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Discovery of a cold stellar stream in the ATLAS DR1 data

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ABSTRACT

We report the discovery of a narrow stellar stream crossing the constellations of Sculptor and Fornax in the Southern celestial hemisphere. The portion of the stream detected in the Data Release 1 photometry of the ATLAS survey is at least 12° long, while its width is ≈0°.25. The colour–magnitude diagram of this halo sub-structure is consistent with a metal-poor [Fe/H] $\lesssim -1.4$ stellar population located at a heliocentric distance of 20 ± 2 kpc. There are three globular clusters that could tentatively be associated with the stream: NGC 7006, NGC 7078 (M15) and Pyxis, but NGC 7006 and 7078 seem to have proper motions incompatible with the stream orbit.

Key words: Galaxy: fundamental parameters – Galaxy: halo – Galaxy: kinematics and dynamics.

1 INTRODUCTION

The last decade has witnessed the arrival of unprecedented amounts of high-quality imaging data from the Sloan Digital Sky Survey (SDSS). Thanks to the depth and the exquisite stability of the SDSS broad-band photometry across thousands of square degrees on the sky, previously unseen low-level fluctuations in the Galactic stellar density field have been unearthed (see e.g. Newberg et al. 2002; Willman et al. 2005; Belokurov et al. 2006; Belokurov 2013). In the Milky Way halo, one striking example of a small-scale overdensity is the GD-1 stellar stream (Grillmair & Dionatos 2006b), only a fraction of a degree in width, but running over 60° from end to end in the SDSS footprint. Such stellar trails are formed in the process of a satellite disruption in the tidal field of the Galaxy. The mechanics of the stream formation and the subsequent dynamical evolution in the host potential have been carefully studied (e.g. Eyre & Binney 2011; Sanders & Binney 2013). The consensus that has emerged from both theoretical considerations and admittedly, very few tests on the actual data (e.g. Koposov, Rix & Hogg 2010), is that these structures can be used to yield powerful, unbiased constraints of the matter distribution in the Galaxy.

In principle, there exists a methodology to model the entire spectrum of tidal debris in the Galactic halo (see e.g. Helmi & White 1999), from very narrow structures like GD-1 to broad luminous streams like that of Sgr (exposed in e.g. Majewski et al. 2003), including the stellar overdensities that do not necessarily even trace out a stream (e.g. Price-Whelan & Johnston 2013). However, the thinnest streams appear doubly interesting. First, given that these are not affected by the progenitor's gravity, methods are now in place to infer the Galactic potential without the need to resort to approximating the stellar tracks with a single orbit (e.g. Bovy 2014; Sanders 2014). Secondly, along these narrow tidal tails it is easiest to observe density fluctuations due to interactions with dark matter sub-haloes in the Galaxy (see e.g. Carlberg 2009; Yoon, Johnston & Hogg 2011), provided that the so-called epicyclic feathering is taken care of (see e.g. Mastrobuono-Battisti et al. 2012). SDSS data have already been thoroughly mined to yield a handful of cold stellar streams. These include, for example, the tails of the Pal 5 globular cluster (Odenkirchen et al. 2001, 2003; Grillmair & Dionatos 2006a), as well as tails around NGC 5466 (Belokurov et al. 2006), NGC 5053 (Lauchner, Powell & Wilhelm 2006), Pal 14 (Sollima et al. 2011) and Pal 1 (Niederste-Ostholt et al. 2010). In addition, Grillmair (2009) found a group of narrow streams Acheron, Cocytos, Lethe and more recently the discovery of the Pisces Stellar Stream was announced (Bonaca, Geha & Kallivayalil 2012; Martin et al. 2013).

