CHEMISTRY OF THE ORPHAN STREAM I: IDENTIFYING STREAM CANDIDATES WITH LOW RESOLUTION SPECTROSCOPY

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ABSTRACT

We present coordinates and properties of K giant members in the Orphan Stream, which have been identified from low resolution spectroscopic data taken with AAOmega on the Australian Astronomical Telescope. With modest S/N and independent cuts in photometry, kinematics, gravity and metallicity we yield self-consistent, highly probable stream members. Our data indicates an overall stream metallicity of $[Fe/H] = -1.74 \pm 0.05$ which is more metal-rich than previously found and unbiased by spectral type. We find a revised stream distance of 24 kpc near the celestial equator, and our kinematic signature peaks at $V_{helio} \sim 218 \, \mathrm{km \, s^{-1}}$. We highlight members for high resolution spectroscopic follow-up.

Subject headings: Galaxy: halo, structure — Individual: Orphan Stream — Stars: K-giants

1. INTRODUCTION

The Milky Way stellar halo has been partly formed through the accretion of smaller satellites. As smaller satellites infall onto the Milky Way, tidal forces disrupt the satellite. Stars which were once gravitationally bound to the satellite are left behind in a stream of stars. Stream members have kinematics which are sensitive to the shape of the galactic potential, allowing us to constrain the Milky Way potential, and reconstruct the formation history of the Milky Way. The level of accreted substructure in the Milky Way has only recently become apparent through multi-band photometric surveys like the Sloan Digital Sky Survey (SDSS). The more prominent of the detectable substructures, like Sagittarius, have been well-studied. One of the more prominent - yet less studied - substructures is that of the Orphan Stream.

The Orphan Stream was independently detected by both Grillmair & Dionatos (2006) and Belokurov et al. (2006), and is unique from other substructures in the halo. The stream stretches over 60° in the sky, has a low surface brightness and a narrow stream width of only $\sim 2°$ and as the name suggests, the parent largely remains a mystery. The stream extends past the celestial equator - outside the SDSS footprint - and is not detectable through bright southern surveys like Super-COSMOS [citation needed]. Whilst the parent system remains elusive, significant effort has been placed on associating the stream with known Milky Way satellites (Zucker et al. 2006; Fellhauer et al. 2007; Jin & Lynden-Bell 2007; Sales et al. 2008). In contrast, there has been relatively limited observational work on the Orphan Stream other than the original discovery papers (Grillmair & Dionatos 2006; Belokurov et al. 2006, 2007) and the work of Newberg et al. (2010). This is largely to be expected given the absence of multi-band photometry

in the southern sky, the difficulty in reliably separating Orphan Stream members from halo stars and the low luminosity of stream members. It is unlikely the full extent of the Orphan Stream will be detected until the SkyMapper telescope surveys this region (Keller et al. 2007).

As Sales et al. (2008) points out, there is a natural observational bias towards more massive and recent mergers like Sagittarius. The fainter end of this substructure distribution has yet to be fully recovered, or thoroughly examined. Interestingly, there are indications that some fainter substructures like the Orphan Stream (Newberg et al. 2010) and the Palomar 5 tidal tails (Odenkirchen et al. 2009) have orbits which seem to be best-fit by Milky Way models with nearly 60% less mass (Newberg et al. 2010) than generally reported by Xue et al. (2008); Koposov et al. (2010). Such a discrepancy in the mass of the Milky Way is worrying. A more complete photometric and kinematic map of the stream may provide the best test as to whether this mass discrepancy for faint substructure orbits is real or an artefact of incomplete observations. Whilst the full spatial extent of the stream remains incomplete, we can examine the detailed chemistry of the stream and investigate the stream history, as well as make predictions about the nature of the progenitor.

In this letter we present a detailed, self-consistent analysis to identify K giant members of the Orphan Stream. Using our selection method we have published the locations of seven highly probable Orphan Stream candidates, all worthy of high resolution spectroscopic follow up. In the following section of this letter we outline our initial photometric target selection. In section §2 we outline our target selection and section §3 describes the low resolution observations. The data analysis, including stream identification, is described in §4. In §5 we discuss our conclusions, predictions, and necessary future work necessary on this topic.

2. TARGET SELECTION

We have targeted K giant members of the Orphan Stream in order to investigate their detailed chemistry. Because K-giants are difficult to unambiguously detect from photometry alone, low resolution spectroscopy is

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required to estimate stellar parameters and determine radial velocities. The Orphan Stream has a low spatial over-density on the order of $\sim 10\%$ [citation needed], which also makes it difficult to separate stream members from halo stars. However, there is a well described distance gradient along the stream (Belokurov et al. 2007; Newberg et al. 2010) which provides an indication on where we should focus our spectroscopic efforts.

