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Discovery of a split stellar stream in the periphery of the Small Magellanic Cloud

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ABSTRACT

I report the discovery of a stellar stream (Sutlej) using *Gaia* DR3 (third data release) proper motions and XP metallicities located ∼15° north of the Small Magellanic Cloud (SMC). The stream is composed of two parallel linear components (‘branches’) approximately ∼8° × 0.6° in size and separated by 2.5°. The stars have a mean proper motion of $(\mu_{\rm RA}, \mu_{\rm Dec.}) = (+0.08\ {\rm mas\ yr^{-1}}, -1.41\ {\rm mas\ yr^{-1}})$, which is quite similar to the proper motion of stars on the western side of the SMC. The colour–magnitude diagram of the stream stars has a clear red giant branch, horizontal branch, and main-sequence turn-off that are well matched by a PARSEC isochrone of 10 Gyr, [Fe/H] = −1.8 at 32 kpc, and a total stellar mass of $\sim 33\,000\ {\rm M}_{\odot}$. The stream is spread out over an area of 9.6 $\rm deg^2$ and has a surface brightness of 32.5 mag $\rm arcsec^{-2}$. The metallicity of the stream stars from *Gaia* XP spectra extends over $-2.5 \leq$ [M/H] ≤ -1.0 with a median of [M/H] = −1.8. The tangential velocity of the stream stars is 214 km $\rm s^{-1}$ compared to the values of 448 km $\rm s^{-1}$ for the Large Magellanic Cloud and 428 km $\rm s^{-1}$ for the SMC. While the radial velocity of the stream is not yet known, a comparison of the space velocities using a range of assumed radial velocities shows that the stream is unlikely to be associated with the Magellanic Clouds. The tangential velocity vector is misaligned with the stream by nearly 90°, which might indicate an important gravitational influence from the nearby Magellanic Clouds.

Key words: Galaxy: halo – Galaxy: structure – Local Group.

1 INTRODUCTION

According to the currently favoured hierarchical galaxy formation paradigm (e.g. Peebles 1965; Press & Schechter 1974), galaxies started small and grew through merger events and accretion of smaller systems, most of which were tidally stripped apart. Starting over three decades ago, mounting evidence of stellar streams in the Milky Way’s (MW) halo was discovered, with the Sagittarius stream (e.g. Ibata et al. 2001; Newberg et al. 2002) being the most prominent with its two tidal tails wrapping around the MW. With the advent of deep, wide-field, multiband photometric surveys, the number of discovered stellar streams rose quickly with the Sloan Digital Sky Survey (SDSS; York 2000) leading the way with the ‘Field of Streams’ that included the Orphan stream, Anticentre stream, and others (Belokurov et al. 2006). Some of the most impressive streams are those produced by disrupted globular clusters that are extremely thin but can stretch over many tens of degrees (e.g. Grillmair & Dionatos 2006a, b). See Newberg & Carlin (2016) for a more detailed review of stellar streams.

Not only are observed stellar streams a striking confirmation of the violent origin of galaxies through mergers and accretion events, but stellar streams can be used as tracers to probe the Galaxy’s mass and constrain the 3D structure of the gravitational potential (e.g. Johnston, Law & Majewski 2005; Koposov, Rix & Hogg 2010). One of the most effective search algorithms is the ‘matched-filter’ method that selects all stars lying close to an old isochrone in the colour–magnitude diagram (CMD) at a certain distance. A range of distances are searched and the resulting on-sky stellar density plots inspected for linear features. Often the filters are heavily weighted towards the blue, main-sequence turn-off portion of the isochrone that has a large number of stars compared to the MW foreground.

Until recently, most stellar stream work was confined to the Northern hemisphere due to the predominance of large surveys such as SDSS, PS1 (The Panoramic Survey Telescope and Rapid Response System, Pan-STARRS 1; Chambers et al. 2016), and Asteroid Terrestrial-impact Last Alert System (ATLAS; Tonry et al. 2018) that covered that region of the sky. However, with the advent of the Dark Energy Camera (DECam; Flaugher et al. 2015), the situation changed dramatically. Using the deep, multiband Dark Energy Survey (DES) photometric catalogue (Dark Energy Survey Collaboration 2016), Shipp et al. (2018) discovered 11 new stellar streams in a southern ‘tour-de-force’ much like the northern SDSS ‘Field of Streams’. The DECam Local Volume Exploration Survey (DELVE; Drlica-Wagner et al. 2021) is systematically covering the entire southern sky with DECam to search for dwarf galaxies and stellar streams and was recently used to discover the jet stream (Ferguson et al. 2022).

Even though deep, multiband photometry has been the mainstay of stellar stream searches for decades, other techniques can also be extremely effective. The second data release of *Gaia* (Gaia Collaboration 2018) produced precise proper motions for over a

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billion stars. This allowed for a kinematic selection of stellar streams. Ibata, Malhan & Martin (2019) used a new systematic search method (STREAMFINDER; Malhan & Ibata 2018) that takes advantage of the kinematics to discover eight new stellar streams throughout the MW, including in the MW mid-plane, which has historically been avoided by stream searches due to the high number of MW disc stars that can confuse search algorithms and generate many false positives.

In the third data release of *Gaia* (DR3; Gaia Collaboration 2023), the low-resolution BP/RP (XP) spectra of 220 million stars were released. While the released stellar parameters (Andrae et al. 2023a) were not as reliable as originally anticipated, Andrae, Rix & Chandra (2023b) determined precise metallicities as well as effective temperatures and surface gravities for 175 million stars using XGBOOST trained on APOGEE (Majewski et al. 2017) spectra and AllWise photometry (Cutri et al. 2021).

In this paper, I report on the discovery of a new stellar stream near the Small Magellanic Cloud (SMC) using the *Gaia* DR3 proper motions and XP metallicities.

This paper is structured as follows. Section 2 discusses the data and catalogues, while Section 3 outlines the discovery and characterizes the main stream properties. The main results are presented in Section 4 and the implications of the results are discussed in Section 5. Finally, the main conclusions are summarized in Section 6.

