
15. The Enceladus stream

THE PAST two decades have witnessed a major advance in our understanding of galaxy formation. Present theories, supported by extensive numerical simulations, argue that large galaxies, such as our own Milky Way, have been built up from a series of mergers with smaller galaxies over the past several billions of years.

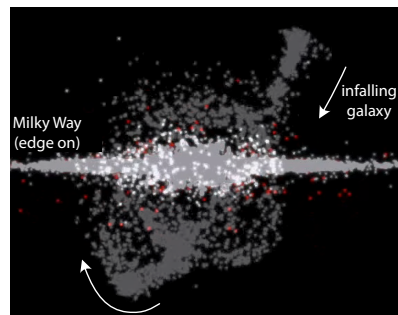
Studies of the structure of our Galaxy identify it as comprising a massive spherical central bulge, and an extended rotating stellar disk in which a few spiral arms (major sites of ongoing star formation) are embedded. On more careful examination, the disk comprises two rather distinct populations: the dominant ‘thin disk’, some 300 pc in vertical extent, and a more extended ‘thick disk’. All of these sit within a vast, more diffuse, and largely spherical halo. This halo is dominated by unseen and still mysterious ‘dark matter’. Over cosmic history, these dark matter halos have been the centres of galaxy formation, and of star formation within them.

CONTROLLED BY long-range gravitational forces, disk stars rotate around the Galactic centre with an orbital period of some 250 million years. They also ‘bounce’ up and down about the Galaxy’s mid-plane with a period of 80 Myr as they rotate. Stars making up the visible component of the halo are generally ‘metal-poor’ (astronomer-speak for low in elements heavier than H and He), these stars having formed when the Universe was itself very young. Halo stars move on much more extended, circular orbits. If they happen to pass through our solar neighbourhood on these vast orbits, they will be moving at relatively high speeds as a result.

Barnard’s Star is one such fast-moving, metal-poor ‘halo-like’ star, passing swiftly through our solar neighbourhood. Some 10–12 billion years old, compared to our Sun’s 4.5 Gyr, it is amongst the oldest stars in the Milky Way. It is moving through space at about 90 km s^{-1} and, because of its proximity at only 1.8 pc (6 light-years), has the largest of all known proper motions. This large angular motion across the sky, at around 10.3 arc-second per year, leads to its displacement of about a quarter of a degree over a human lifetime, i.e. roughly half the angular diameter of the full Moon.

MODELS OF structure formation suggest that our Galaxy’s inner stellar halo should be dominated by the debris of just a few massive progenitor galaxies merging with our own early on in its formation history. This explanation finds convincing support with the new Gaia data, where there is compelling fossil evidence for one such merger event which took place around 10 Gyr ago, and whose debris in the solar neighbourhood reveals much about this enormous and disruptive event.

Before looking at the details, let us take a look at the bigger picture. How is it possible to piece together evidence for such an ancient event? To visualise the principles, the figure shows an edge-on schematic of our Galaxy’s disk, and a less massive galaxy falling onto it from the upper right.

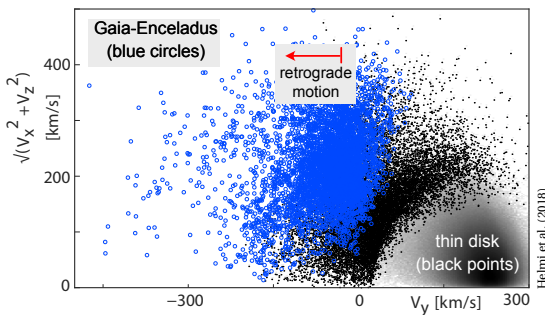


The lower mass incoming galaxy is captured by the gravity of the more massive galaxy, and leads to a stream of stars which becomes progressively more torn apart as it encircles and merges with the cannibalising galaxy. Over the subsequent few billion years, over several orbits, the disrupted stellar stream becomes progressively more mixed into the stars of the more massive host. But it is not difficult to imagine that these infalling stars might still be recognisable as interlopers if their parent galaxy had distinctive chemical signature.

It is perhaps less obvious, but nevertheless crucial to the recent discoveries, that these stars are likely to retain some common and inherited features of their orbital motion around the more massive galaxy which has entrapped them. Specifically, although after a few billion years, and after several disruptive orbits, they end up being well-spread throughout space, their angular momentum around our Galaxy’s centre retains some memory of their original orbital motion.