In this Letter, we present the discovery of a new stellar stream in the Southern celestial hemisphere based on photometry from Data Release 1 (DR1) of the VST ATLAS survey (Shanks et al. 2013). ATLAS is one of the three imaging surveys being currently undertaken within the remit of the ESO VST Public Surveys Program, the other two being KiDS (de Jong et al. 2013) and VPHAS+ (Drew et al. 2014). The aim of the ATLAS survey is to obtain photometry in the SDSS *ugriz* filters down to $r \sim 22$ for approximately 4500 deg^2 of the southern sky. The primary motivation for the survey is to identify large numbers of $z \lesssim 2$ QSOs and luminous red galaxies out to redshifts of $z \sim 0.6$ for studies of the cosmological

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matter power spectrum. The ability to use these data to also detect low-level Galactic halo stellar sub-structure spanning several hundred square degree survey fields is testament to the quality and the stability of the ATLAS photometric and astrometric calibration. Section 2 briefly describes the data being used, while Section 3 gives the details of the newly discovered stream. The final section summarises the main results.

2 VST ATLAS DR1

The ATLAS survey makes use of the VLT Survey Telescope, VST, a 2.6 m ESO telescope on Paranal. Images are taken with the OmegaCAM camera mounted at the Cassegrain focus of the VST. The camera consists of 32 individual 4k × 2k CCDs with a pixel size of ∼0.21 arcsec, providing a field of view of 1 deg^2. Compared to the SDSS, total exposure times are slightly longer, to account for a smaller pixel size, namely 120 s in *u*, 100 s in *g* and 90 s in each of *riz*. The specified survey seeing is <1.4 arcsec and the actual median seeing of the ATLAS DR1 is just under 1 arcsec. The resulting median limiting magnitudes in each of the five bands corresponding to 5σ source detection limits are approximately 21.0, 23.1, 22.4, 21.4, 20.2.

The raw data are automatically transferred to the Cambridge Astronomical Survey Unit (CASU) for further quality checks and subsequent processing. CASU processes VST data on a nightly basis including all three of the VST public surveys together with any calibration data. The processing sequence is similar to that used for the IPHAS survey of the northern Galactic plane (e.g. González-Solares et al. 2008); however, the higher level control software is based on that developed for the VISTA Data Flow System (Irwin et al. 2004). Science images are first de-biased and flat-fielded (using series of twilight sky flats) with particular care taken of four detectors suffering from inter-detector cross-talk. The flat-field sequences plus bad pixel masks are used to generate confidence maps (e.g. Irwin et al. 2004) for subsequent use in stacking and cataloguing. The integration time for each band for ATLAS data is split into two dithered exposures which are stacked in the pipeline based on derived individual image World Coordinate System (WCS) solutions and then catalogued.

Catalogue generation is based on IMCORE[1] (Irwin 1985) and makes direct use of the aforementioned confidence maps to downweight unreliable parts of the images. At this stage, objects are detected, parametrized and classified morphologically. With catalogues in hand, the WCS solution based on the telescope pointing and general system characteristics is progressively refined using matches between detected objects and the 2MASS catalogue (Skrutskie et al. 2006). The source photometry is calibrated in two stages. A first-pass solution is obtained using the observations of standard star fields (observed each night). This is then refined and adjusted to correct for the scattered light systematics using APASS all-sky photometric *g*, *r*, *i* catalogues (http://www.aavso.org/apass). The ATLAS DR1 VST photometry is only in Vega magnitudes.[2] Subsequent releases will provide an independent AB magnitude calibration based on the APASS photometry. For the analysis that follows we use the Vega system and correct the magnitudes for Galactic extinction using the dust maps of Schlegel et al. (1998).

[1] Software publicly available from http://casu.ast.cam.ac.uk

[2] The transformation between Vega and AB systems can be found in Blanton & Roweis (2007).

3 THE ATLAS STREAM

To test the quality of the ATLAS photometry across a range of colours and magnitudes, density maps of stars close to the expected location of halo main-sequence turnoffs at various distances were produced. As reported previously (Shanks et al. 2013), such maps reveal a smooth slowly varying stellar density field with several overdensities superposed. Most of this sub-structure is well known, for example, the southern Sgr stream and the Fornax and Sculptor dwarf spheroidals; however, a narrow, approximately 12° long stream of stars centred around $(\alpha, \delta) = 25°, -30°$ was immediately apparent.

