AN ORPHAN NO LONGER? DETECTION OF THE SOUTHERN ORPHAN STREAM AND A CANDIDATE PROGENITOR

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ABSTRACT

Using a shallow, two-color survey carried out with the Dark Energy Camera, we detect the southern, possibly trailing arm of the Orphan Stream. The stream is reliably detected to a decl. of $-38^\circ$, bringing the total known length of the Orphan Stream to $108^\circ$. We find a slight offset or “S” shape in the stream at $\delta \approx -14^\circ$ that would be consistent with the transition from leading to trailing arms. This coincides with a moderate concentration of 137 $\pm$ 25 stars (to $g = 21.6$) that we consider a possible remnant of the Orphan progenitor. The position of this feature is in agreement with previous predictions.

Key words: Galaxy: halo – Galaxy: structure

1. INTRODUCTION

The Orphan Stream was among the first stellar debris streams detected in the Sloan Digital Sky Survey (SDSS; Belokurov et al. 2006, 2007; Grillmair 2006). Populous and roughly $2^\circ$ wide on the sky, the stream is clearly much broader and stronger than known globular streams such as Pal 5 (Odenkirchen et al. 2003; Grillmair & Dionatos 2006a). This, along with subsequent findings of a metallicity dispersion of $\sigma_{\text{[Fe/H]}} = 0.56$ dex (Casey et al. 2013) and a metallicity gradient amplitude of 0.3 dex (Sesar et al. 2013) led researchers to conclude that the Orphan Stream must be the remnant of a dwarf galaxy. Early modeling efforts suggested that the stream might be related to the neutral hydrogen Complex A (Fellhauer et al. 2007; Jin & Lynden-Bell 2007) and that the progenitor of the stream might be the nearby dwarf galaxy UMa II (Fellhauer et al. 2007). However, subsequent work by Sales et al. (2008) and Newberg et al. (2010) does not support these ideas.

Newberg et al. (2010) used measured positions and velocities to derive an orbit of the stream and determined that the orbit is prograde, moderately inclined to the Galactic plane ($i \approx 34^\circ$), fairly eccentric ($e \approx 0.7$), extending out to $\approx90$ kpc from the Galactic center, and the portion of the stream visible in the SDSS footprint is the leading arm. Based on the rising surface density of the stream at the southern edge of the SDSS footprint (in the direction of decreasing Galactocentric radius and far from apogalacticon), they also suggested that the progenitor would most likely be found between decl. of $0^\circ$ and $-16^\circ$.

In this Letter, we describe the first results of a shallow imaging survey designed to trace the Orphan Stream well south of the SDSS footprint. We briefly describe the observations in Section 2. We analyze the spatial and color–magnitude characteristics of the stream in Section 3. Concluding remarks are given in Section 4.

2. OBSERVATIONS

Using the Orphan orbit estimation of Newberg et al. (2010) as a guide, we imaged a $9^\circ-15^\circ$ wide swath of sky extending from the celestial equator to $\delta \approx -53^\circ$ and covering an area of 487 deg$^2$. This was carried out during just two observing nights using the remarkably efficient Dark Energy Camera (DECam) on the Blanco 4-m telescope at the Cerro Tololo Interamerican Observatory (CTIO). Observations were made in $g$ and $i$, and exposures were kept to two 30 s dithers per field to maximize the area covered while still reaching well past the main-sequence turnoff of the stream. Observations were carried out over two observing seasons, with one night in 2014 March and another in 2015 March. Conditions were photometric during both nights, with typical seeing of 0.9″ in $i$ and 1″–1.2″ seeing in $g$, though with excursions of $>2$″ for a short period during the 2014 run.

The resulting 6.3 TB of data were processed using the 2015 version of the DECam Community Pipeline (Valdes et al. 2013). (2014 data were reprocessed with the 2015 pipeline to take advantage of several improvements.) The data were subsequently transferred to the University of Toronto, where a photometry pipeline based on SExtractor and PSFEx (Bertin & Arnouts 1996) was constructed to photometer individual images using point-spread function (PSF) fitting.

PSFs, aperture corrections, and second-order color terms were computed for each individual detector. The photometry was calibrated against the SDSS catalog using $\approx20$ deg$^2$ of imaging in the Sloan footprint. Average atmospheric extinction coefficients for CTIO were used throughout. Stars were typically observed at least twice in each filter (with the exception of a small number of stars falling within the CCD gaps), and the individual photometric measurements were combined over all relevant fields and over both observing runs. Within the SDSS footprint, calibration is good to 0.02 mag rms.

