208. Gaia science highlights to 2024

In my previous essay, I gave an overview of the many scientific areas being impacted by Gaia, divided into five categories: solar system; uses of the photometry and RVS spectra; stellar physics; Galaxy structure and dynamics; and local group and cosmology.

Here, I will say a little more on some of the highlights, with references to my earlier essays for further details.

Solar system: Gaia has provided state-of-the-art orbits of 157 000 asteroids for the 66-month data interval used for Data Release 4 [159], reflectance spectra from the BP/RP spectrophotometry [180], and rotation periods from Gaia's multi-epoch photometry [181, 182].

This combination is being used to study their dynamical and taxonomic properties; masses from mutual orbit perturbations; asteroid 'families' resulting from collisional fragmentation (which can remain clustered in orbit space, with similar spectra); space 'weathering'; the origin of near-Earth asteroids via solar-radiation driven (Yarkovsky) migration; the excess of fast and slow rotators as a result of the solar-radiation driven (YORP) effect; and sizes and morphologies from the many occultation events that can now be accurately predicted.

Stellar physics: The enormous and strictly defined census of stars within the solar neighbourhood, including the CNS5 within 25 pc [129], and the Gaia Catalogue of Nearby Stars within 100 pc [33], yield the accurate placement of more than 200 000 stars in the colour–magnitude ($M_{\rm G}$ versus $G_{\rm BP}-G_{\rm RP}$) analogue of the Hertzsprung–Russell diagram [42]. Many advances are being made by connecting these observations with theoretical models of stellar structure and evolution.

Variable stars have long been recognised as offering deep insights into stellar structure and evolution, and more than 10 million variable sources have been classified as part of Data Release 3 [76]. Accurately locating them in the HR diagram reveals the specific occurrences of (for example) pulsating, eruptive, and cataclysmic variables, as well as stars that show apparent variability due to stellar rotation or binary eclipses. A movie of the changing loci of representative variable stars across the colour–magnitude diagram has been given at `cosmos.esa.int/web/gaia/gaiadr2_cu7`.

As one example, the classical ZZ Ceti stars (white dwarfs featuring fast non-radial gravity-mode pulsations) are particularly concentrated in magnitude and colour, with variability seen in about half of them. This concentration is attributed to the partial ionisation of H in their outer envelopes, which is only developed over a narrow range of temperature, and therefore colour.

The fidelity of both the Gaia astrometry and photometry is nicely demonstrated by three striking new features of the Hertzsprung–Russell diagram.

The first of these is a clear discontinuity at the location of the radiative–convective boundary of M dwarfs, today also known as the Jao gap. It has recently been explained in terms of the non-equilibrium burning and mixing of ^{3}He in the stellar core [152].

The second is the prominent bifurcation in the hydrogen- and helium-dominated atmospheres of the white dwarf sequence. Not predicted by previous evolutionary models, this is now attributed to trace amounts of carbon added by convective dredge-up [178].

Another feature addressed in several follow-up papers is a discontinuity in the white dwarf sequence now attributed to ongoing core crystallisation. This is a phase transition that holds up the release of heat, leads to a discontinuity in the rate of cooling, and affects the inferred 'cooling-age' estimates of white dwarfs [108, 139].

More generally, the substantial increase in white dwarf numbers from Gaia [29] is leading to many other insights into their physics, including the mass–radius relation, their asteroseismic properties, and mass-based inferences on stellar mergers [107, 108].

On another topic, many new insights into binary and multiple stars are flowing from Gaia's joint astrometric, photometric, and spectroscopic survey. Amongst these are the occurrence of equal-mass 'twin binaries' [138], and the detailed orbital characterisation of wide binary systems, allowing studies of their origin [193]. Both have important implications for star formation models.

GALAXY STRUCTURE AND DYNAMICS: With Gaia representing a step-change in the observational characterisation of our Galaxy's origin and evolution, the topics of Galactic structure and cosmology now overlap considerably. I will defer the mention of halo streams, although intimately tied to our Galaxy's structure and dynamics, to my next 'cosmology' section.

I will gather the whole subject of star formation under the first highlight of this section. Here, big progress has been made in identifying many new open star clusters [74, 144], and further characterising some of the best known clusters and associations [18]. Amongst these are the superbly-defined main sequence of the Hyades [151]; resolution of the distance controversy of the Pleiades [13]; the identification of various tidal tails [20]; their possible harbouring of black holes [175]; the origin of runaway stars [165], and the somewhat connected hypervelocity stars [22, 166].

