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Sagittarius Tidal Debris 90 kpc from the Galactic Center

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ABSTRACT

A new overdensity of A-colored stars in distant parts of the Milky Way's stellar halo, at a dereddened SDSS magnitude of $g_0 = 20.3$, is presented. Identification of associated variable RR Lyrae candidates supports the claim that these are blue horizontal branch stars. The inferred distance of these stars from the Galactic center is 90 kpc, assuming the absolute magnitude of these stars is $M_{g_0} = 0.7$ and that the Sun is 8.5 kpc from the Galactic center. The new tidal debris is within 10 kpc of same plane as other confirmed tidal debris from the disruption of the Sagittarius dwarf galaxy, and could be associated with the trailing tidal arm. Distances to the Sagittarius stream estimated from M stars are about 13% smaller than our inferred distances. The tidal debris has a width of at least 10°, and is traced for more than 20° across the sky. The globular cluster NGC 2419 is located within the detected tidal debris, and may also have once been associated with the Sagittarius dwarf galaxy.

Subject headings: Galaxy: structure — Galaxy: halo — galaxies: individual – Sagittarius

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1. Introduction

The discovery of the Sagittarius dwarf galaxy (Ibata, Gilmore, and Irwin 1994), which is in the process of being tidally disrupted by the gravitational field of the Milky Way galaxy, has sparked a decade of research on the nature, extent, and formation history of its tidal tails. Underlying the quest for the details of this merger event in our own galaxy is the hope that it will lead to a better understanding of halo formation processes in general and the formation of the Milky Way galaxy in particular. Additionally, the tidal streams can be used as a probe of the Galactic potential, and the clumpiness of the halo dark matter component.

In this letter, we present evidence that a piece of the Sagittarius dwarf tidal stream extends to a distance of up to 90 kpc from the Galactic Center. This doubles the known extent of the trailing tidal tail. These stars will help constrain models of the Galactic potential and the disruption of the Sgr dwarf.

2. Observations and Data

The SDSS scans the sky in 2.5 degree wide stripes that follow great circles on the sky. Details of the survey geometry may be found in Stoughton et al. (2001) and Abazajian et al. (2003). Other SDSS technical details can be found in: Fukugita et al. (1996), Gunn et al. (1998), Hogg et al. (2001), Pier et al. (2002), Smith et al. (2002), and York et al. (2000).

SDSS imaging data available 2003 March was searched for clumps of faint blue stars, following the techniques described in Yanny, Newberg et al. (2000), hereafter Paper I, for selecting stars of type A. These stars are bluer than the turnoff of the Galactic thick disk, thereby minimizing contamination from this component. A-type stars (including many Blue Horizontal Branch - BHB - objects), are selected with $(u-g)_0 > 0.4$ (to avoid contamination from extragalactic quasars) and $-0.3 < (g-r)_0 < 0$. This 'standard candle' population was used to explore the stellar halo structure out to distances of ~ 100 kpc from the Sun.

Table 1 lists the SDSS stripes examined for which detections near the plane of the Sgr dwarf orbit (Ibata et al. 2001b) were noted. Listed are the stripe number, stripe inclination, Galactic latitude and longitude of the center of intersection of the Sagittarius stream with the observed SDSS stripe, mean g magnitude of the BHB stars in the stream, a derived distance to the stream stars, and rough number counts, N, of type A stars in each stripe which crosses the stream, along with the angle between the A star distribution and the end of the stripe. Note that the stripes overlap and thus the numbers may not be summed without accounting for the overlap. About 20% of the BHBs are listed twice in the Table, due to the overlap of adjacent stripes. The number counts of A stars were determined by counting the number of A stars within 0.2 magnitudes of the tabulated g magnitude, and within 20° of the tabulated position. A reasonable background A star count was estimated from a histogram of apparent magnitudes in each direction and has been subtracted. We note qualitatively that the spatial density of BHB stars remains approximately as high at 90 kpc from the Galactic Center (stripes 27 through 37) as it does for trailing tail stripes 82 and 86, only 30 kpc from the G.C.

