
41. The age of our Milky Way Galaxy

THE AGE OF THE EARTH has been pieced together from a complex story involving the geological and fossil record, radioactive dating, and evidence from the Moon and meteorites. The oldest known meteorites in the solar system are around 4.56 billion years old, and it appears that the Sun was born at around the same time.

The oldest white dwarfs in our Galaxy have been ‘cooling’ for about 12.7 billion years. The oldest globular clusters are about 13.4 billion years old. Distant Cepheid variable stars, which trace the expansion age of the Universe, suggest that it has been expanding, at around the current rate, for about 13.7 billion years.

And maps of the cosmic microwave background radiation, interpreted in terms of the temperatures and structures that existed when the radiation was emitted, yield ages close to 13.77 billion years (or 13.77 Gyr).

ACCORDING TO TODAY’S ‘standard model’ of Big Bang cosmology (Lambda cold dark matter, or Λ CDM cosmology), the Universe contains three main constituents: dark energy, cold dark matter, and ordinary matter. One of its great triumphs is its success in describing structure formation in the early Universe, and its growth over cosmological time, leading to the galaxies and clusters of galaxies that we observe today.

Observations of the stellar populations of our Galaxy, supported by these cosmological models, suggest that our Milky Way comprises both a thin and thick disk population, along with a central spherical bulge and more extended central bar. All are embedded in a vast spherical halo, itself containing extended stellar ‘tidal’ streams which originated from the capture of smaller galaxies much earlier in our Galaxy’s history.

We now have a rather secure understanding of the age of our solar system, and of the oldest stars and stellar populations making up our Galaxy. Today, we are in a position to ask – and answer – more detailed questions about the sequence of events that made up our Galaxy’s history. How old is the thin disk, and the thick disk? How old is the stellar halo? And can we discern the age of the stellar streams that are contributing to it?

THE MOST GENERAL METHOD for estimating stellar ages rests on mathematical models of stellar evolution. A star’s mass and chemical composition are the most important inputs, and its luminosity and temperature provide the main observational constraints.

Detailed physical models and extensive computer calculations predict the changing state of the star over time, yielding a data grid that can be used to determine the evolutionary track of the star across the Hertzsprung–Russell diagram (charting absolute magnitude versus temperature), or the closely-related colour–magnitude diagram. The age of any particular star is estimated by comparing its physical properties with those of stars along a matching evolutionary track.

Spectroscopic observations provide both the star’s temperature and its chemical composition, while the star’s distance is the most crucial quantity in determining its luminosity. Gaia distances for hundreds of millions of stars out to many kiloparsec distance hold the key to unravelling their ages, and the ages of entire stellar populations throughout our Galaxy, both as a function of location and of their kinematics.

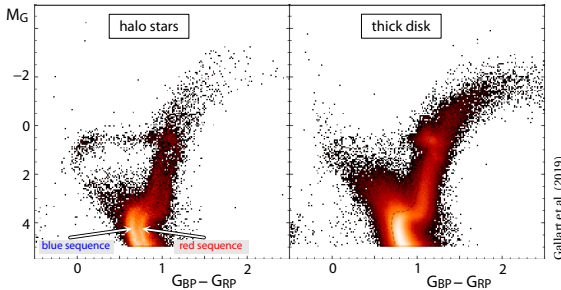
APPLIED TO OUR GALAXY’S main stellar populations, Gallart et al. (2019) used Gaia DR2 astrometry to extract two large samples of halo stars and thick disk stars. Both samples were restricted to stars within 2000 pc of the Sun, such that accurate distances and absolute magnitudes could be derived *directly* from the parallaxes.

For their halo star sample, they selected stars with large tangential velocities ($> 200 \text{ km s}^{-1}$) relative to the Sun, such extreme space velocities being characteristic of the halo population. Their sample of a kinematically defined halo population contains about 60 000 stars.

For their thick disk sample, they employed the same distance limit, while using the distance and directional information to retain only those stars more than 1100 pc above or below the Galactic plane (and not included in the halo sample). At these distances, the majority of stars are expected to belong to the thick disk, rather than the younger thin disk component.

Their thick disk sample contains around 500 000 stars. In comparison with previous studies of the thick disk population, it is worth stressing that their sample is defined purely morphologically, rather than being based on chemical or kinematic properties.

