207. Gaia science synopsis to 2024

IN THIS ante-penultimate essay of 2024, I will give a concise 'run through' of the scientific areas impacted by Gaia so far. I divide this into five categories: solar system; applications of the photometry and radial velocity spectrometer (RVS) spectra; stellar physics; Galaxy structure and dynamics; and local group and cosmology. In my next essay (208), I will focus on a few highlights.

References for such a concise overview would be challenging – and none are given. To follow-up on these many topics, my 'Gaia Science Tree' links to the various essays giving more details.

SOLAR SYSTEM: Data Release 3 (DR3, June 2022) gave an all-sky catalogue of 1.8 billion sources, providing a reference system for the pointing of ground-based telescopes, for interplanetary spacecraft navigation (e.g. the New Horizons flyby of Arrokoth in 2019), and for predicting occultation events in unprecedented numbers (including Europa and Triton), with insights into object sizes, shapes, and atmospheres. The positions also provide an absolute reference frame for the measurement of gravitational light-bending by the Sun and Jupiter.

DR3 gave reconstructed orbits for 155 000 minor solar system bodies, based on 34 months of data. One of DPAC's Focused Product Releases (Oct 2023) gave improved results over the 66-month coverage planned for DR4. These orbits are yielding further insights into their migration and their complex dynamical resonances.

Accurate photometry is yielding the solar-radiation driven Yarkovsky and YORP effects for several hundred near-Earth asteroids, throwing light on their orbital migration, the origin and orbits of Near-Earth Asteroids, and their spin states. Reflectance spectra for 60 000 are advancing studies of their classification, and collisional and orbital evolution, where the effects of space 'weathering' are seen as an increase in spectral slope with age.

The positions and velocities of nearby stars are being used for determining the chronology of stellar flybys and their correlation with past extinction events on Earth, and in efforts to trace back the origins of stellar 'vagabonds', exemplified by Oumuamua and Borisov.

PHOTOMETRY AND SPECTRA: Gaia's multi-epoch photometry is allowing variability classification for tens of millions of stars, of all spectral types, including Cepheids, non-radial pulsators, and eclipsing and ellipsoidal variables, with stellar rotation determined for millions of stars. It provides the basis of an alerts system, which is flagging microlensed events, supernovae, tidal disruption events, and others.

The radial velocity spectrometer is providing tens of millions of radial velocities. The spectra are yielding stellar parameters ($T_{\rm eff}$, $\log g$, and [M/H]), extinction measures, mapping of diffuse interstellar bands, and synthetic photometry in arbitrary passbands.

Constraints on physical effects include the determination of gravitational redshift, asteroseismology models, and limits on the variation of $\dot{G}$, on gravitational waves, and effects of modified (MOND-type) gravity.

STELLAR PHYSICS: Gaia is providing an unparalleled census of nearby stars (to 25 pc, 50 pc and 100 pc). This is allowing searches for solar analogues and solar siblings, and mapping out the Local Bubble, diffuse interstellar bands, and the effects of extinction.

The substantial improvement in content and accuracy of the Hertzsprung–Russell diagram, over all evolutionary phases, is providing a massive framework for advances in modelling stellar evolution, determining the initial mass function, constraining important effects such as convection (and the mixing length), and identifying subtle features such as the Jao gap in M dwarfs.

Open clusters are being discovered and mapped in unprecedented numbers. This is revealing the structure (and main sequence) of the Hyades, the distance to the Pleiades, and the nature of complex clusters such as Westerlund 1. Gaia is probing the origin of OB associations, moving groups and their traceback ages, and the structure of nearby molecular clouds.

Accurate distances and proper motions are allowing the identification and characterisation of runaway stars and their birth clusters, and the identification of many new hypervelocity stars, and determining their origin.

Gaia's multiple star census has yielded many new results, based on an unparalleled survey out to 1000 pc. This includes samples of spectroscopic binaries, of twin binaries, triple and quadruple star systems, eclipsing binaries, and cataclysmic variables. There are new results on stellar masses from SB2 binaries, and on the nature and origin of wide and ultra-wide binaries. And on variable stars including Cepheids, RR Lyrae, and Mirae.

Studies of white dwarfs have been revolutionised, with deeper and more complete surveys, new results on the mass–radius relation, on their interior physics, and the detailed structure of their HR diagram, including the effects of core crystallisation, and of convective dredge-up as the cause of the prominent bifurcation.