3. Detection of a new density enhancement in the Galactic halo

Figure 1 shows a polar wedge (magnitude, angle) diagram for type A/BHB objects in the SDSS stripe 29. The most striking new feature is the overdensity of A-type stars at $g_0 = 20.3$ (where the subscript indicates the magnitude has been dereddened by the standard Schlegel, Finkbeiner, & Davis (1998) maps) and $(l, b) = (195°, 29°)$. There is another apparent overdensity of A-type stars with $g_0 \sim 17.5$ (apparent also in Figure 2). The source of these stars is unclear. They could be blue stragglers in the new structure discovered in the plane of the Milky Way (Yanny, Newberg et al. 2003). Alternatively, they could be associated with a Galactic disk structure or a closer piece of debris from the Sgr dwarf galaxy.

Figure 2 shows the g_0 magnitude of all A-type stars in stripes 27-37 with $100° < \alpha < 170°$ and within 15 kpc of the Sgr dwarf tidal plane, as defined in Majewski et al. (2003) (see §4), as a function of $\Lambda_\odot$. $\Lambda_\odot$ was defined by Majewski et al. (2003) to be the angular distance from the Sgr dwarf, in the plane of the Sgr dwarf orbit. This figure can be compared with Figure 8 of Majewski et al. (2003). From Figure 2, this tidal fragment (at $g_0 \sim 20.3$) extends at least 20° on the sky ($-173° < \Lambda_\odot < -148°$). If one adjusts for the fact that the stripe in Figure 1 is not perpendicular to the Sgr orbit (which makes the stream appear wider), we find that the stream is at least 10 degrees across. When this overdensity was discovered, it was not in a targeted search for stars in the Sgr stream, but it was the most significant new substructure discovered in a routine search through the entire SDSS data set collected to date.

Since this identified overdensity is narrowly concentrated in apparent magnitude, we tentatively identify this as a population of blue horizontal branch (BHB) stars associated with a tidal stream in the outer halo. Using an absolute magnitude of $M_g \sim 0.7$ (Paper I), the tidal stream is 83 kpc from the Sun and at least 15 kpc in width. With a position $(l, b) = (190°, 30°)$, the overdensity is 90 kpc from the Galactic center.

Note the 'finger of God' at $(\Lambda_\odot, g_0) = (-170°, 20.3)$. These are the horizontal branch stars from the globular cluster NGC 2419 ($[l, b] = [180°, 25°]$). The magnitude of the horizontal branch is less than a tenth of a magnitude different from those of our newly identified distant tidal stream. NGC 2419 is 13 kpc above the Sgr dwarf orbital plane. This cluster could have once belonged to the Sgr dwarf galaxy or some parent progenitor to today's Sgr dwarf. The fact that this cluster is relatively close the the plane of the Sgr dwarf tidal debris has also been noticed by Zhao (1998).

The globular cluster NGC 2419 has a heliocentric radial velocity of -20 km/s (Peterson, Olszewski, & Aaronson 1986). This translates to a radial velocity of -14 km/s in the rest frame of the Galactic center, but as seen from the Sun. Since the Sun and the Galactic center are only about 2° apart as seen from NGC 2419, the radial velocity as seen from the Sun should be close to the radial velocity as measured from the Galactic center. If the globular cluster is in a portion of the stream that is near apogalacticon, as suggested by our results, the galactocentric radial velocity should be near zero. With a velocity dispersion of 20 km/s (Yanny, Newberg et al. 2003), the observed radial velocity is consistent with its association with the Sgr dwarf tidal stream near its apogalacticon.

We have confirmed the identification of the A-colored stars as horizontal branch stars by identifying an excess of RR Lyrae candidates with the correct apparent magnitudes in this position. We selected stars in the overlaps of stripes 27 through 37 which were observed at multiple epochs. Ordinarily this SDSS stripe-to-stripe overlap is about 20% of the area of the sky. However, since these observations are near the beginning and ends of SDSS survey stripes (near the survey poles) the stripes converge, significantly increasing the overlap. The matching routine first selected objects with $16 < g_0 < 22$ in the color range $-0.2 < (g - r)_0 < 0.3$, and chose stellar objects at the same spatial position (within $1''$) from the list which were observed more than once. We compared the matches in the area $110° < \alpha < 130°$, $20° < \delta < 50°$ with a wider 'control' area with a similar number of matches over the whole of the stripes covering $165° < \alpha < 260°, 20° < \delta < 65°$.

