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SLOAN SNAPS THE SAGITTARIUS STREAM

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ABSTRACT

We use Sloan Digital Sky Survey (SDSS) u, g, r, i, z data to trace the tidal debris of the Sagittarius dwarf spheroidal through the North Galactic Cap. The overall structure of the stream is revealed by a simple color cut $g - i < 0.45$. Two branches (A and B) of the stream are clearly visible in a true-color image composed of magnitude slices. They probably correspond to different wraps of the stream. These data strongly suggest 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

The Sagittarius dwarf spheroidal (dSph) was discovered by Ibata, Gilmore & Irwin (1995). It has a heliocentric distance of ~ 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 4 and 8 Gyrs), but there is evidence for a much older population (15 Gyrs) as well. The mean metallicity is -0.41 ± 0.20 with a tail extending below -2 dex (Monaco et al. 2005, and references therein). It was realised early on that there was some tidal debris in the neighbourhood of the Sagittarius dSph (Ibata et al. 1997; Majewski et al. 1999) and that the distribution of this material determined the Sagittarius' 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 $(\ell, b, R) = (350°, 50°, 46$ kpc$)$ and $(157°, -58°, 33$ kpc$)$. These were later identified with the Sagittarius stream (Ibata et al. 2001).

The best panorama of the Sagittarius 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 to provide a picture of the leading arm with dazzling clarity, together with possible multiple wraps in the vicinity of the North Galactic Cap.

2. A SIMPLE COLOR CUT

SDSS imaging data are produced simultaneously in five photometric bands, namely u, g, r, i, and z (Fukugita et al. 1996). Data Release 5 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 artefacts removed [1], together with a magnitude limit $r < 22$. We use PSF magnitudes which have been de-reddened using the Schlegel et al. (1998) maps.

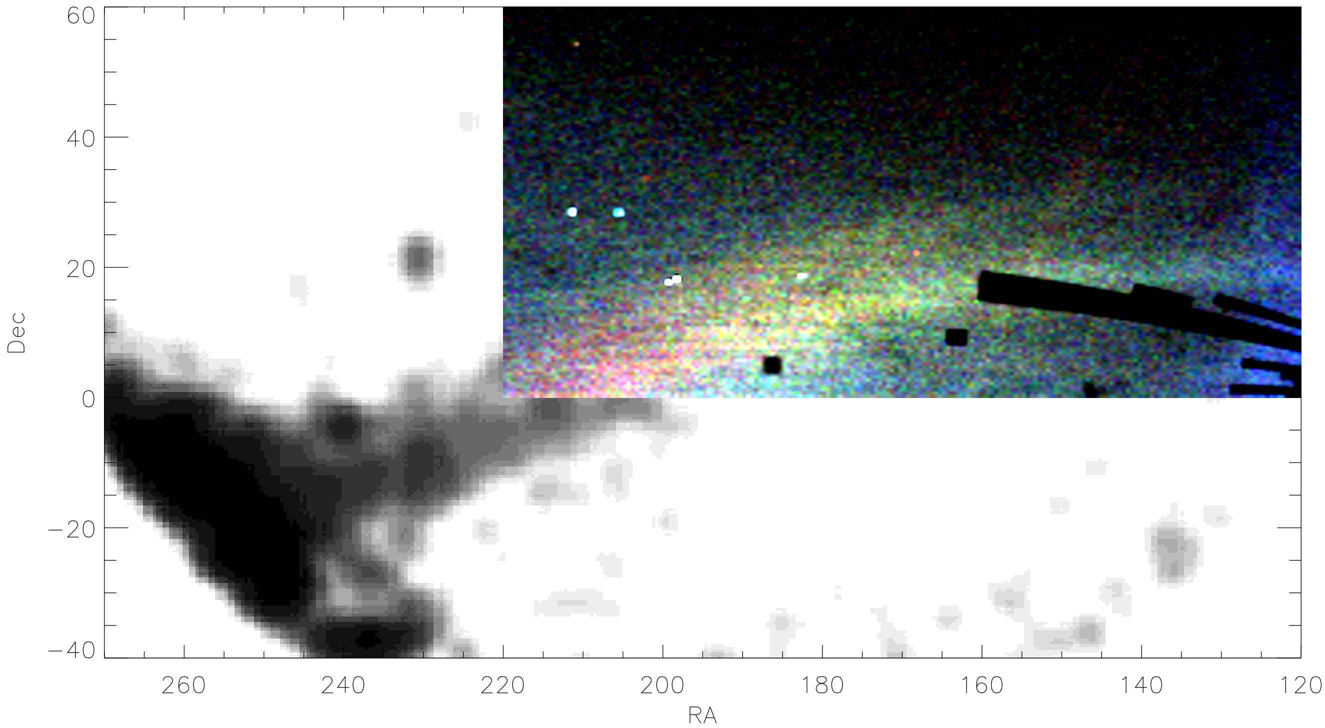
Figure 1 shows the density of stars in the Sagittarius stream, with grey representing the M giants taken from Majewksi et al's (2003) analysis of 2MASS, and color representing hot stars from SDSS. The latter are chosen by implementing the color cut $g - i < 0.45$ corresponding to an effective temperature in excess of 5500 K to select stars bluer than the old field halo turn-off. As we will show shortly, these are upper main sequence and turn-off stars belonging to the Sagittarius stream. The inset is a true-color image assembled from three greyscale images colored red, green and blue corresponding to the density of the hot stars in the following three magnitude bins: red is $21.3 < r <\leq 22.0$, green is $20.6 < r \leq 21.3$ and blue is $20.0 < r \leq 20.6$. The map has 200×120 pixels which are 0.5° on a side.

