Ghostly Tributaries to the Milky Way: Charting the Halo’s Stellar Streams with the Gaia DR2 catalogue

Khyati Malhan,1⋆ Rodrigo A. Ibata,1† Nicolas F. Martin,1,2‡
1 Université de Strasbourg, CNRS, Observatoire Astronomique de Strasbourg, UMR 7550, F-67000 Strasbourg, France
2 Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany

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ABSTRACT

We present a panoramic map of the stellar streams of the Milky Way based upon astrometric and photometric measurements from the Gaia DR2 catalogue. In this first contribution, we concentrate on the halo at heliocentric distances beyond 5 kpc, and at Galactic latitudes |b| > 30°, using the STREAMFINDER algorithm to detect structures along plausible orbits that are consistent with the Gaia proper motion measurements. We find a rich network of criss-crossing streams in the halo, often with striking kinematic coherence. Some of these structures were previously-known, several are new discoveries, but others are potentially artefacts of the Gaia scanning law and will require confirmation. With these initial discoveries, we are starting to unravel the complex formation of the halo of our Galaxy.

Key words: Galaxy : halo - Galaxy: structure - stars: kinematics and dynamics - Galaxy: kinematics and dynamics

1 INTRODUCTION

The central position that stellar streams hold for Galactic Archeology studies motivates conducting a thorough census of such structures in the Milky Way. Besides testing the hierarchical merging scenario of Galaxy formation (Johnston et al. 1996; Helmi & White 1999), the number of stellar streams can, in principle, be used to put a lower limit on past accretion events into the Galactic halo, their orbital structures can be used to probe the mass distribution and shape of the Milky Way dark matter halo (Johnston et al. 1999; Ibata et al. 2001; Eyre & Binney 2009; Koposov et al. 2010; Law & Majewski 2010; Küpper et al. 2015; Bovy et al. 2015), stream-gaps can provide indirect evidence for the existence of dark matter sub-halos (Johnston et al. 2002; Carlberg et al. 2012; Erkal et al. 2016; Sanders et al. 2016), and these structures can also be used to constrain the models of the formation and evolution of globular clusters (Babbinot & Gieles 2018). Furthermore, analyses based on the quantity and the collective phase-space distribution of stellar streams hold great promise in addressing some small-scale ΛCDM problems (such as the “missing satellite problem” and the “plane-of-satellites” problem, see, e.g. Bullock & Boylan-Kolchin 2017).

Such considerations have motivated many previous studies to detect and analyse stellar streams in our Galaxy. Notable efforts in the past include the “Field-of-streams” map (Belokurov et al. 2006) of the region around the North Galactic Cap based on the SDSS DR5, which was expanded to cover both the Northern and Southern Galactic Cap regions in later SDSS releases (see, e.g. Grillmair & Carlin 2016); Bernard et al. (2014) created a panoramic map of the entire Milky Way halo north of δ ∼ −30° (∼ 30,000 deg²) based on the Pan-STARRS1 dataset; Mateu et al. (2018) applied a pole-counts stream-finding method to the Catalina RR-Lyrae survey revealing 14 candidate streams in the inner Galaxy; and most recently Shipp et al. (2018) discovered 11 stellar streams out to a distance of d⊙ ∼ 50 kpc by making use of the data from the Dark Energy survey (DES). The regions of sky covered by presently-known streams have been conveniently compiled in the GALSTREAMS python package (Mateu et al. 2018), which we reproduce in Figure 1 for comparison to our results.

Given the arrival of all-sky data of unprecedented astrometric quality from the ESA/Gaia survey (de Bruijne 2012; Gaia Collaboration et al. 2016), we built a stream-finding algorithm (the STREAMFINDER, Malhan & Ibata 2018, hereafter Paper I) to make use of the kinematic information that Gaia provides. The idea that we incorporated in the STREAMFINDER algorithm is that stellar-streams can be found more efficiently by searching along possible orbital trajectories in the underlying gravitational potential of the Galaxy.

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Figure 1. Schematic stellar Stream map of the Milky Way sky prior to Gaia DR2. Here we show the Milky Way stellar stream map (minus some stellar clouds) from the GALSTREAMS package (Mateu et al. 2018), transformed into polar ZEA projections. The colour represents the Galacto-centric distances to these structures. The left and right panels show, respectively, the projection from the North and South Galactic poles. The names of a few streams are labelled to help the reader’s orientation in this coordinate system. Galactic longitude increases clockwise in the north panel and counter-clockwise in the south panel, while Galactic latitude changes radially as shown.