There are about 50 excess variable objects with magnitude differences of at least 0.4 magnitudes between the two observations in the magnitude range $20 < g < 21$ (57 in the first region vs. 5 in the control region). This sample of RR Lyrae candidates provides strong confirmation that the blue A-type stars seen in Figure 1 and 2 near the plane of the Sgr dwarf orbit, some 81-85 kpc from the Sun, are indeed BHB stars and not intrinsically fainter (and thus more nearby) blue straggler objects of the same color (Paper I).

4. The trailing tail of the Sagittarius tidal stream

We compare our detection with the positions of the Sgr tidal tails of 2MASS M-stars as presented by Majewski et al. (2003). In order to put our data on their Figure 11, showing the tidal tails, we adopt their distance from the Sun to the center of the Galaxy of 8.5 kpc. Our Galacitic X-axis is along the line from the Sun to the center of the Galaxy, but incontrast to Majewski et al. (2003) it is measured from the Galactic center towards $l = 0°$, so that the Sun is at $X = -8.5$ kpc. Y ($l = 90°$) and Z ($b = 90°$) are unchanged. Using our definitions, the Sgr plane is:

$$-0.064X + 0.970Y + 0.233Z + 0.232 = 0.$$

The same paper defines another coordinate system, $(X_{Sgr,GC}, Y_{Sgr,GC}, Z_{Sgr,GC})$, where $Z_{Sgr,GC}$ is perpendicular to the plane of the orbit, and $Y_{Sgr,GC} = 0$ in the Galactic plane. Figure 3 shows the 2MASS M stars from Figure 11 of Majewski et al. (2003), along with the positions (large open circles) of the stream we detect in SDSS A-stars in stripes 29-37. Also shown are other detections of the tidal tails of Sgr in SDSS A-stars, by methods described in Newberg, Yanny et al. (2002). Open circles denote the trailing tail, and filled circles mark the leading tail. The error bars are three sigma error bars, but do not include systematic error which would arise if the absolute magnitudes of our selected A stars were not $M_{g_0} = 0.7$. We measure the central apparent magnitude of each overdensity to within 0.05 magnitudes in g_0, and the position along the stripe of data to within one degree. We added in quadrature the errors in distance from the center of the Galaxy that would arise from a difference of 0.15 magnitudes in apparent magnitude and from a difference of 3° in stream center. The data points for the distant portion of the stream were determined from the entire dataset of A-type stars converted to Λ_0, g_0 coordinates; their positions are not tied to individual SDSS stripes, but spaced according to the density of stars in Figure 2, excluding NGC 2419.

There appears to be a systematic scale difference between the distance to the Sgr stream from 2MASS M star statistics and from A star statistics. The A star distance scale used in Paper I was based on the somewhat arbitrary assumption that the blue horizontal branch (BHB) stars in the sample had absolute magnitudes of $M_{g_0} = 0.7$. Note, however, that the distances given in Paper I to pieces of the Sgr tidal stream from BHB stars are not far from the distances quoted in Ivezić et al. (2000) and Vivas et al. (2001) to similar sections of the stream using RR Lyrae stars. The nominal distance to NGC 2419 is 81 kpc (Harris, et al. 1997) from the Sun, in excellent agreement with our measured distance to the tidal stream. The M-star distance scale is calibrated assuming a distance of 24 kpc from the Sun to the Sgr dwarf, 12.5% smaller than the distance to M54 measured by Layden & Sarajedini (2000) using RR Lyrae stars. If the larger distance scales for A-stars and RR Lyraes are correct, then either the M-star population changes as a function of position along the stream (as suggested by Martinez-Delgado 2003), or the Sgr dwarf is somewhat more distant than typically assumed. Alternatively, the absolute magnitudes of the BHB and RR Lyrae stars could be ~ 0.26 magnitudes fainter than we have previously assumed.