The Orphan Stream is closest to us in two locations on the edge of the SDSS footprint: at the celestial equator (Belokurov et al. 2007), and along outrigger SEGUE Stripe 1540 (Newberg et al. 2010). These two locations are unequivocally the best place to recover bright stream members. We have targeted two fields centered on (α, δ) = (10:48:15, 00:00:00) and (10:48:15, -02:30:00), and employed a combination of colour cuts with the SDSS DR 7 (Abazajian et al. 2009) data set in order to identify likely K giants:

$$(g - i)_0 > 0.6 \tag{1}$$
$$0.86i_0 + 3.30 > g_0 > 0.95i_0 + 1.35 \tag{2}$$
$$19.00 > g > 15.75 \tag{3}$$

Stefan can you see if you can find your original selection SQL - I deduced these relationships from cross-matching against SDSS and fitting boundary lines.

Given our colour selection we expect to recover giants and dwarf contaminants. At a given temperature, K dwarfs exhibit a infrared excess relative to giants which allows a clean selection of giants (Bessell & Brett 1988). However, given the apparent magnitude of the Orphan Stream in this region ($g \sim 18$), no 2MASS infrared photometry is available. Thus we expect our sample to be contaminated by foreground dwarfs to some extent.

3. OBSERVATIONS

Observations took place on the Australian Astronomical Telescope using the AAOmega spectrograph in April 2009. AAOmega is a fibre-fed, dual beam multi-object spectrograph which is capable of simultaneously observing spectra of 400 (science and sky) targets across a $2°$ field of view. We used the $5700\,\text{Å}$ dichroic in combination with the 1000I grating in the red arm, and the 580V grating in the blue arm. This provides a spectral coverage between $800 \leq \lambda \leq 950\,\text{nm}$ in the red at $\mathcal{R} \approx 4400$, and between $370 \leq \lambda \leq 580\,\text{nm}$ with a lower resolving power of $\mathcal{R} \approx 1300$.

The data were reduced using the supplied 2DFDR reduction pipeline [3]. After flat-fielding, throughput calibration for each fibre was achieved using the intensity of skylines in each fibre. The median flux of dedicated sky fibres was taken for sky subtraction, and wavelength calibration was performed using arc lamp exposures between science frames. Three thirty minute science exposures were median combined to assist with cosmic ray removal. The median S/N obtained in the red arm for our fields is modest at $35\,\text{px}^{-1}$. With the presence of strong Ca II triplet lines in the red arm we are able to ascertain reliable radial velocities and reasonable estimates

on overall metallicity (Starkenburg et al. 2010, and references therein). Our spectral region also includes gravity-sensitive magnesium lines: Mg I at $8807\,\text{Å}$, and the Mg Ib $3p$-$4s$ triplet lines. As we demonstrate in the next section, these lines are sufficient to discriminate dwarfs and giants even with weak signal.

The blue and red arm were normalised using a third order cubic spline after multiple iterations of outlier clipping. We used defined knot spacings of 20 nm in the red arm, and 5 nm in the blue arm in order to accommodate often poor S/N, and varying strengths of molecular band-heads.

4. ANALYSIS

We have employed a combination of separate criterion to identify likely Orphan Stream members: kinematics, a giant/dwarf indication from Mg I lines, and metallicity from Ca II triplet lines. Each criterion is discussed here separately.

4.1. *Kinematics*

Radial velocities were measured by cross-correlating our normalised spectra against a K-giant synthetic template with a temperature of $4500\,\text{K}$, $\log g = 2$ and [Fe/H] $= -1.5$ across the range $845 \leq \lambda \leq 870\,\text{nm}$. Heliocentric velocities were translated to the galactic rest frame by adopting the local standard of rest velocity as $220\,\text{km}$ s^{-1} towards $(l, b) = (53°, 25°)$ (Kerr & Lynden-Bell 1986; Mihalas & Binney 1981)[4]. Newberg et al. (2010) presented a comprehensive kinematic dataset on the Orphan Stream using BHB stars and employed a slightly different galactocentric transformation. This systematic difference equates to our galactocentric rest frame velocities being on average $\sim 5\,\text{km}\,\text{s}^{-1}$ lower than those of Newberg et al. (2010).