2 DATA

For this project, I used solely the *Gaia* DR3 data set. DR3 contains astrometric information, including proper motions, for 1.46 billion sources and three-band photometry (G, BP, and RP) for 1.54 billion sources. In addition, it contains object classification from the BP/RP (XP) spectra for 470 million sources, although the stellar parameters ($T_{\rm eff}$, $\log g$, and [M/H]) in the official data release have some systematics that make the values unsuitable for most scientific analyses. Instead, I use the stellar parameters from the Andrae et al. (2023b) catalogue that used a machine-learning model (XGBOOST; Chen & Guestrin 2016) trained on APOGEE (Majewski et al. 2017; Abdurro'uf et al. 2022) and other data to derive primarily [M/H], but also $T_{\rm eff}$ and $\log g$ along the way, for 175 million stars from the average XP spectra that were released in *Gaia* DR3. Note that Zhang, Green & Rix (2023) released a similar catalogue but used a generative model to derive $T_{\rm eff}$, $\log g$, [M/H], and extinction for 220 million stars from the XP spectra.

3 DISCOVERY AND CHARACTERIZATION

While investigating the *Gaia* DR3 data for substructure in the periphery of the Magellanic Clouds (MCs) and looking through a variety of longitude versus proper motion figures in narrow ranges of metallicity, I serendipitously discovered an overdensity of stars. Fig. 1 shows an example of the type of figure that I was inspecting. It shows the distribution of stars in the Andrae et al. catalogue with $[{\rm M/H}] < -1.7$ in the MC region in the $\mu_{\rm B,MS}$ versus $L_{\rm MS}$[1] colour-coded by the metallicity. A stellar substructure or stream should appear as a clump in this type of figure. While the figure is quite 'messy', a linear feature is visible in the bottom left-hand corner highlighted by the green ellipse ($-40^\circ \lesssim L_{\rm MS} \lesssim -20^\circ$, $\mu_{\rm B,MS} \approx -0.3$ mas yr^{-1}). Further inspection showed that this feature is not spurious, but rather a real structure elongated spatially not far from the SMC.

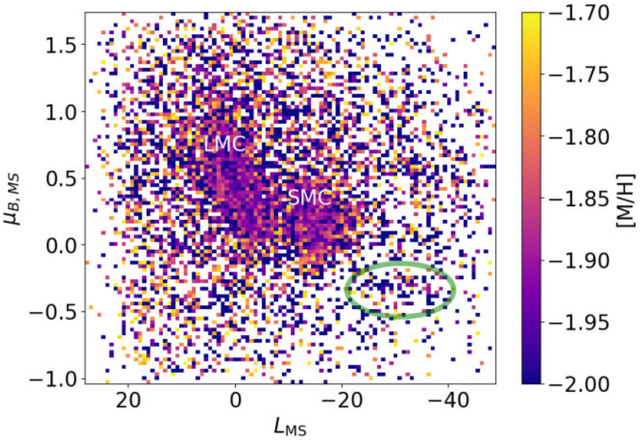

Figure 1. Density of Magellanic *Gaia* DR3 XP stars with $[{\rm M/H}] \leq -1.7$ in the $\mu_{\rm B,MS}$ versus $L_{\rm MS}$. The overdensity of stars with $-35^\circ \leq L_{\rm MS} \leq -20^\circ$ and $\mu_{\rm B,MS} \approx -0.3$ mas yr^{-1} is highlighted with the ellipse.

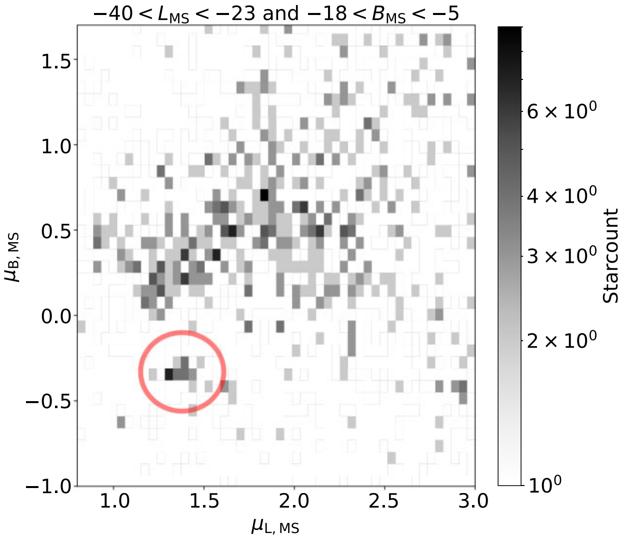

Figure 2. Density of Magellanic giant stars in $\mu_{\rm L,MS}$ versus $\mu_{\rm B,MS}$. The stream stars are indicated by the ellipse.

Fig. 2 shows the proper motion distribution of the stars in that spatial region ($-40^\circ < L_{\rm MS} < -23^\circ$, $-18^\circ < B_{\rm MS} < -5^\circ$) exhibiting an even stronger overdensity at ($\mu_{\rm L,MS}$, $\mu_{\rm B,MS}$) = ($+1.4$ mas yr^{-1}, -1.3 mas yr^{-1}). The stars selected by the red circle, centred at ($\mu_{\rm L,MS}$, $\mu_{\rm B,MS}$) = ($+1.38$ mas yr^{-1}, -1.33 mas yr^{-1}) and with radius 0.23 mas yr^{-1}, are plotted on the sky in Fig. 3 as red and blue filled circles. The background image shows the density of MC stars selected via proper motion, XP $T_{\rm eff}$/$\log g$, and a red giant branch (RGB) box in the CMD. The new stellar structure is composed of two nearly parallel stellar streams ('branches') with angular sizes of roughly $\sim 8^\circ \times 1^\circ$ and separated from each other by $\sim 2.5^\circ$. At the closest point, the stream is only $\sim 1.5^\circ$ from the SMC Northern Overdensity (SMCNOD; Pieres et al. 2017) and $\sim 11^\circ$ from the centre of the SMC. This obviously begs the question of whether the new stream is associated with the SMC, which I explore in depth in Section 5.