Fig. 1 shows an enhanced version of the density distribution of main-sequence stars of an area of the sky around the discovered stream. This particular map was obtained using the so-called matched-filter technique (e.g. Rockosi et al. 2002). A matched-filter assigns higher weights to stars in the regions of the colour–magnitude diagram (CMD) dominated by the target stellar population of chosen age, metallicity and distance, and least contaminated by foreground stars. These weights, obtained from the ratios of CMD densities of the target population to the background, are then summed in pixels on the celestial sphere to expose structures whose stellar populations are similar to the target. In practice, we assume that the stream stellar population is old and metal poor and only search for an optimal distance match. Therefore, a model isochrone with [Fe/H] = −2.1 and 12.5 Gyr age is chosen from the synthetic library produced by Girardi et al. (2004); the CMD tests described below show that this simplifying assumption is reasonable. The selected isochrone is placed at different trial distance moduli, the matched-filter density map is produced and the signal-to-noise ratio of the stream is estimated. The best signal-to-noise ratio is obtained for a heliocentric distance of 20 kpc – the distance used to produce the final map shown in the left-hand panel of Fig. 1. In order to enhance the contrast of the small-scale structures in the map, we fitted the large-scale stellar distribution by two-dimensional sixth-order polynomial and subtracted it. The right-hand panel of Fig. 1 shows the distribution of the Galactic extinction in the same area as the stream. There is no evidence in the extinction map of any structures related to the dust distribution that are coincident with the stream.

To analyse the properties of the newly discovered sub-structure, we switch from equatorial coordinates to a system aligned with the stream great circle. This is achieved by rotating the equatorial coordinate pole to a new position at $(\alpha, \delta) = (77.°16, 46.°92)$ to give the along-stream and the across-stream coordinates ϕ_1 and ϕ_2 (see e.g. Koposov et al. 2010); the origin of the rotated coordinates is defined to be near the centre of the observed part of the stream $(\alpha, \delta) = (20.°0, -26.°8902)$. The left-hand panel of Fig. 2 shows the Hess difference, that is the CMD density difference between the region of the sky dominated by the stream stars, namely $-3° < \phi_1 < 8°$ and the Galactic background. Fainter than $i \sim 18$, there are several familiar features visible, including a sub-giant branch and a main-sequence turn-off. Brighter than $i \sim 17.5$ the Hess difference reveals several artefacts of imperfect background subtraction. While the isochrone with metallicity [Fe/H] = −2.1 seems to describe the CMD of the stream reasonably well, so does the more metal rich one, with [Fe/H] = −1.45. The χ^2 fit of the Hess diagram by the [Fe/H] = −2.1 stellar population reveals the best-fitting distance of 20 kpc and the formal error of 2 kpc with the expected larger systematic error associated with the lack of knowledge of metallicity and age of the stellar population in the stream. We conclude that while the assumption of an old and metal-poor stellar population in the stream is not inadequate, based on the currently available

