.5°	11.2°	13°	13.75°	15°	16	-	-	18.4°	19°	19.4°	19.5°	19.5°	19.5°
δ_B	-	-	9°	13°	16°	18.5°	20.2°	22°	22.75°	24°	25.5	26.3°	27.7°	28.4°	29°	-	-	-	-

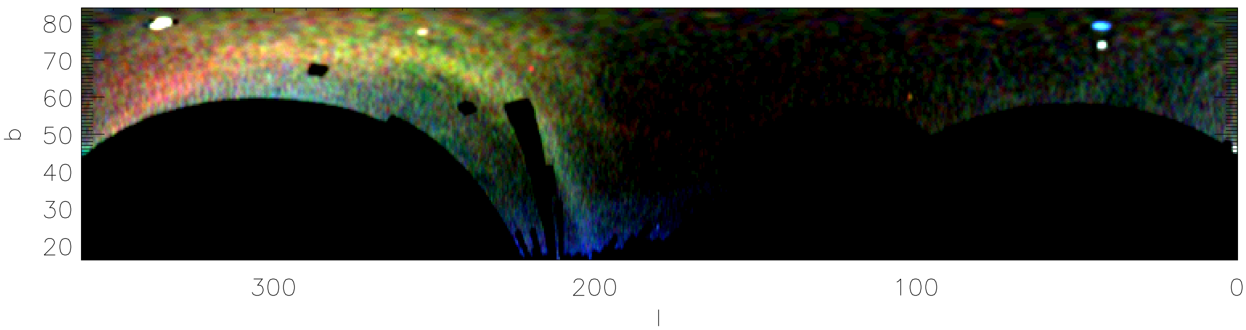

Fig. 3.— An RGB composite of the SDSS stars as in Figure 1, but now in Galactic coordinates (ℓ, b). Note in addition to the branches of the Sgr stream, a second orphan stream is clearly visible at latitudes of $b \approx 50^\circ$ and with longitudes satisfying $180^\circ \lesssim \ell \lesssim 230^\circ$. The Monoceros Ring is also discernible at low latitudes.

of the Monoceros Ring (Newberg et al. 2002) are visible as the blue-colored structure at $\alpha \approx 120^\circ$. Figure 3, an RGB-composite image of the SDSS stars in Galactic coordinates (ℓ, b), also shows the arc-like structures of the Monoceros Ring, as predicted by the simulations of Peñarrubia et al. (2005). Two of the globular clusters with tidal tails previously identified in SDSS data – namely Pal 5 (Odenkirchen et al. 2001) and NGC 5466 (Belokurov et al. 2006) – can be discerned in the figures, together with their streams. Finally, a new stream is shown clearly, running from $\alpha, \delta \approx 160^\circ, 0^\circ$ to $\alpha, \delta \approx 140^\circ, 50^\circ$ ($b \approx 50^\circ$ and $180^\circ \lesssim \ell \lesssim 230^\circ$ in Figure 3). It is distinct from the Sgr stream, which it crosses; we discuss its progenitor in a future contribution.

3. TOMOGRAPHY OF THE SGR STREAM

To analyze the three-dimensional structure of the stream, we set up a series of $6^\circ \times 6^\circ$ fields along branches A and B, shown as red (for A) and black (for B) squares in Figure 2. The first three A fields actually probe both the A and B branches, which are merging at these locations. The coordinates of the field centers are listed in Table 1. For each on-stream field, there is a companion off-stream field of size $15^\circ \times 15^\circ$, which has the same right ascension but is offset in declination as noted in Table 1. The off-stream fields are larger, so that the background is as smooth as possible.

Color-magnitude diagrams (CMDs, $g - i$ versus i) are constructed for each of the fields and then normalised by the number of stars. The difference between each on-stream field and its companion off-stream field reveals the population of stars belonging to the Sgr stream. An example for the field A7 is shown in Figure 4(a), together with a one-dimensional slice at $g - i = 0.55$ in Figure 4(b). The subgiant branch is clearly visible and its location can be found to good accuracy. In fact, we fit a Gaussian to the one-dimensional slice to obtain its i band magnitude and uncertainty. For the example in Figure 4(a), there are two subgiant branches visible in the CMD, and two distinct peaks in the luminosity functions in Figure 4(b). These correspond to two distinct structures at different distances, possibly different wraps of the Sgr stream. Although they could correspond to different populations at the same distance, this seems unlikely as the magnitude difference between the two subgiant branches changes on moving along the stream.

The Sgr dSph is known to contain a variety of stellar populations with different ages and metallicities. The most recent study of this is by Belokurov et al. (2006), who presented a comprehensive CMD of the body of Sgr. Rather than attempting to fit multiple theoretical isochrones to our CMDs, we show a direct comparison between Belokurov et al. (2006)'s CMD and a composite CMD for the whole of the stream. The composite CMD is created by using the subgiant branch location to measure the magnitude offset. We use fields A4 to A16, with A16 as the reference. The result, transformed to $B - V$ versus V (Smith et al. 2002), is shown as the black contours in Figure 4(c). This is overlaid upon the colored contours of Bellazzini et al.'s (2006) CMD, corrected for extinction in $B - V$ and V by -0.12 and -0.4 magnitudes, respectively. The upper main sequence, turn-off, and subgiant branches are all well-matched. The only significant difference occurs in the sparsely populated upper red giant branch (the dark blue contours). Hence, this stream is entirely consistent with being composed of the same mix of populations as the Sgr dSph. The 0.6 magnitude offset between our composite CMD and Bellazzini et al.'s is a direct measure of distance.