Majewski et al. (2003) have traced the Northern stream of the Sagittarius for right ascensions α between 270° and 190°. For $\alpha < 190°$, Majewski et al. (2003) do not see a clear continuation of the stream. The combination of Majewski et al.'s (2003) M giants together with the SDSS hot stars in Figure 1 shows for the first time the entirety of the Northern stream, including its continuation through the Galactic Cap and into the Galactic plane. 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 a bifurcation visible in the stream starting

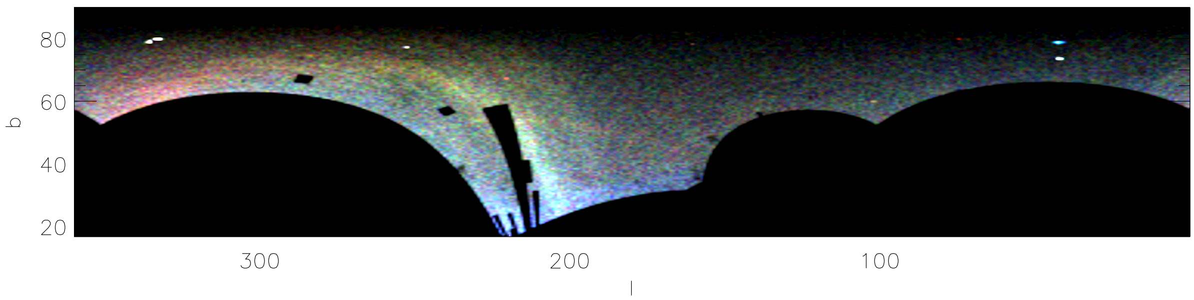
TABLE 1
L - A (α, δ_A) B (α, δ_B). T - A
$+20°$ $\alpha > 150°$ $-12°$. F B, - $+13°$.

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	-	-	7°	13°	16°	18.5°	20.2°	22.°	22.75°	24°	25	25.8°	26.7°	27.4°	30.°	-	-	-	-

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



F . 1.— A panoramic view of the Northern Sagittarius stream, obtained by combining the 2MASS M giants of Majewski et al. (2003) and the SDSS hot stars ($g - i < 0.45$). The color-plot is an RGB composite with red for the most distant stars with $21.3 < r <\leq 22.0$, green for stars with $20.6 < r \leq 21.3$ and blue for the most nearby stars with $20.0 < r \leq 20.6$. Note the bifurcation in the stream starting at about $\alpha \approx 180°$. The lower declination branch is branch A, the higher is branch B. For more details, see text.