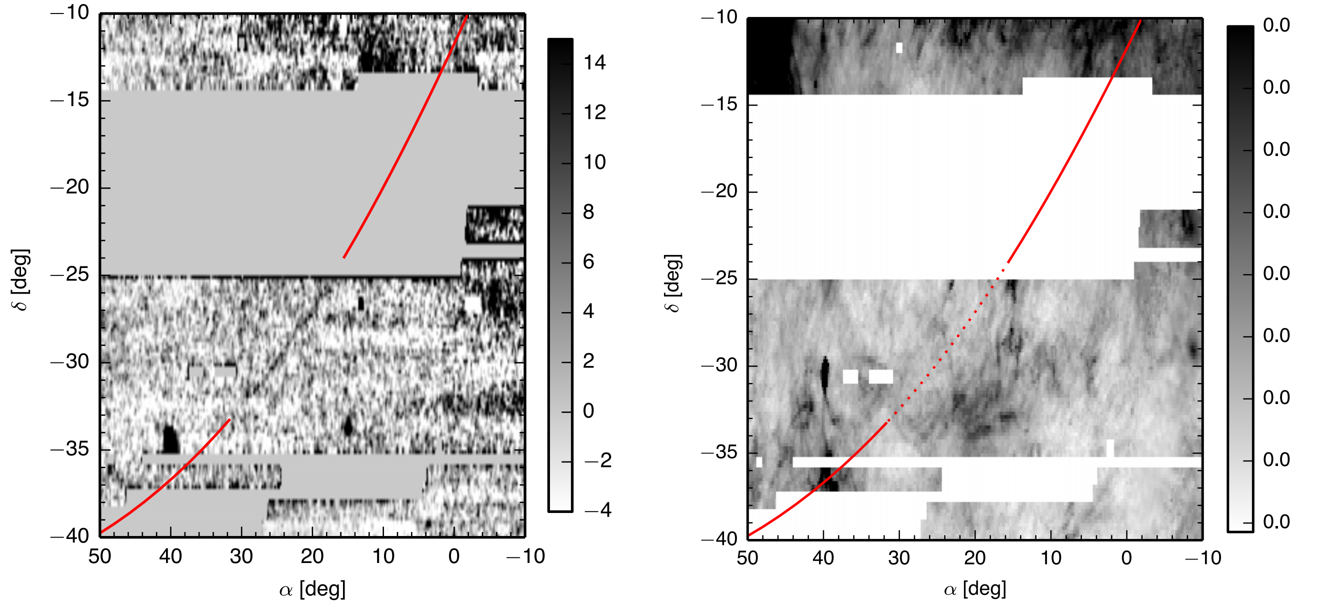

Figure 1. Left: background subtracted density map of stars optimally weighted by proximity to an isochrone with [Fe/H] = −2.1 and an age of 12.5 Gyr at a distance of 20 kpc. Darker shades of grey correspond to enhanced stellar densities. A narrow stellar stream is clearly visible crossing the area diagonally from $\alpha \sim 15°$ to $\alpha = 30°$. The red line shows the great circle with the pole at $(\alpha, \delta) = (77\overset{\circ}{.}16, 46\overset{\circ}{.}92)$ aligned with the stream. The Fornax and Sculptor dwarf spheroidals are visible at $(\alpha, \delta) \approx (40°, -35°)$ and $(15°, -33°)$, respectively, while much of the darker shading to the north and west is due to the southern Sgr stream. Right: a map of the Galactic dust extinction $E(B-V)$ around the stream area (Schlegel, Finkbeiner & Davis 1998) does not seem to reveal any features coincident with the stream.

