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Discovery of a New, Polar-Orbiting Debris Stream in the Milky Way Stellar Halo

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ABSTRACT

We show that there is a low metallicity tidal stream that runs along $l = 143°$ in the South Galactic Cap, about 34 kpc from the Sun, discovered from SEGUE stellar velocities. Since the most concentrated detections are in the Cetus constellation, and the orbital path is nearly polar, we name it the Cetus Polar Stream (CPS). Although it is spatially coincident with the Sgr dwarf trailing tidal tail at $b = -70°$, the metallicities ([Fe/H] = -2.1), ratio of blue straggler to blue horizontal branch stars, and velocities of the CPS stars differ from Sgr. Some CPS stars may contaminate previous samples of Sgr dwarf tidal debris. The unusual globular cluster NGC 5824 is located along an orbit fit to the CPS, with the correct radial velocity.

Subject headings: Galaxy: structure — Galaxy: halo — Stars: kinematics

1. Introduction

Over the past decade, spatial substructure from tidally disrupted satellites has been discovered in the Milky Way's stellar spheroid (Newberg et al. 2002; Belokurov et al. 2006; Jurić et al. 2008; Grillmair 2008). However, we expect that a more detailed accretion history of the Milky Way can be assembled by including the kinematics of the stars (Harding et al. 2001), since the kinematic signature of each tidally disrupted satellite remains long after the spatial density has become such a small fraction of the stellar halo density that the stream cannot be identified from spatial information alone.

Recently, Yanny et al. (2009b) noticed a co-moving population of low metallicity blue horizontal branch stars (BHBs) with positions and velocities near, but not coincident with, the Sagittarius dwarf spheroidal trailing tidal stream in the South Galactic Cap, while studying spectra of Milky Way stars from the Sloan Digital Sky Survey (SDSS; York et al. 2000)

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and the Sloan Extension for Galactic Understanding and Exploration (SEGUE; Yanny et al. 2009a). The piece of this stream that nearly intersects with the Sgr tidal stream is at $(l, b) = (140°, -70°)$ and at a distance of 34 kpc from the Sun, with a line-of-sight, Galactic Standard of Rest velocity $v_{gsr} = -50$ km s^{-1} and metallicity [Fe/H] $\sim$ -2.0 (see figures 13 and 17 of Yanny et al. 2009b). In this paper, we explore the extent and kinematics of this new stream.

2. Observations and Data Analysis

We first identify SDSS/SEGUE data release 7 (DR7; Abazajian et al. 2009) spectra that are likely to be associated with the new stream. Figure 1 shows a color-magnitude diagram of all stellar objects in the South Galactic Cap with essentially zero proper motion and surface gravities of giant stars. Most of these stars are members of the stellar halo. Circled observations have the velocity and metallicity we expect for the new tidal stream.

SDSS/SEGUE data has very complex criteria for selecting the stars for spectroscopic observation, so structure in the distribution of stars in Figure 1 is dominated by selection effects. Since it is not possible to know the velocity of a star and it is difficult to determine the metallicity of a star before the spectrum is obtained, the selection is blind to these two quantities; therefore substructure can be identified by looking for regions of Figure 1 in which the ratio of circled to uncircled points is high. The three boxes labeled blue horizontal branch (BHB; $-0.3 < (g-r)_0 < 0.2, 0.8 < (u-g)_0 < 1.6, 17.7 < g_0 < 18.4$), red giant branch (RGB; $-12.75(g-r)_0 + 25.62 < g_0 < -12.75(g-r)_0 + 27.12$, $16.8 < g_0 < 17.8$), and lower red giant branch (LRGB; $0.47 < (g-r)_0 < 0.53, 18.5 < g_0 < 19.7$) in Figure 1 have a relatively high fraction of stars likely to be in the tidal stream, and comparison with M92 and M3 fiducials (An et al. 2008), shifted to 34 kpc, shows that they are also likely to be from the same stellar population. From the BHB fiducials we extracted from the An et al. (2008) data and distance moduli from Harris (1996), we estimate the absolute magnitude of the BHBs in the color range $-0.3 < (g-r)_0 < -0.2$, where most of the BHBs lie, is $M_{g_0} = 0.45$.