Perhaps owing to the variable nature of the PSFs over a field as large as that of DECam, we found that the star/galaxy separation parameter “CLASS_STAR” was rather unreliable, with a spread that varied considerably from the center to the edge of each field. Hence, we relied primarily on the “FWHM_WORLD” and “ELLIPITCITY” parameters to excise sources that were clearly extended. Imposing limits of FWHM_WORLD $< 3^\circ$, ELLIPITCITY $< 0.2$, FLAGS = 0, and $16 < g < 21.6$ reduced a catalog of 15 million sources to 3.5 million. The FWHM_WORLD and ELLIPITCITY cuts were deliberately somewhat generous, as tighter constraints resulted in an obvious diminution of source counts from the
center to the edge of each field. These limits necessarily entail
the inclusion of some background galaxies, which will
contribute additional noise to the filtered maps, but with a
limit of $g = 21.6$ this should not be excessive.

Some calibration issues remain unresolved. For example,
star counts appear rather more sensitive to airmass than we
expect. While many of our fields are essentially complete to
$g \approx 23$, others (with airmasses $\geq 2$) are complete to only $g \approx 21.7$. These issues will be further explored in a forthcoming
collection. For our present purposes, we avoid these issues
by simply cutting off our sample at $g = 21.6$.

3. ANALYSIS

We used a matched filter to optimally separate the metal-
poor stars of the Orphan Stream from the much larger
population of foreground disk stars (Rockosi et al. 2002;
Grillmair 2009). This technique has been used to detect several
streams at surface densities as low as 10 stars deg$^{-2}$ (Grillmair
2006, 2009, 2011; Grillmair & Dionatos 2006a, 2006b; Bonaca
et al. 2012). We generated a filter based on the Padova database
of theoretical stellar isochrones (Marigo et al. 2008; Girardi
et al. 2010), selecting for stars with $[\text{Fe}/H] = -1.6$. All stars
with $16 < g < 21.6$ were used, and we dereddened the
photometry as a function of position on the sky using the
DIRBE/IRAS dust maps of Schlegel et al. (1998), corrected
using the prescription of Schlafly & Finkbeiner (2011). The
foreground population was sampled in stream-free regions
extending along the edges of our survey area. Figure 1 shows
the filtered star count distribution using a filter based on an
isochrone with $Z = 0.0005$ and an age of 12 Gyr, optimized for
populations at a distance of 18 kpc.

Nearly centered within the survey area is a long, broad
feature extending to nearly $-40^\circ$. The 18 kpc distance used in
Figure 1 corresponds to the strongest stream signal and roughly
matches the 19–21 kpc range of distances expected on the basis
of an orbit fit to Newberg et al.’s (2010) data compilation for
the northern Orphan Stream. Differences may be due to
inaccurate matching of the DECam $g$ and $i$ photometry to the
Sloan filters assumed by the Padova isochrones, or possibly a
metallicity gradient in the Orphan Stream (Sesacer et al. 2013).
It may also be that 18 kpc is the correct distance of the stream in
this region, and that the actual orbit of stream stars in this
region needs to be refined.

The northern $10^\circ$ of the detected stream matches nicely with
the portion of the stream detected in the Sloan footprint. An
FWHM of $\approx 1.5–2^\circ$ is also consistent with that observed in
the northern stream. The stream appears to be reliably detected to
$\delta \approx -38^\circ$, below which the character of the distribution
changes significantly (see below). This brings the known length
of the stream to $\approx 108^\circ$. Over the southern interval
$-18^\circ < \delta < -38^\circ$, we find the stream is well fit (to within
$0.25^\circ$) by a polynomial of the form:

$$\alpha = 163.147 - 0.0896 \times \delta + 0.00804 \times \delta^2. \quad (1)$$

Figure 2 shows the distribution of $E(B - V)$ over our survey
area from the maps of Schlegel et al. (1998). A comparison of
Figures 1 and 2 shows that the pattern of the star counts in the
region $-39^\circ > \delta > -45^\circ$ closely matches the filamentary
distribution of dust emission and enhanced reddening.
Dereddening our photometry has evidently pulled an excess
of fainter and redder stars into the sample. Whereas $E(B - V)$ is
fairly uniform and ranges from 0.02 to 0.06 over the northern