Figure 2. Unsharp-mask map of the $|b| > 10^\circ$ sky, derived using Gaia sources brighter than $G_0 = 20$. This simple filtering procedure highlights the stripy artefacts that arise due to the inhomogeneous scanning of the sky in the DR2 catalogue. The same ZEA projections are used here as in Figure 1. To create this map, we binned the catalogue into pixels of size $5\,5' \times 5\,5'$, and subtracted from this the same map but smoothed with a two-dimensional Gaussian of standard deviation $53'$. The holes seen in the image correspond to the excised regions around known clusters and satellite galaxies that were omitted in our analysis.

In Paper I, our tests, based on a suite of N-body simulations embedded in a mock Galactic survey, showed that the algorithm is able to detect distant halo stream structures containing as few as $\sim 15$ members ($\Sigma_G \sim 33.6 \text{ mag arcsec}^{-2}$) in the End-of-mission Gaia dataset.

The purpose of this contribution is to present an updated stellar stream map of the halo of the Milky Way (at $D_\odot > 5 \text{kpc}$) obtained via the application of our STREAMFINDER algorithm onto the recently published Gaia Data Release 2 (DR2) (Gaia Collaboration et al. 2018; Lindegren, L. et al. 2018; Luri, Xavier et al. 2018; Evans, D. W. et al. 2018; Helmi, A. et al. 2018). In this first analysis, we restrict ourselves to analysing the outer halo at distances beyond 5 kpc as our algorithm takes longer to compute in inner regions where the density of both the field stars and the possible candidates is large (as is the case when considering closer structures or indeed in the vicinity of the Galactic Plane).

The paper is organized as follows: Section 2 details the selections made on the Gaia data; Section 3 explains how
we built a model of the contaminating populations of the Milky Way; the analysis using our STREAMFINDER algorithm is detailed in Section 4; the results are presented in Section 5; finally we discuss these findings and draw our conclusions in Section 6.

2 DATA AND STREAM SEARCH ANALYSIS

We use the Gaia DR2 catalogue for all of our present analysis. This dataset provides positions, parallaxes and proper motions (a 5D astrometric solution) for over 1.3 billion stars down to $G \sim 20.7$ in our Galaxy, along with the Gaia broadband photometry in the $G, G_{\text{BP}}, G_{\text{RP}}$ pass-bands. The information that is useful for our purpose are the stellar positions ($\alpha, \delta$), parallaxes ($\pi$), proper motions ($\mu_\alpha, \mu_\delta$), magnitudes ($G, G_{\text{BP}}, G_{\text{RP}}$) and the associated observational uncertainties.

We correct all Gaia sources from extinction using the Schlegel et al. (1998) maps, assuming $A_G = 2.8$. A large number of stripy residuals can be seen, which could in principle masquerade as streams. Any structures following this pattern are almost certainly artefacts.

The Gaia DR2 is based on only 22 months of observations, and not all areas of sky have been observed to uniform depth. Gaia scans the sky while spinning, and this naturally imprints great circles into the depth map. In Figure 2 we show the result of applying an unsharp-mask to all data at Galactic latitudes $|b| > 10^\circ$ and with $G < 20$. A large number of stripy residuals can be seen, which could in principle masquerade as streams. Any structures following this pattern are almost certainly artefacts.

After extensive tests of the STREAMFINDER using the Gaia Universe Model Snapshot (GUMS, Robin et al. 2012), we decided to limit the sample for the present contribution to $|b| > 30^\circ$ and $G < 19.5$. The chosen magnitude limit mitigates against the effect of completeness variations due to inhomogenous extinction, while also reducing the number of sources that need to be examined. Likewise, the Galactic latitude constraint also greatly diminishes the size of the sample. We retained only those sources that had a full 5-parameter astrometric solution, along with valid magnitudes in all three photometric bands.

We further omitted all Gaia DR2 catalogue stars within two tidal radii of the Galactic globular clusters listed in the compilation by Harris (2010), as well as all the stars within 7 half-light radii around Galactic dwarf satellite galaxies (as compiled by McConnachie 2012). This was implemented so as to avoid creating spurious stream detections that might be caused by the presence of a compact over-density of stars in a given region of phase-space rather than an actual extended stream of stars.

