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Serendipitous discovery of a thin stellar stream near the Galactic bulge in the Pan-STARRS1 3π Survey

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ABSTRACT

We report the discovery of a thin stellar stream found in Pan-STARRS1 photometry near the Galactic bulge in the constellation of Ophiuchus. It appears as a coherent structure in the colour-selected stellar density maps produced to search for tidal debris around nearby globular clusters. The stream is exceptionally short and narrow; it is about 2$^{\circ}\!\!.$5 long and 6 arcmin wide in projection. The colour–magnitude diagram of this object, which harbours a blue horizontal-branch, is consistent with an old and relatively metal-poor population ([Fe/H] ~ -1.3) located 9.5 ± 0.9 kpc away at $(l, b) \sim (5^{\circ}, +32^{\circ})$, and 5.0 ± 1.0 kpc from the Galactic centre. These properties argue for a globular cluster as progenitor. The finding of such a prominent, nearby stream suggests that many streams could await discovery in the more densely populated regions of our Galaxy.

Key words: surveys – globular clusters: general – Galaxy: halo – Galaxy: structure.

1 INTRODUCTION

Ever since the discovery of massive tidal tails emerging from the globular cluster Palomar 5 (Odenkirchen et al. 2001), the Milky Way field population has been the subject of intense scrutiny to find more of these cold stellar streams. The main incentives for finding streams are their potential use to constrain the shape and mass of the Milky Way dark matter halo (e.g. Johnston, Law & Majewski 2005; Koposov, Rix & Hogg 2010; Varghese, Ibata & Lewis 2011; Peñarrubia, Koposov & Walker 2012; Lux et al. 2013; Vera-Ciro & Helmi 2013; Deg & Widrow 2014), their ability to constrain the existence of mini-haloes (Ibata et al. 2002; Siegal-Gaskins & Valluri 2008; Yoon, Johnston & Hogg 2011; Carlberg 2012), as well as the fossil record they provide of the mass assembly history of the Milky Way.

While a few streams have been revealed by kinematics alone (e.g. Helmi et al. 1999; Newberg, Yanny & Willett 2009; Williams et al. 2011), the vast majority were found by searching for coherent stellar overdensities in the homogeneous, wide-field photometric catalogue provided by the *Sloan Digital Sky Survey* (SDSS; York et al. 2000) (e.g. Belokurov et al. 2006, 2007; Grillmair 2006a,b, 2009, 2012; Grillmair & Dionatos 2006; Grillmair & Johnson 2006; Bonaca, Geha & Kallivayalil 2012; Grillmair et al. 2013), and more recently in VST ATLAS (Koposov et al. 2014). As a result of SDSS's predominant high-latitude, Northern hemisphere coverage, the known streams are located far from the Galactic disc and bulge that were mostly avoided by these surveys.

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The Pan-STARRS1 (PS1; Kaiser et al. 2010) 3π Survey, observing the whole sky visible from Hawaii, has the advantage of providing some of the first deep imaging of the dense inner regions of our Galaxy. With a sky coverage spanning twice that of the SDSS footprint, it offers the possibility to survey these less well-studied areas to seek new tidal streams as well as further extensions of already known ones.

In this Letter, we report the discovery of a very thin stellar stream located in the inner Galaxy close to the Galactic bulge. It was found serendipitously when analysing PS1 data of wide areas around nearby globular clusters for the presence of tidal debris. We briefly describe the PS1 survey in Section 2, and present the new stream and measurements of its properties in Section 3. A summary is given in Section 4.

2 THE PS1 3π SURVEY

The PS1 3π Survey (Kaiser et al. 2010; Chambers et al., in preparation) is being carried out with the 1.8 m optical telescope installed on the peak of Haleakala in Hawaii. Thanks to the 1.4-gigapixel imager (Onaka et al. 2008; Tonry & Onaka 2009) covering a 7 deg^2 field of view ($\sim 3\overset{\circ}{.}3$ diameter), it is observing the whole sky north of $\delta > -30°$ in five optical to near-infrared bands ($g_{\rm P1}r_{\rm P1}i_{\rm P1}z_{\rm P1}y_{\rm P1}$; Tonry et al. 2012b) up to four times per year. The exposure time ranges from 30 to 45 s, leading to median 5σ limiting AB magnitudes of 21.9, 21.8, 21.5, 20.7 and 19.7 for individual exposures in the $g_{\rm P1}r_{\rm P1}i_{\rm P1}z_{\rm P1}y_{\rm P1}$ bands, respectively (Morganson et al. 2012). At the end of the survey, the 12 or so images per band will be stacked, increasing the depth of the final photometry by $\sim$1.2 mag (Metcalfe et al. 2013).

