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## 246. Star formation episodes

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**M**ANY GAIA STUDIES target an understanding of the early formation of our Milky Way galaxy, and its subsequent chemical and dynamical evolution. Its most ancient ‘proto-Galactic component’, for example, can be identified through the orbits of very low-metallicity stars within the solar radius (Rix et al., 2022).

In another example, using metallicity as a proxy for age, and based on 9.9 million red giants, Chandra et al. (2024) identified three distinct evolutionary phases: a disordered/chaotic protogalaxy, a (kinematically) hot old disk, and a cold young disk. Analogues are seen in cosmological simulations such as TNG50, in which the protogalaxy spins up into a thin high- $\alpha$  disk, before being heated and torqued by a major gas-rich merger. This adds low-metallicity gas and angular momentum, from which the kinematically cold low- $\alpha$  stellar disk is born.

And Gaia studies are demonstrating how orbiting satellites can induce observable phase-space features in their disks, such as spiral structures and vertical heating.

**A**MONGST WORK on halo streams, including Sagittarius (Sgr) and Gaia Sausage–Enceladus (GSE), Ruiz-Lara et al. (2020) used Gaia DR2 to model the colour-magnitude diagram within 2 kpc. They identified three episodes of enhanced star formation, occurring 5.7, 1.9 and 1.0 Gyr ago. These coincide with modelled Sgr pericentre passages, with the Sgr perturbations triggering major episodes of localised star formation.

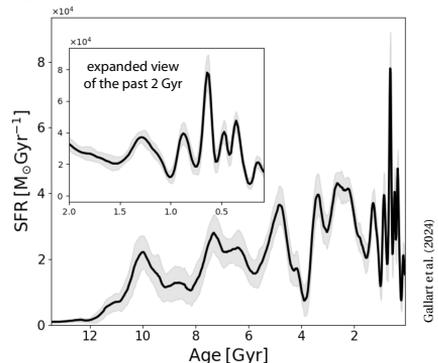
Rather than appealing to spectroscopy or asteroseismology to estimate individual stellar ages, their approach used Gaia’s accurate colour-magnitude diagrams to infer precise stellar ages for large samples of stars, from which the star-formation history of these complex stellar populations could be disentangled.

Here, I will mention four recent studies that have exploited the same technique to study our Galaxy’s evolutionary history. These are focused on (1) the star-formation history of the solar neighbourhood; (2) the evolution of the thin and thick disk populations; (3) the age and metallicity of GSE stars near the Sun; and (4) the age distribution of stars of the inner Milky Way.

**I**N THE FIRST, Gallart et al. (2024) aimed to determine the ‘dynamically evolved’ star-formation history of the solar neighbourhood. They used the Gaia Catalogue of Nearby Stars (GCNS), derived from Gaia EDR3 (Gaia Collaboration et al., 2021), which is a complete census of the (mostly thin disk) stars within 100 pc.

I will not describe their details, their comparisons with ages inferred from isochrone fitting, or metallicities from spectroscopy, and the various complexities including the effects of binarity. But they emphasise that their method makes no *a priori* assumptions on the age-metallicity relation or the metallicity distribution, or on the functional form of the star-formation rate as a function of time. They estimate an accuracy  $< 6\%$  in the dating of stellar populations, even at old ages.

Their conclusions (see figure below), are that star formation started 11–10.5 Gyr ago from solar-metallicity gas, possibly triggered by mergers. The small number of stars older than 10 Gyr, with  $[M/H] \lesssim -1$ , typical of the stellar halo, may correspond to the remnant of the Gaia Sausage–Enceladus merger. Star formation continued with a slightly decreasing metallicity trend until 6 Gyr ago. Then, between 6–4 Gyr ago, there was a break in the age–metallicity distribution, with three distinct metallicity populations suggesting some dramatic impact event – perhaps the first infall of the Sagittarius dwarf galaxy. Star formation resumed 4 Gyr ago with a somewhat episodic behaviour, metallicity near solar, and a higher mean star-formation rate.

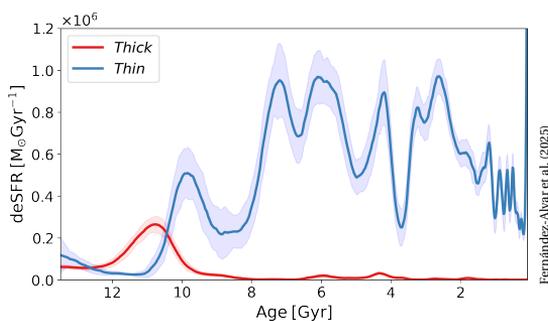


**I**N A SUBSEQUENT STUDY using the same approach, Fernández-Alvar et al. (2025) targetted the star-formation history of the thin and thick disk components, using Gaia DR3 data within 250 pc of the Sun, and covering 1 kpc in height (see figure below). They worked with a kinematic definition of thick disk stars (based on eccentricities and velocities), rather than with a geometric (based on scale-height) or metallicity-based selection.