We will later show that this tidal debris stream follows fairly constant Galactic longitude, which will justify our current choice of plotting the velocities and apparent magnitudes of the stars as a function of Galactic latitude. The upper panel of Figure 2 shows the velocities of stars in the three color-magnitude boxes in Figure 1. The ones with lower metallicity are circled. The solid outline identifies stars with velocities of the Sgr trailing tidal tail (compare with Law, Johnston & Majewski 2005; Yanny et al. 2009b; $60° < \Lambda_{\odot} < 140°$). The dashed outline shows velocities of stars in the new stream. At higher Galactic latitude we relied primarily on the locus of low metallicity RGBs to select the velocities of stars in the new stream. The new stream has lower metallicity than those of the Sagittarius trailing tidal tail, as demonstrated by the fraction of larger to smaller, point-like symbols within the upper outlined region compared with the lower region with Sgr velocities.

We explore the distance to the tidal stream in the lower panel of Figure 2, which shows g_0 vs. b for the stars in the upper plot that are likely stream members, and photometrically selected BHBs in the region of the newly identified Cetus Polar Stream (CPS). We find an approximately linear relationship between g_0 and Galactic latitude ($g_0 = -0.0162b + 17.09$) in this portion of the stream. Distances were estimated and assuming $M_{g_0} = 0.45$. Distance estimates are tabulated in Table 1, with only statistical errors included. Distance errors may be systematically too high or too low by 10%, depending on the determination of the absolute magnitude of BHBs (Sirko et al. 2004).

The four panels of Figure 3 show (upper left) an estimate of the positions of the F turnoff stars in the CPS, and the positions of the photometrically selected BHB stars; (upper right) the (l, b) distribution of spectra with colors and magnitudes similar to those in the CPS; (lower left) the distribution of F turnoff stars in Sgr and the CPS, with the stars with CPS velocities superimposed; and (lower right) the same F turnoff stars with the stars with Sgr stream velocities superimposed. Note that there is an overdensity of photometrically selected BHB stars that lines up with the background-subtracted F turnoff star overdensity, and the CPS velocity-selected BHB, RGB, and LRGB stars, running approximately along Galactic latitude $l \sim 143°$. Stars that are velocity selected to be candidate Sgr stream stars follow a different path in the sky, along the Sgr dwarf tidal tail as tabulated in Newberg et al. (2003). Although the two streams cross near $b = -70°$, they are about 30° apart at $b = -30°$. The lack of significant numbers of colored points at $l < 110°$ or at $l > 160°$ (where the Sagittarius stream is located) gives us confidence that this stream is not an artifact, and is distinct from the previously identified Sagittarius trailing tail. The Galactic longitude of the stream center in each of the four SDSS stripes 76, 79, 82, and 86, was estimated by comparing the positions of the F turnoff stars, photometrically selected BHB stars, and velocity-selected BHB, RGB, and LRGB stars. One sigma errors were also estimated by eye. The stream centers and estimated errors are given in Table 1.

To estimate the metallicity of the CPS we histogramed spectroscopically selected candidate stream stars from Figure 3 that have $105° < l < 160°$. The peak of the distribution for BHB, RGB, and LRGB stars is [Fe/H] ~ -2.1. The formal mean metallicity of the stars is [Fe/H] $\sim -1.98 \pm 0.04$. There is a population of LRGB stars that is higher metallicity ([Fe/H] ~ -1.3). If this population is removed, then the formal mean is [Fe/H] $= -2.08 \pm 0.04$. Figure 17 of Yanny et al. (2009b) shows that the BHB stars in the CPS are slightly more metal poor than those of the Sgr dwarf trailing tidal stream, but both tidal streams may plausibly have a broad distribution of stellar ages and metallicities.