The individual frames are automatically processed with the Image Processing Pipeline (Magnier 2006) to produce a photometrically and astrometrically calibrated catalogue. A detailed description of the general PS1 data processing is given in Tonry et al. (2012a). The analysis presented in this Letter is based on the photometric catalogue obtained by averaging the magnitudes of objects detected in individual exposures (Schlafly et al. 2012). At the end of the survey, the point source catalogue will be based on detections in the stacked images, leading to a significantly deeper photometry and better constraints on the tidal streams.

The catalogue used here was first corrected for foreground reddening by interpolating the extinction at the position of each source using the Schlafly et al. (2014) dust maps with the extinction coefficients of Schlafly & Finkbeiner (2011). In this part of the sky, $E(B-V)$ ranges from 0.17 to $\sim$1.2 (see Fig. 1). We then cleaned the catalogue by rejecting non-stellar objects using the difference between point spread function and aperture magnitudes, as well as poorly measured stars by keeping only objects with a signal-to-noise ratio of 10 or higher.

3 A NEW STREAM IN OPHIUCHUS

The stream appears as a coherent structure in the maps showing the stellar density of objects with colours and magnitudes corresponding to the old, metal-poor main-sequence turn-off (MSTO) of nearby globular clusters. The colour and magnitude cuts were then refined based on the distribution of stars in the colour–magnitude diagram (CMD) of the stream region (see below). The resulting map is shown in Fig. 1 in both equatorial and Galactic coordinates, along with the corresponding reddening maps from Schlafly et al.

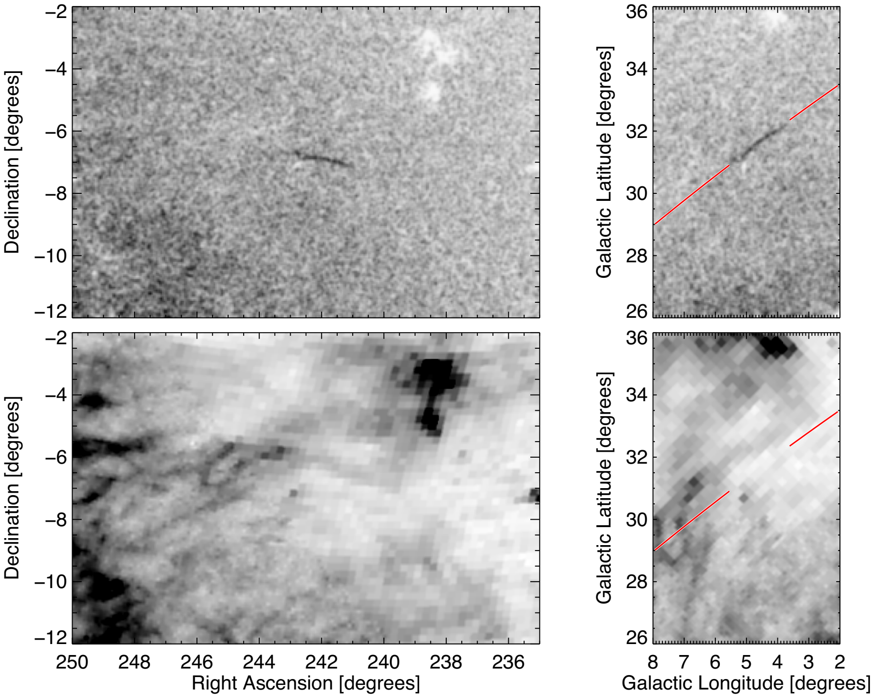

Figure 1. Top: density of stars with dereddened colours and magnitudes consistent with the main-sequence turn-off of an old and metal-poor population at heliocentric distances of 8–12 kpc (see selection box in Fig. 2), shown in equatorial (left) and Galactic (right) coordinates. Darker areas indicate higher stellar density. Bottom: reddening maps of the corresponding fields, derived from Pan-STARRS1 stellar photometry (see Schlafly et al. 2014). The colour scale is logarithmic; white (black) corresponds to $E(B-V) = 0.17$ (0.58). The stellar density and reddening maps have been smoothed with a Gaussian kernel with full-width at half-maximum of 12 and 6 arcmin, respectively. The stream is located close to the centre of each panel. The thick lines in the right-hand panels trace the best-fitting great circle containing the stream.