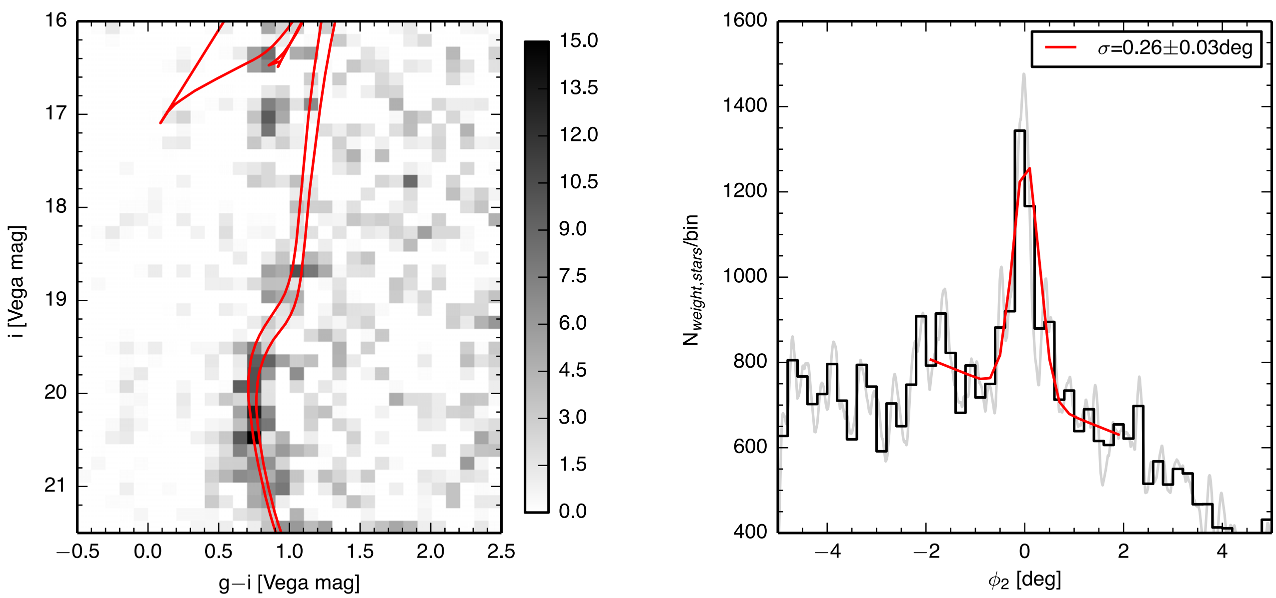

Figure 2. Left: extinction-corrected $g-i$, i Hess diagram of the stream in the range $-3° < \phi_1 < 8°$ obtained by weighted background subtraction. The magnitudes are in the Vega system. The two red lines show isochrones from the Girardi et al. (2004) synthetic library with [Fe/H] = −2.1 and −1.45 (for an age of 12.5 Gyr) at a distance of 20 kpc. Based on the current photometry alone, it is not possible to assign metallicity, age and distance to the stream robustly. Right: the profile of the stream across the range of $-3° < \phi_1 < 8°$ obtained using the same optimal isochrone weighting as for Fig 1. The stream appears as a highly significant overdensity on top of the background and can be approximately described by a Gaussian with a width (sigma) of $\sim 0\overset{\circ}{.}25$. Grey line shows kernel density estimation with Epanechnikov kernel.

photometry alone it is not possible to assign metallicity, age and distance to the stream more robustly. Furthermore, the existing photometry and the shortness of the visible part of the stream does not seem to allow us to constrain the distance gradient along the stream.

The right-hand panel of Fig. 2 shows the stellar density distribution across the stream for a range of $-3° < \phi_1 < 8°$, confirming that the stream detection is highly significant. Additionally to the density computed by making the histogram of stars, we show the density measured by the kernel density estimation using the Epanechnikov