Table 1 summarizes the properties of the CPS at four Galactic latitudes, shown in Figures 2 and 3. In addition to the position, velocity, and distance of the stream as estimated from Figures 2 and 3, we list the approximate velocity dispersion of the line-of-sight velocities (σ_v), and the number of spectra at each location. The velocity dispersion for each stripe 76, 79, 82, and 86 is computed from the spectra with $120^\circ < l < 165^\circ$ that are shown in the lower left panel of Figure 3, and tabulated in Table 1. Since the intrinsic SDSS/SEGUE radial velocity errors are about 4 km s^{-1}, the intrinsic velocity dispersion of the CPS is about 4.5 km s^{-1} in stripes 76, 82, and 86, and about 10 km s^{-1} in stripe 79.

3. Discussion

The Cetus Polar Stream solves a puzzle long pondered by the authors. In Yanny et al. (2000) we discovered the Sgr dwarf tidal tails along the Celestial Equator, including the trailing tidal tail in stripe 82. We have always wondered why, in Fig. 3 of that paper, the BHB stars at $g_0 = 18$ in the South Galactic Cap appear offset in position in the sky from the Sgr blue straggler (BS) stars that are two magnitudes fainter. The counts of BHB and BS stars, as defined by Yanny et al. (2000), along southern SDSS stripes 79, 82, and 86 are presented in Figure 4. From this figure, we determine that many of the SDSS BHB stars in the southern stripes that had previously been attributed to the Sgr trailing tidal tail are actually in the CPS. The ratio of BS (higher surface gravity A-colored stars) to BHB stars varies amongst globular clusters (i.e. see Figures 12-16 of An et al. 2008), and can be used as an identifying marker in the halo to help separate two populations with distinct origins or evolutionary histories. From Figure 4, it is clear that the Sgr trailing tidal tail has a much larger BS/BHB ratio than the CPS.

We fit an orbit to the four CPS locations in Table 1, following the procedure used by Willett et al. (2009) and a spherical halo potential ($q = 1.0$). The average of the best fit orbit from five random starts of the fitting algorithm is shown by the solid black lines in Figures 2 and 3. The formal chi-squared per degree of freedom for this orbit is 1.08. Varying the halo flattening from 0.3 to 1.25 does not significantly change the goodness-of-fit, and changes the best fit orbit by less than the formal errors.

The CPS stars in the lower left panel of Figure 3 are spread over quite a range of Galactic latitudes (at least 15°, or $\sim$ 10 kpc), which argues in favor of a dwarf galaxy progenitor, though the low velocity dispersion ($\sim$ 5 km s^{-1}) argues for a diminutive dwarf galaxy or possibly a globular cluster. No known dwarf galaxies lie close to the best fit orbit, but the globular cluster NGC 5824, at $(l, b) = (332.5^\circ, 22^\circ)$ is located within 3° of the orbit, at a very plausibly correct distance, and has a radial velocity that matches the predicted orbit radial velocity within one sigma. NGC 5824 has a well-populated BHB and a measured [Fe/H]=-1.85. NGC 5824 measurements are taken from Harris (1996). Additionally, the tidal distortion of NGC 5824 measured by Grillmair et al. (2005) and Leon, Meylan & Combes (2000) is aligned with the CPS orbit. Grillmair et al. (2005) show that NGC 5824 has a central cusp; this massive globular cluster could have once been a dwarf galaxy core (Georgiev et al. 2009). Alternatively, it could be associated with the dwarf galaxy progenitor or be the sole progenitor.

4. Conclusions

A previously unknown, low metallicity tidal debris stream is identified at $l = 143^\circ$ and 34 kpc from the Sun in the South Galactic Cap. Although it is spatially coincident with the Sgr dwarf trailing tidal tail at $b = -70^\circ$, the metallicities ([Fe/H] = -2.1), ratio of BS/BHB stars, and velocities of the Cetus Polar Stream stars are significantly different. Some BHB stars that have been attributed to the Sgr trailing tidal tail by previous authors are instead part of the CPS. Both the width of the tidal stream ($\sim$ 10 kpc) suggests a dwarf galaxy progenitor, though the velocity dispersion ($\sigma \sim 5$ km s^{-1}) opens the possibility for a globular cluster progenitor. The globular cluster NGC 5824 is located on the CPS orbit with the correct radial velocity, distance, and plausible metallicity. It is additionally elongated along the orbit. NGC 5824 could be the progenitor, the core of a dwarf galaxy progenitor, or associated with a dwarf galaxy progenitor. This stream was discovered from a study of SDSS/SEGUE velocities, which allowed us to separate it from the Sgr trailing tidal tail even though they intersect spatially.