Figure 1. Filtered surface density map of our Decam survey area, overlaid on
the SDSS DR10 footprint. The stretch is linear, with lighter areas indicating
higher surface densities. The map is the result of a filter based on a Padova
isochrone with $[\text{Fe}/H] = -1.6$, an age of 12 Gyr, and shifted to a distance of
18 kpc. The Sloan data have been smoothed with a 0.3 Gaussian kernel while
the Decam map, owing to its somewhat shallower depth, has been smoothed
with a 0.5 kernel. Seeing was $0.9–1.7^\prime$ over most of the survey area, with two
stripes ($-37^\circ > \delta > -41^\circ$, $-45^\circ > \delta > -48^\circ$) having seeing in excess of $2^\prime$.
The highest airmasses ($>1.8$) occurred at $\delta > -7^\circ$.

Figure 2. Distribution of $E(B - V)$ over the field shown in Figure 1. Lighter
areas indicate higher color excesses. Values of the color excess range from 0.02
in the darkest, northern reaches of the survey to 0.3 in the brightest filaments at
$\delta = -43^\circ$. 

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half of the survey area, the filamentary structures at \( \delta \approx -43^\circ \) show color excesses ranging from 0.2 to 0.3. Arbitrarily scaling down the Schlafly & Finkbeiner (2011) absorption coefficients reduces the effect, but does not yield any convincing signatures of an underlying stream. Tracing the stream through this region would presumably benefit in the near term from a deep, near-infrared survey, though it should ultimately be detected in \textit{Gaia} proper motion data.

Figure 3 shows a color–magnitude distribution of stars chosen to lie within \( \pm 1^\circ \) of the centerline of the Orphan Stream north of \( \delta = -36^\circ \). Overplotted are isochrones for populations with \( Z = 0.0001 \) ([Fe/H] = −2.1) and \( Z = 0.0005 \) ([Fe/H] = −1.6). \( Z = 0.0005 \) appears to match the main sequence somewhat better than \( Z = 0.0001 \), which corresponds to the metallicity found by Newberg et al. (2010) for the blue horizontal branch stars. The value [Fe/H] = −1.6 used in Figure 1 matches a measurement of [Fe/H] = −1.63 found by Casey et al. (2013) for red giants. Note that Sesar et al. (2013) see evidence for a metallicity gradient in the northern stream, with the nearer, more southerly stars being \( \approx 0.3 \) dex more metal rich than the more northerly, more distant stars.

Figure 4 shows the southern Orphan Stream in greater detail. Overplotted is an orbit fit to the data collected by Newberg et al. (2010) for the northern Orphan Stream. This orbit was computed using the Galactic model of Allen & Santillan (1991), which assumes a spherical halo. The orbit generally matches the trajectory of the southern stream, though offset somewhat toward the east below \( \delta \approx -14^\circ \). There are a number of possible reasons for the offset: (i) the orbit calculation did not take into account the southern stream (which as of yet has no velocity information), (ii) the effects of halo flattening or triaxiality have not been considered, or (iii) we may be looking at the trailing arm of the stream.

If we use the northern orbit fit as a guide, we see that while it appears to fit the stream reasonably well north of \( \delta \approx -14^\circ \), an eastward offset of \( \approx 1.5^\circ \) begins rather suddenly south of \( \delta = -14^\circ \) and stays roughly constant to \( \delta = -38^\circ \). At (R.A., dec.) = (167°, −14°), midway between the northern orbit fit and the run of Equation (1), there is a moderate but significant, \( 1.5^\circ \) wide overdensity of stars that is somewhat larger and stronger than the clumps to the immediate north or south. This clump appears to be the extended, northern portion of a feature found by Newberg et al. (2010) in an “outrigger” SEGUE stripe at \( \delta \approx -15^\circ \). We hypothesize that the transition from the northern to the southern portions of the stream is the “S-shape” signature expected from a progenitor losing stars from its first and second Lagrange points. We further suggest that this clump of stars could be the remnant of the progenitor of the Orphan Stream.

Based on the rise and fall of stream surface density with position along the stream, Newberg et al. (2010) predicted that the progenitor of the Orphan Stream should be situated between \( \delta = 0^\circ \) and \( \delta = -16^\circ \). This is consistent with the position of our overdensity at \( \delta \approx -14^\circ \). Moreover, Newberg et al. (2010) determined that the northern portion of the Orphan Stream must be the leading arm. Tidal stripping in a constant-\( V_c \) potential requires that the leading arm should be made up of stars released from progenitor’s first Lagrange point into orbits.
of lower Galactocentric radius $R$. Conversely, the trailing arm will be made up of stars lost from the second Lagrange point, falling behind the progenitor and orbiting at larger $R$. This is consistent with Figure 4; the westward offset of the southern portion of the stream takes it further away from the Galactic center, which is to the left in the figure.