Figure 1 shows a histogram of our galactocentric velocities, compared to the predicted smooth halo velocity distribution for this region from the Besançon model (Robin et al. 2003). It is clear that our target selection has yielded mostly nearby thick disk dwarf stars with $V_{\text{GSR}} \approx -120\,\text{km}\,\text{s}^{-1}$. The expected kinematic signature for the Orphan Stream, as Newberg et al. (2010) reported, is labelled in Figure 1. No statistically significant peak representative of the Orphan Stream exists in our sample. From kinematics alone, our targets appears largely indistinguishable from a smooth halo distribution.

In this region Newberg et al. (2010) found the Orphan Stream to have $V_{\text{GSR}} = 110\,\text{km}\,\text{s}^{-1}$ from BHB stars, approximately $105\,\text{km}\,\text{s}^{-1}$ on our scale. We have nominated a relatively wide kinematic selection region between $75 \leq V_{\text{GSR}} \leq 135\,\text{km}\,\text{s}^{-1}$, which yields 25 Orphan Stream candidates. The typical uncertainty in our kinematics is $\pm 3.5\,\text{km}\,\text{s}^{-1}$, although for our fainter targets this quickly increases to $\sim 10\,\text{km}\,\text{s}^{-1}$.

4.2. *Dwarf/Giant Discrimination*

We have measured the equivalent widths of the gravity-sensitive Mg I line at 8807 Å to distinguish dwarfs from giants. At a given temperature (or $g - r$) and metallicity, giant stars present narrow Mg I absorption lines

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[3] http://www.aao.gov.au/2df/aaomega/aaomega_2dfdr.html

[4] Where $V_{\text{GSR}} = V_{\text{HELIO}} + 220 \sin l \cos b + 16.5 \times [\sin b \sin 25 + \cos b \cos 25 \cos (l - 53)]$
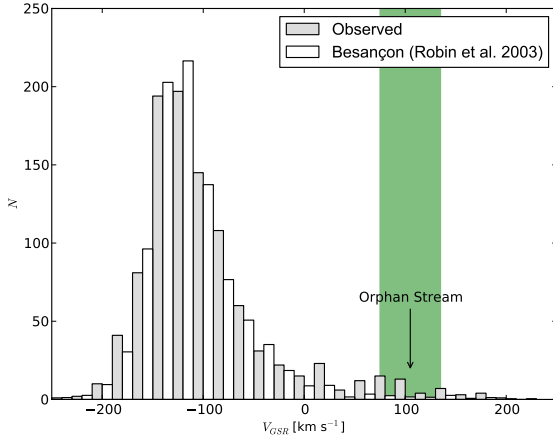
FIG. 1.— Galactocentric rest frame velocities for our observed sampled (grey), and predicted Besançon velocities (white) which have been scaled to match our observed sample size. The expected kinematic signature from Newberg et al. (2010) for the Orphan Stream is highlighted, as is our kinematic selection window (green).

than their dwarf contaminants. Given our target selection, our sample is likely to contain many more dwarfs than giants. In four cases no Mg I 8807 Å line was apparent, so an upper limit was estimated based on the S/N. In these cases the candidate was considered a "non-dwarf" because we cannot exclusively rule out a metal-poor sub-giant with this criterion alone. For these purposes we are only looking for a simple indication as to whether a star is likely a dwarf or not. Figure 2 illustrates the trend with $EW_{\lambda 8807}$ against SDSS $g - r$ de-reddened[5], illustrating the dominant upper dwarf branch we wish to exclude. The adopted dwarf/giant separation line is shown. Admittedly this selection criterion appears extremely inclusive of dwarfs, but we are allowing multiple inclusive cuts and taking the union of these selections to identify Orphan Stream giants.
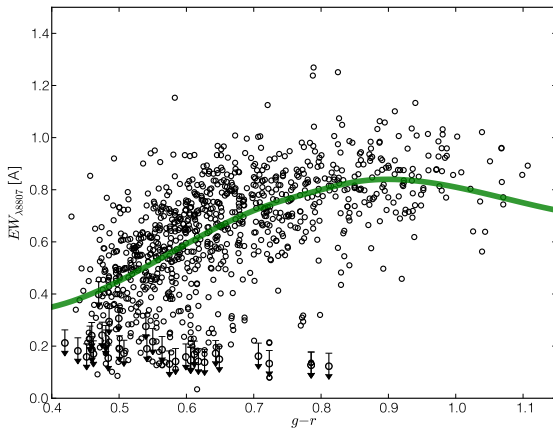

FIG. 2.— De-reddened $g - r$ against the measured equivalent width of the Mg I transition at 8807 Å. Dwarf contaminants occupy the more populous upper branch. Our separation line between dwarfs and giants is shown in green.

