
156. Update on stellar streams

KNOWLEDGE OF OUR Galaxy's halo has advanced substantially over the past two decades, through a combination of astrometric, photometric, and spectroscopic surveys. We now know, for example, that tidal debris from the disrupted Sagittarius dwarf satellite (Ibata et al., 1994) dominates from 20–50 kpc. Hipparcos subsequently provided evidence for another ‘disrupted event’, identified on the basis of the correlated space motions of the constituent stars (Helmi et al., 1999).

With Gaia DR2, Helmi et al. (2018) demonstrated that the inner halo, between 5–25 kpc, includes debris from an object slightly more massive than the Small Magellanic Cloud (at the time of infall), with stars on highly eccentric and slightly retrograde orbits, and which the authors referred to as Gaia–Enceladus.

Importantly, such halo structures nicely confirm the predictions of the latest Λ CDM cosmological simulations (e.g. Koppelman et al., 2018; McCarthy et al., 2023).

A GROWING NUMBER of accreted components are being identified. Some are attributed to captured dwarf galaxies, others to disrupted globular clusters. Some, like the early Arcturus stream (Eggen, 1971; see essay 116) were of uncertain and contested origin.

Some have been discovered from the Sloan Digital Sky Survey, amongst them the Acheron, Cocytos, Lethe, and Styx streams (Grillmair, 2009), as well as the polar-orbiting Cetus stream (Newberg et al., 2009).

The LAMOST 1 stream of more than 20 000 stars was found from the LAMOST spectroscopic survey (Vickers et al., 2016), while the Phoenix stream was the first from the Dark Energy Survey (Balbinot et al., 2016).

I described the features and relevance of the Gaia–Enceladus event in essay 15, and updated this with some of the subsequent Gaia stream discoveries in essay 71 (May 2022). Amongst these, Ibata et al. (2019b) used their ‘Streamfinder’ algorithm, applied to the Gaia astrometry and photometry alone, to identify eight new structures at heliocentric distances between 1–10 kpc, which they named (from Norse mythology) Slidr, Sylgr, Ylgr, Fimbulthul, Svöl, Fjörm, Gjöll, and Leiptr.

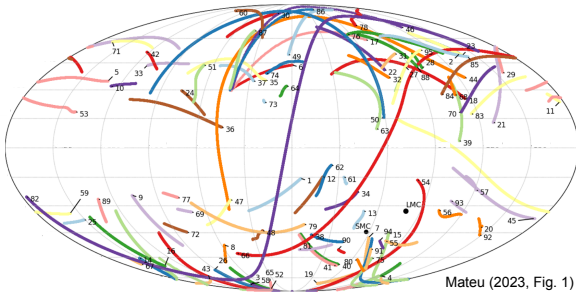
STILL MORE are now being discovered, especially with Gaia, and I will bring the topic more up-to-date here. The task is a challenging one: the number of new streams reported in the literature has gone from 20 tabulated by Grillmair & Carlin (2016) to nearly a hundred today. But the challenge has been greatly simplified by a recent impressive compilation of these discoveries.

Mateu (2023) has searched the literature, collated and homogenised the information in a consistent format in the form of the publicly available `galstreams` library, and computed a set of uniform features: the stream length, its mean pole and end points, the stream's coordinate frame, its polygon footprint, and its pole and angular momentum tracks. Currently, the compilation lists 95 Galactic stellar streams, and they are illustrated in the accompanying figure.

She wrote: *‘The field of stellar streams is currently in a golden era. It has increasingly grown and all but exploded in the last decade, thanks to deep wide-area photometric surveys and, more recently, to the amazing possibilities opened by the all-sky astrometric information provided by the Gaia mission since its Second Data Release, DR2’.*

GAIA'S LARGE-SCALE kinematic information is not only enabling many new discoveries. It is also revealing links between well-separated streams, such as Orphan/Chenab (Koposov et al., 2019), and ATLAS/Aliqa Uma (Li et al., 2021); linking known streams to their globular cluster progenitors, as in the case of Fimbulthul to ω Cen (Ibata et al., 2019a), and Gjöll to NGC 3201 (Palau & Miralda-Escudé, 2021); and revealing detailed features in GD–1, possibly attributed to dark matter subhaloes (Price-Whelan & Bonaca, 2018; Bonaca et al., 2019; Malhan & Ibata, 2019; de Boer et al., 2020).

Unexpected features like the misalignment of velocities with stream tracks found first in the Orphan–Chenab stream by Koposov et al. (2019), and later in several of the Dark Energy Survey streams (Shipp et al., 2018), are now thought to be perturbations caused by a recent close passage of the Large Magellanic Cloud. More on this later.