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Table 1. Cetus Polar Stream Detections

l °	δl °	b °	v_{gsr} km s^{-1}	σ_v km s^{-1}	N	d kpc	δd kpc
144	2	-71	-29.8	6.4	4	36.1	1.9
144	3	-62	-42.7	6.5	8	33.8	1.8
142	3	-54	-39.2	11.1	16	31.8	1.7
142	4	-46	-59.2	5.8	14	30.1	1.6

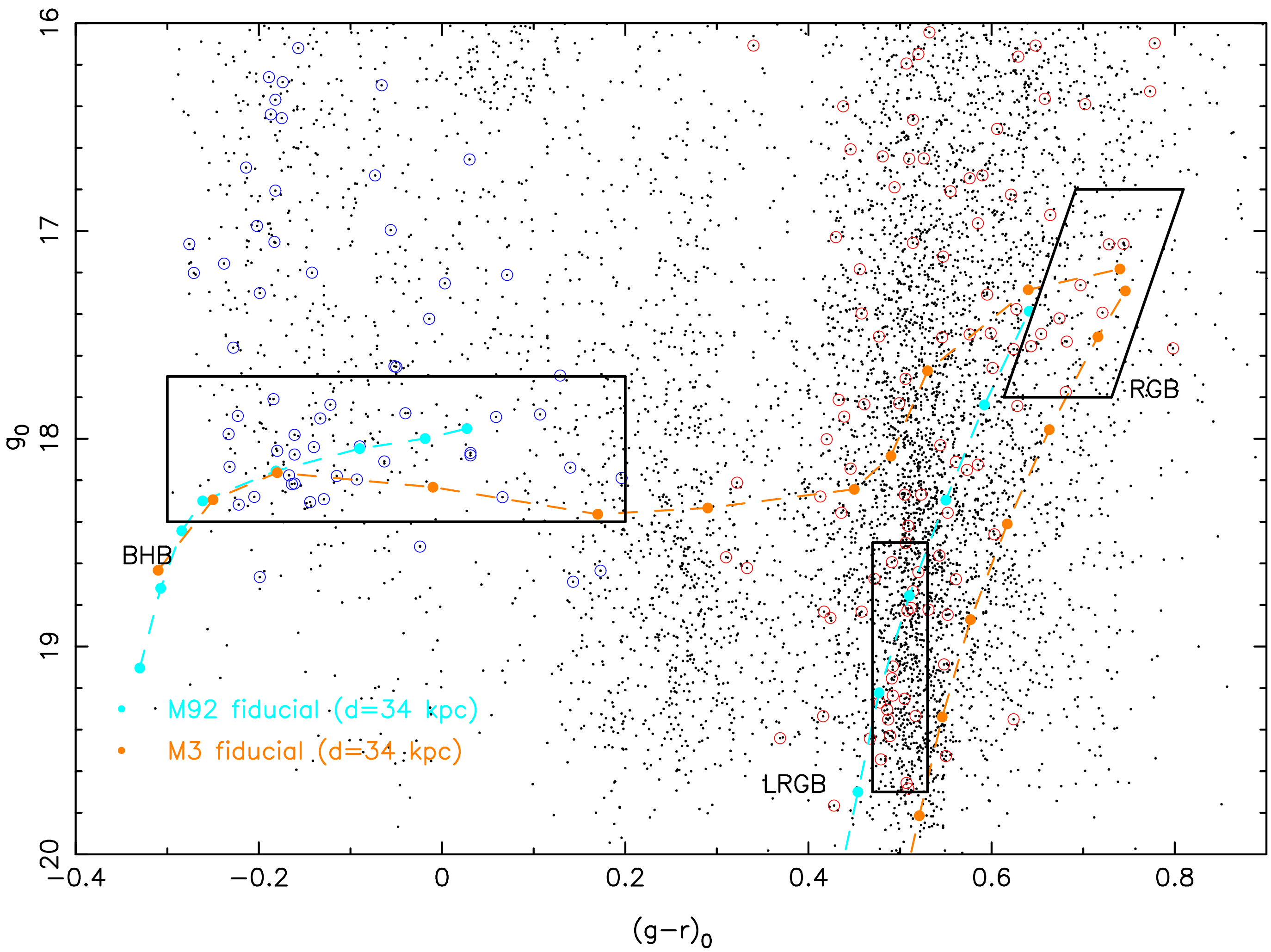

Fig. 1.— We show as small black dots the color and g_0 magnitude for all the SDSS DR7 stellar spectra in the South Galactic Cap ($b < 0°$) with surface gravities of giant stars ($1 < \log g < 4.0$), and essentially zero proper motion ($|\mu_l| < 6$ mas yr^{-1}, $|\mu_b| < 6$ mas yr^{-1}). These cuts select objects likely to be in the stellar halo. The circles show those points that have velocities and metallicities consistent with membership in the new stellar stream ($-77 < v_{gsr} < 0$ km s^{-1}, $-4 <$ [Fe/H] < -1.9. Stars with $-0.3 < (g-r)_0 < 0.2$ are likely BHB stars, so for these stars we used the SDSS [Fe/H]$_{WBG}$ metallicity measurement (blue circles). The stars with $0.3 < (g-r)_0 < 0.8$ are likely giant stars, so in this color range we used the SDSS [Fe/H]$_a$ metallicity measurement (red circles). Fiducial sequences for M92 and M3, shifted to 34 kpc, are shown for reference.

