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 the Sloan Extension for Galactic Understanding and Exploration 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 stragglers 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 fitted to the CPS, with the correct radial velocity.

Key words: Galaxy: halo – Galaxy: structure – 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; Juric 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 so small a 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) 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] = −2.0 (see Figures 13 and 17 of Yanny et al. 2009b). In this Letter, 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 have 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; $-12.75 < (g-r)_0 + 25.62 < 90 < -12.75(g-r)_0 + 27.12, 16.8 < g_0 < 17.8$), 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 $M_{g0} = 0.45$.

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 et al. 2005; Yanny et al. 2009b; $60° < l_0 < 140°$). 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 (Sgr) trailing tidal tail, as demonstrated by the fraction of larger to smaller, pointlike 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 $g_0$ versus $b$ 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 assuming $M_{g0} = 0.45$. 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 $l \sim 143^\circ$. 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 $b = -70^\circ$, they are about 30$^\circ$ apart at $b = -30^\circ$. The lack of significant numbers of colored points at $l < 110^\circ$ or at $l > 160^\circ$ (where the Sgr stream is located) gives us confidence that this stream is not an artifact, and is distinct from the previously identified Sgr 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. 1$\sigma$ 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 histogrammed spectroscopically selected candidate stream stars from Figure 3 that have $105^\circ < l < 160^\circ$. The peak of the distribution for BHB, RGB, and LRGB stars is $[\text{Fe/H}] \sim -2.1$. The formal mean metallicity of the stars is $[\text{Fe/H}] \sim -1.98 \pm 0.04$. There is a population of LRGB stars that is higher metallicity ($[\text{Fe/H}] \sim -1.3$). If this population is removed, then the formal mean is $[\text{Fe/H}] = -2.08 \pm 0.04$. 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,
3. DISCUSSION

The CPS 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 Figure 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 2 mag 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 $15^\circ$, or $\approx 10$ kpc), which argues in favor of a dwarf galaxy progenitor, though the low-velocity dispersion ($\approx 5$ 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 $(l, b) = (332.5, 22^\circ)$ is located within $3^\circ$ of the orbit, at a very plausibly correct distance, and has a radial velocity that matches the predicted orbit radial velocity within $1\sigma$. NGC 5824 has a well populated BHB and a measured $[\text{Fe/H}] = -1.85$. NGC 5824 measurements are taken from Harris (1996). Additionally, the tidal distortion of NGC 5824 measured by Grillmair et al. (2005) and Leon et al. (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 CPS 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. The width of the tidal stream ($\approx 1$ kpc) suggests a dwarf galaxy progenitor, though the velocity dispersion ($\sigma \approx 5$ 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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