They found that the kinematic thick disk is mostly older than 10 Gyr, undergoing three main metallicity enrichment episodes: firstly, over 12 Gyr ago, peaking at  $[M/H] \sim -0.5$  dex;  $\sim 11$  Gyr ago, rapidly increasing to solar  $[M/H]$  and spanning  $[\alpha/Fe]$  from 0.3 to solar; and just over 10 Gyr ago, reaching supersolar metallicities.

Meanwhile, the kinematic thin disk began forming  $\sim 10$  Gyr ago, just as thick disk star formation ended, characterised by supersolar metallicities and low  $[\alpha/Fe]$ . This transition coincides with the Milky Way's last major merger: the Gaia Sausage–Enceladus (GSE). They also found that sustained star formation in the thin disk could only begin after the last major merger had concluded, resulting in a more stable period. This provides independent evidence for the timing of the Milky Way's last major merger.

They also identified a subset of kinematic thin disk stars older than 10 Gyr with high/intermediate  $[\alpha/Fe]$ , indicating a transition phase. The age–metallicity relation of the thin disk suggests overlapping star-formation episodes and radial mixing in the solar neighbourhood, with the greatest spread  $\sim 6$  Gyr ago. Finally, they detected an isolated thick disk star formation event at solar metallicity around 6 Gyr ago, coinciding with the first pericentre passage of the Sagittarius dwarf galaxy.



**I**N THE THIRD PAPER of this series, González-Koda et al. (2025) studied the Gaia Sausage–Enceladus (GSE) stream, considered to be the last major merger that contributed to the formation of the Milky Way, and whose remnants dominate the nearby accreted stellar halo. They used Gaia DR3 to define three GSE samples with different criteria and possible degrees of contamination from other substructures in the halo, deriving the age and metallicity distributions using the CMDf<sub>t</sub> package detailed by Gallart et al. (2024).

They identified three main stellar populations (and a fourth smaller one) following an almost linear age– $[M/H]$  relation. They associated the three oldest populations with the bulk of the star formation that lasted for  $\gtrsim 3 - 4$  Gyr and ended about 10 Gyr ago, with metallicities ranging from  $-1.7$  to  $-0.8$ . They assigned these populations to two main epochs: the evolution of GSE in isolation, and the merger event itself. This separation gains independent support from the age–metallicity relation of GSE globular clusters. The fourth population is younger and more metal-rich, at  $\sim 8.5$  Gyr and  $[M/H] \sim -0.4$ , although its link to GSE is uncertain.

The small number of GSE stars with adequate phase-space information leaves it unclear whether the first phases of star formation were continuous or episodic. More insight should come with Gaia DR4.

**I**N THE FOURTH paper of this series, Ruiz-Lara et al. (2025) used the star-formation histories of the solar neighbourhood to infer the evolution of the Galaxy's central regions. Although the inner region is known to be dominated by a stellar bar, and a boxy peanut-shaped bulge, the complexities of crowding and extinction means that their precise stellar populations, and how star formation proceeded, are unknown.

Their approach was to obtain age distributions for the super-metal-rich stars ( $[M/H] \sim 0.5$ ) in the solar neighbourhood, which account for more than 5% of stars within 400 pc of the plane. Assuming that these stars were born in the inner Galaxy and migrated outwards, these distributions should be representative of the stellar age distribution in the inner Galaxy.

They found that these age distributions are not continuous but show clear signs of episodic star formation (around 13.5, 10.0, 7.0, 4.0, 2.0, and less than 1 Gyr ago). With the exception of the 4 Gyr event, these timings coincide with the formation of the primitive Milky Way, and with known merging events or satellite encounters with the Sagittarius dwarf galaxy, GSE, and the Magellanic Clouds. This suggests that these events could indeed have triggered global star-forming episodes.

Their results are compatible with the accretion of the Gaia Enceladus–Sausage structure being responsible for the formation of the bar 10 Gyr ago, while leaving open the possibility of a later formation of the bar associated with the 4 Gyr event.

Support for the possible origin of the super metal-rich stars comes from the Auriga Superstars suite of cosmological simulations (Pakmor et al., 2025). These confirm that metal-rich stars in regions analogous to our solar neighbourhood formed at discrete times, and migrated from the inner parts of barred galaxies, in turn suggesting a possible link to bar dynamics and satellite accretion. This allows us, they argue, to indirectly witness the evolution of the inner Milky Way, and to further constrain dynamical models of the Milky Way's bar.