As described in Paper I, it is convenient to reject disk contaminants based on parallax information since we are interested in finding halo structures. The number of these potential nearby contaminants was reduced by removing those sources whose parallax is greater than $1/3000$ arcsec at more than the $3\sigma$ level (i.e. objects that are likely to be closer than $3\,\text{kpc}$). Contrary to the analysis in Paper I, we also use the Gaia parallax measurements in the likelihood calculation (although these measurements provide only very weak constraints on the orbit solutions).

We feed this filtered data to the STREAMFINDER.

3 CONTAMINATION MODEL

Before running the STREAMFINDER, we first calculate an empirical smooth model of the Milky Way “contamination” (i.e. a model of the smoothly-varying population of stars that lie both in the foreground and the background of the stream-like structures of interest). This contamination model is used as a global probability density function estimate to calculate the likelihood function for identifying substructures. The procedure will be more fully explained in a future contribution (Ibata et al. 2018, in prep.), but briefly, we construct a library of number-density maps of the Galaxy as a function of $G_{\text{BP}} - G_{\text{RP}}$ colour and $G$ magnitude in polar Zenithal Equal Area projection with a pixel scale of $1/4 \times 1/4$, which are smoothed on a spatial scale of $2^\circ$. Furthermore, over spatial regions of $5/6 \times 5/6$ (also in polar ZEA projection), we fit the four-dimensional distribution of $G_{\text{BP}} - G_{\text{RP}}$ colour, $G$ magnitude, and proper motion $\mu_\alpha, \mu_\delta$, with a Gaussian Mixture Model (GMM), with 100 Gaussian components, using the Armadillo C++ library (Sanderson & Curtin 2017). Together, the density maps and the GMM fitted maps allow one to estimate the smoothed probability of finding a star in the Galaxy in the 6-D parameter space of $\alpha, \delta, G_{\text{BP}} - G_{\text{RP}}, G, \mu_\alpha, \mu_\delta$.

4 STREAMFINDER ANALYSIS

We used the STREAMFINDER to analyse the Gaia DR2 data in a similar way to that described in Paper I. The orbits are integrated within the Galactic potential model 1 of Dehnen & Binney (1998), and these orbits are then projected into the heliocentric frame of observables for comparison with the data. For this coordinate transformation, we assume a Galactocentric distance of the Sun of $8.20\,\text{kpc}$ (Karim & Mamajek 2017), a circular velocity $V_{\odot} = 240\,\text{km\,s}^{-1}$ and in addition we adopt the Sun’s peculiar velocity to be $V_\odot = (u_\odot, v_\odot, w_\odot) = (9.0, 15.2, 7.0)\,\text{km\,s}^{-1}$ (Reid et al. 2014; Schönrich et al. 2010). As explained in Paper I, STREAMFINDER uses pre-selected isochrone models in order to sample orbits in distance space. The selected isochrone model(s) essentially correspond to the proposed Single Stellar Population (SSP) model of the stream. Here, we chose to work with Padova SSP models (Marigo et al. 2008) in the Gaia photometric system, with age 10 Gyr and with 7 metallicity values between $[\text{Fe}/\text{H}] = -2.2$ to $[\text{Fe}/\text{H}] = -1.0$ (spaced at 0.2 dex intervals). These isochrone models cover plausible values for Milky Way halo globular clusters (from which stellar streams are ultimately derived). The candidate model streams were selected to have a Gaussian width.

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1 These extinction ratios are listed on the Padova model site http://stev.oapd.inaf.it/cgi-bin/cmd2.8.

2 In subsequent papers, we plan to run the algorithm over a fine grid in metallicity and age.
of 100 pc, and to be 10° long on the sky. Other parameter ranges used to integrate orbits in the Galaxy were identical to those detailed in Paper I.

In contrast to Paper I, the likelihood function that we use here takes the Galaxy into consideration via the smooth background model discussed above. Our log-likelihood function is simply:

\[
\ln \mathcal{L} = \sum_{\text{data}} \ln \left( \eta \mathcal{P}_{\text{signal}} + (1 - \eta) \mathcal{P}_{\text{contamination}} \right),
\]

where \( \mathcal{P}_{\text{signal}} \) is the stream PDF presented in Paper I, \( \mathcal{P}_{\text{contamination}} \) is the PDF of the smooth contamination model that we obtain as explained in Section 3, and \( \eta \) is the fraction of the data present in the signal (i.e. the stream structure that we wish to detect).