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[1] Where $L_{\rm MS}$/$B_{\rm MS}$ refer to the Magellanic Stream coordinate system defined in Nidever, Majewski & Butler Burton (2008), and $\mu_{\rm L,MS}$/$\mu_{\rm B,MS}$ are the corresponding proper motions.

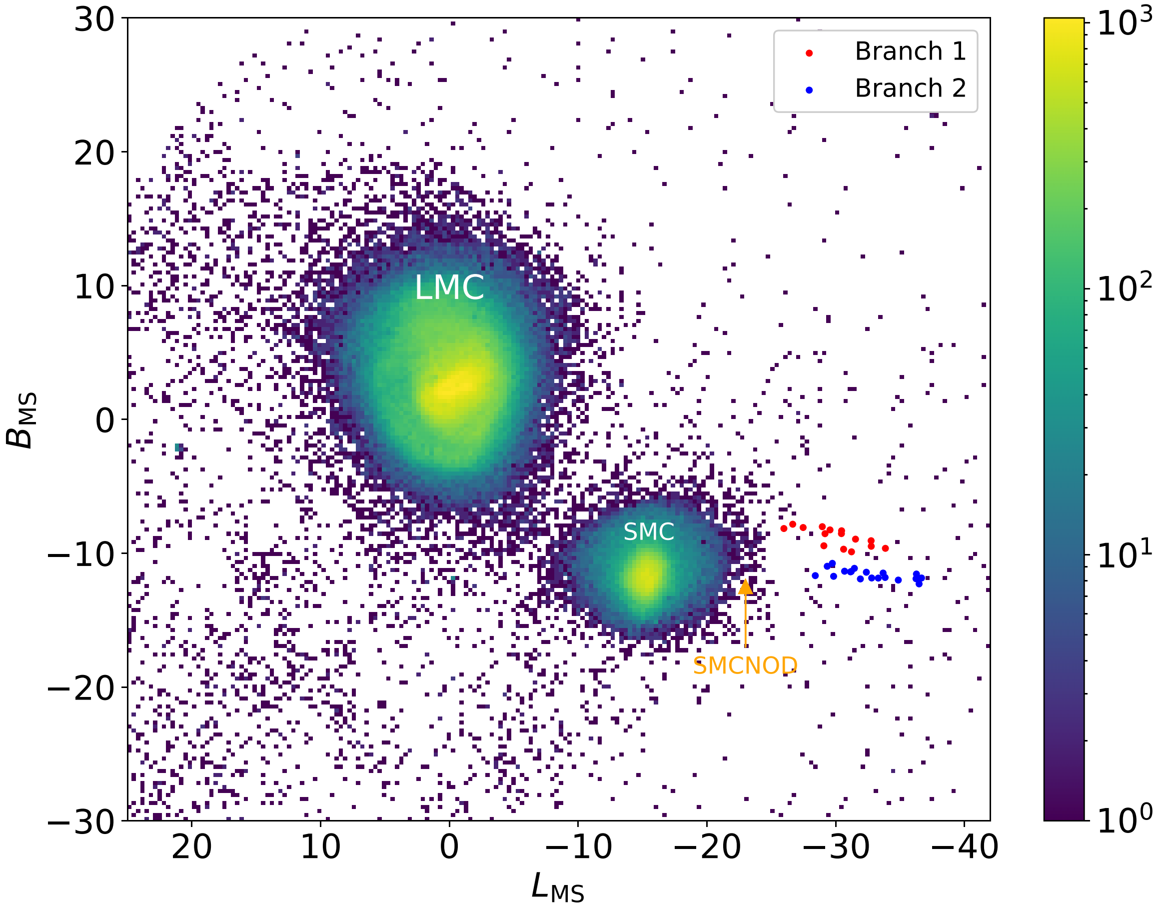

Figure 3. Density of Magellanic giant stars as selected from *Gaia* DR3 XP. The position of the two stellar stream branches are indicated by the red (Branch 1) and blue (Branch 2) filled circles.

I will follow the naming convention of Shipp et al. (2018) who named their stellar streams in this region of the sky after rivers in Pakistan and India, in particular after the Indus river and its tributaries Jhelum, Cheneb, and Ravi (in geographical order from northwest to southeast). I shall name the new stream ‘Sutlej’ (/ˈsʌtlədʒ/) after the remaining main tributary of the Indus river that continues the geographical progression of the tributaries in northern India to the southeast and is nicely mirrored on the sky as the new stream is to the east of Ravi and Cheneb (see Fig. 10).

4 RESULTS

The mean proper motion of the stream stars is ($\mu_{\rm L,MS}$, $\mu_{\rm B,MS}$) = (+1.4 mas yr^{-1}, −0.322 mas yr^{-1}). As can be seen in Fig. 4, the tangential velocity vector (after correcting the proper motion for the solar motion) is *not* aligned with the stream, and almost perpendicular to it. This might be due to the influence of the nearby Large Magellanic Cloud (LMC) and SMC, which has been shown to produce such a misalignment in the Orphan stream (Erkal et al. 2019).

Fig. 5 shows the CMD of all *Gaia* DR3 stars in the vicinity of the two stream branches. A well-defined RGB, blue horizontal branch (BHB), and main-sequence turn-off are apparent. Both stellar branches are well represented in these features with no large difference visible between them (except for the BHB; see below). The black line shows a [Fe/H] = −1.8, 10 Gyr at 32 kpc PARSEC isochrone fit by-eye to the data.