Figure 4(d) shows the i band magnitude of the subgiant branch versus right ascension of the fields. The triangles and stars correspond to the two structures in the A branch, the diamonds to the B branch. Only one sequence is detected in the B fields. Although its dis-

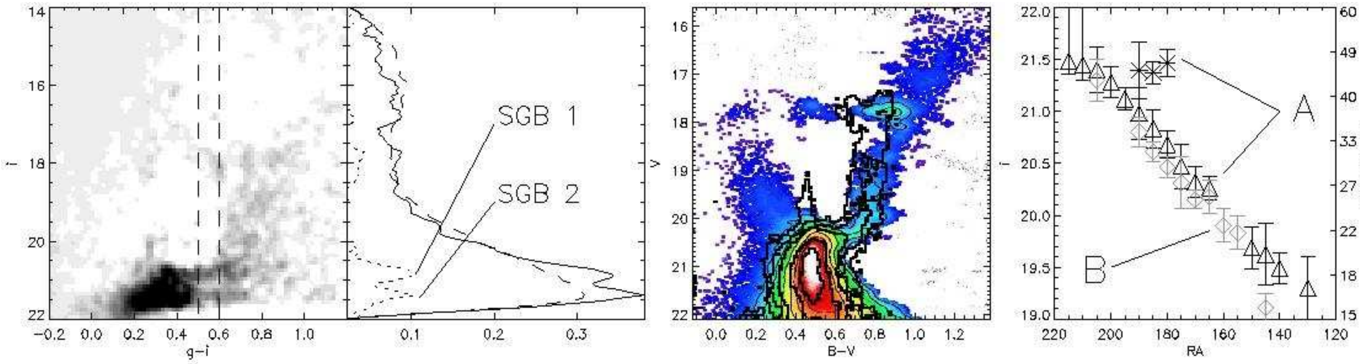

Fig. 4.— (a): Color-magnitude histogram (Hess diagram) of the on-stream field A7 (that is, the 7th field on the A branch) minus the number-scaled corresponding off-stream field. The color bin used to construct the one-dimensional slice is marked. (b): The luminosity functions of the one-dimensional slices for the on-stream field (unbroken), the off-stream field (broken) and the difference (dotted). Notice the two subgiant peaks corresponding to two structures at different distances or two distinct stellar populations. (c): A composite CMD for branch A referenced to field A16 (black contours) overplotted on the CMD from Belokurov et al. (2006) (colored contours) of the body of the Sgr dSph. (d): Magnitude versus right ascension of the subgiant branch for the A fields (stars and triangles) and for the B fields (squares). The distance in kpc is given on the right-hand side axis. If a datapoint is missing, a detection was not possible in that field.

tance offset is significant only at about the 1 σ level, the B branch is systematically brighter and hence probably slightly closer. Assuming the distance to the Sgr dSph is ~ 25 kpc, then Figure 4(d) can be converted directly into heliocentric distance versus right ascension, as shown on the right-hand axis. The two distinct structures in the A fields are separated by distances up to ≈ 15 kpc. Note that there is no evidence for any part of the Sgr stream passing close to the Solar neighbourhood, as has sometimes been conjectured (Freese et al. 2004).

This structure of three branches – two close together and one more distant – is understandable on comparison with the numerical simulations. For example, the effect is clearly visible in the lower panel of Figure 3 of Helmi (2004), where there are two close branches representing material stripped between 3 Gyr and 6.5 Gyr ago, and less than 3 Gyr ago. Branches A and B are therefore probably tidal debris, torn off at different times. The older material, stripped off more than 6.5 Gyr ago, lies well behind the two close branches in Helmi's simulations. This earlier wrap of the orbit may correspond to the distant structure seen behind the A branch.

4. CONCLUSIONS

We used a simple color cut $g - r < 0.4$ to map out the distribution of stars in SDSS DR5. The "Field of Streams" is an RGB-composite image composed of magnitude slices of the stellar density of these stars. It reveals a super-abundance of Galactic substructure, including the leading arm of the Sgr stream, as well as a number of sibling streams (some hitherto unknown).

Part of the Sgr stream has previously been seen in the Northern hemisphere by Majewski et al. (2003). Here, we have mapped out the continuation of the stream, as it passes by the Galactic Cap and returns to the Galactic Plane. At least two branches of the stream – labelled A and B – have been identified, corresponding to material torn off at different epochs. There is also evidence for a still more distant structure behind the A branch.

The Sgr stream provides a probe of the shape of the Galactic halo. Previous work has been hampered by the absence of data in the most important regions of the sky. For example, Helmi (2004) provides simulations of the Sgr stream for a range of halo shapes from extreme oblate to prolate, all of which broadly agree with the data available at that time. Our data covers the critical region where the models differ substantially. Examination of the simulations displayed in Figure 2 of Helmi (2004) enables some preliminary conclusions to be drawn. In oblate haloes, the Sgr stream is much fatter and the stars much more scattered than shown in our Figure 1. Only the spherical and very mildly prolate haloes ($1 \lesssim q < 1.1$, where q is the axis ratio in the potential) seem reasonable matches to the data. In both these simulations, the Sgr stream shows the same bifurcation and overall morphology as in the SDSS data. We suggest that this may be a powerful discriminant of halo shape (Fellhauer et al. 2006).

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