71. More halo streams from Gaia

IN AN EARLIER ESSAY, #15, I looked at the discovery, using data from Gaia DR2, of the stellar 'debris' stream referred to as Gaia–Enceladus.

That study, by Helmi et al. (2018), and reported in the Journal *Nature*, demonstrated that the inner halo of our Galaxy is dominated by debris from an object which, at infall, was slightly more massive than the Small Magellanic Cloud. These authors concluded that the merger between Gaia–Enceladus and the Milky Way contributed to the formation of our Galaxy's thick disk component some 10 Gyr ago, and that it probably represented the last significant merger that our Galaxy experienced.

Their findings were in line with current cosmological simulations of galaxy formation, which predict that the inner stellar halo should be dominated by debris from just a few of these massive progenitors.

THE GALACTIC DISK has long been recognised as having been formed by the rapid collapse of a rotating galaxy-sized gas cloud, billions of years ago. But the idea that the Galaxy halo has been built up over billions of years from infalling low-mass objects, such as dwarf galaxies of $10^7 - 10^8\,M_\odot$, only dates back to the seminal paper by Searle & Zinn (1978).

Their study of 177 red giants in 19 globular clusters at distances beyond about 8 kpc, suggested that halo clusters originated within transient protogalactic fragments that gradually lost gas while undergoing chemical evolution, and continued to fall into the Galaxy after the collapse of its central regions had been completed.

This model, evidenced by the wide range of globular cluster metallicities independent of Galactocentric radius, a wide age spread of halo field stars and globular clusters, and a subset of intermediate abundance globular clusters with retrograde mean motions, has been the paradigm for the halo formation for the past two decades (e.g. Bland-Hawthorn & Freeman, 2000).

It is useful to recall that these ancient signatures of tidal infall remain accessible for study because the orbital time-scales in the outer parts of the Galaxy are several billion years. As a result, the halo retains kinematic evidence of the surviving remnants of accretion, as well as a chemical 'memory' of early low-mass stars as a result of their very long evolutionary lifetimes.

Put another way, a low-mass stellar stream follows closely its progenitor's orbit, so that the locus of any one tidal stream provides a historical tracer of an ancient Galaxy orbit. Thus mapping the line-of-sight velocities and proper motions along a stream allows the mapping of the acceleration that the stream has been subject to. And with several streams on different orbits it becomes possible to build up a reliable three-dimensional map of the acceleration field throughout the region of the Galaxy traversed by such streams.

OVER THE PAST 25 years, various of these dynamically evolved 'stellar streams' have been identified, all originating from this sort of tidal stripping. Some have their origin in disrupted satellite galaxies, others in specific globular clusters.

The first to be identified was the Arcturus stream (Eggen, 1971), comprising some 50 ancient stars deficient in heavy elements. The gaseous Magellanic stream, associated with the Large and Small Magellanic Clouds, and the Sagittarius stream associated with the Sagittarius dwarf spheroidal galaxy, were discovered in subsequent years.

Revealed by their correlated angular momentum in the Hipparcos data, and corroborated by their prominent metal deficiency, the 'Helmi stream' started life as a dwarf galaxy of $10^7 - 10^8$ solar masses, captured by the Milky Way some 6–9 billion years ago. It may be responsible for some 10% of the metal-poor stars in our Galaxy's halo beyond the Sun's orbit (Helmi et al., 1999).

Others streams have been discovered since, and variously attributed to globular cluster or dwarf galaxy origins. Several 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).

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

BY PROVIDING THE DISTANCES and space motions of more than two billon stars, from which orbital distances and motions can be calculated, Gaia is opening a new chapter in the study of stellar streams.

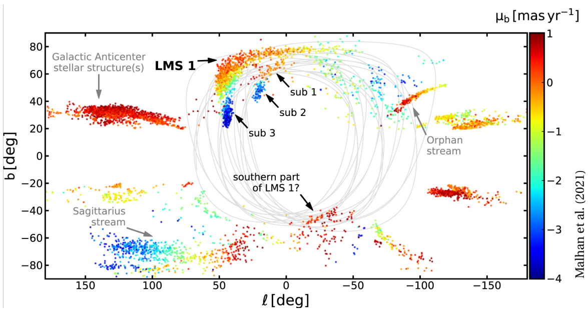
First amongst these, from Gaia DR2, was the Gaia–Enceladus stream (Helmi et al., 2018), mentioned above, and which I described in some detail in essay #15.