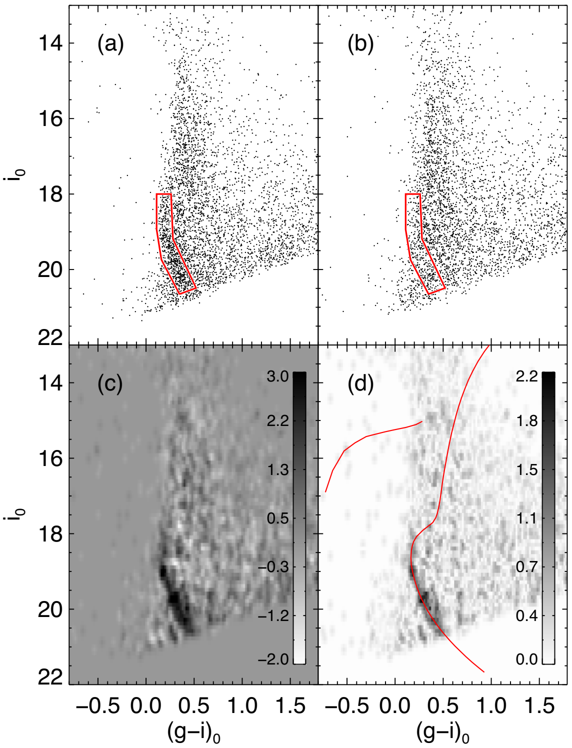

Figure 2. Extinction-corrected CMDs of the stream (a), a nearby field (b), the difference between the two (c), and the significance (d). The MSTO selection box used to produce Fig. 1 is shown by a red line in the top panels. The red lines in the last panel show the fiducial and HB of NGC 5904 (M 5) calculated from the PS1 photometry by Bernard et al. (2014). A few blue HB stars are visible in panel (a) at $(g_{\rm P1} - i_{\rm P1})_0 \sim -0.5$ and $i_{P1,0} \sim 16$.

(2014). While there is a little residual substructure due to the strong differential reddening in this part of the sky, the stream is obvious at $\alpha \sim 242^{\circ}$ and $\delta \sim -7^{\circ}$ ($l \sim 5^{\circ}$, $b \sim +32^{\circ}$). There are no features in the dust map that could produce such an artefact. In fact, we checked that we recover the stream whether or not we apply the reddening correction.

Fig. 2 shows the CMD of a 9 arcmin wide box centred on the stream and extending within the range $241^{\circ}.5 < \alpha < 243^{\circ}.5$, as well as a nearby comparison region of the same area. The bottom panels show the residuals and the significance of the residuals in Poissonian sigmas. The MSTO is visible as an overdensity at $(g_{\rm P1} - i_{\rm P1})_0 \sim 0.2$ and $i_{P1,0} \sim 19$, and is highlighted in the top panels by a red box. A few blue horizontal-branch (HB) stars are also detected at $(g_{\rm P1} - i_{\rm P1})_0 \sim -0.5$ and $i_{P1,0} \sim 16$. As expected from such a sparse HB, no RR Lyrae star could be found at the location and distance of the stream in the catalogue of Drake et al. (2013). The lack of obvious sub-giant and red giant branches does not allow tight constraints on the constituent stellar populations, although the presence of a blue HB suggests an old and metal-poor population ($\gtrsim$10 Gyr old, [Fe/H] $\lesssim -1.0$). The features of the stream CMD are well fitted by the fiducial of the old globular cluster NGC 5904 (M 5, [Fe/H] ~ -1.3) shown as red lines (from Bernard et al. 2014). The fiducial was first corrected for the reddening along the line of sight to NGC 5904 ($E(B-V) \sim 0.09$; Schlafly et al. 2014), then shifted by +0.5 mag to match the luminosity of the stream MSTO. A small colour shift (0.07 mag to the blue) improves the fit to the MSTO, possibly due to the high and varying reddening in this region. The HB of the fiducial also provides a good fit to the observed blue HB stars, giving further support that the estimated distance is reliable. Assuming $(m-M)_0 = 14.44 \pm 0.02$ for NGC 5904 (Coppola et al. 2011) yields a true distance modulus of $(m-M)_0 = 14.9 \pm 0.2$ (i.e. 9.5 ± 0.9 kpc) for the Ophiuchus stream. Finally, if we assume that the Sun is located 8 kpc from the Galactic Centre (GC), we find a Sun–GC–stream angle of ~89 deg, placing the stream almost directly above the Galactic bulge at a Galactocentric distance of 5.0 ± 1.0 kpc.