EARLIER STUDIES WHICH considered both the stellar chemistry (i.e. the elements which dominate their spectra) and the dynamical motions of the nearby halo stars together have hinted at the presence of such infalling stellar streams and clumps, and of correlations between the stars' chemical abundances and their orbital parameters. Indeed, the publication of the Hipparcos star catalogue in 1997 allowed the discovery of one such 'disrupted event' identified from this type of correlated space motion (Helmi et al., 1999).

More recently, analysis of data from the Sloan Digital Sky Survey, and from Gaia DR2, has revealed the presence of two distinct sequences in the colour–magnitude diagram, and of a prominent kinematic structure, all in the nearby halo. These may well be traces of an important accretion event experienced by the Galaxy. Interestingly, this kinematic feature is slightly 'retrograde', that is, the stars within it are moving around our Galaxy in the opposite sense to the bulk of the disk and halo stars.

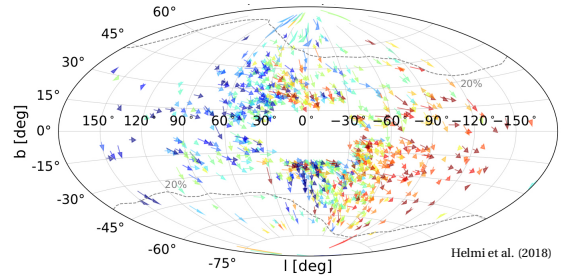


The Gaia–Enceladus stream in velocity space

The type of structure observed in the joint SDSS and Gaia DR2 data nicely confirms predictions from cosmological simulations, namely that this type of sub-structure in our solar neighbourhood is most apparent among the fastest moving stars, typically reflecting more recent accretion events (Koppelman et al., 2018).

THE GAIA DR2 DATA was then used to study the kinematics, chemistry, age and spatial distribution of stars in a relatively large volume around the Sun. As we have seen, this volume samples two major Galactic components, the disk and the stellar halo.

This study, by Helmi et al. (2018), and reported in the *Journal Nature*, demonstrated that the inner halo is dominated by debris from an object which at infall was slightly more massive than the Small Magellanic Cloud, and which the authors referred to as Gaia–Enceladus. In Greek mythology Enceladus was one of the Giants (Titans), the offspring of Gaia (representing the Earth), and Uranus (representing the Sky), buried under Mount Etna and held to be responsible for earthquakes in the region (the specification as Gaia–Enceladus avoids confusion with the Saturnian moon of the same name).



Gaia–Enceladus: proper motions, coloured by radial velocity

The stars originating from the Gaia–Enceladus accretion event cover nearly the entire sky, and their motions reveal the presence of streams and slightly retrograde and elongated trajectories. Hundreds of RR Lyrae stars and thirteen globular clusters following a consistent age–metallicity relation can be associated to the merger on the basis of their orbits.

With an estimated 4:1 mass-ratio between the young Milky Way and Gaia–Enceladus, the merger would have led to the 'dynamical heating' of the precursor of the Galactic thick disk, increasing their space velocities, and therefore increasing their scale height with respect to the Galaxy mid-plane. It seems highly plausible 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. Most probably, this was the last significant merger that our Galaxy experienced.

THE FINDINGS are in line with simulations of galaxy formation, which predict that the inner stellar halo should be dominated by debris from just a few massive progenitors. But the agreement goes further.

Amongst these very large-scale cosmological simulations, the EAGLE project has been shown to produce a realistic population of galaxies reproducing a broad range of observed galaxy properties. The largest of the EAGLE simulations, L100N15043, has a cubic volume of 100 Mpc in size, and includes the effects of both baryonic and dark matter. Its huge volume of simulated space–time provides numerous Milky Way–type galaxies, and with a wide range of merger histories.

Amongst these mergers, Bignone et al. (2019) identified one with remarkably similar properties to the Gaia–Enceladus event, also occurring around 9 Gyr ago. These specific simulations result in merger debris on a slightly retrograde orbit (as found for Gaia–Enceladus), bursts of star formation in the early disk, the formation of a dynamically heated thick disk (as seen in our Milky Way), and with a large fraction of the debris deposited at large heights above the Galactic disk, corresponding to our Milky Way's stellar halo.

All-in-all, a most remarkable triumph of state-of-the-art space observations combined with state-of-the-art cosmological simulations!