The newly discovered overdensity of A-type stars may coincide with an overdensity of M giants on the left edge of Figure 9 of Majewski et al. (2003). These stars appear to extend the trailing tail of the Sgr dwarf back up through the Galactic plane into the northern Galactic hemisphere. Our result suggests that these M-stars may in fact be a part of a longer trailing tail of the Sgr dwarf, which extends to 90 kpc from the Galactic center.

Figure 4 shows the positions of the same pieces of tidal debris, but shown as a cross section through the plane of the Sgr dwarf tidal stream. The exact position of the center of the tidal stream is uncertain for the distant portion of the tidal stream, since we do not unambiguously detect the entire cross section in any stripe, and in many stripes we detect only a portion of the cross section. The 3σ asymmetrical error bars reflect this fact. If we adopted a larger absolute magnitude for the A-type stars, then position of the points on the X-axis would shift somewhat but the positions and errors on the Z-axis would hardly change. Notice that the leading arm of Sgr shifts towards larger (positive) Z_{Sag} as we go back towards the Sgr dwarf. The trailing arm (closer than 50 kpc) is less well sampled, but possibly shifts towards smaller (negative) Z_{Sag} as we go towards the Sgr dwarf. This may indicate that the leading arm originates at positive Z_{Sag} and the trailing arm at negative Z_{Sag}. The slight deviations from the plane might alternatively result from a non-spherical Galactic potential. These deviations cannot be reduced by redefining the Sgr orbital plane.

5. Conclusions

We have detected an overdensity of A-type stars with an estimated distance of 90 kpc from the Galactic center. The globular cluster NGC 2419 appears to be within this overdensity, which is in nearly the same plane as the previously discovered tidal tails of the Sgr dwarf galaxy. The radial velocity of NGC 2419 is consistent with its association with the tidal stream, near the apogalacticon of its orbit. The position of the overdensity is consistent with identification as a distant piece of the trailing tail of the Sgr dwarf galaxy, and coincident with the positions of Sgr dwarf M giants discovered in 2MASS. The inferred distances to the M giants are 13% smaller than those from BHB and RR Lyrae stars in the Sgr stream. This may indication a systematic error in one or both of the distance scales.

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Fig. 1.— Polar wedge diagram of color-selected ($-0.3 < g_0 < 0$) A-type stars in stripe 29. The g_0 apparent magnitude is plotted radially, and the angle is angular position along the great circle navigated by stripe 29. The diagram has been oriented so that the horizontal line at the base is the intersection of the plane of stripe 29 and the Galactic plane. Notice the new overdensity of A-type stars at $g_0 = 20.3$ at the right side of the figure. The dashed line that defines the intersection of the plane of orbit of the Sgr dwarf and the observation plane.

Fig. 2.— Plot of A-colored stars in SDSS stripes 27 through 37 ($100° < \alpha < 170°$). The x-axis shows $\Lambda_\odot$, in degrees, which is the angle, in the orbital plane of the Sgr dwarf galaxy, between each measured A-type star and the dwarf. It is the longitude, in a coordinate system where plane of the Sgr dwarf tidal debris has a latitude of zero degrees, and is the same angle plotted in Figure 8 of Majewski et al. (2003). The y-axis gives the g_0 magnitude for the same stars. Notice the overdensity of stars at about $g_0 = 20.3$ extending from $-148° < \Lambda_\odot < -172°$. This is a tidal tail of stars, close to the plane of the Sgr orbit, but at an implied distance of 90 kpc from the Galactic center.

Fig. 3.— The plane of the Sagittarius dwarf tidal debris. The 2MASS M giants from Figure 11 of Majewski et al. (2003) are reproduced here, along with the position and direction of motion of the Sgr dwarf galaxy (dark filled circle and line). Superimposed on the M giants are detections of SDSS A-colored stars in stripes 9-14, 27-37, 82 and 86 (points with error bars going counter-clockwise starting from the upper right). The Sun is at (X,Y,Z) = (-8.5,0,0) kpc. There is a 13% discrepancy in distance scale between the two data sets, reflecting uncertainties in the distance to Sgr and in the absolute magnitudes of A-colored stars and M giants. The four large open circles, showing the new tidal debris from stripes 27-37, could be a continuation of the trailing tail of the Sgr dwarf galaxy.