To estimate the total luminosity of the stream, we used IAC-STAR (Aparicio & Gallart 2004) to generate the CMD of an old population (11.5–12.5 Gyr) containing 10^5 stars with a metallicity comparable to that of NGC 5904 and with the same depth as our observations – stars fainter than our detection limit have a negligible contribution to the total magnitude. In Fig. 2, we find that there are about 500 more stars in panel (a) containing the stream than in the comparison field (panel b). Summing the luminosity of a sample of 500 stars extracted randomly from the synthetic CMD gives the total flux. We repeated this step 10^4 times, extracting between 300 and 700 stars each time, and found a total magnitude and luminosity of $M_V = -3.0 \pm 0.5$ and $L_V = 1.4 \pm 0.6 \times 10^3\,{\rm L}_{\odot}$, respectively. These are comparable to some of the fainter halo clusters (e.g. Whiting 1, Terzan 9, Palomar 1, Palomar 13: Harris 1996, 2010 Edition), although a significant fraction of the stars may have already been stripped off and lie further out along the stream orbit.

The extent of the stream on the sky was calculated by reprojecting the stellar maps to a new spherical coordinate system (Λ,B) with the pole located at $(\alpha,\delta) = (184^{\circ}.32, +77^{\circ}.25)$ [$(l,b) = (125^{\circ}.37, +39^{\circ}.72)$]. In this system the stream approximately lies along the equator – shown by the red lines in Fig. 1 – making it easier to measure its width and length. In Fig. 3, we show the distribution of MSTO stars across the Λ and B dimensions. The left-hand panel shows the stellar density across the stream, where all the MSTO stars in the range $-1^{\circ} < \Lambda < 1^{\circ}$ have been used. The stream is detected as a significant overdensity at $B \sim 0^{\circ}$. The profile is best fitted by a Gaussian with $\sigma = 2.99$ arcmin$\pm$0.33 arcmin, corresponding to a full-width at half maximum (FWHM) of 7.0 arcmin$\pm$0.8 arcmin, i.e. 19 ± 2 pc at the distance of the stream. However, we note that in Fig. 1, the stream appears slightly more curved than the great circle shown, implying that the intrinsic width may be even smaller. The right-hand panel shows the profile along the length of the stream, for which we used the MSTO stars in a narrow strip (12 arcmin) centred on the stream. To estimate the background, we selected MSTO stars in six identical strips at higher and lower B; their average and dispersion are shown as the blue line and the shaded area. The on-stream histogram shows a significant overdensity within the range $-1^{\circ}.2 \lesssim \Lambda \lesssim 1^{\circ}.3$, and is therefore about $2^{\circ}.5$ long (i.e. ~400 pc in projection).

Table 1 summarizes the estimated properties of the stream: we list the approximate coordinates of its centre, the heliocentric and Galactocentric distances, the extent on the sky, and the estimated luminosity.

4 DISCUSSION AND CONCLUSIONS

We have identified a new stellar stream in the constellation of Ophiuchus, a part of the sky that has rarely been searched for streams because of the high stellar density and significant differential and foreground reddening. Both the morphology of the MSTO and the presence of a blue HB are typical of an old and metal-poor population ($\gtrsim$10 Gyr old, [Fe/H] $\lesssim -1.0$). These properties, along with the small width of the stream and absolute magnitude suggest a globular cluster as progenitor.