5 RESULTS

In Figure 3 we show, for two representative metallicity values, the spatial distribution of the stars in the processed sample that have a high-likelihood of belonging to a stream structure. These data are selected as having \( \ln \mathcal{L}_{\text{max}}/\ln \mathcal{L}_{\eta=0} > 15 \), where \( \mathcal{L}_{\eta=0} \) is the model likelihood when no stream is present, and \( \mathcal{L}_{\text{max}} \) is the maximum likelihood stream solution found by the algorithm. Thus, our criterion corresponds to > 5σ when the noise distributions are Gaussian. We would like to point out that the \( \ln \mathcal{L}_{\text{max}}/\ln \mathcal{L}_{\eta=0} \) likelihood ratio is calculated for every star in the (filtered) catalogue, yet in the maps presented here we only show those stars where this value exceeds 15. Many other neighbouring stars may partake in a given stream structure, contributing to the high \( \ln \mathcal{L}_{\text{max}}/\ln \mathcal{L}_{\eta=0} \) valued-

Figure 4. Properties of a sample of previously-discovered streams, as recovered by the STREAMFINDER. The first, second, third and fourth rows show the properties of the GD-1, Jhelum, Indus and Orphan streams, respectively. The columns reproduce, from left to right, the equatorial coordinates of the structures, the distance solutions found by the algorithm (for representative metallicity values), the proper motion distribution (with observations in red, model solutions in blue, and the full DR2 sample in grey), and the colour-magnitude distribution of the stars selected by STREAMFINDER. The distance solutions found by the algorithm match closely the distance values that have been previously derived for these streams: $D_\odot \sim 8$ kpc for GD-1 (Grillmair & Dionatos 2006), $D_\odot \sim 13.2$ kpc and $\sim 16.6$ kpc for Jhelum and Indus, respectively (Shipp et al. 2018) and $D_\odot = [33 - 38]$ kpc for Orphan (Newberg et al. 2010). The colour-magnitude diagram of the Orphan stream might seem peculiar, but here we only see the red-giant branch due to the trimming of the data sample below $G = 19.5$.

points marked in the figure, yet they may not themselves pass the criterion and so are not shown. A given stream-like structure seen in the figure is thus composed of many $> 5\sigma$ points. However, the points are not statistically independent, as by construction information is correlated over the chosen $10^\circ$ trial stream length. We further stress that the aim of the STREAMFINDER algorithm is to enable the detection of streams; a complete characterization and statistical analysis of a given detection should be accomplished with other tools, for instance, by careful modelling with N-body simulations.

The left and right panels of Figure 3 show, respectively, the projection from the North and South poles. As STREAMFINDER integrates orbits in order to detect stream structures, the primary by-product that the algorithm naturally returns are the possible set of orbital solutions along which the stream might lie (as explained in Paper I). The distance solutions displayed here are the ones obtained by the algorithm and span the inner halo range $D_\odot = [5, 15]$ kpc. The most visible feature in the northern hemisphere is the GD-1 stellar stream (Grillmair & Dionatos 2006; de Boer et al. 2018), which appears as a $> 60^\circ$ stream in these spatial density maps of candidate stream members. It is possible that it continues to lower Galactic latitude, where we have not yet run the algorithm. Other notable detections are the Jhelum and Indus streams (Shipp et al. 2018) seen in the Southern hemisphere in the more metal-poor map. As a demonstration of the power of the algo-
rithm, we display the properties of GD-1, Jhelum and Indus, as recovered by the STREAMFINDER, in Figure 4. Note that the distance solutions to these streams that we obtain from STREAMFINDER match closely the distance values that have been previously derived for these streams (as explained in Figure 4). We summarize some of the properties of these structures in Table 1, providing the averaged proper motion values for the Jhelum and Indus streams.