Fig. 4.— Cross section through the Sgr orbital plane. We show the positions of the stream centers of SDSS A-colored stars perpendicular to the plane of Sgr taken from Majewski et al. (2003). While the stars within 50 kpc of the Galactic center are very close to the plane, those at 90 kpc are as much as 10 kpc from the nominal orbital plane. The rightmost open circle shows the approximate position of the Sgr dwarf galaxy, with a nearly horizontal line showing the range of possible positions for heliocentric distances between 21 and 29 kpc. The leading tail (filled circles), trailing tail (open circles), and the newly detected disrupted material (larger open circles) are also shown. Note that the leading tail has a trend towards positive $Z_{Sag,GC}$ as one goes towards the Sgr dwarf, and the trailing tail tends towards more negative $Z_{Sag,GC}$ as one goes towards the Sgr dwarf.

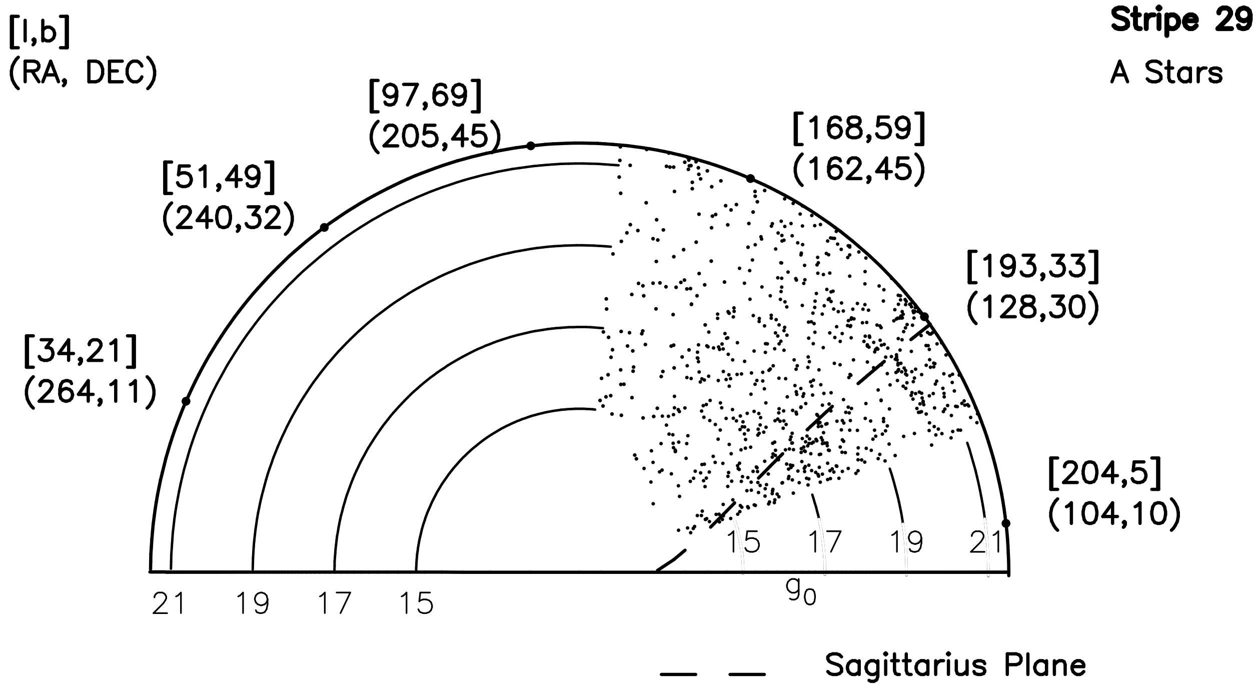
Table 1. Table of SDSS Stripes with Sgr Stream BHBs

