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A Study of the Sagittarius Tidal Stream Using Maximum Likelihood

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Abstract. Modern surveys are producing enormous amounts of data that can only be navigated via the use of the ever increasing computational resources available. For example, the SDSS has taken a large amount of photometric data that can be used to discover and study substructure in the Galactic spheroid. A maximum likelihood method was developed and applied to color-selected F turnoff stars from two stripes of SDSS data, to determine the spatial characteristics of the Sagittarius dwarf tidal debris that exists within these stripes. The Sagittarius tidal debris in stripes 79 and 86 were detected at the positions (l, b, R) = (163°.311, -48°.400, 30.23 kpc) and (l, b, R) = (34°.775, -72°.342, 26.08 kpc) and were found to have a FWHM of 6.53 ± 0.54 kpc and 5.71 ± 0.26 kpc and also to contain $\approx 9,500$ and $\approx 16,700$ F turnoff stars, respectively. The debris pieces are axially aligned with the directions $(\hat{X},\hat{Y},\hat{Z})$ = (0.758 kpc, 0.254 kpc, -0.600 kpc) and $(\hat{X},\hat{Y},\hat{Z})$ = (0.982 kpc, 0.084 kpc, 0.167 kpc), respectively. The results of probabilistically separating the tidal debris from the stellar spheroid are also presented.

1. Introduction

The Sagittarius dwarf spheroidal galaxy (Sgr dSph) has been of great interest since its discovery in 1994 by Ibata et al. (1994). The Sgr dSph is currently being tidally disrupted by the Milky Way and has created a very prominent tidal stream that stretches across much of the sky. This stream traces out the structure of our Galaxy as it follows the Galactic potential. By studying this stream we can greatly constrain the Galactic potential and determine the distribution of dark matter within the Milky Way. However, a very robust, accurate, and efficient means is required to study the Sgr tidal stream in the detail required and to utilize the enormous amount of data being generated by the large surveys of today. The maximum likelihood method has proven to be a good solution to fully utilize the data in a robust manner.

In Cole et al. (2008), hereafter C08, a method of utilizing the maximum likelihood technique was described and proven to be highly successful in describing the spatial characteristics of tidal debris over a small volume: specifically over one stripe from the SDSS (Sloan Digital Sky Survey). Each stripe consists of a

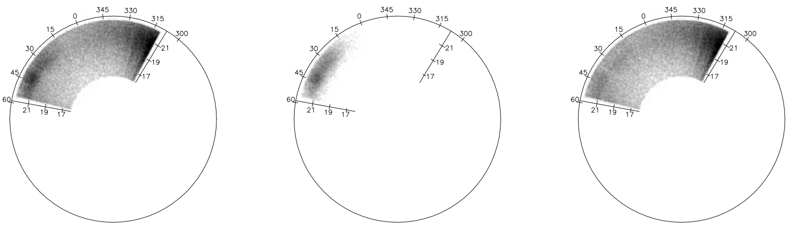

Figure 1.: Density plot of SDSS stripe 79. Here we plot stripe 79 face on with apparent magnitude denoted on the radial spoke, the circle at constant apparent magnitude of 23, and angle, μ, about the stripe given in degrees. Left: the data fit using the algorithm with tidal debris clearly visible around $(\mu, g_0), = (45°, 21.5)$. Center: the tidal debris after being separated from the spheroid stars using the algorithmic results. Right: the smooth spheroid left after removing the tidal debris.

wedge-like volume that is only 2.°5 thick. Over this small volume it was proven that a cylinder with Gaussian falloff from its axis is a suitable model for the density of the tidal debris within a stripe, thereby approximating the tidal debris through space as a series of line segments. This model allows for the position, orientation, and width (the standard deviation of the Gaussian falloff) of the tidal debris to be accurately calculated. This model of the tidal debris is then combined with a model of the stellar spheroid of the Milky Way, a Hernquist profile (Hernquist (1990)), and a normalization factor describing the number of stars present in each feature of the data.

Here we apply the C08 algorithm to two additional SDSS stripes in the southern portion of the survey: stripe 79 and stripe 86. The algorithm has been expanded in order to accommodate the removal of parts of the data volume. This was done to remove tightly bound structures such as globular clusters that may influence the algorithm, as well as sections of data that are not high quality. This addition to the algorithm was required for the analysis of stripe 86, since there is a small solid angle of bad data, in the center of the Sgr stream.

2. Data Analysis

Stars with the colors of blue F turnoff stars, with reddening corrected color $0.1 < (g - r)_0 < 0.3$ and $(u - g)_0 > 0.4$, and magnitudes $16.0 < g_0 < 22.5$ were selected from the SDSS DR6 photometric catalog. The C08 algorithm was then applied to these datasets and the results presented below are the average of five successful fits conducted with random starting points. Error analysis and data separations were conducted in the same manner as described in the same paper.

SDSS stripe 79 crosses the trailing Sgr tidal tail farther from the Sgr dSph core than that of stripe 82 (which is on the Celestial equator) and has SDSS stripe coordinates $(311° < \mu < 416°(56°); -1.25° < \nu < 1.25°)$. Here we have limited the angular length of the stripe to 105°. The stripe 79 dataset contains 92,789 F turnoff stars. The fits to this dataset resulted in a position of $(\mu, \nu, R) = (38.°27 \pm 0.°32, 0.°0, 30.23 \pm 0.25$ kpc); angle from the Galactic Z axis $\theta = 2.21 \pm 0.06$ radians; azimuthal angle $\phi = 0.32 \pm 0.07$ radians; width $\sigma = 2.77 \pm 0.23$ kpc; and

Table 1.: The results of the fits for SDSS stripe 79 and 86. Measurements of the debris center, direction, width, and approximate number of stars are given. The center is presented in Galactic coordinates (l,b,R), and the direction is presented with a Galactic Cartesian unit vector ($\hat{X}$,$\hat{Y}$,$\hat{Z}$). The results for stripe 82 found in C08 are also given for reference.