Figure 5 shows the results at intermediate distances in the halo in the range $D_\odot = [15, 30]$ kpc, while the outer halo distribution, beyond 25 kpc is displayed in Figure 6 (again selecting $\ln L_{max}/\ln L_{eq} > 15$). The algorithm highlights a very deluge of stream-like structures, which are seen over a range of distances and metallicities. Comparison to Figure 1 shows that we detect the Sagittarius stream (Ibata et al. 2001; Majewski et al. 2003) over a large swathe of the outer halo. This is somewhat surprising, since we set the stream model width to 100 pc, which is appropriate for a globular cluster, but is actually a very poor template for this wide stream. We suspect that the spatial inhomogeneities in Gaia due its scanning law may partially explain the striated aspect of the Sagittarius stream in our maps (see, e.g., Figure 6).

The algorithm also detected a short arc of length $\sim 10^\circ$ of the $\sim 60^\circ$ long Orphan stream (Grillmair 2006) in our outer halo spatial maps (again, the chosen stream width of the model was not an appropriate template for this structure, which may explain why the full length was not recovered). For the position of the arc on the sky shown in Figure 4, we find the distance solutions for the Orphan stream members to be compatible with the study by Newberg et al. (2010). Also, we find that its member stars have a tight proper motion distribution (Table 1 provides averaged proper motion values for the Orphan stream).

Careful visual inspection of these maps indicated that the stream-like structures recovered by the algorithm are not associated with the extinction correction. In Figures 7 and 8, we combine the distance and metallicity samples for the north and south hemispheres, respectively. The bottom panels of these diagrams show an estimate of the magnitude of the tangential velocity, calculated using the measured Gaia proper motions combined with the distance estimates provided by the algorithm. Many structures are beautifully resolved in this multi-parameter space.

Our aim in this contribution is not to present a thorough or complete census of halo streams (since it would require considerable more time to examine the necessary parameter space), but rather to present a preview of the large-scale stream structure of our Galaxy. Nevertheless, we have selected by hand a small number of structures that appear clearly in our maps, with kinematic properties that distinguish them from the contaminating Galactic population, and that are clearly not artefacts produced by Gaia’s scanning law. A large number of other stream candidates have a clearly-defined stream-like morphology, but possess proper motions distributions that are similar to that of the halo, and we deem that they require further follow-up to be confident of their nature.

The locations of the five structures we selected are marked in Figures 3 and 5, and their properties are shown in Figure 9, and are also summarised in Table 1. All these structures that we find have significance $> 5\sigma$.

5.1 Gaia-1

Gaia-1 has an angular extent of $\sim 15^\circ$ and projected width of $\sim 0.5^\circ$. The orbital solutions provided by the algorithm imply that it is situated at a distance of $D_\odot \sim 5.5$ kpc, which is in reasonable agreement with the Gaia parallax measurement of $0.216 \pm 0.038$ mas (i.e. 4.6 kpc). This means that Gaia-1 has a physical width of $\sim 40$ pc. The narrowness of the stream suggests that the progenitor likely is or was a globular cluster. Moreover, Gaia-1 has a strikingly high proper motion value of $\sim 23.5$ mas yr$^{-1}$, implying that it has a transverse motion $\lesssim 500$ km s$^{-1}$. It will be worthwhile to measure the radial velocity of this system, as it may provide an interesting constraint on the Galactic potential simply from the requirement that the system is bound to the Milky Way.

5.2 Gaia-2

Gaia-2 turns out to be a considerably thin structure in our spatial maps. Extending over $\sim 10^\circ$ in length, we find that it possesses a distance gradient ranging from $D_\odot = [10–13]$ kpc. Given its narrowness and the location in the halo, we also suspect it to be a remnant of a globular cluster. We find Gaia-2 to be a highly coherent structure in proper motion space with an average proper motion magnitude of $\sim 6.5$ mas yr$^{-1}$.

5.3 Gaia-3

This structure appears to be different from the other streams. In Figure 9 (third row), Gaia-3 clearly shows two distinct possible sets of distance solutions. The clear distinction of these two different sets of solutions in position, distance and colour-magnitude distribution space, while not so much in proper motion space, suggests that what we detect here as Gaia-3 might in fact be a superposition of two streams, or a more complicated structure aligned along the line of sight. We shall describe this structure collectively here.