While the CMDs of the two branches look nearly identical, Branch 1 (red) has a horizontal branch that extends 0.25 mag bluer than Branch 2 (blue) does. The distances of the BHB stars can be directly estimated and contrasted with the isochrone distance and the distances of the two branches can be compared as well. I converted the *Gaia* photometry to the SDSS system using the photometric transformation equations in the *Gaia* release documentation.[2] The Barbosa et al. (2022) relation was used to compute the BHB absolute magnitude M_g as a function of $g - r$ colour and the distance calculated by comparing to the apparent magnitudes. Fig. 6 shows the BHB distances of the stream stars with a mean distance of 32.4 kpc for all stars and 33.0/31.8 kpc for Branch 1/2. This is in excellent agreement with the isochrone-fitting distance of 32 kpc. While Branch 1 shows almost no variation in distance with $L_{\rm MS}$, the Branch 2 distances increase the farther away they are from the SMC at a rate of ∼0.9 kpc deg^{-1}.

We can also investigate the metallicities of the brighter stream stars (G < 17.65) using the *Gaia* DR3 XP metallicity provided by Andrae et al. (2023b). Fig. 7 shows the metallicity distribution function

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[2] https://gea.esac.esa.int/archive/documentation/GDR2/Data_processing/chap_cu5pho/sec_cu5pho_calibr/ssec_cu5pho_PhotTransf.html

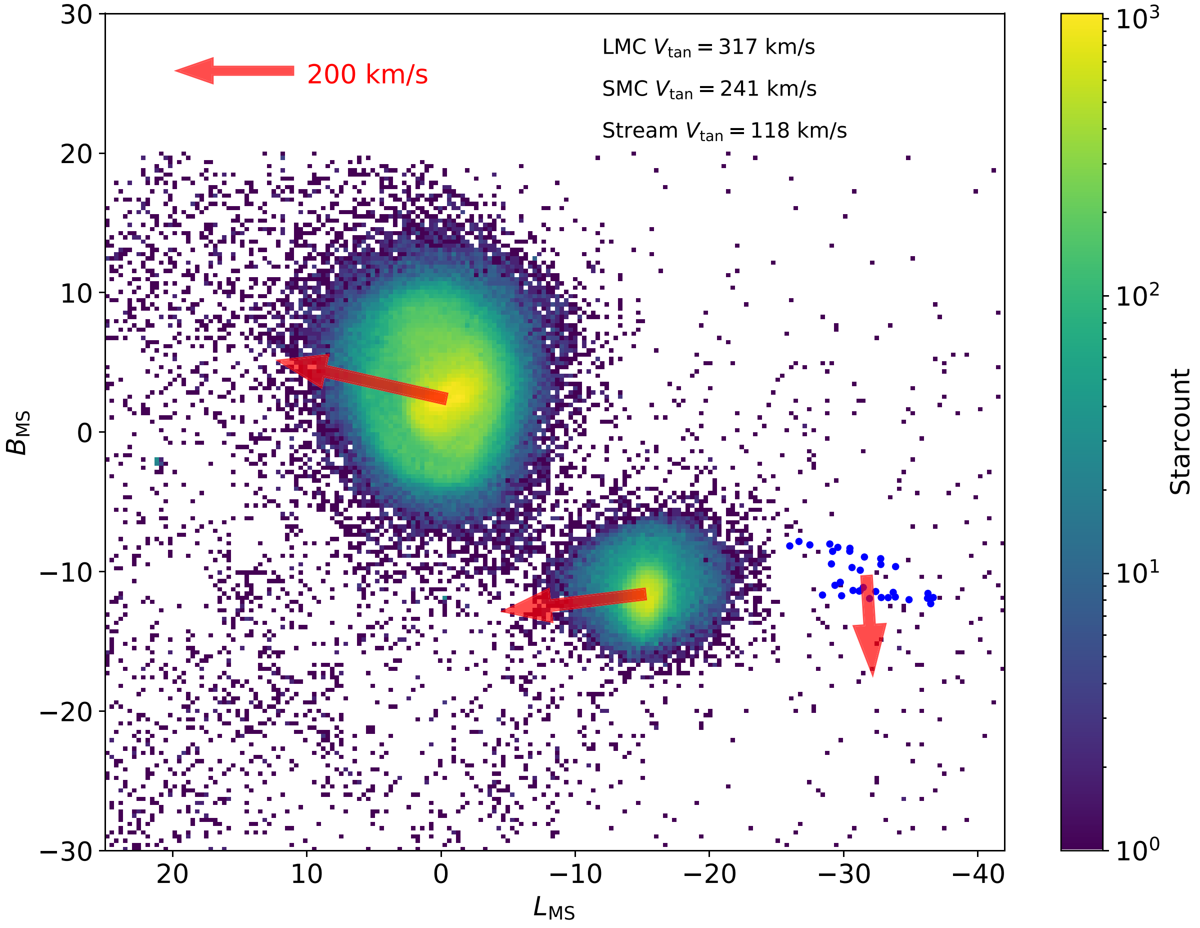

Figure 4. The tangential motion of the LMC, SMC, and the stream stars. The length of the arrows indicates the magnitude of the velocity. The tangential velocity vector of Sutlej is almost perpendicular to that of the MCs as well as the Sutlej stream track. This might indicate that the stream has been gravitationally perturbed by the MCs. Note that the tangential motion vectors of the two stream branches are nearly identical.

(MDF) of RGB stars from the stream (blue and red) as well as the SMC (purple) and SMCNOD (green). To provide a smoother representation of the data (similar to a kernel density estimate), each star is presented as a Gaussian with unity amplitude and a full width at half-maximum (FWHM) of 0.2 dex. The curve from each group is then divided by the number of stars to produce a density curve that makes the comparison between the stellar populations easier. While the MDFs of the two stream branches look similar to each other (given the small number statistics), they are significantly more metal-poor than the majority of the SMC and SMCNOD distributions. This alone is a strong indication that the stream did not originate from the SMC (but see Section 5 for more on the origin). In addition, the broad stream MDF with an FWHM width of ∼1 dex suggests that the progenitor was a dwarf galaxy rather than a globular cluster.