Others have followed. Ibata et al. (2019a) 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. Spectroscopic measurements of seven of the streams have confirmed their reality, and have shown that these streams are predominantly metal-poor.

One of these, Fimbulthul, is the trailing arm of, and (gratifyingly) the same age as, the tidal stream of the massive globular cluster ω Centauri (Ibata et al., 2019b).

LMS–1/Wukong is another Gaia DR2 discovery, independently reported as 'Low-Mass Stream 1' (based on RR Lyrae and blue horizontal-branch stars) by Yuan et al. (2020), and as Wukong, using the combination of Gaia and the H3 Spectroscopic Survey, by Naidu et al. (2020).

This image, from the study of LMS–1/Wukong by Malhan et al. (2021), shows the distribution of proper motions in Galactic latitude (μ_b, the scale ranging from 0 to just 4 milli-arcsec per year!), illustrating the rich substructure in the various streams, along with their derived orbit for LMS–1, shown as the grey curve.



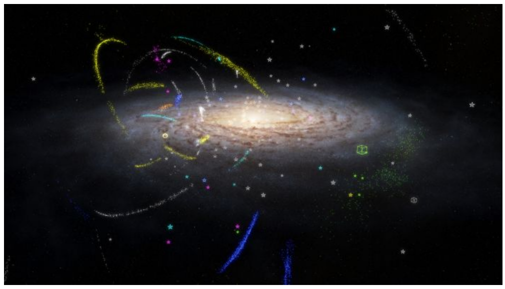
Meanwhile, the retrograde Arjuna/Sequoia/I'itoi group appears to result from three independent mergers (Myeong et al., 2019; Naidu et al. 2020).

Indeed, from their study of 5684 giants within 50 kpc from the Galactic centre, Naidu et al. (2020) attributed at least 95% of their sample stars to one of their listed structures, suggesting a halo built entirely from accreted dwarfs and the associated 'heating' of the disk.

Another stellar stream, named Nyx, comprises some 200 stars in the solar vicinity (Necib et al., 2020a; Necib et al., 2020b). These authors attribute Nyx to a massive dwarf galaxy dragged into the disk plane before being completely disrupted, although its extragalactic origin has been questioned (Re Fiorentin et al., 2021).

WITH THE RELEASE of Gaia EDR3, Malhan et al. (2022) assigned 170 globular clusters, 41 streams, and 46 satellite galaxies to six distinct groups, including the previously known mergers Sagittarius, Cetus, Gaia–Enceladus, LMS–1/Wukong, Arjuna/Sequoia/I'itoi, and a new merger that they named Pontus. An image from their `animation` is shown here.

The three most-metal-poor (C-19 with [Fe/H] = –3.4 dex; Sylgr with [Fe/H] = –2.9 dex, and Phoenix with [Fe/H] = –2.7 dex) are associated with LMS-1/Wukong, making it the most-metal-poor merger known to date.



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BY MID-2022, several other studies of these halo streams have been published, and more will become possible with the future Gaia data releases. But let me now briefly consider some of the wider studies that these results of stellar streams are starting to enable.

Firstly, Malhan et al. (2021) have shown that the morphology and dynamics of accreted globular cluster streams are sensitive to the central dark matter density profile and mass of their parent satellites. Specifically, globular cluster that accrete within 'cuspy' cold dark matter sub-haloes produce streams that are physically wider and dynamically hotter than streams that accrete inside cored sub-haloes.

A second spin-off is that these very low-metallicity streams can probe the contribution of r-process and s-process enrichment early in their formation history. First results by Gell et al. (2021) suggest that the progenitors of some of these streams experienced one or more r-process events (such as neutron star mergers) early on, in advance of their accretion by the Milky Way.

Tutukov et al. (2021) examined the possible role of star formation and collisions of gas-rich galaxies, leading to the emergence of low-surface brightness galaxies. Stellar streams, from the decay of satellite galaxies, may thus contain the remaining dense star clusters and include stars, exoplanets, and interstellar comets.

Finally, Peñarrubia (2021) considered their role in the formation of binary stars with extremely large separations, whose origin remains poorly understood (essay #37). He found that ultra-wide binaries can arise via chance entrapment of unrelated stars in tidal streams of disrupting clusters, suggesting that these streams may be the birthplace of hundreds of ultra-wide binaries.