Gaia-3 is found to be extended over $\sim 16^\circ$ in sky with a distance range of $D_\odot = [9–14]$ kpc with an average proper motion magnitude of $\sim 7.4$ mas yr$^{-1}$. Given its peculiarity, as suggested above and shown in Figure 9, it is hard to comment on its physical width or the progenitor. The distance estimate of this structure too was found to be in good agreement with the Gaia parallax measurement of $0.101 \pm 0.013$ mas (i.e. 9.8 kpc).

5.4 Gaia-4

Gaia-4 appears to be a fine linear structure, found at a distance of $\sim D_\odot = 11$ kpc. Given its narrowness and distance, we suspect the progenitor to be a globular cluster. Although we find Gaia-4 sitting within the range of halo field stars in proper motion space with an average value of $\sim 0.36$ mas yr$^{-1}$, the fact that it emerges as a highly coherent structure in our maps makes it a confident structure.
Figure 5. Spatial distribution of stream candidates at intermediate distances. Here we show the stellar stream density map as obtained from the STREAMFINDER based on 3 representative isochrone models. Each row corresponds to a particular isochrone model of age (in Gyr) and metallicity, as labelled. The left panels represent the North side of the ZEA projection system and the right panels represent the South. The colour scale is proportional to the heliocentric distances to the stellar members of the detected structures obtained as a by-product from the STREAMFINDER analysis (Paper I). All streams displayed here have detection significance > 5σ. New high confidence stream detections are marked on the map.
Figure 6. As Figure 5, but for the outer halo beyond 25 kpc. The dominant structure seen out to large heliocentric distances in both hemispheres is the Sagittarius stream, which is detected despite the narrowness of the stream template model that we set in our algorithm. The interesting bifurcation of this structure is seen in the top-left panel. In addition, the lower-left panel shows an overdensity of stars in the region where the Orphan stream lies (Grillmair 2006). Many other stream-like features are also detected, but most are confined to the nearer limit of the distance range shown.
Figure 7. Summary diagrams of the distance ($D_\odot > 5$ kpc) and tangential velocity $V_T$ of stream-like structures in the northern Galactic sky. The tangential velocities are calculated based on the observed proper motion of the stars in DR2 and the corresponding distance estimates that we obtain from the algorithm. Most of the structures that we report here are visible in these diagrams, as are many others that we intend to investigate further in future contributions.
Figure 8. As Figure 7, but for the southern Galactic sky.
5.5 Gaia-5

We include Gaia-5 as another interesting detection, as it is parallel to the GD-1 stream, and could easily have been confused with GD-1 without Gaia’s excellent proper motion information. The properties of this object are shown in blue on the bottom row of panels in Figure 9, where we also include GD-1 (in green) for comparison. The proper motions of Gaia-5 stars are distributed over a compact region that is very far from the region inhabited by GD-1; also the two colour-magnitude distributions (CMDs) are very different. The (error-weighted mean) parallax value we calculate for this structure would imply that it is substantially closer to the Sun than GD-1, which is both inconsistent with the model solutions of ~20 kpc, and is very difficult to reconcile with the CMD. However, our simple combination of the parallax measurements is highly susceptible to contaminants, which may explain the inconsistency.

We plan to examine these structures (and the many other stream candidates visible in Figures 7 and 8) in detail in later contributions. Careful analysis based on their astrometry and photometry, along with the mapping of these structures in deeper astrophysical catalogues (e.g. SDSS, PS1, DES), would render a fuller insight into their origin, orbits and phase-space distribution.

6 DISCUSSIONS AND CONCLUSIONS

In this contribution, we present a new stellar stream map of the Milky Way halo, obtained by the application of our STREAMFINDER algorithm (described in Paper I) on the recently published ESA/Gaia DR2 catalogue. This is the first time a map of the stellar streams of the Milky Way’s halo has been made based on kinematic measurements. Our algorithm detects numerous previously-known streams, which were discovered in much deeper photometric datasets (e.g. SDSS, PS1, DES), confirming that our method, which includes proper motion information, works as designed. Indeed, the fidelity of the GD-1 detection is striking, and reveals that the excellent Gaia proper motions provide very powerful discrimination.