I estimated the Great Circle Pole for each branch by searching a grid of pole coordinate values $0^\circ \leq \alpha \leq 360^\circ$ and $0^\circ \leq \delta \leq +90^\circ$ in steps of 1° and calculated the *rms* (root-mean-square) of the transformed latitude for each pole. I found the points coordinates with the lowest *rms* values and refined the search for more precision. The pole for Branch 1 is $(\alpha, \delta) = (68.7^\circ, 16.3^\circ)$ and for Branch 2 is $(\alpha, \delta) = (73.5^\circ, 10.7^\circ)$. The FWHM widths in latitude are 0.56°/0.68° for Branch 1/2, which at a distance of 32 kpc corresponds to 0.31 kpc/0.38 kpc. A summary of the stream values is shown in Table 1.

The total number of member stars in *Gaia* is low in the Sutlej stream. There are only 34 stream stars in the *Gaia* XP sample and 80 in the full *Gaia* DR3 sample down to $G = 20.0$ (RGB and BHB stars). It is therefore worth estimating the stellar mass in the stream. I estimated the total stellar population mass by creating synthetic photometry from a 10 Gyr, $[\mathrm{Fe/H}] = -1.8$ PARSEC isochrone at 32 kpc with a total stellar mass of 10^6 $\mathrm{M}_\odot$. All RGB and BHB synthetic stars down to a magnitude of $G = 20.0$ were selected and the same operation performed on the data. This resulted in 80 *Gaia* stars and 6056 synthetic stars. My proper motion cut has removed faint member stars with larger proper motion errors. To model this incompleteness, I fit the logarithm of the declination proper motion error as a quadratic function of G magnitude for *Gaia* stars in the Sutlej region with $13.3 < G < 20.8$ and used 0.0113 mas yr^{-1} for the brighter stars. Random proper motion errors were generated using this uncertainty distribution and the proper motion cut (radius of 0.23 mas yr^{-1}) applied. Comparing the synthetic and observed magnitude distributions revealed that the isochrone vastly overpredicts the number of BHB stars. Since it is difficult for isochrones to model the horizontal branch (Percival & Salaris 2011),

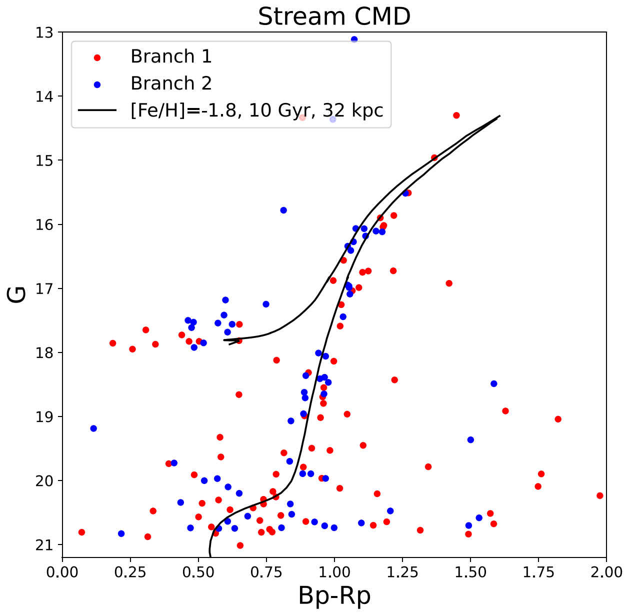

Figure 5. The CMD of the region around the new stellar streams. A clear RGB, horizontal branch, and main-sequence turn-off are visible. A PARSEC isochrone with [Fe/H] = −1.8, 10 Gyr, and a distance of 32 kpc is shown in black.

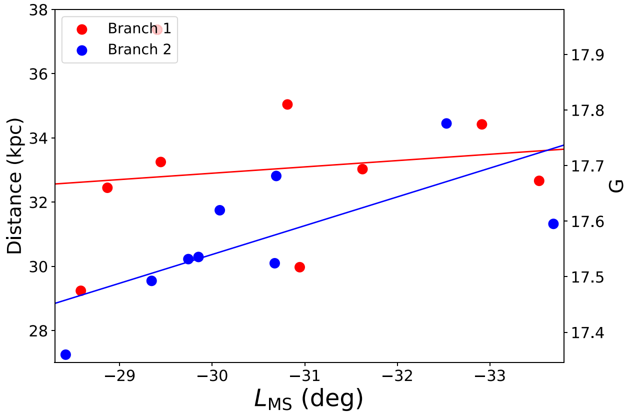

Figure 6. The distance (kpc) of the BHB stars versus $L_{\rm MS}$ for the two stream branches. An estimate of the *GaiaG* magnitude assuming an average BHB colour is shown on the right-hand side. The average BHB distance of Branch 1 is 33.0 kpc and for Branch 2 is 31.8 kpc. Branch 1 is ∼1.0 kpc farther away than Branch 2. While Branch 1 does not show much of a distance gradient, the distance of the Branch 2 BHB stars grow larger with increasing angular distance from the SMC at a rate of ∼0.9 kpc deg^{-1}.

I decided to only use the RGB stars to determine the stellar mass. The total number of synthetic RGB and AGB stars down to $G = 20$ mag is 1223 and the observed number is 59. Scaling the input isochrone mass of 10^6 M$_\odot$ by 59/1223 gives 48 242 M$_\odot$. The formal Poisson uncertainty of the derived stellar mass is 13 per cent or 6280 M$_\odot$, however, the uncertainty is likely higher due to the mismatch of the isochrone model and the data.

Finally, I calculate the surface brightness by summing up the flux from all synthetic stars and scaling to the total mass of 33 333 M$_\odot$. The area of each stream branch is 0.6° × 8° or 9.6 deg^2 combined. The total flux is divided by the area in arcsec squared and converted back to magnitude to obtain 32.3 mag arcsec^2. Another way to calculate the surface brightness is to sum up the flux of the observed stars and then correct for incompleteness. Using the same procedure with the 80 RGB and BHB stars down to $G = 20.0$ gives a surface brightness of 33.1 mag arcsec^2. However, this is incomplete because of the stars that we are not seeing. We can use the theoretical isochrone to calculate a good estimate for this completeness by calculating the cumulative fraction of total flux as a function of G. At $19 \leq G \leq 20$ mag, this is fairly constant with a value of ∼55 per cent. Applying this correction to the total observed flux gives a surface brightness of 32.5 mag arcsec^2 that is quite close to the 32.3 mag arcsec^2 calculated with the ischrone method above.