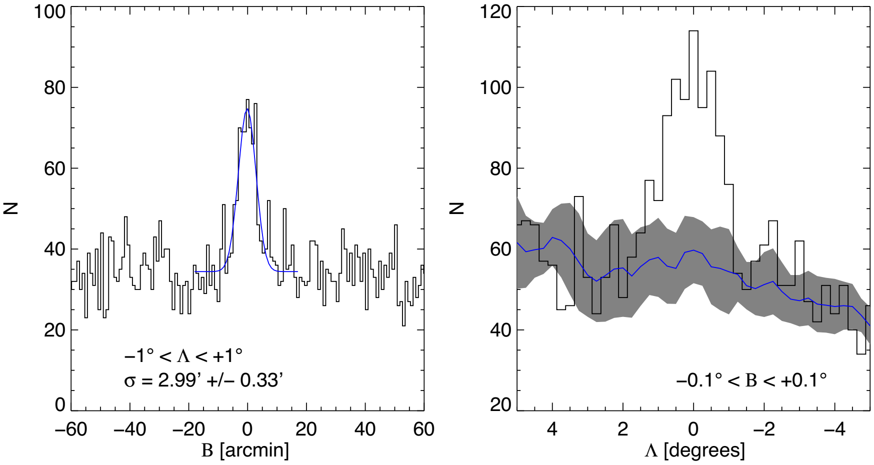

Figure 3. Left: MSTO star density as a function of stream latitude. The stream is detected as a strong overdensity that is well fitted by a Gaussian with $\sigma = 2.99\,\mathrm{arcmin} \pm 0.33\,\mathrm{arcmin}$. Right: stellar density as a function of stream longitude. The blue line and shaded area represent the mean background contamination and its dispersion (see text).

Table 1. Summary of the stream properties.

Parameter	Value
RA (J2000.0)	16:07:12
Dec. (J2000.0)	−06:55:30
l	$4\overset{\circ}{.}53$
b	$+31\overset{\circ}{.}69$
$(\mathrm{m-M})_0$	14.9 ± 0.2
Median $E(B-V)$	0.23
Heliocentric distance	9.5 ± 0.9 kpc
Galactocentric distance	5.0 ± 1.0 kpc
Width (FWHM)	7.0 arcmin ± 0.8 arcmin (19 ± 2 pc)
Length	$\sim 2\overset{\circ}{.}5$ ($\sim$400 pc)
M_V	-3.0 ± 0.5
L_V	$1.4 \pm 0.6 \times 10^3\ \mathrm{L}_\odot$

We find that the stream is exceptionally short ($\sim 2\overset{\circ}{.}5$, i.e. $\sim$400 pc, in projection) compared to all the other streams found so far, that are usually several tens of degrees long. For comparison, the shortest stream known to date is the Pisces–Triangulum stream, which has been traced over $\sim 15^\circ$ (i.e. $\sim$7 kpc) on the sky (e.g. Bonaca et al. 2012; Martin et al. 2014). We have explored shifting the MSTO selection box in magnitude to account for possible effects of differential reddening residuals and extension of the stream along the line of sight, but failed to detect any overdensity beyond the current extent. This experiment did reveal a possible distance gradient along the stream, with the eastern tail being closer to the Sun, although the apparent change in MSTO magnitude could simply be a consequence of the differential reddening.

Surprisingly, neither the stellar density along the stream nor a careful visual inspection of the images reveals a potential remnant of the progenitor. This suggests that it has already been completely disrupted. Given that the length of a tidal stream is a function of the time since the stars became unbound, a short stream may indicate that the progenitor has been disrupted only recently. However, this scenario is hard to reconcile with the lack of an obvious progenitor in the vicinity of the stream. Another possibility is that we are observing the stars of a fully disrupted cluster at apogalacticon on a highly elliptical orbit: at this point of the orbit, unbound stars tend to clump together because of the slower orbital velocity (e.g. Dehnen et al. 2004; Küpper, Lane & Heggie 2012). The data currently available are not sufficient to reliably trace the orbit of the progenitor, which would help us understand its past evolution and likely fate; radial velocities and proper motions of a sample of stream members will be crucial for this purpose.

Spectroscopic metallicities of stream stars will also shed light on the nature of the progenitor, and help understand how such events may contribute to the stellar populations in the central regions of the Galaxy. For example, recent spectroscopic surveys of the outer Galactic bulge have revealed the presence of a significant number of metal-poor stars ($[\mathrm{Fe/H}] < -1$; e.g. Gonzalez et al. 2011; García Pérez et al. 2013). Their origin may be linked to tidal stripping events such as the one we are witnessing with this stream.

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