These unprecedented observations are providing great advances in the astrophysical questions that have motivated the growing interest in stellar streams, such as:

- reconstructing the assembly history of the Milky Way (Naidu et al., 2020; Bonaca et al., 2021; Malhan, 2022);
- inferring the shape and mass of its dark matter halo (e.g. Malhan & Ibata, 2019; Reino et al., 2021; Vasiliev et al., 2021; Cautun et al., 2020);
- constraining the dark matter sub-haloes (e.g. Erkal et al., 2017; Bonaca et al., 2019; Bonaca et al., 2020; Banik et al., 2021; Malhan et al., 2021; Gialluca et al., 2021).

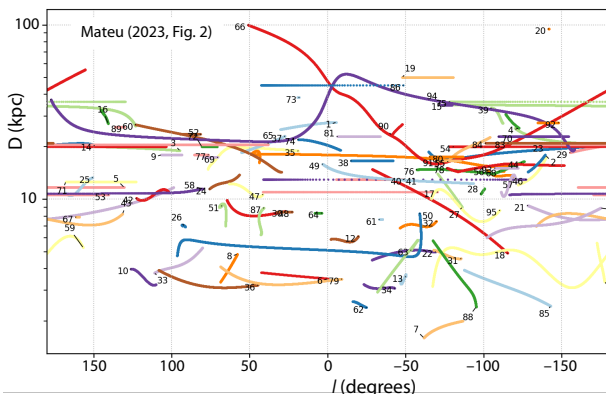
I will not go further into the more astrophysical aspects of these individual streams here, but restrict the following discussion to some of the more general features of Mateu's present compilation.

THE *galstreams* library does not include information on the individual stellar members of each stream, but details are given as to how the assembled 'track' is constructed for each of the discoveries.

For example, Fimbulthul's celestial track, distance track, and proper motion track were implemented by fitting a 7th degree polynomial to the stream members reported by Ibata et al. (2021, their Table 1).

As another example, the Sagittarius stream's celestial and proper motion tracks are those derived by Antoja et al. (2020), supplemented by the distance track from Ramos et al. (2020) for their RR Lyrae 'strip' sample.

The figure below shows the distances, along the tracks, of these 95 stellar streams.



A FEATURE OF THE compilation worth emphasising is the exclusion of various 'classes' of previously reported stream-like structures. For example, despite their velocity coherence, some are too close to the Sun to result in well-defined celestial or proper motion tracks: amongst these are the 'Helmi' streams, S1–S4, Nyx, and Icarus. Early accretion events, now at an advanced stage of phase-mixing, are similarly omitted: amongst these are Gaia–Sausage–Enceladus, Thamnos, and Sequoia.

Tidal tails (and related features) have been reported for many globular clusters, and only those where such features clearly extend several degrees beyond the tidal radius are included. Others excluded are the Virgo Stellar Stream (VSS) and Virgo Overdensity (VOD) whose nature remains under discussion (essay 95).

Streams are associated with surviving globular clusters include M2, M5, M68–Fjörm, M92, NGC 288, NGC 2298, NGC 3201–Gjöll, NGC 5466, Pal 5, and ω Cen–Fimbulthul. Streams without known progenitors include AAU, Cetus/Cetus–Palca, GD–1, Jet, Jhelum, Kwando, LMS–1, Ophiuchus, and Orphan–Chenab.

Amongst features evident in the collective distance and velocity information are the observational bias against the detection of stellar streams near the Galactic plane. There is also an evident (and of course expected) bias in the detection of nearby streams, $\lesssim 20$ kpc, seen in the clustering observed around the Sun's Galactocentric location. Another apparent (but unconfirmed) clustering of several streams is seen in the direction of the Magellanic Clouds.

IMPORTANTLY, Gaia provides data allowing the construction of detailed proper motion tracks, which are now available for more than half of the known streams (while less than 10% have radial velocities). These allow the computation of angular momentum along the track.

In an undisturbed stellar stream, stars would move predominantly along the stream. But the Gaia DR2 data have revealed several cases in which the proper motions are significantly misaligned with the stream's track. First observed in Orphan–Chenab, Erkal et al. (2019) attributed this to the dynamical effect of the LMC during a recent (< 350 Myr) close encounter. Similar features in the Indus and Jhelum streams have also been attributed to the perturbing effects of the LMC (Shipp et al., 2020).

A number of other streams, often much shorter, also show signs of misalignment at their ends (including Gaia–8, NGC 1261, and M92), while some very long streams exist with no apparent misalignments (including GD–1, NGC3201–Gjöll, Phlegethon, Leiptr and, for most of its length, the Sagittarius track).

THE *galstreams* library, including the stream's tracks, is publicly available as a [Python package](#). What a valuable contribution to this burgeoning field!