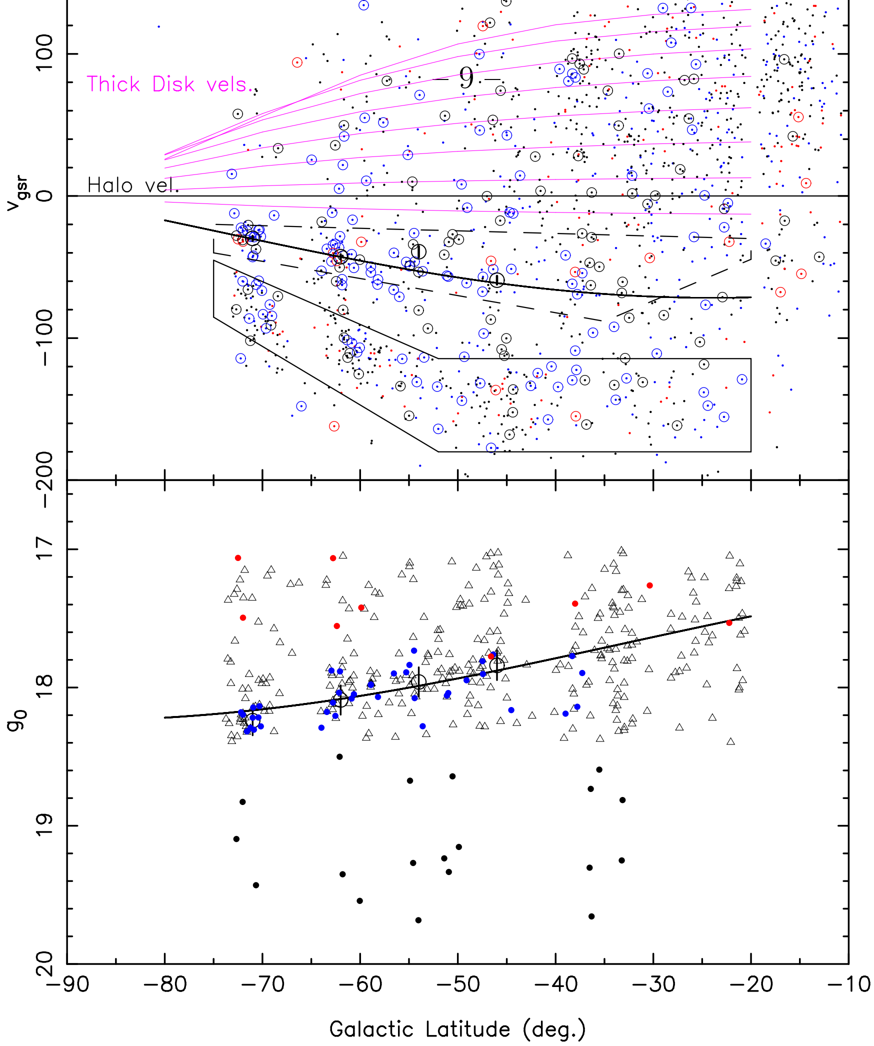

Fig. 2.— The top panel shows velocities of the stars in the color-magnitude boxes in Figure 1. Spectra with metallicities of $-4 < [Fe/H] < -1.9$ are circled. (Note that the circled points are not selected in velocity as they were in Figure 1.) The solid line boxed region shows stars with the velocities of the Sgr dwarf trailing tidal tail. Note that many of the stars in this stream have metallicities higher than -1.9, and are therefore not circled. The boxed region with the dashed line shows the velocity of the newly identified tidal debris. Note in particular that there are very few RGB candidates with low metallicity outside of the Sgr stream and the new stream. There are a few low metallicity RGB stars with $v_{gsr} \sim 150$ km s^{-1} that may have a kinematic association with another (unrelated) structure. We overlay the calculated velocities of thick disk stars with $50° < l < 190°$ (top to bottom) in magenta to show there is no confusion with stream candidates even if log g is misidentified. Filled circles in the lower panel show the apparent magnitudes of the stars in the upper panel that have metallicities and velocities of the new stream (all circled stars inside the dashed box in the upper panel, using the same color code). The triangles show photometrically selected BHB stars (see Yanny et al. 2000 for photometric selection technique) that have $120° < l < 165°$. The trend of distance with b is consistent between photometrically selected BHBs and those with spectra. Note that many of the LRGB stars in the new stream are too faint to be included in the SDSS/SEGUE spectroscopic survey, and the intrinsic magnitude distribution of RGB and LRGB stars is very broad. The adopted mean stream velocities (upper panel) and apparent magnitude of the BHB stars (lower panel) are shown as open circles with errors, and a solid black curve shows the best fit orbit through those stream locations in both panels.