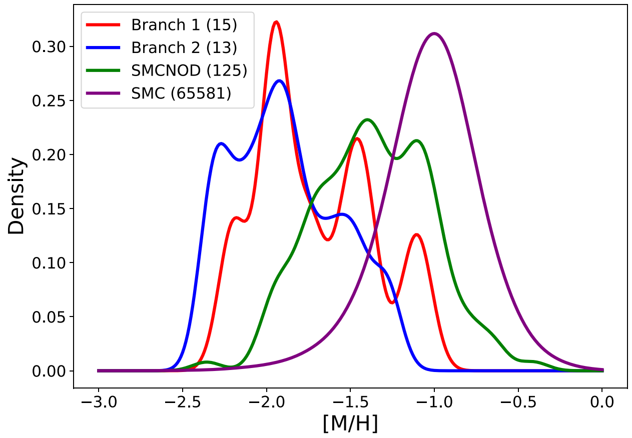

Figure 7. The MDF of the SMC (purple), the SMCNOD (green), and the stream stars (red and blue) using Andrae et al. (2023b) *Gaia* DR3 XP metallicities. The majority of the stream stars are more metal-poor than both the SMC (green) and SMCNOD (purple) stars with an average of [M/H] = −1.65 and peak around [M/H] = −1.9.

5 DISCUSSION

As previously mentioned, an obvious question, due to its proximity, is whether Sutlej is related to the MCs. The edge of the stream is only a couple of degrees away from the SMCNOD and the two stream branches are elongated almost parallel to the LMC's and SMC's tangential velocity vectors (see Fig. 4). In addition, the stream distance of 32 kpc is not too dissimilar to the MCs' distance of 50 kpc (LMC) and 60 (SMC). This is, however, where the similarities end. The tangential velocity vector of Sutlej is almost perpendicular to those of the MCs (Fig. 4), and its total tangential velocity of 214 km s^{-1} is almost a factor of 2 smaller than that of the MCs (∼430 km s^{-1}). And although we do not know Sutlej's radial velocity (RV) yet, we can compare space velocities with the MCs. Fig. 8 shows the 3D space velocities of the stream stars compared to the APOGEE MC stars assuming a wide range of stream RVs. Irrespective of the stream RV, the space velocities are always offset from the MC space velocities by more than $\gtrsim$200 km s^{-1}. In addition, as the MDF shows (Fig. 7), the stream stars are much more metal-poor than the MCs' metallicity distributions (LMC is ∼0.4 dex more metal-rich than the SMC). This indicates that these stars are too metal-poor to have been directly stripped from the MCs, but are more consistent with a dwarf spheroidal origin. In conclusion, a Magellanic origin or association of Sutlej seems unlikely.

However, I must point out one interesting spatial pattern in the two Sutlej branches that reminds me of features in the two filaments of

Table 1. Table of coordinates of the stellar streams.

Name	Equatorial coordinates	Magellanic Stream coordinates	Great Circle Pole	Width
Branch 1	[(3.2°, −55.2°), (11.0°, −61.6°)]	[(−33.9°, −9.7°), (−26.4°, −8.0°)]	(68.7°, 16.3°)	0.24°
Branch 2	[(357.9°, −53.2°), (2.9°, −60.3°)]	[(−36.7°, −12.0°), (−29.0°, −11.2°)]	(73.5°, 10.7°)	0.29°

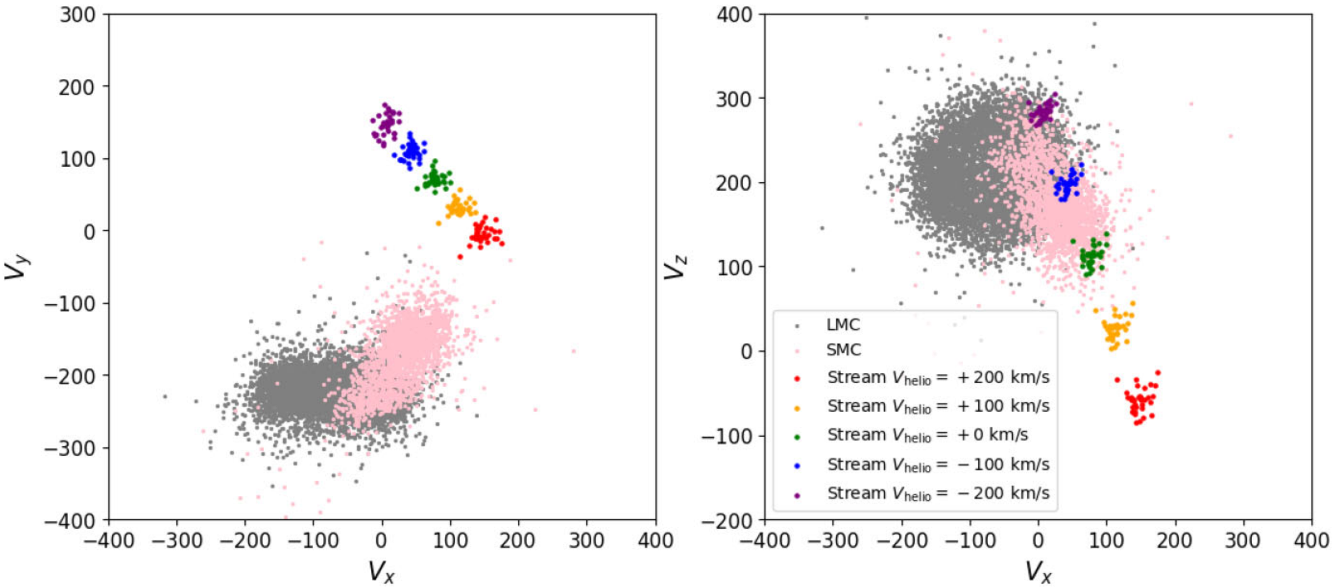

Figure 8. The galactocentric space velocities of the LMC (grey), SMC (pink), and the Sutlej stream stars (coloured points). The coloured points show the space velocities of the stream stars assuming a range of radial velocity: −200 km s^{-1} (purple), −100 km s^{-1} (red), 0 km s^{-1} (green), +100 km s^{-1} (orange), and +200 km s^{-1} (red). For all radial velocities, the space velocities of the stream stars are significantly offset from the LMC and SMC making a Magellanic origin unlikely.

