198. The Sagittarius stream

In my previous essay, I summarised our knowledge of the Gaia Sausage–Enceladus halo stream. This was discovered in the Gaia DR2 data, and is now known to dominate the stellar halo within 25 kpc. Beyond that, and out to some 50 kpc, the halo is significantly populated by the Sagittarius stream, the subject of this essay.

Debris of these two massive ($10^8 - 10^9\,M_\odot$) accreted dwarfs together appears to comprise 80% of the halo (Naidu et al., 2020). Along with the many other streams discovered over the past few years, they confirm the picture of hierarchical structure formation in the Universe, parameterised by the ΛCDM cosmological model.

The Sagittarius dwarf galaxy is a nearby satellite of our own, discovered by Ibata et al. (1994). It was soon recognised as being tidally distorted, and inferred to have completed several close orbits around the Milky Way (Ibata et al., 1995; Mateo et al., 1996). With a mass of $4 \times 10^8\,M_\odot$, and distance ~24 kpc, it is a most striking example of galaxy disruption and ongoing accretion.

Subsequent studies, initially with 2MASS and SDSS, progressively revealed an elongated and weakly rotating central core, with tidally stripped stars forming two long tidal tails, both bifurcated, tracing an orbit almost perpendicular to the Milky Way disk, with much other complexity (Yanny et al., 2000; Newberg et al., 2002; Majewski et al., 2003; Newberg et al., 2003; Martínez-Delgado et al., 2004; Belokurov et al., 2006; Newberg et al., 2007; Łokas et al., 2010.; Koposov et al., 2012; Slater et al., 2013). The tidal debris traces out an orbit with an apogee of 50 kpc for the leading arm, and 100 kpc for the trailing (Belokurov et al., 2014; Hernitschek et al., 2017).

Other work has aimed to further characterise the system's orbit, mass, chemistry, and velocity dispersion (e.g. Frinchaboy et al., 2012; Majewski et al., 2013; Gibbons et al., 2017; Navarrete et al., 2017), as well as its use in determining the Galaxy potential (Law & Majewski, 2010b; Price-Whelan et al., 2016; Fardal et al., 2019). The two most distant known halo stars, at 200 kpc (Bochanski et al., 2014), appear consistent with the simulations of Sgr's maximal extent (Dierickx & Loeb, 2017), and perhaps with the 'edge' of our Galaxy (Deason et al., 2020).

With N-body simulations having to satisfy these many, detailed, observational constraints, a key question is whether the present elongated, prolate, bar-like shape of the core is a result of tidal forces on an initially spherical galaxy (Johnston et al., 1995; Ibata et al., 1997; Helmi & White, 2001; Vasiliev & Belokurov, 2020), or attributable to a more disk-like progenitor (Peñarrubia et al., 2010; Łokas et al., 2010; del Pino et al., 2021).

Łokas (2024) selected an Sgr analog from the IllustrisTNG simulations (essay 194) to demonstrate how such a dwarf, with initial mass $> 10^{11}\,M_\odot$, evolves around a Milky Way-like host on a tight orbit over seven pericentre passages, with a period of 1 Gyr. At the second pericentre, the disk transforms into a bar, and the bar-like shape is preserved thereafter. Strong mass loss leaves a dwarf with final mass $\lesssim 10^9\,M_\odot$. The gas is lost, and star formation ceases, at the third pericentre. The dwarf then retains a bar-like shape, small rotation, and a metallicity gradient, mirroring the observations.

Gaia is providing deep insight into this spectacular system. With DR2, investigations included identifying specific stellar types within the tidal arms, e.g. 400 O-rich AGB stars (Mauron et al., 2019), 164 M giants (Li et al., 2019), 6000 RR Lyrae stars with 5D phase-space coordinates (Ramos et al., 2020), and 3500 RR Lyrae with full 6D phase-space coordinates (Ibata et al., 2020). The latter work also concluded that the global properties of the Sgr stream were still reasonably well reproduced by the earlier model of Law & Majewski (2010b).

DR2 was also used to: determine the mean proper motion over 2π rad along the stream, using 1500 intensity peaks comprising 100 000 stars (Antoja et al., 2020); to identify a low-metallicity population inferred to have originated in the stellar halo of the Sagittarius progenitor (Johnson et al., 2020); to identify a faint globular cluster torn from the Ophiuchus stream by a close (5 kpc) passage of the Sgr core 100 Myr ago (Lane et al., 2020); and to define 260 000 members from which the mean proper motions provide the basis for a model in which the Sgr galaxy will be fully disrupted over the coming 1 Gyr (Vasiliev & Belokurov, 2020).

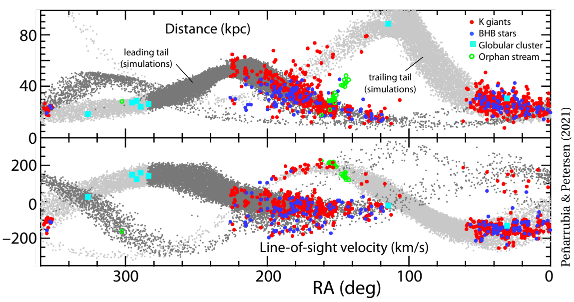
I WILL EXPAND a little on three of the Gaia DR2 results. First, del Pino et al. (2021) used 120 000 stars from DR2 to reveal a bar structure 2.5 kpc long, with the main body of the galaxy, strongly sheared by tidal forces, being a triaxial (almost prolate) ellipsoid. The inner core, of dimension $500 \times 330 \times 300\,\mathrm{pc}^3$ shows no net expansion, but it is rotating, mainly about its intermediate principal axis, with a maximum velocity of $4.13 \pm 0.16\,\mathrm{km\,s^{-1}}$.