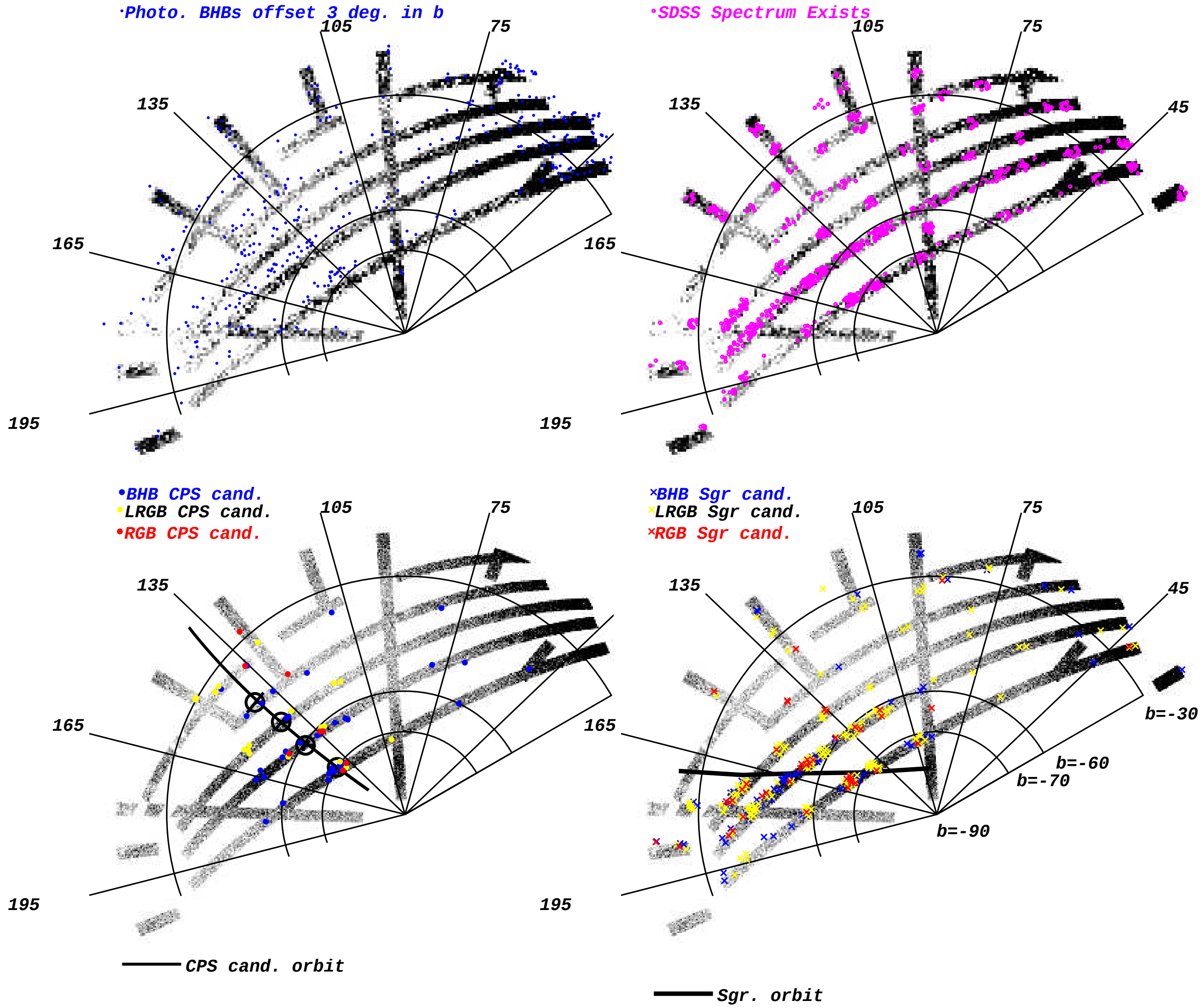

Fig. 3.— The upper left panel shows the density of turnoff stars in a CPS color magnitude box ($20.25 < g_0 < 21.5, 0.22 < (g-r)_0 < 0.36$) minus the density of stars in a Sgr box ($20.35 < g_0 < 21.85, 0.10 < (g-r)_0 < 0.20$) in polar Galactic coordinates, origin at the SGP. The overdensities (dark areas) running along $l = 140°$ from $b = -70°$ up to $b = -40°$ show the CPS. The blue dots in the upper left panel show the positions (offset 3° in b for clarity) of photometrically selected CPS candidate BHBs, with $-0.0162b+16.94 < g_0 < -0.0162b+17.24$. Note the excess along $130° < l < 150°, -70° < b < -40°$. The upper right panel shows (magenta circles) the locations of stars with SDSS/SEGUE spectra in the color-magnitude selection boxes of Figure 1, showing the completeness coverage of the spectroscopy relative to the imaging. The lower left panel shows the density of turnoff stars with $20.5 < g_0 < 22.5, 0.26 < (g-r)_0 < 0.30, (u-g)_0 > 0.4$, highlighting both the Sgr and Cetus debris streams (the Sgr tidal stream is more prominent). The filled circles show the stars with velocities and metallicities consistent with membership in the new CPS, color coded by spectral type. The heavy black curve shows the best fit orbit for the CPS structure. The lower right panel shows (crosses) the positions of low metallicity stars with spectra in the upper panel of Fig. 2 that have the velocities of the Sgr trailing tidal tail (the low metallicity subset of SDSS/SEGUE Sgr spectra), along with a Sgr locus (heavy line).