Stripe	l [°]	b [°]	R [kpc]*	$\hat{X}$	$\hat{Y}$	$\hat{Z}$	FWHM	# stars
79	163.31	-48.40	30.23	0.76	0.25	-0.60	6.53	9,500
82	159.22	-57.56	29.22	0.99	0.04	-0.13	6.74	16,000
86	134.78	-72.34	26.08	0.98	0.08	0.17	5.71	16,700

*Assuming $M_g = 4.2$.

the spheroid parameters $q = 0.34 \pm 0.01$ and $r_0 = 25.95 \pm 0.67$ where q is the flattening in the Galactic Z direction and r_0 is the core radius. Table 1 presents these values in more traditional coordinate systems and quantities. The debris in stripe 79 contains $9,500 \pm 240$ stars which equates to there being 0.5% as many stars in stripe 79 as there are currently in the Sagittarius dwarf. This quantity was derived by performing a calculation that parallels that found in Freese, Gondolo & Newberg (2005); an estimate of the number of F turnoff stars currently in the Sgr dwarf and the number of F turnoff stars found in stripe 79 were compared. These results were then used to separate the tidal debris from the spheroid using the method from C08. The separation is shown in Figure 1.

SDSS stripe 86 crosses the trailing Sgr tidal tail between the Sgr dSph core and stripe 82. Stripe 86 has the SDSS stripe coordinates ($310° < \mu < 420°(60°); -1.°25 < \nu < 1.°25$). Here we have limited the angular length of the stripe to 110°. A small solid angle of corrupt data, centered about the angle $\mu = 29.°95$, exists in stripe 86. To address this corrupt data, we have removed all data having angles $21.°6 < \mu < 22.°3$. After these cuts are made, the dataset for stripe 86 contains 111,642 stars. Fitting stripe 86 resulted in a position of $(\mu, \nu, R) = (16.°31 \pm 0.°40, 0.°0, 26.08 \pm 0.2$ kpc); angle from the Galactic Z axis $\theta = 1.40 \pm 0.03$ radians; azimuthal angle $\phi = 0.086 \pm 0.017$ radians; width $\sigma = 2.42 \pm 0.11$ kpc; and the spheroid parameters $q = 0.63 \pm 0.01$ and $r_0 = 16.66 \pm 0.37$. Again, Table 1 contains these values in more traditional coordinate systems and quantities. It was determined that the debris in stripe 86 contains $16,700 \pm 500$ stars, which equates to there being 0.9% as many stars in stripe 86 as there are currently in the Sagittarius dwarf. This value was calculated in the same manner as for stripe 79. Figure 2 shows the original dataset as well as the results of using these results to separate the tidal debris from the spheroid as before. Comparing our debris position with that found in BHB stars by Newberg et al. (2003), we see that their position of $(l, b, R) = (148.°8, -70.°8, 30$ kpc) is very different from ours at $(l, b, R) = (134.°8, -72.°3, 26$ kpc). However, our results fit

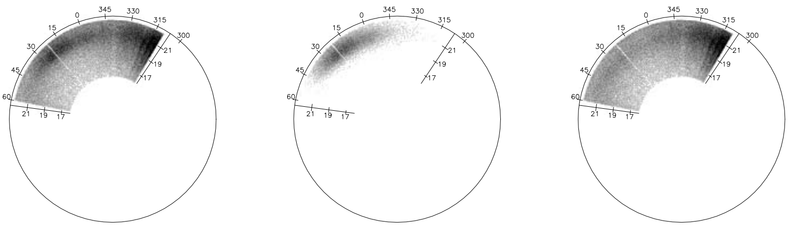

Figure 2.: Density plot of SDSS stripe 86. Here we plot stripe 86 face on with apparent magnitude denoted on the radial spoke, the circle at constant apparent magnitude of 23, and angle about the stripe, μ, given in degrees. Left: the data fit using the algorithm with the tidal debris clearly visible around $(\mu, g_0) = (20°, 21.5)$. Center: the tidal debris after being separated from the spheroid stars using the algorithmic results. Right: the smooth spheroid left after removing the tidal debris. Note also the section of data at $21^{\circ}\!.6 < g_0 < 22^{\circ}\!.3$ that has been removed.

more readily on a smooth orbit connecting the Sgr dSph core and stripe 82 than those values found by Newberg et al. (2003).

3. Conclusions

The C08 algorithm was used to analyze two more SDSS stripes (79 and 86) and determine the spatial properties of the Sgr tidal stream pieces that are found within these two datasets. There is some evidence from these results that the tidal stream becomes wider the farther its distance from the core. This can be seen in the values of FWHM for stripe 86 (5.71 ± 0.26 kpc) as compared to that of stripe 82 (6.74 ± 0.14 kpc) and within the errors of stripe 79 (6.53 ± 0.54 kpc). Also, it was found that stripe 79 contains significantly fewer stars than those of the other two studied stripes. This may be due to the manner in which the data plane intersects this stripe. The spheroid parameters were found to vary greatly over the three studied stripes ($0.34 < q < 0.63; 17 < r_0 < 26$). This could imply that there is no "smooth" spheroid component, the Hernquist model is not a good match, there are other pieces of tidal debris present in the stripes that exist at high enough density to influence the algorithm, or the spheroid parameters are simply not well constrained over such a small volume.

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