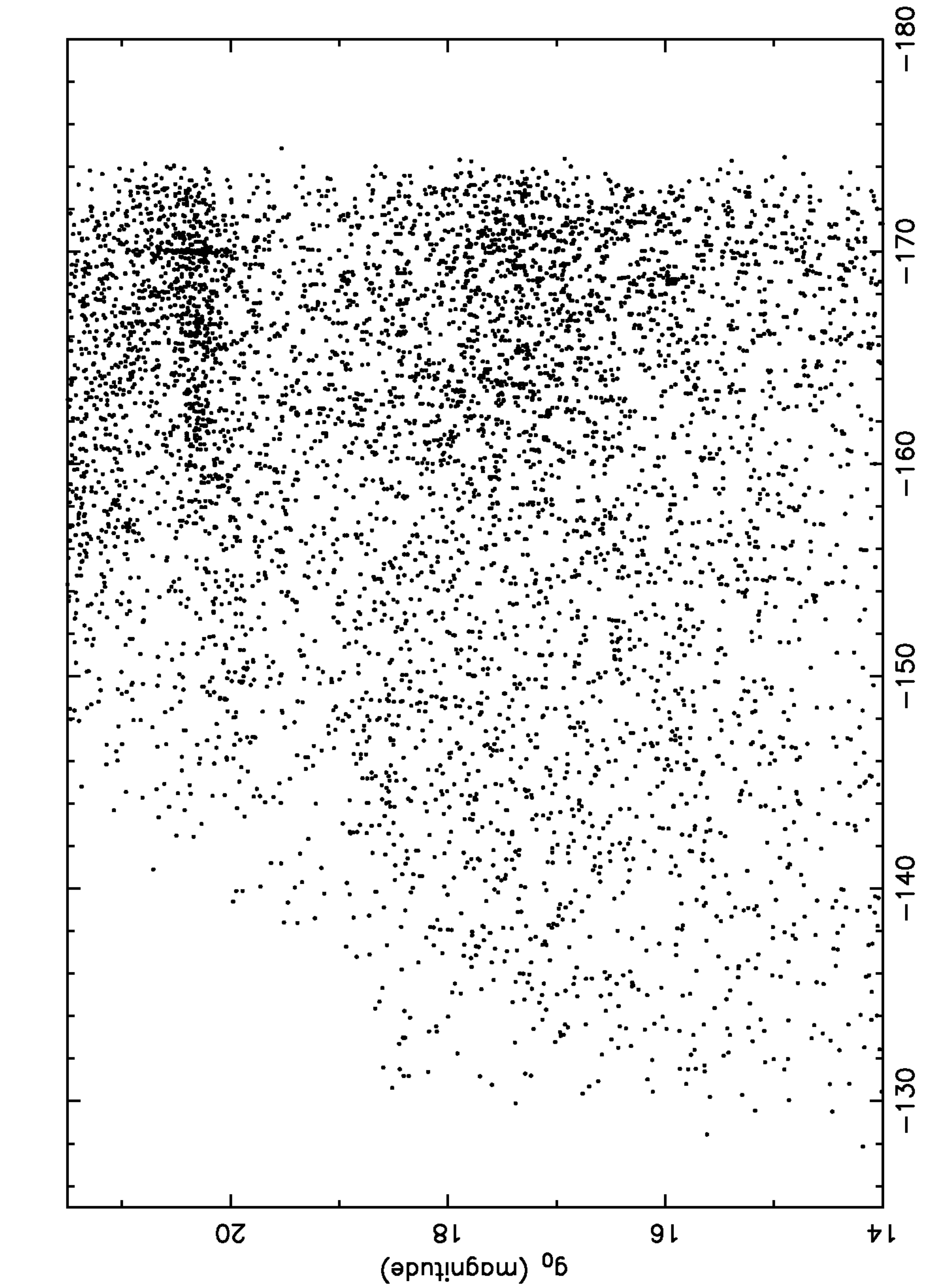
Stripe Number	incl.[1] °	l °	b °	g mag	d[2] kpc	N	angle to edge °
9	-2.5	347.9	51.4	19.15	49	115	19
10	0.0	343.2	56.1	19.12	48	125	34
11	2.5	330.2	62.6	18.9	44	58	37
12	5.0	323.7	66.3	18.8	42	60	38
14	10.0	284.0	72.0	18.6	38	25	30
27	42.5	197.0	34.0	20.30	83	55	13
28	45.0	194.0	34.0	20.30	83	48	11
29	47.5	195.4	28.5	20.30	83	58	10
30	50.0	194.3	27.0	20.30	83	31	10
31	52.5	191.7	28.1	20.30	83	39	11
32	55.0	190.1	27.3	20.30	83	24	9
33	57.5	188.7	26.5	20.30	83	45	9
34	60.0	187.2	25.6	20.35	85	39	9
35	62.5	184.4	26.1	20.35	85	31	7
36	65.0	186.7	21.3	20.35	85	16	3
37	67.5	182.5	23.2	20.35	85	113[3]	3
82	0.0	163.2	-56.1	18.0	29	35	42
86	10.0	148.8	-70.8	18.1	30	24	45