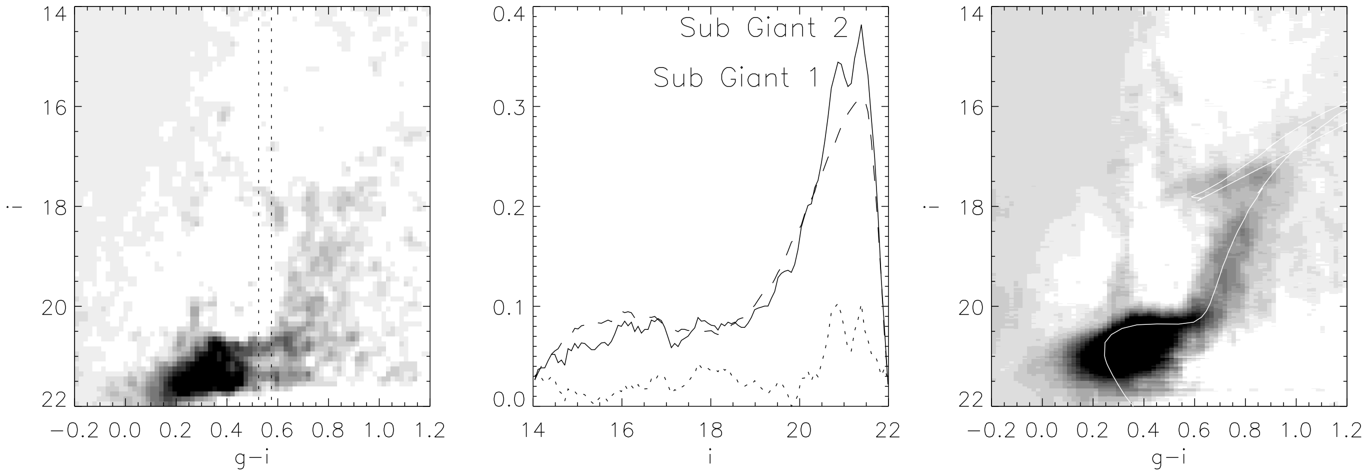
F . 2.— An RGB composite of the SDSS stars as in Figure 1, but now shown in Galactic coordinates (ℓ, b). Note in addition to the branches of the Sagittarius stream, a second, thin orphan stream is clearly visible at latitudes of $b \approx 50°$ and with longitudes satisfying $180° \lesssim \ell \lesssim 230°$.

at about the North Galactic Pole. We will refer to the lower declination branch as branch A, and the higher declination as branch B. It is natural to identify these as two distinct wraps of the stream.

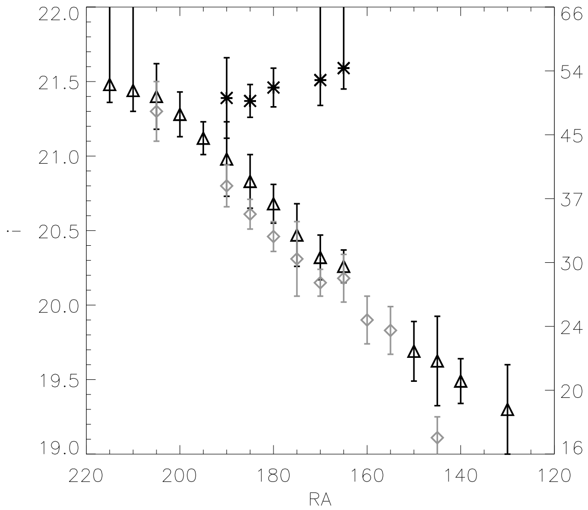
A number of other prominent Galactic structures are also visible on Figure 1. There is the blue-colored, and hence nearby, overdensity in hot stars centered at ($\alpha \approx 185°, \delta \approx 0°$). This was found by Jurić et al. (2005) and named "the Virgo Overdensity". This is perhaps the same structure as the nearby 2MASS "Northern Fluff" (Majewski et al. 2003). Also, parts of "the Monoceros Ring" (Newberg et al. 2002) are visible as the blue-colored structure at $\alpha \approx 120°$. These structures can also be discerned in Figure 2, which is a true-color image of the SDSS stars in Galactic coordinates (ℓ, b). This map also clearly shows an new, high latitude stream, whose progenitor is most likely the unusual globular cluster, Ruprecht 106. This is discussed elsewhere (Belokurov et al. 2006).

Finally, we remark that we first identified the Sagittarius stream stars in the SDSS data through the use of neural networks to estimate quantities such as temperature and metallicity directly from the u, g, r, i and z photometry (c.f. Jordi et al. 2005). Only later did we realize how well a simple color cut alone can reproduce the structure. Although there are some advantages to the neural network approach (e.g., in studying metallicity gradients), we only present the simple color cut here.