In addition, we find a large number of streams and stream candidates throughout the distance range probed. In this first exploration, we selected five good streams (named here as Gaia-1,2,3,4,5), to showcase the results, but many other candidates will require careful follow-up. In particular, the fact that Gaia scans the sky along great circles, but with an inhomogeneous number of visits, causes density inhomogeneities that appear like great circle streaks on the sky. This could cause some spurious stream detections (although the kinematics test in the STREAMFINDER algorithm should allow us to reject most such fake streams). Nevertheless, these spatial inhomogeneities in the Gaia DR2 necessarily make the survey noise properties very complex, invalidating the assumptions behind our $\ln L_{\text{max}}/\ln L_{\eta=0} > 15$ selection criterion. This means, unfortunately, that the effective stream detection threshold is not uniform in our sky maps, and the significance of the detections is lower in regions where the Gaia inhomogeneities are more pronounced.

A further caveat relates to the model distances we report. These distances are calculated by the algorithm based on an assumption of the metallicity of the stream stars. We expect that we do, in fact, have some ability to estimate the metallicity of the candidate streams with our procedure, since using the correct metallicity model should enhance the contrast of the streams. This is borne out, for instance, for the case of GD-1, where we recover the largest number of stream stars when using the model corresponding to the actual metallicity of the system. Nevertheless, this is a poor substitute for actual metallicity measurements. Ongoing sky surveys, such as the Canada-France Imaging Survey (CFIS; Ibata et al. 2017a,b), or future large photometric surveys such as LSST (LSST Dark Energy Science Collaboration 2012), can help overcome this issue by providing good photometric metallicities that will break the distance degeneracy (and improve stream detection). The third Gaia data release (DR3), currently planned for 2020, will provide low-resolution prism spectra, also allowing metallicity measurements for the brighter stars.

As we showed in Paper I, our algorithm naturally delivers the possible set of orbital solutions of the detected stream structures. This means that the algorithm predicts both the radial velocities and the distances of the stream stars. In Figure 10 we use the orbital solutions to the GD-1 stream to demonstrate that this works very well: the predicted STREAMFINDER radial velocities match the stream velocities measured by Koposov et al. (2010). Furthermore, our parallax measurement of $0.107 \pm 0.010$ mas yr$^{-1}$ for GD-1, based on the sample we obtain with the STREAMFINDER, also matches well the distance range of the orbital solutions shown in Figure 4 (these are not independent measurements, however the algorithm “sees” the potential stream stars diluted in a gigantic Galactic contaminating population). This success gives us confidence that we will be able to use the predicted STREAMFINDER radial velocities to probe the orbital properties of the stellar stream population as a whole.

In the present contribution, we took several shortcuts to improve algorithm’s processing speed. We allowed the algorithm to only make use of stars that are brighter than $G_0 = 19.5$ at that lie at $|b| > 30^\circ$, partially to reduce the number of stars that needed to be examined. For the purpose of estimating the distance of the survey stars, we employed only 7 isochrone models in the algorithm; while we covered plausible metallicity values for Milky Way halo globular clusters, only a single population age was tested. A single value for the model stream width (100 pc) was used. Moreover, we set the possible range of distance solutions to [5–200] kpc within which the algorithm attempts to make detections. In subsequent contributions, we intend to relax these constraints allowing for a more complete census to be established. Additionally, we intend to examine different models of the Galactic potential; presumably our stream detection method should reveal the highest contrast for long stellar streams when using the correct potential.

Thanks to the amazingly rich phase-space information provided by the Gaia spacecraft and consortium, we are now starting to unravel the very fine details of galaxy formation in action. While the results presented here are but a first step in the comprehensive mapping of the Milky Way’s stellar halo and accretion events, they already show the promises borne out by the deep, multi-dimensional space unveiled in DR2. The harvest of previously unknown thin stellar streams, likely stemming from the tidal disruption of
Figure 9. As Figure 4 but for the selected set of newly-discovered streams. Oddly, for Gaia-3, we found two distinct possible sets of solutions based on distance estimates that we obtained from our algorithm, as highlighted in the respective panel. The more distant stars are coloured in green, while the relatively nearby ones are shown in red. This clear distinction of these two different sets of solutions in position, distance and colour-magnitude distribution space, while not so much in proper motion space, suggests that what we detect here as Gaia-3 might in fact be a superposition of two streams, or a more complicated structure aligned along the line of sight. The bottom row shows the properties of Gaia-5, which is found to lie parallel, but slightly offset, to GD-1 (shown on this bottom row in green). Nevertheless, it is very distinct from GD-1 both in its proper motion distribution and in its colour-magnitude distribution.