[1]Inclination of stripe relative to celestial equator, node is at $\alpha = 95°$.

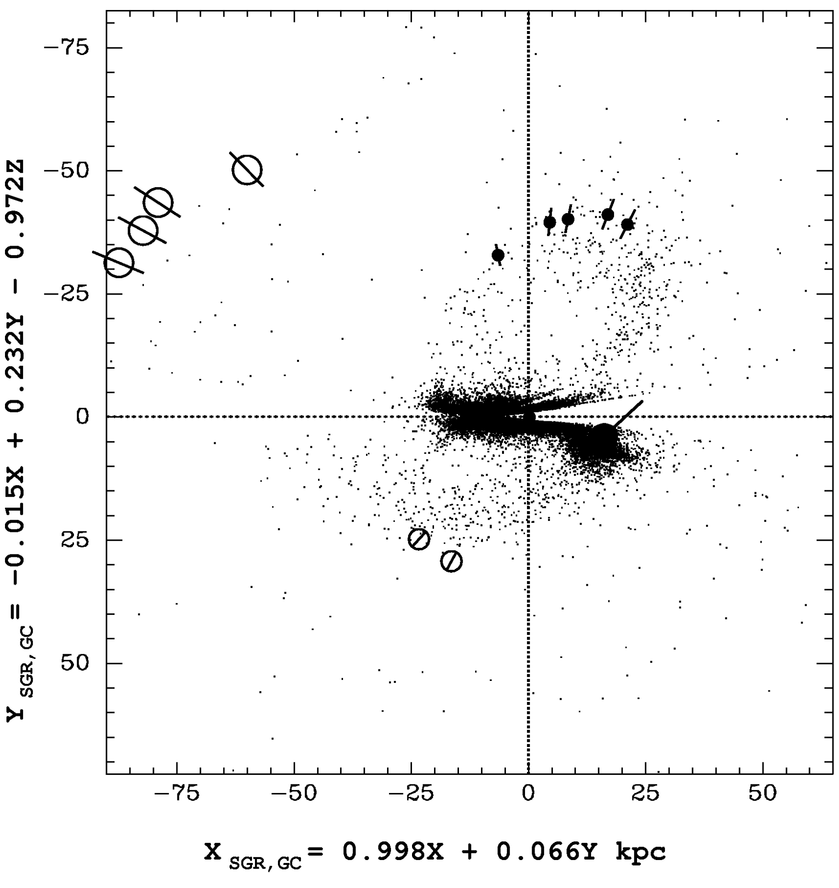
[2]Inferred distance of stars from the Sun, assuming $M_g(\mathrm{BHB}) = +0.7$.

[3]Includes NGC 2419 BHB stars.