3. TOMOGRAPHY OF THE STREAM



F . 3.— Left: Difference color-magnitude diagram between the on-stream field A 7, together with the corresponding off-stream field. The color bin used to construct the one-dimensional slice is marked, Center: 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. Right: A difference CMD for branch A built using all the fields from A4 to A10, referenced to field A8. The best-fitting Padova isochrone is overplotted.



F . 4.— Magnitude versus right ascension of the subgiant branch for the A fields (stars and triangles) and for the B fields (diamonds). The distance in kpc is given by the right-hand side axis. If a datapoint is missing, a detection was not possible in that field.

To analyze the three-dimensional structure of the stream, we set up a series of $6° \times 6°$ test fields along branches A and B. The coordinates of the field centers are listed in Table 1. For each test field, there is a companion off-stream field of size $15° \times 15°$, 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 ($g - i$ 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 Sagittarius stream. An example for the field A7 is shown in Figure 3, together with a one-dimensional slice at $g - i = 0.55$. The sub-giant branch is clearly visible and its location can be found to good accuracy. In fact, we fit a one-dimensional Gaussian to obtain its i band magnitude and uncertainty. For the example in Figure 3, there are two subgiant branches visible in the CMD, and two distinct peaks in the middle panel. These correspond to two distinct structures at different distances, possibly different wraps of the Sagittarius stream. To estimate the age and metallicity, we can create a composite CMD using the subgiant branch location to measure the offset. We use fields A4 to A10, with A8 as the reference. The result is shown in the right-hand panel of Figure 3. The upper main sequence, turn-off, giant and horizontal branches are clearly visible. We use theoretical isochrones calculated by Girardi et al. (2004) to estimate the age of the stellar population as between 10 and 15 Gyr and the metallicity as [Fe/H] = −1.3. This is consistent with the old population in the Sagittarius dSph.

Figure 4 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 distance offset is significant only at about the 1 σ level, the B branch is systematically brighter and hence slightly closer. Assuming an age and metallicity for these populations, Figure 4 can be converted directly into heliocentric distance versus right ascension, as shown on the right-hand axis of the Figure. The B branch is typically $\approx$ 1kpc closer in heliocentric distance. Note that there is no evidence for any wrap of the Sagittarius stream passing close to or through the Solar neighbourhood, as has sometimes been conjectured (Freese et al. 2004).

4. CONCLUSIONS

We have used a simple color cut $g - i < 0.45$ to map out the distribution of hot stars in the Sloan Digital Sky Survey (SDSS) Data Release 5. This has revealed the leading arm of the Sagittarius stream with exceptional clarity. The stream has already been seen in the Northern hemisphere by Majewski et al. (2003), who tracked out the 2MASS M giants. Here, we have mapped out the entirety 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 two distinct wraps. The B branch is at higher declinations and is $\approx$ 1 kpc closer in heliocentric distance than the A branch. There is also evidence for a still more distant structure – possibly another wrap – behind the A branch, extending out to heliocentric distances of $\approx$ 55 kpc.

The Sagittarius stream provides a very direct probe of the shape of the Galactic halo. Previous work, based on simulations of the disruption of the Sagittarius dSph, already suggested that the Galactic halo was very nearly spherical (Ibata et al. 2001; Majewski et al. 2003). However, Helmi (2004a) argued persuasively that many of the stars had only recently been torn off the Sagittarius dSph and hence were dynamically very young. Therefore, they had not diffused in the Galactic potential and were consistent with either oblate or prolate haloes. The identification of multiple wraps of the Sagittarius stream solves this problem and provides a golden opportunity to find the shape of the halo. Examination of the simulations displayed in Figure 2 of Helmi (2004b) enables some preliminary conclusions to be drawn. In oblate haloes, the Sagittarius stream is much fatter and the stars much more scattered than shown in our Figure 1. Only the spherical and very mildly prolate haloes ($1 \lesssim q \lesssim 1.1$, where q is the axis ratio in the potential) seem reasonable matches to the data. In both these cases, the Sagittarius stream shows the same bifurcation and overall morphology as in the SDSS data. We conclude that the density profile along the Sagittarius stream is a powerful discriminant of halo shape. Further simulations are underway to test this.

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