Studies of many other star types include Wolf–Rayet stars, brown dwarfs, planetary nebulae, carbon stars, S stars, and the nature of the tip of the red giant branch; also of young stellar objects and chromospheric activity.

Various studies of the end stages of stellar evolution include neutron stars and pulsars, supernova remnants, nearby black holes in non-active binaries, and black holes in open clusters, stellar streams, and in M4.

For exoplanets, distances are being used to characterise host stars, calibrate exoplanet radii, and pinpoint locations for direct imaging. Gaia's first two transiting exoplanets, and first microlensed exoplanet, have been reported. Constraints are being placed on the nature of Boyajian-type stars, and the existence of Dyson spheres.

GALAXY STRUCTURE AND DYNAMICS: Improved structural insights include the Sun's height above the disk, its motion with respect to the Local Standard of Rest, and the distance to the Galactic centre.

Gaia has provided an improved understanding of the morphology and dynamics of the central bar, the spiral arms and their 'breathing motion', the global warp, and a new structural feature termed the 'Radcliffe Wave'.

Insights have been gained into the resonance origin of velocity structures in the solar vicinity, including the Hercules, Arcturus, and HR 1614 streams, and the complex Gaia 'phase-space spiral' perturbations.

Major advances have been made on the discovery and characterisations of stellar streams in the halo, notably for the Gaia-Sausage-Enceladus, Sagittarius, and Cetus streams. Other clues about our Galaxy's formation include studies of its ancient 'heart', and its infall history inferred from cerium abundances.

Gaia is elucidating the structure and motion of globular clusters (including Omega Cen, and Palomar 5), of their tidal tails, and of our companion dwarf spheroidal galaxies. It is providing an improved rotation curve of our Galaxy, and revealing the tiny effects of aberration arising from our Galaxy's rotation with respect to quasars. It is providing improved knowledge of the local mass density, total mass, escape velocity, and age.

LOCAL GROUP AND COSMOLOGY: With more than 10 million Gaia stars in the Large Magellanic Cloud, nearly two million in the Small Magellanic Cloud, and more than a million in M31/Andromeda, there has been much progress in clarifying the morphology, rotation, interaction, and disruption of our neighbouring galaxies. Improved mass estimates of the Local Group are being derived from dynamical modelling, the 'timing method', and from cosmological N-body simulations.

As noted above, an important contribution from Gaia has been the identification and modelling of many new stellar streams over a range of distances within the halo. Tests of the ΛCDM cosmological paradigm follow from the comparison of these observations with numerical simulations. As part of these, halo streams are also being probed for the presence of black holes, and cosmological 'sub-halos'.

Gaia's global survey embraces not only stars. Gaia's overall survey, all part of DR3, contains more than a million galaxies (whose radial profiles can be determined), and amongst which are found a number of dual active galactic nuclei, signalling past galaxy mergers.

Also identified by Gaia are around one million quasars. These provide the key sample of objects defining Gaia's quasi-inertial reference frame. More than 60 000 show clear evidence for their underlying host galaxy. The quasar sample includes many previously known, as well as newly identified, strongly lensed quasars, including the important class of quadruply-imaged 'Einstein crosses'. Of several cosmological investigations based on Gaia's quasar, the present DR3-based results appear to be compatible with the Planck value of the 'matter overdensity variance', S_8.

Contributions have been made to the problem of the cosmic distance scale (aka the 'Hubble tension') based on the local Universe expansion rate derived from Cepheids. A number of studies have focussed on supernovae, and supernovae remnants and their associated pulsars (including Cygnus, Vela, and Tycho). Searches for the orbital motion of luminous objects around a dark companion should throw more light on the many complexities of the late stages of binary star evolution.

The rich phase-space complexities revealed in the Gaia data, indicators of past galaxy mergers and tidal disruptions, are being tested against the latest suites of large cosmological simulations. Such tests include the occurrence of Gaia-Sausage-Enceladus type mergers in these simulations, as well probing the overall merger and spin-up history of our Galaxy.

Contributions to other cosmological challenges include the 'plane of satellites' problem, and the 'core–cusp' problem, further elucidated by Gaia's discovery of the enormous dwarf galaxy Antlia II in 2019. Another test that may be possible is whether our Galaxy's disk is indeed 'tumbling' with respect to the halo.