The location of both samples in the Gaia colour-magnitude diagram, M_G versus $G_{BP} - G_{RP}$, are shown here. Again, it is worth emphasising that both axes, absolute magnitudes in the G band, and colours in the $G_{BP} - G_{RP}$ bands, are as measured by Gaia.



WHAT GAIA REVEALS is that the halo population consists of two distinct sub-groups: a ‘blue’ sequence and a ‘red’ sequence, indicating the presence of two distinct sub-populations within the halo.

At this point, a little history is probably useful. In trying to understand the ‘big picture’ of galaxy formation and evolution, a lengthy debate started more than 50 years ago, when two different possibilities were being considered: either that galaxies formed by a sort of ‘monolithic collapse’ of the available gas, or that formation and evolution was mediated by satellite accretion.

Support for the latter has been growing over the past two decades, including the discovery of stars from an ancient merger seen in the Hipparcos data (Helmi et al. 1999). And evidence for two populations within the ‘hot’ (high-velocity) halo stars has also been accumulating from stellar abundance data (e.g. Nissen et al. 2010).

Based on Gaia data, the blue sequence has recently been associated with a significant merging event, which has been named Gaia–Enceladus. This occurred early during the Milky Way formation (Helmi et al. 2018), and has been described separately in these ‘essays’.

The nature of the red sequence has been less clear. One hypothesis is that it is somehow associated with the thick disk, perhaps being ancient disk or bulge stars ‘heated’ to halo kinematics by a galaxy merger.

THE RECENT GAIA results from Gallart et al. (2019) represent a further important advance in understanding our Galaxy’s halo for the following reasons.

Comparing the halo colour-magnitude diagram with theoretical stellar evolution models shows that the red and blue sequences arise from two populations with different chemical compositions, but of *the same age*.

That they are coeval is a remarkable finding. But their models also show that these populations formed very early on in the life of the Universe. Thus, while current estimates put the age of the Universe at around 13.77 Gyr, this halo population formed with a peak age of 13.4 Gyr, and with half of the star having formed by 12.3 Gyr. Indeed, not only did they form at similar times, but they also stopped forming at similar times.

We can go still further in this cosmological sleuthing. There is, today, a well-established relation between a galaxy’s mass and the fraction of ‘metals’ (elements heavier than H and He in astronomy-speak) in its stars. This means that the stars in the red sequence, being more metal rich, must have formed in a galaxy more massive than that in which the blue sequence formed.

AN IMPORTANT CONCLUSION appears to be inevitable: both populations were involved in a merger event, with the red sequence belonging to the main progenitor of the Milky Way, and the blue sequence belonging to a smaller accreted galaxy, the one now referred to as Gaia–Enceladus. The metallicity difference between the more massive Milky Way progenitor and the smaller accreted galaxy suggests that their mass ratio was about 4:1.

The inference is that this ancient galaxy–galaxy encounter heated some of the main progenitor stars that had been forming in a disk-like structure, increasing their space velocities (through close encounters) to the sort of extreme kinematics that lead them to be classified as halo stars. Encouragingly, the existence of this type of halo star had already been predicted by cosmological simulations of Milky Way-type galaxies based on kinematic results from Gaia DR1 (Bonaca et al. 2017).

THE CONCLUSIONS OF Gallart et al. (2019) clearly summarises the current picture of our Galaxy’s formation, deduced from the Gaia DR2 data.

New stellar age distributions enabled by Gaia, aided by state-of-the-art cosmological simulations of disk galaxy formation, present a clear picture of the formation of our Galaxy: a primitive Milky Way had been forming stars during some 3 Gyr when a smaller galaxy, which had been forming stars on a similar timescale but was less chemically enriched owing to its lower mass, was accreted by it.

This merger heated a fraction of the existing stars in the main progenitor to a stellar halo-like population. A ready supply of infalling gas during the merger ensured the maintenance of a disk-like configuration, with the thick disk continuing to form stars at a substantial rate.

The measured age distributions indicate that the thick disk reached its peak star formation rate around 9 Gyr ago, or some 4.5 Gyr after the first stars formed in the Milky Way. Subsequently, around 8–6 Gyr ago, the gas settled into a thin disk that has continued to form stars up to the present day.