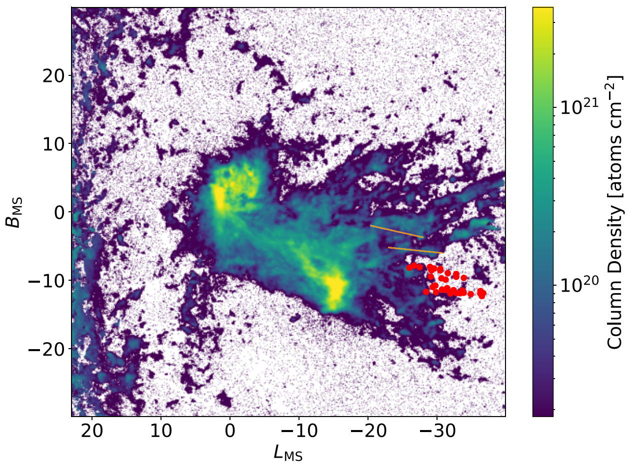

Figure 9. Column density map of H I from the GASS survey (McClure-Griffiths et al. 2009). The new stellar stream is shown in filled circles. Orange lines indicate the new stellar stream offset by +6° in $L_{\rm MS}$ and +6° in $B_{\rm MS}$.

the Magellanic Stream (MS) that are quite nearby in the sky. Fig. 9 shows the Galactic All Sky Survey (GASS; McClure-Griffiths et al. 2009) H I column density map of the Magellanic System including the Stream and the Sutlej stars (red filled circles). The two MS filaments show structures that are roughly 2° × 10° in size and offset from each other by a few degrees. This pattern looks very similar to the Sutlej branches. In fact, I have fit lines to the Sutlej branches and offset them both by +6° in $L_{\rm MS}$ and +6° in $B_{\rm MS}$ (thin orange lines). They match the length and the orientation of the MS features quite well, although one of them is offset by roughly a degree. Even if Sutlej and these MS features were related, it does not seem realistic that the gas is *leading* the stars in their orbit. The Price-Whelan 1 star cluster (Nidever et al. 2019; Price-Whelan et al. 2019) was born in the Magellanic Stream Leading Arm 117 Myr ago and has since separated from and is leading the gas by ∼10°. This is understandable and expected due to the ram pressure effects of the MW's hot halo gas on the Leading Arm gas. In fact, this can be used to constrain the density of the hot halo (see section 4.5 of Nidever et al. 2019). However, if the Sutlej branches and the MS linear features are somehow causally related, then it is unlikely that the stars would be trailing the gas. In addition, figuring in all of the discrepancies of an MC origin of Sutlej mentioned earlier, this linear feature in Sutlej and the MS is likely a curious coincidence.

Could the Sutlej stream be related to any of the streams or dwarf galaxies discovered in the MC region by DES, DELVE (Drlica-Wagner et al. 2021), and others? Fig. 10 shows the streams (as tabulated by Mateu 2023) and dwarf galaxies near the MCs with distances of 10–65 kpc colour-coded by distance. None of the nearby stellar streams are aligned with Sutlej. Moreover, although there are dwarf galaxies nearby, they are either at larger distances (Phoenix II at 84 kpc, Bechtol et al. 2015; Tucana IV at 47 kpc and Tucana V at 55 kpc, Drlica-Wagner et al. 2015) or moving in a different direction (Tucana III; Drlica-Wagner et al. 2015). The only exception is Hydrus 1 (Koposov et al. 2018) that is at a distance of 28 kpc and on the

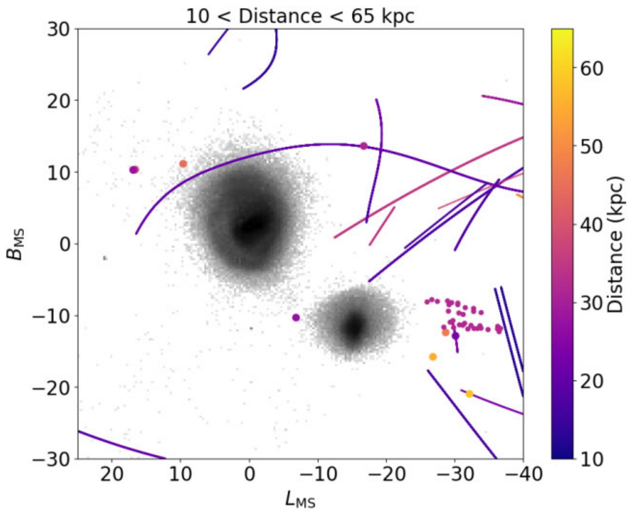

Figure 10. The density of Magellanic giant stars from *Gaia* DR3 with the known stellar streams (Mateu 2023) and dwarf spheroidal galaxies between 10 and 65 kpc away colour-coded by their distance. The new stellar stream is indicated by purpled filled circles.

opposite side of the SMC from Sutlej but close to an extrapolation of the Sutlej branch tracks. Selecting *Gaia* DR3 stars near Hydrus 1, I was able to determine a significant overdensity of 17 stars in proper motion space corresponding to $(\mu_{\rm L,MS}, \mu_{\rm B,MS}) = (+3.787$ mas yr^{-1}, $+1.68$ mas yr$^{-1})$. The CMD of these stars indicates that these are the Hydrus 1 RGB and BHB stars. Using $V_{\rm helio} = +80.4$ km s^{-1} and 28 kpc distance from Koposov et al. (2018), we can calculate the galactocentric space velocity of Hydrus 1 to be $(V_x, V_y, V_z) = (-435.0$ km s^{-1}, -82.8 km s^{-1}, -11.1 km s$^{-1})$. Comparing these values to Fig. 8, it is clear that Hydrus 1 has a significantly different space velocity from the LMC, SMC, and Sutlej by $\gtrsim$200 km s^{-1}. In addition, while they are both metal-poor, Hydrus 1 is more metal-poor ([Fe/H] = −2.5) than Sutlej ([Fe/H] = −1.9) and comparing the Sutlej MDF in Fig. 7 with the Hydrus 1 MDF in fig. 19 from Koposov et al. (2018) indicates that the metallicity distributions are quite different.