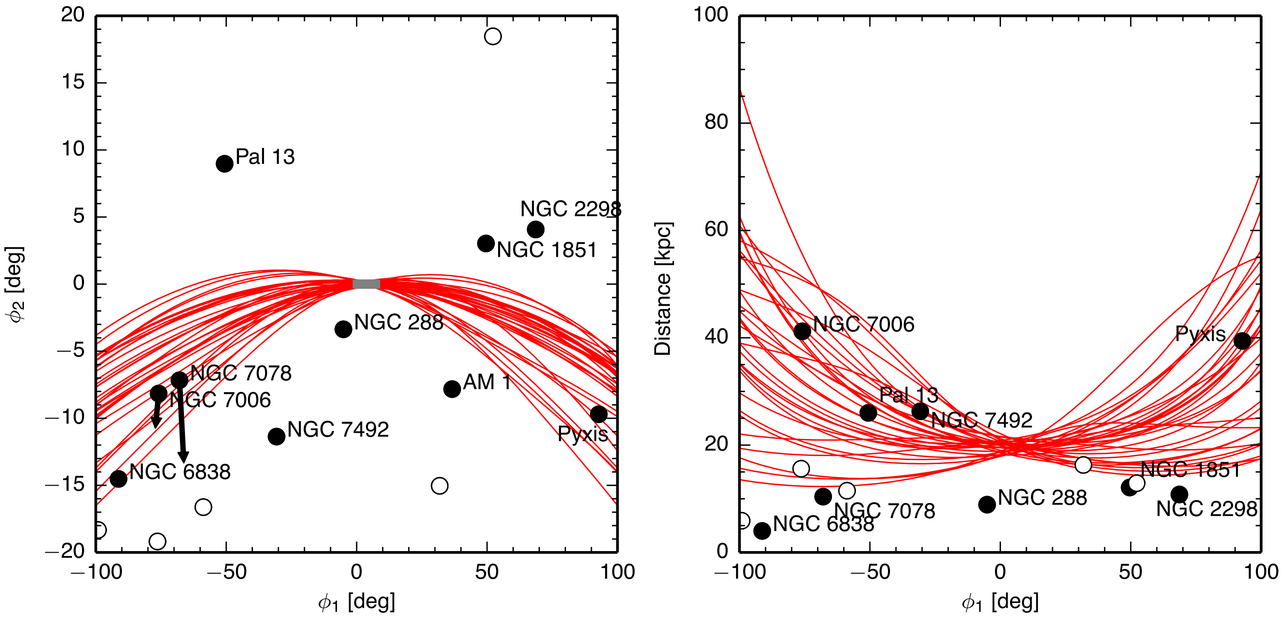

Figure 3. 30 plausible orbits passing through the detected portion of the stream. Left: orbit distribution on the sky, in ϕ_1, ϕ_2 coordinates, aligned with the stream. Circles mark the location of known globular clusters. Filled (empty) circles represent clusters with the across-stream coordinate ϕ_2 within (outside) the range $-15^{\circ} < \phi_2 < 10^{\circ}$. The grey band near $\phi_1 \sim 0$ shows the extend and width of the observed part of the stream. Right: heliocentric distance change along the test orbits as a function of the along-stream coordinate ϕ_1. The only three globular clusters within 90° of the stream that could possibly lie on orbits passing through the stream piece detected are NGC 7006, NGC 7078 and Pyxis. Note however that the measured proper motions of NGC 7006 and NGC 7078, indicated with black arrows, seem inconsistent with the predicted orbital motion.

kernel (Epanechnikov 1969; Wand & Jones 1994), as this density measurement is invariant to the location of the bin edges of the histogram. Also shown is a Gaussian model fitted with width $\sigma \approx 0.^{\circ}25$. At the distance of 20 kpc, the stream angular width corresponds to ~90 pc. Similarly, modest thickness is observed in several previously detected cold streams that are either known to originate from star clusters like that of Pal 5 or are believed to be so, for example GD-1. In order to calculate the total luminosity of the stream, we have calculated the number of stream stars in the colour–magnitude box of $0.1 < (g - i) < 0.9$ and $18 < i < 21$ by fitting a Gaussian model to the across-stream profile (see Fig. 2). Within the region of $-3^{\circ} < \phi_1 < 8^{\circ}$, the total number of stars ~1200 ± 140. According to the isochrone with the age of 12.5 Gyr [Fe/H] = −2.1 and Chabrier initial mass function, this would correspond to a total stellar mass $\sim 4 \times 10^4\,M_{\odot}$ and luminosity around $M_V \sim -6$. The corresponding average surface brightness of the stream is estimated to be ~28–29 mag arcsec^{-2}.