[5] All magnitudes presented in this paper are de-reddened

It is worth noting that we initially performed this analysis using the total equivalent width of the Mg Ib triplet near 5175 Å. As expected, this region has a consistently lower S/N than the Mg I line at 8807 Å. However, the separation between giants and dwarfs was arguably more distinguished when using the Mg I b triplet equivalent width instead of using the $\lambda 8807$ line. In either case, both analyses were entirely consistent with each other: the same candidate selection was found using both techniques. However, given the poorer signal at the Mg Ib triplet, we were forced to adopt many more upper limits than when using the 8807 Å line. Because we classify all upper limits as being "non-dwarfs" (i.e. potential OSS giants), we deduced a slightly larger candidate sample for the Mg Ib analysis, which was primarily populated by upper limits. In conclusion, we found the Mg I line at 8807 appeared to be a more consistent dwarf discriminant given our weak S/N – particularly for our fainter stars – and thus we have used the 8807 Å Mg I selection throughout the rest of our analysis.

Our dwarf/giant separation line in Figure 2 yields 425 potential giants. This fraction of giants ($\sim 44\%$) is much larger than what would be expected given our selection criterion (e.g. see Casey et al. (2012)). Hence, our gravity criterion is extremely inclusive and susceptible to dwarf contamination. Upon taking the union of our kinematic and gravity selections, we deduce eighteen stars that appear likely Orphan Stream K giants.

4.3. Metallicities

We have measured the equivalent widths of the Ca II near-infrared triplet lines for stars which meet our kinematic and surface gravity criteria. After correcting for luminosity, the equivalent width of the Ca II triplet lines provide a good indication for the metallicity of a RGB star (Armandroff & Da Costa 1991). We have employed the Starkenburg et al. (2010) relationship and corrected for luminosity in g against the horizontal branch magnitude at $g_0 = 17.1$ (Newberg et al. 2010). Strictly speaking, the Ca II-[Fe/H] relationship is only valid for stars brighter than the horizontal branch, although the situation only becomes dire at $g - g_{HB} \sim +1$ [citation needed]. Many of our candidates are fainter than this valid luminosity range, and therefore they should not be excluded solely because of their derived metallicities. Stars fainted than g_0 will have slightly lower metallicities than predicted by our Ca II-[Fe/H] relationship, and for these stars we will only use metallicities to assign a relative qualitative likelihood for stream membership.

Figure 3 illustrates all eighteen candidates which meet both our kinematic and surface gravity criterion. Candidates are coloured by their metallicity deduced from the Ca II triplet. There are four candidates above $g_0 \sim 17.1$ which are within our valid luminosity range. Two of these objects at $g - r \sim 0.57$ are slightly metal-rich than expected for the stream, and are excluded from membership. There appears to be an extremely metal-poor star in this sample with an estimated [Fe/H] = -2.70 which may be associated with the Orphan Stream. The likely parent system of the Orphan Stream is a Milky Way dwarf spheroidal (Belokurov et al. 2007; Sales et al. 2008), which are known to have a wide metallicity distribution function [citation needed?], including an over-
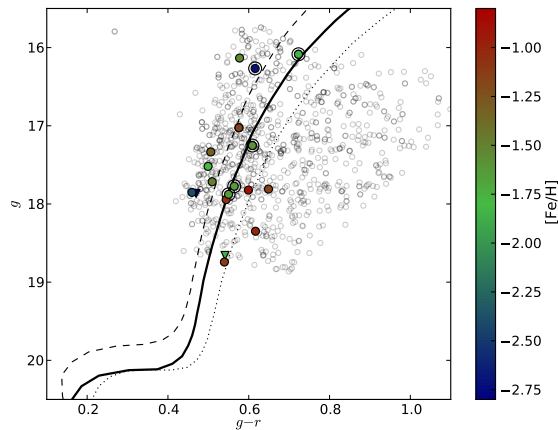
FIG. 3.— Color magnitude diagram showing our observed candidates (grey) and highlighting candidates which meet our kinematic and gravity cuts. Candidates are colored by their metallicity, and those with upper limiting gravities are marked as triangles. Highly probable stream members are marked. Relevant 10 Gyr Marigo et al. (2008) isochrones at [Fe/H] = −1.5 (dotted), −2.0 (dashed) at 21.4 kpc (Newberg et al. 2010) are shown, as well as our best-fitting 10 Gyr isochrone of [Fe/H] = −1.74 at 24 kpc (solid).

represented population of extremely metal poor stars (Frebel et al. 2010; Kirby et al. 2010). Thus, we keep this extremely metal-poor star as a potential stream member for follow-up chemical analysis.