At a distance of 18 kpc, a 1.25 offset corresponds to $\approx 470$ pc. The L1 and L2 lagrange points will always be aligned along a radial to the Galactic center. At the current position of the putative progenitor, we would be viewing it at an angle of $\approx 23^\circ$ from the L1–L2 radial. If indeed the northern and southern Orphan Streams are leading and trailing arms, respectively, then the implied physical separation would be 1.2 kpc. We consequently take the upper limit on the tidal radius of the progenitor to be 600 pc.

The number of stars within the putative progenitor is not large. Examining a square region 1°x1 on a side and centered on (R.A., decl.) = (167°125. −14°273) and comparing with background fields to the east and west, we count stars with $0.16 < g < 0.44$ and $19.9 < g < 21.6$. Scaling by the area ratios, we find a background-subtracted count of 137 ± 24 stars. Integrating over the luminosity function of Omega Cen (de Marchi 1999), we arrive at an approximate total population of 2100 ± 400 stars. If this clump is indeed the progenitor of the Orphan Stream, then it would appear to be virtually the last remnant of the original satellite. The surface density of the object is proportional to $r^{-0.7 \pm 0.3}$, making it unlikely that the feature could be gravitationally bound.

By definition, the tidal radius $r_t = (M_p/2M_G(R))R^3$ in a flat rotation curve, where $M_G(R)$ is the mass of the Galaxy within Galactocentric radius $R$ and $M_p$ is the mass of the progenitor. If we take $R = 21$ kpc and $M_G(R) = 1–2 \times 10^{11}$ $M_\odot$, we arrive at an upper limit on the progenitor’s recent mass of $\sim 4.7–9.3 \times 10^6$ $M_\odot$. Depending on the number of red giants, the luminosity of the object could range from $1 \times 10^4$ to $4 \times 10^5 L_\odot$. If a bound object remains, then $M/L \sim 120–930$ $M_\odot/L_\odot$.

Using the luminosity–metallicity relation of Kirby et al. (2011), the [Fe/H] = −1.6 measurement of Casey et al. (2013) suggests a total luminosity of the original progenitor of $2.5 \times 10^6 L_\odot$. On the other hand, Newberg et al.’s (2010) value of [Fe/H] = −2.1 implies $6 \times 10^5 L_\odot$. Our luminosity estimate above would suggest that the progenitor has lost between 94% and 100% of its original mass.

There are other surface density peaks evident in Figure 4, but we are less inclined to consider these as progenitor candidates as they do not show the morphological indicators (e.g., offsets) we would associate with the transition from leading to trailing arms. Given the orientation of the Orphan Stream and our view of it, such a feature should be readily apparent.

We note also that near the southernmost end of the survey area is the globular cluster Ruprecht 106. This cluster is situated along the plausible extension of the Orphan Stream. However, while its metallicity of [Fe/H] = −1.67 (Harris 1996) is similar to that of the Orphan Stream, its distance of 12 kpc and radial velocity of $-44$ km s$^{-1}$ are at odds with values of 21 kpc and $+72$ km s$^{-1}$ predicted by the orbit fit to the northern Orphan Stream. We conclude that Ruprecht 106 is unlikely to be physically associated with the stream.

4. CONCLUSIONS

Using a large, shallow DECam survey, we have traced the Orphan Stream from the celestial equator to $\delta \sim -38^\circ$. The stream appears to be roughly 18 kpc distant, and its trajectory generally agrees with expectations based on orbit fits to the northern stream. The color–magnitude distribution is clearly metal poor and appears similar to that of the northern Orphan Stream. We find a stellar concentration and apparent offsets in the stream that would be consistent with a remnant progenitor.

This southern extension of the Orphan Stream should enable significant improvements in constraining the overall orbit and, ultimately, the shape of the Galactic potential. This is particularly interesting in that the Orphan Stream passes through quadrants of the halo not probed by the Sagittarius stream. Slightly deeper than the present survey, the Pan-STARRS survey may enable us to improve the signal-to-noise ratio somewhat for $\delta > -30^\circ$. For more southerly regions, where we are strongly affected by reddening, a deep, near-infrared survey may help to trace the stream still further south.

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