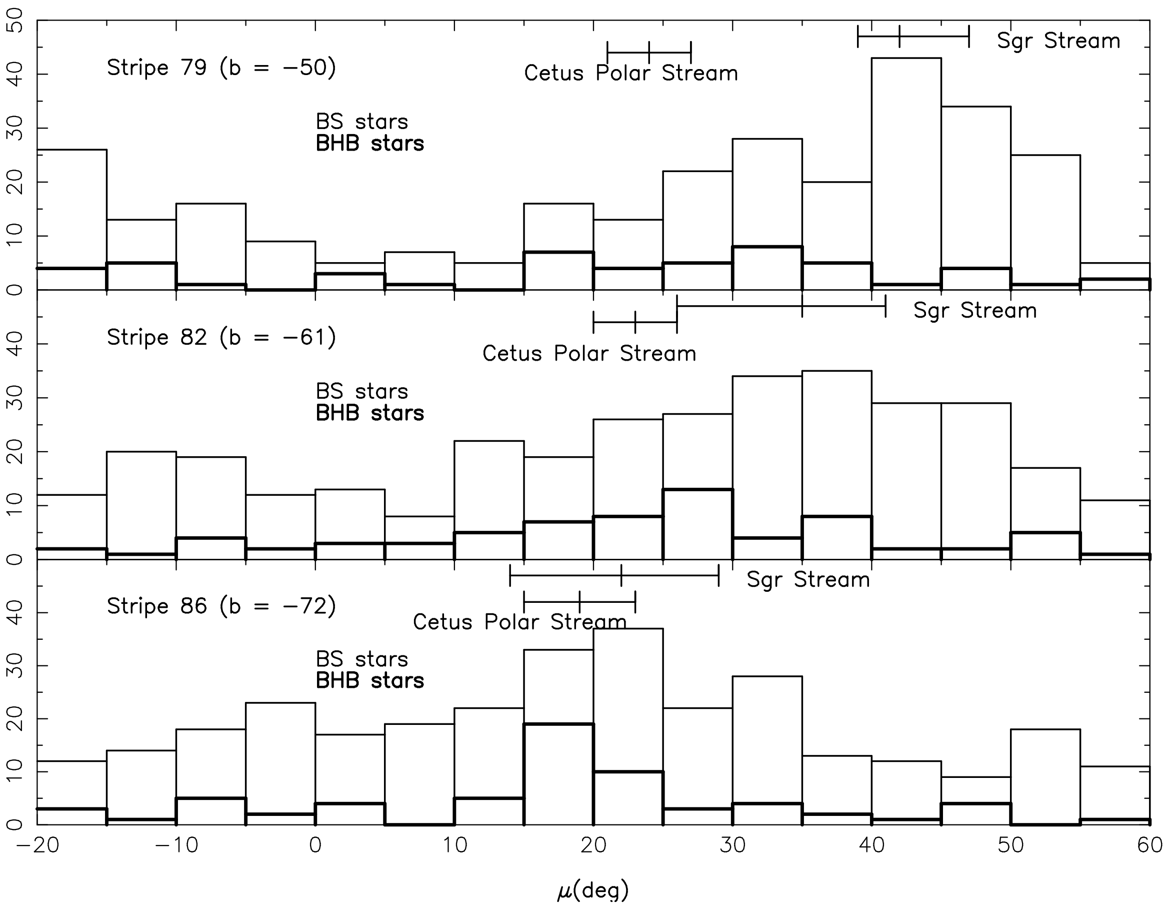

Fig. 4.— We show the number of photometrically selected BHB and BS stars in SDSS stripes 79, 82, and 86, in the South Galactic Cap. The stars are selected from SDSS imaging data with $-0.3 < (g-r)_0 < 0.0$, $0.8 < (u-g)_0 < 1.6$ and color separated into BHBs and BSs using the line in Figure 10 of Yanny et al. (2000), and the BSs are 2 mags fainter intrinsically than the BHBs. The x-axis gives angular distance along the SDSS stripe (SDSS survey longitude, μ), which is identical to right ascension α for stripe 82, and deviates from α by less than two degrees for the nearby stripes 79 and 86. The regions where the Cetus Polar Stream and the Sgr stream intersect each stripe are indicated by the horizontal bars near the top of each panel. Note that there is considerable overlap between the two streams in stripe 86 (lower panel), while they are largely disjoint in stripe 79 (upper panel). The relative number of BS/BHB stars, a ratio which may be regarded as an intrinsic property of a region of an individual stream, differs significantly between the two streams.