The 'peculiar motion' of nearby stars has been known since the time of William Herschel, and the detailed nature of various nearby moving groups and dynamical streams has long been debated. Many studies with Gaia have confirmed that some are 'evaporating' open clusters, and some are the tidal debris of accreted satellite galaxies. Of many new results, the Hercules stream has been associated with a dynamical resonance with the Galaxy's central bar, perhaps even consistent with the bar's deceleration through dynamical friction with the Galaxy's dark halo [115].

Amongst several other profound dynamical insights are the discovery of the Gaia phase-space spiral, a remarkable large-scale feature possibly associated with a passage of the Sagittarius dwarf galaxy [117]; a dynamical estimate of the distance to the Galactic centre [111]; measurement of the micro-acsec level effects of aberration due to Galactic rotation [32]; and an increasingly coherent picture of our Galaxy's three-phase formation, involving spin-up, merger, and cooldown [190].

Data Release 3 in 2022, I should recall, included a catalogue of distances, metallicities, temperatures and gravities for 470 million sources [89], while at least four other community-generated catalogues of [M/H], $T_{\rm eff}$, and $\log g$ have been made available since [189]. DR3 also provides estimates of radius for 470 million sources, mass (140 million), age (120 million), chemical abundances (5 million), diffuse interstellar bands (0.5 million), activity indices (2 million), Hα equivalent widths (200 million), and further classification of spectral types (220 million) and emission-line stars (50 000).

Such huge numbers of uniform metallicities and other stellar properties, which provided accurate chemical abundances across all stellar populations throughout the Galaxy, are now being used as crucial inputs for studies of star formation, detailed nucleosynthesis modelling, and Galactic chemical and dynamical evolution.

LOCAL GROUP AND COSMOLOGY: It is the number and variety of complex phase-space features in our Galaxy that has been one of Gaia's greatest contributions to studies of its structure and evolution to date. And some of these can only easily be interpreted within the context of our Local Group of galaxies, and indeed within the framework of ΛCDM cosmology.

Of those phase-space features with a more cosmological origin, I have already mentioned the Gaia phase-space spiral, a complex phase-space feature possibly associated with a passage of the Sagittarius dwarf galaxy [117], and the possible imprints of a decelerating bar attributable to the Galaxy's dark matter halo [112].

Over the past 20–30 years, through a combination of observations, theory, and simulations, aided by N-body simulations of the large-scale structure of the ΛCDM Universe, it became clear that our Galaxy's halo should be the graveyard of many other galaxies, gravitationally captured by the Milky Way galaxy over its lifetime.

Within this framework is one of Gaia's key advances: the ongoing discovery of large numbers of ancient stellar streams making up our Galaxy's halo. While a few were suspected pre-Gaia, more than 100 are known today, confirming this picture of halo accretion, and their influence on (for example) the dynamics of the thick disk [156]. Many detailed insights are flowing from these discoveries, and the detailed kinematic and chemical data from Gaia associated with them.

The 'Gaia Sausage–Enceladus' stream, lying within 25 kpc, is one of the most prominent and well studied. It was a radial merger that occurred some 9.5 Gyr ago, and which now dominates the local metal-poor halo. The 'head-on' collision resulted in rapid phase mixing, evident today only in its clustered integrals of motion. Beyond 25 kpc, the halo is dominated by the Sagittarius (Sgr) dwarf galaxy and stream, $[{\rm Fe/H}] = -1.0$, one of the first identified halo streams. Here, both the residual galaxy core, as well as two vast preceding and trailing streams, are clearly discernable.

The phase-space information provided by Gaia is also allowing the search for black holes within these stellar streams [176], and probing the observational consequences of the dark matter sub-halos (halos within halos) that are predicted, in the standard ΛCDM cosmology, to exist surrounding the Milky Way [184].

More widely, Gaia is confirming many of the detailed predictions of the large-scale cosmological simulations such as Millennium, Illustris, and EAGLE, and helping in their interpretation [194]. Topics range from simulations of the merger epochs, the occurrence of bars, the orbits of globular clusters [30] and dwarf spheroidals [31], the bulk motions of the Magellanic Clouds [38], as well as the ΛCDM 'missing satellites' problem, the 'core–cusp' problem, the 'too-big-to-fail' problem, and the 'plane of satellites' problem.