Newberg et al. (2010) found the median Orphan Stream metallicity to be [Fe/H] = −2.1 from BHB stars, and a distance of 21.4±1.0 kpc in this region. In Figure 3 we have overlaid 10 Gyr old isochrones from Marigo et al. (2008) with metallicities of [Fe/H] = −2.0 and −1.5 at a distance of 21.4 kpc (Newberg et al. 2010). Four of our most probable Orphan Stream members fall between these isochrones. Assuming the three highly probable members outside our valid luminosity range are over-predicted by ∼ +0.1 dex [citation needed], when combining our four Orphan Stream members we yield a stream metallicity of [Fe/H] = −1.74 ± 0.05. This is slightly more metal-rich than the [Fe/H] = −2.1 found by Newberg et al. (2010) from BHB stars. This is to be expected as BHB stars are intrinsically representative of an older, more metal-poor population.

Given that our four Orphan Stream stars cover range along the giant branch, we are in a good position to revise the distance estimate to the stream. Given a 10 Gyr Marigo et al. (2008) isochrone at [Fe/H] = −1.74, we find a best-fitting distance to the stream of 24 kpc at (l,b) = (250°, 50°). This isochrone is also shown in Figure 3, and it is clear that the four most probable member stars lie almost precisely on this isochrone. Our derived distance is slightly farther than the 21.4 ± 1.0 kpc found by Newberg et al. (2010), but given the inherent uncertainties in determining distance we argue these distances are largely in agreement.

5. CONCLUSION

We have presented a detailed analysis to isolate individual Orphan Stream K giants from low resolution spectroscopy using a combination of photometric, kinematic, gravity, and metallicity information. Although each individual criterion is likely to induce some level contamina-

tion, the resulting union of these selections reveal highly probable, self-consistent, Orphan Stream K giants. We deduce a stream metallicity of [Fe/H] = −1.74 ± 0.05 which is not biased by spectral type. Recall that the metallicity determination was performed after kinematic and gravity cuts, and our most probable members lay perfectly on a 10 Gyr isochrone of [Fe/H] = −1.74. Our stream members indicate a revised distance to the stream of 24 kpc at (l, b) = (250°, 50°), slightly farther than that deduced by Newberg et al. (2010).

If the Orphan Stream continues through SEGUE stripe 1540 at (l, b) = (271°, 38°) as Newberg et al. (2010) found, then the stream is even closer there than in the region analysed here. Thus, if our observations and analyses are repeated at (271°, 38°), we predict brighter (and subsequently more numerous) K giant stream members will be recovered.

The K giants presented here can provide great insight into the chemistry, and history of the Orphan Stream. High resolution spectroscopic observations have been taken for our most highly probable members and a detailed chemical analysis will be presented in an accompanying paper (Casey et al. 2012c, in preparation). Detailed chemical abundances can help determine both the nature of the host system, and allow us to compare peculiar chemical signatures with those of the known Milky Way satellites in order to associate likely parents. However at least for the moment, the Orphan Stream remains appropriately named.

TABLE 1
Identified Orphan Stream Members

Star Name	α (J2000)	δ (J2000)	g	$g - r$	V_{helio} (kms^{-1})	V_{GSR} (km s^{-1})	V_{err} (km s^{-1})	$EW_{\lambda 8807}$ (Å)	[Fe/H] (dex)	Comment
OSS 1	10 46 50.6	−00 13 17.9	17.33	0.50	215.5	77.0	4.0	0.416	-1.31	Unlikely member!
OSS 2	10 47 17.6	+00 25 07.7	16.09	0.73	215.7	79.2	3.3	0.212	-1.84	Highly probable member
OSS 3	10 47 30.1	−00 01 24.6	17.25	0.61	221.4	83.6	3.4	0.123	-1.62	Highly probable member
OSS 4	10 49 08.3	+00 02 00.2	16.27	0.62	218.5	81.5	4.6	0.034	-2.70	Possible EMP member
OSS 6	10 48 20.9	+00 26 34.4	17.88	0.55	254.9	118.8	11.7	0.469	-1.65	Highly probable member
OSS 7	10 46 29.3	−00 19 38.5	17.77	0.56	217.3	78.4	5.2	0.126	-1.63	Highly probable member

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