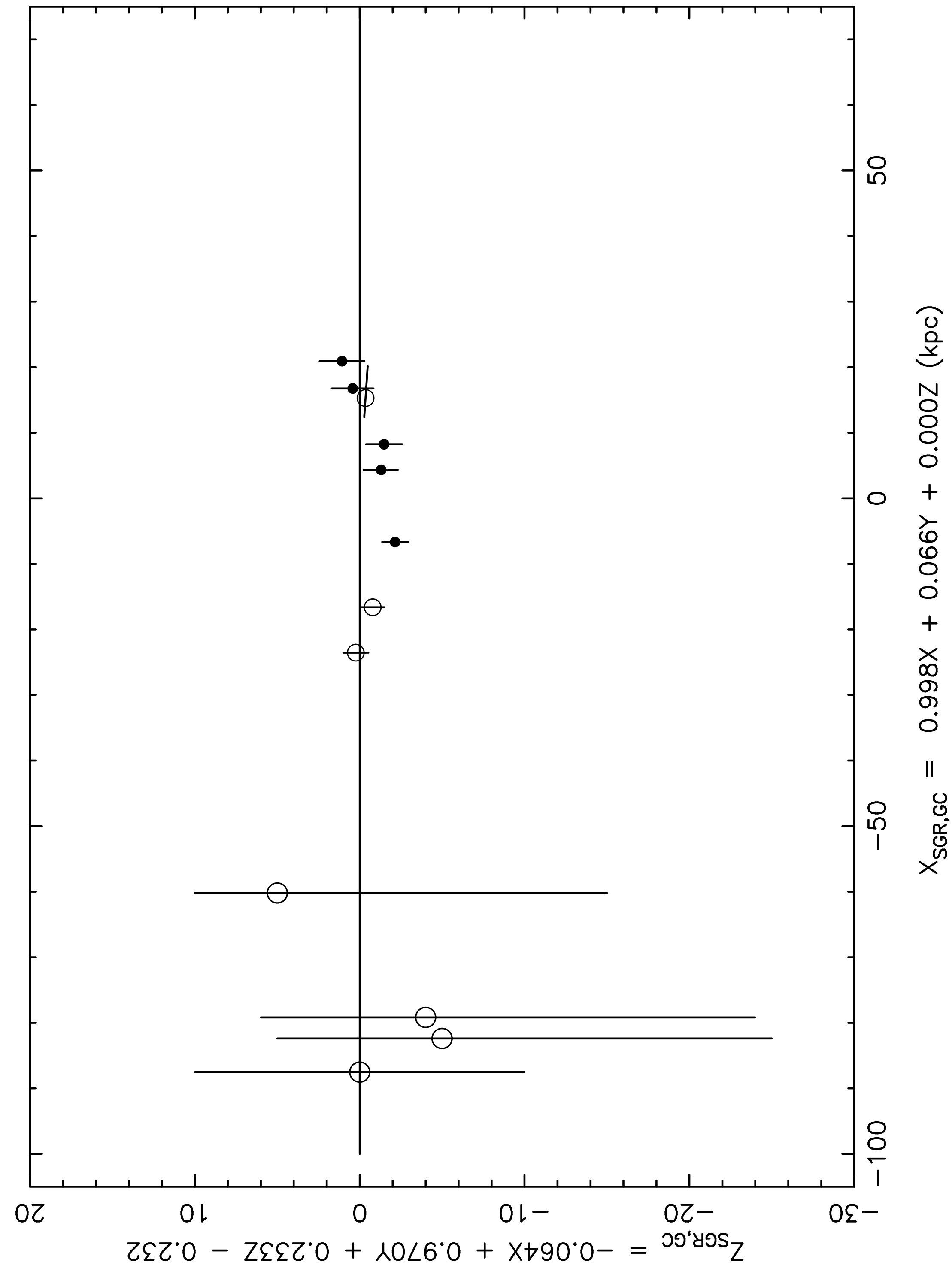

[l,b]
(RA, DEC)
Stripe 29
A Stars
[97,69]
(205,45)
[168,59]
(162,45)
[51,49]
(240,32)
[193,33]
(128,30)
[34,21]
(264,11)
[204,5]
(104,10)
15
17
19
21
21
19
17
15
g_0
Sagittarius Plane



−180
−170
−160
−150
−140
−130
$\Lambda_\odot$
14
16
18
20
g_0 (magnitude)



−75
−50
−25
0
25
50
−75
−50
−25
0
25
50
Y SGR,GC = −0.015X + 0.232Y − 0.972Z
X SGR,GC = 0.998X + 0.066Y kpc



$X_{SGR,GC}$ = 0.998X + 0.066Y + 0.000Z (kpc)
$Z_{SGR,GC}$ = −0.064X + 0.970Y + 0.233Z − 0.232
−100
−50
0
50
20
10
0
−10
−20
−30