Another curious feature of Sutlej is the two parallel split branches, which is quite uncommon in stellar streams. Some other examples are the Sagittarius stream (e.g. Majewski et al. 2003; Koposov et al. 2012) that has bifurcated branches in both the leading and trailing arms and the Anticentre/Monoceros stream (e.g. Grillmair 2006). The Sagittarius stream wraps around the MW due to the multiple passages its host galaxy made, and it is quite likely that the multiple pericentric passages created the bifurcation of the two tidal arms. After much debate over the origin of Monoceros (Martin et al. 2006; Conn et al. 2008), it is now thought that this broad feature was produced by a perturbation of the outer MW disc by a large satellite like the Sagittarius dwarf spheroidal galaxy or the LMC (Slater et al. 2014; Morganson et al. 2016; Hayes et al. 2018). Since the two Sutlej branches have nearly identical metallicity, distance, age, and space velocity, it seems quite likely that they have the same progenitor galaxy. However, it is not impossible. How exactly a small dwarf spheroidal galaxy could produce two parallel stellar streams offset by ∼2.5° or 1.4 kpc (at 32 kpc) perpendicular to their orbit remains unclear. Yavetz et al. (2021) showed that parallel streams, or orbit families, having the same origin can occur in flattened axisymmetric galactic potentials, but it is unclear whether the LMC/SMC/MW system is too complex to generate separatrix in the SMC vicinity.

Whatever its origin, the split feature of Sutlej should put tight constraints on simulations trying to reproduce it. Another possibility is that two objects gave rise to the Sutlej stream, such as two dwarf galaxies or globular clusters that interacted with each other. In fact, there are differences seen in the BHB morphologies in the CMD between the two branches that could suggest a different origin. Moreover, the similarity of the MDFs of the two branches might be explained by the fact that many dwarf galaxies and globular clusters are metal-poor. Further dynamical work on this option would be useful.

Erkal et al. (2019) used the Orphan stream to constrain the LMC's total mass to 1.38×10^{11} M$_\odot$ by using the perturbations that the LMC made on the Orphan stream's proper motions that are misaligned with the stream's track. This is the most accurate mass estimate of the LMC to date. The SMC's mass, on the other hand, is not well constrained and it is not unusual to scale the LMC's total mass by the ratio of the SMC's and LMC's stellar masses (∼1/9.6) as done by Besla et al. (2012). Having a more accurate SMC total mass would help improve simulations of the Magellanic system. The Sutlej stream provides a tantalizing possibility of being able to constrain the SMC's total mass since the Sutlej proper motion vector is misaligned with its stream track. Orbit modelling of the *Gaia* kinematics and follow-up spectroscopic radial velocities should be able to determine whether this feat is possible.

6 SUMMARY

I report the discovery of a split stellar stream, Sutlej, near the SMC using *Gaia* DR3 proper motions and metallicities from the low-resolution XP spectra. The main conclusions are as follows:

(i) Sutlej has two nearly parallel branches that are roughly ∼8° × 0.6° in shape and separated by ∼2.5°. They are situated ∼15° north of the SMC.

(ii) The *Gaia* CMD shows a clear signature of a simple stellar population (with RGB, BHB, and main-sequence turn-off) that is well fitted with an isochrone of age 10 Gyr, [Fe/H] = −1.8, and distance of 32 kpc.

(iii) Sutlej has a prominent BHB. Measured distances of these standard candles give a mean distance of 32.4 kpc for all Sutlej stars and 33.0/31.8 kpc for Branch 1/2. While Branch 1 shows little distance variation, Branch 2 has a distance gradient of ∼0.9 kpc deg^{-1}, where the distance increases as the angular distance from the SMC grows larger.

(iv) The *Gaia* XP metallicities show that Sutlej has a broad MDF stretching from [Fe/H] = −2.5 to −1.0 with a median of [Fe/H] = −1.9. The broad MDF strongly suggests that the progenitor was a dwarf galaxy rather than a globular cluster.

(v) The total stellar mass of Sutlej is 33 333 M$_\odot$ and its surface brightness is 32.5 mag arcsec^{-2}.

(vi) Sutlej's tangential velocity vector is nearly perpendicular to its stream track, providing evidence that it has likely been gravitationally perturbed by the nearby MCs.

(vii) Sutlej is likely not associated with the SMC because no matter what the RV of Sutlej is, the 3D space velocity of Sutlej is significantly offset from the SMC by at least ∼200 km s^{-1}. In addition, Sutlej's MDF is much more metal-poor than the MCs' MDFs and the tangential velocity vectors are misaligned by nearly 90°.

Follow-up spectroscopic observations to measure the RV and chemical abundances should help resolve the origin of Sutlej. Orbital modelling of Sutlej has the potential of constraining the mass of the SMC.

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Software: ASTROPY (Astropy Collaboration 2013, 2018), MATPLOTLIB (Hunter 2007), NUMPY (Harris et al. 2020), and SCIPY (Virtanen et al. 2020).

DATA AVAILABILITY

All *Gaia* DR3 data are available from the *Gaia* Archive (https://gea.esac.esa.int/archive/). The Andrae et al. (2023b) catalogue of *Gaia* DR3 XP stellar parameters and metallicities is available at https://zenodo.org/record/7945154.

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