globular clusters, opens up exciting times as these are powerful probes of the distribution of dark matter sub-halos in our surroundings (Johnston et al. 2002; Ibata et al. 2002; Carlberg et al. 2012; Bovy 2016), they can provide an independent inference of the location of the Sun in phase space (Malhan & Ibata 2017), and they can be used as sensitive seismographs to constrain the shape and depth of the Milky Way potential (Ibata et al. 2013; Bonaca & Hogg 2018). The combination of Gaia DR2 and detections provided by STREAMFINDER places us in a unique position to disentangle the numerous detections accretion events in the Milky
Table 1. Parameters of the stellar streams. The “Position” column gives the extent of these structures, \( D_\odot \) is the approximate range of the distance solution as obtained by our algorithm, while column 4 lists the average observed proper motion vector of the structure (though note that spatial gradients in proper motion are detected, and we therefore refrain from listing the corresponding proper motion uncertainties). The parallax \( \pi \) is an uncertainty-weighted average of the Gaia measurements; for those objects where the parallax uncertainty is less than 33\% of the parallax, we also provide the corresponding distance.

| Name | Position (extent) | \( D_\odot \) (model) (kpc) | \((\mu_\alpha \cos \delta, \mu_\delta)\) (mas \( \cdot \) yr\(^{-1}\)) | \( \pi \) (mas) | \( \frac{1}{\pi} \) (kpc) |
|------|------------------|-----------------------------|-------------------------------------------------|--------|-----------------|
| GD-1 | \( 135^\circ < \alpha < 190^\circ \) \( 17^\circ < \delta < 58^\circ \) | 6.5 – 10 | \(-5.6, –11.9\) | 0.107 ± 0.010 | 9.3 |
| Jhelum | \( 320^\circ < \alpha < 360^\circ \) \( -53^\circ < \delta < -47^\circ \) | 11.7 – 15 | 6.4, –4.8 | 0.086 ± 0.013 | 11.6 |
| Indus | \( 320^\circ < \alpha < 360^\circ \) \( -67^\circ < \delta < -53^\circ \) | 16 – 18 | 3.1, –4.8 | 0.167 ± 0.013 | 6.0 |
| Orphan | \( 145^\circ < \alpha < 153^\circ \) \( 20^\circ < \delta < 40^\circ \) | 33 – 38 | \(-0.72, –0.40\) | \(-0.006 ± 0.022\) | |
| Gaia-1 | \( 184^\circ < \alpha < 197^\circ \) \( -18^\circ < \delta < -2^\circ \) | 5 – 6 | \(-13.8, –19.0\) | 0.216 ± 0.038 | 4.6 |
| Gaia-2 | \( 6^\circ < \alpha < 15^\circ \) \( -27^\circ < \delta < -22^\circ \) | 10 – 13 | 4.1, –5.0 | 0.117 ± 0.062 |
| Gaia-3 | \( 171^\circ < \alpha < 179^\circ \) \( -32^\circ < \delta < -15^\circ \) | 9 – 14 | \(-0.2, –7.4\) | 0.101 ± 0.013 | 9.9 |
| Gaia-4 | \( 163^\circ < \alpha < 167^\circ \) \( -11^\circ < \delta < -3^\circ \) | 10.7 – 11.5 | \(-0.3, –0.2\) | 0.006 ± 0.105 | |
| Gaia-5 | \( 137^\circ < \alpha < 154^\circ \) \( 23^\circ < \delta < 42^\circ \) | 18.5 – 20.5 | \(-1.0, –3.7\) | 0.156 ± 0.031 | 6.4 |

Figure 10. Retrieving the missing phase-space information of streams stars with STREAMFINDER. The red dots represent the radial velocity solutions of the GD-1 stars that are derived as a by-product of the application of the algorithm, whereas the blue markers are the observed radial velocities of GD-1 stars as tabulated by Koposov et al. (2010). The STREAMFINDER sampled orbits in radial velocity space at intervals of 10\( \text{km} \cdot \text{s}^{-1} \) (which effectively causes an uncertainty of 10\( \text{km} \cdot \text{s}^{-1} \) on the red dots). The good agreement with the observations illustrates the power of our algorithm in predicting the missing phase-space information of stream stars.

Way halo and open the most exciting Galactic archaeology playground to date.

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