In their paper entitled 'Tango for Three', Vasiliev et al. (2021) found a misalignment between the stream track and the proper motion directions in the leading arm, which they interpret as a time-dependent variation of the gravitational potential, in turn attributed to the recent passage of the LMC (of mass $1.3 \pm 0.3 \times 10^{11} M_\odot$). They argue that the stream cannot be modelled accurately in a static Galaxy potential, but rather the Milky Way is 'lurching' toward the massive infalling LMC, giving the Sgr stream its peculiar shape and kinematics.

In a very different application, Hayes et al. (2018) used the stream geometry to estimate the solar reflex velocity, and hence the velocity of the Local Standard of Rest, independently of an assumed value of R_0.

WITH THE availability of Gaia EDR3, still outstanding questions included the origin of the bifurcated tails (or parallel streams) in both northern (Belokurov et al., 2006) and southern (Koposov et al., 2012) Galactic hemispheres, although further progress in defining these was made with EDR3 (Ramos et al., 2022).

And while all models imply that Sgr has completed several orbits around the Milky Way, only tidal debris from the last pericentric passage had ever been detected. Peñarrubia & Petersen (2021) introduced a new method to identify clustering in angular momentum space, and identified 925 stars spanning 800° on the sky, thus wrapping the Galaxy *twice*.



In other work, 60 high-velocity stars, including 2 hypervelocity stars, originating from Sgr were identified by Li et al. (2022). The effect of Sgr on other streams was investigated by Dillamore et al. (2022a), and on the Jhelum stream in particular by Woudenberg et al. (2023). Stream properties as a function of metallicity were investigated by Limberg et al. (2023), and using Gaia DR3 by Cunningham et al. (2024). Searches for other candidates are also continuing with Gaia DR3 (Li et al., 2024).

THAT THIS SORT OF accretion process should also perturb the disk of the Milky Way had been predicted using test particle simulations (e.g. Ibata & Razoumov, 1998; Quillen et al., 2009; Gómez et al., 2012b). And some evidence of such disk perturbations preceded the Gaia data (e.g. Minchev et al., 2009; Gómez et al., 2012a; Widrow et al., 2012; Carlin et al., 2013; de la Vega et al., 2015; Schönrich & Dehnen, 2018; Laporte et al., 2018).

Gaia DR2 provided unambiguous evidence of such gravitational disturbances of the disk with the discovery of the so-called Gaia 'phase-space spiral', or phase-space 'snail' (essay 117), where ongoing 'phase mixing' from an out-of-equilibrium state is evident in the phase-space projection in the $Z - V_Z$ plane (Antoja et al., 2018).

The Gaia phase-space spiral (and some low latitude overdensities such as the Monoceros Ring) has been widely attributed to pericentric passages of Sgr (e.g. Binney & Schönrich, 2018; Khanna et al., 2019; Laporte et al., 2019a; Laporte et al., 2019b; Laporte et al., 2020; Vasiliev & Belokurov, 2020; Bland-Hawthorn & Tepper-García, 2021; Gandhi et al., 2022; Das et al., 2024).

Others suggest that it may have arisen from several smaller disturbances, rather than a single dominant one (e.g. Hunt et al., 2022; Tremaine et al., 2023).

A remarkable finding along similar lines, using Gaia DR2, was reported by Ruiz-Lara et al. (2020). They modelled the colour–magnitude diagram within 2 kpc of the Sun to identify three conspicuous and narrow episodes of enhanced star formation, estimated as having occurred 5.7, 1.9 and 1.0 Gyr ago. They found that these episodes coincide with modelled Sgr pericentre passages, with the perturbations from Sgr repeatedly triggering major episodes of local star formation.

A SUBJECT WITH ITS own substantial literature is the presence of globular clusters within the Sagittarius system. Ibata et al. (1994) had already noted that M54 (NGC 6715) lies in its densest region. Later work suggested that others probably formed in its gravitational potential well, and have been stripped from it during its extended interactions with the Milky Way.

Pre-Gaia, nine globular clusters associated with Sgr were known (Majewski et al., 2003; Law & Majewski, 2010a), although several of these were only subsequently confirmed by means of the Gaia DR2 data (Bellazzini et al., 2020): M54 in the nucleus; Arp 2, Terzan 7 and 8 in its core; and NGC 2419, NGC 4147, NGC 5634, Pal 12, and Whiting 1 in the tidal streams.

Using VISTA near-infrared data to identify potential RR Lyrae members, and Gaia EDR3 proper motions to confirm membership, 12 new clusters were identified by Minniti et al. (2021b), and a further 8 by Minniti et al. (2021a). This rich system, 29 in total, quite likely completes the census of globular clusters associated with the Sgr system (Arakelyan et al., 2020; Peñarrubia & Petersen, 2021; Kundu et al., 2022).