The question of the likely stream progenitor can be addressed by exploring the possibility that the stream is produced through the disruption of one of the known Galactic globular clusters. Fig. 3 displays a representative sample of 30 random possible orbits that pass through the ends of the stream, i.e. points with $(\phi_1, \phi_2) = (-1, 0)$, $(\phi_1, \phi_2) = (8.5, 0)$, in a realistic Galactic potential. In this experiment, it is assumed that at $\phi_1 = 4^{\circ}$ the distance modulus of the stream debris $m - M = 16.5 \pm 0.1$. The orbits have been obtained by sampling the posterior on orbital parameters given the distance and positional constraints, broad prior on radial velocity and a limit of 100 kpc on the apocentre (to avoid unbound or extremely excentric orbits). The gravitational potential of the Galaxy employed here is identical to that described in Fellhauer et al. (2006) and Koposov et al. (2010). The left-hand panel of the figure shows the distribution of the possible stream orbits on the sky in the ϕ_1, ϕ_2 coordinate system, while the right-hand panel presents the change of heliocentric distance along each orbit. From comparing the two panels of the figure it is clear that within ~90° of the stream there are only three globular clusters whose three-dimensional positions could be coincident with an orbit passing through the portion of the stream observed in ATLAS DR1. These three are NGC 7006, NGC 7078 (M15) and Pyxis. The proper motions of the first two globulars have been measured and therefore can be compared to the model orbit predictions at the cluster location. According to Jacoby et al. (2006), the components of the proper motion of NGC 7078 are $(\mu_{\alpha}, \mu_{\delta}) = (-0.6, -4.0) \pm (0.4, 0.8)$ mas yr^{-1}. In the stream coordinate system, and after removing the contribution of the solar motion in the Galaxy, this corresponds to $(\mu_{\phi_1}, \mu_{\phi_2}) = (0.59, -2.21) \pm (0.6, 0.68)$ mas yr^{-1}. Similarly, for NGC 7006, Dinescu et al. (2001) give $(\mu_{\alpha}, \mu_{\delta}) = (-0.96, -1.14) \pm (0.35, 0.4)$ mas yr^{-1}, or $(\mu_{\phi_1}, \mu_{\phi_2}) = (-0.49, -1.00) \pm (0.37, 0.38)$ mas yr^{-1}. As is clear from the left-hand panel of Fig. 3 these measured proper motions are inconsistent with the predicted orbits giving significant non-zero across-stream components μ_{ϕ_2}. But we also note that in the case of NGC 7078 and NGC 7006, the significance of the across-stream proper motions is ~3.2σ and 2.6σ respectively, so the inconsistency of the stream and proper motion alignment is only marginally significant.

If the reported proper motions of NGC 7006 and NGC 7078 are correct, the only globular cluster that cannot be ruled out as the stream progenitor is Pyxis (Irwin, Demers & Kunkel 1995). The spectroscopic metallicity of Pyxis is [Fe/H] = −1.4 (Palma, Kunkel & Majewski 2000), which is consistent with the, admittedly noisy, CMD presented here. Pyxis stands out somewhat when compared to the rest of the Galactic globular clusters. First, at 40 kpc it falls in between the inner and the outer halo globulars. Secondly, it is 1–2 Gyr younger that the globulars of similar metallicity

(Dotter, Sarajedini & Anderson 2011). Finally, Pyxis is very sparse, much like similarly puny Palomar clusters. Perhaps, Pyxis was the first example of an ultrafaint satellite discovered given its size (in excess of 10 pc) and luminosity ($M_V \sim -5$). We remark also that the velocity dispersion of Pyxis has been measured using six stars (Palma et al. 2000) and is in the range between 2 and 6 km s^{-1} (1σ). While it is entirely possible that the juxtaposition of one of the tentative stream progenitor orbits and the three-dimensional position of Pyxis is accidental, wide-angle deep imaging observations of this peculiar globular are warranted.

4 CONCLUSIONS

We have presented the discovery of a new narrow stream in the VST ATLAS DR1 data. The portion of the stream detected has the following properties.

(1) The stream lies on a great circle with a celestial pole at $(\alpha, \delta) = 77\overset{\circ}{.}16, 46\overset{\circ}{.}92$.

(2) The heliocentric distance to the stream is ∼20 kpc.

(3) The width of the debris distribution on the sky is $0\overset{\circ}{.}25$ which at the distance of the stream corresponds to ∼90 pc physical size.

(4) The CMD of the stream appears to be well described by an old and metal-poor isochrone. But in order to pinpoint the precise metallicity and age of the stream, we will need spectroscopic measurements of the stream members.

(5) There are three Galactic globular clusters that could plausibly act as stream progenitors, based on their proximity to the stream orbit: NGC 7006, NGC 7078 (M15) and Pyxis. However, given the proper motions available in the literature, NGC 7006 and NGC 7078 are unlikely to be associated with the stream. It is more difficult to rule out Pyxis at this stage.

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