180. The spectra of solar system objects

I OUTLINED Gaia's contribution to the study of solar system objects in two earlier essays. In essay 64 (March 2022) I described the main goals of these observations, the associated data processing, and the first haul of just 14 000 asteroids included in the DR2 release (covering observations from July 2014–May 2016).

Data Release 3, in June 2022 (see essay 76) was based on 34 months of observations (July 2014–May 2017), and provided astrometry for 157 000 solar system objects, orbits for 154 787, and BP/RP reflectance spectra (the focus of this essay) for 60 518. Orbit determination was described by Tanga et al. (2023), who also gave a summary of the associated photometric and spectral data.

In essay 159 (Jan 2024) I described the special solar system objects 'Focused Product Release'. This was an intermediate product between DR3 (June 2022) and DR4 (expected in late 2025), treating the same 157 000 asteroids as in DR3, but now providing the epoch astrometry and orbit reconstruction based on the much longer data interval of DR4, viz. 66 months compared to the 34 months of DR3 (David et al., 2023).

AS FORESEEN in the science case for Gaia in 2000, the observation of all objects brighter than 20–21 mag would yield a deep, uniform detection of minor planets and other solar system bodies, enabling detailed studies of their dynamics and taxonomy.

These small bodies preserve relatively unaltered materials that date back to the formation of the solar system from the proto-solar nebula 4.567 Gyr ago (e.g. Amelin et al., 2002; Johansen et al., 2015). And they provide insights into the early accretion of primordial material from the protoplanetary disk, the transport of water and other organic material to Earth (e.g. Morbidelli et al., 2000), and collisional events leading to asteroid 'families' (e.g. Nesvorný et al., 2002; Nesvorný et al., 2015).

Gaia's accurate multi-epoch astrometry also allows characterisation of binarity, e.g. for (4337) Arecibo and the Pluto–Charon system (Tanga et al., 2023), measurement of the Yarkovsky effect, the secular orbital drift due to the anisotropic emission of thermal photons, which is important in their migration (Tanga et al., 2023; Dziadura et al., 2023), and the identification of more complex dynamical resonances (Carruba et al., 2024).

WHILE THE EMPHASIS of my earlier essays was on the astrometry and resulting orbits, I will look here at the photometry obtained from Gaia's blue and red photometers, and the derived reflectance spectra published as part of DR3 (Galluccio et al., 2023). The multi-epoch multi-colour photometry had always been expected to provide information about their physical properties, including their shape and rotation (Cellino & Dell'Oro, 2012), and their composition and taxonomic classification (Delbo' et al., 2012; Klimczak et al., 2022).

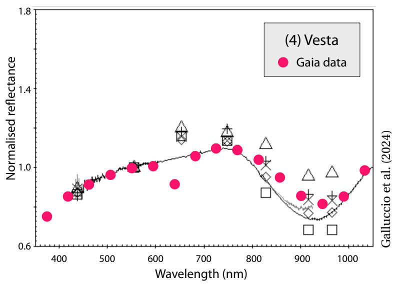
One of the reasons why these sorts of observations are of great interest is that the asteroid population does not remain unchanged over time, and various physical processes play a role in their evolution (e.g. Galluccio et al., 2023). These include collisional evolution (which affects the number and size distribution of the main belt asteroids as well as their surface structure); space weathering (due to surface irradiation from cosmic rays, the solar wind, and micro-meteorites, which all modify their reflectance spectra); and the evolution of the regolith structure and properties due to the continuous thermal cycling of their surfaces.

SUCH CONSIDERATIONS have driven a dozen asteroid flyby missions, as well as numerous ground-based spectrophotometric surveys. Amongst the earliest of these were an 8-colour survey by Zellner et al. (1985), a 52-colour survey by Bell et al. (1988), a 7-colour infrared survey by Clark et al. (1993), and numerous others since. Galluccio et al. (2023) estimate that more than 1.5 million spectrophotometric observations of asteroids exist, covering more than 7600 asteroid spectra.

Amongst Gaia's advantages are its accurate multi-epoch multi-colour photometry, its extensive sky coverage (solar elongations 45 – 135°), the large numbers of objects (expected to total around 350 000), and its broad wavelength range (covering 400–1000 nm).

Gaia's multi-colour photometry, designated BP and RP, is achieved by two fused-silica prisms which disperse the spectra over ~45 pixels in the along-scan direction (see essay 68). The downstream processing of the resulting low-resolution spectra is detailed by De Angeli et al. (2023).

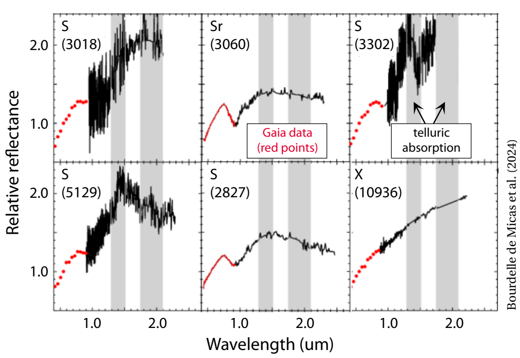
The reflectance spectrum at each epoch was derived by dividing the object spectrum by a solar-type composite (Galluccio et al., 2023). A mean reflectance spectrum was then calculated in 16 spectral bands. Comparison with ground-based observations under similar illumination geometry show very good agreement across taxonomic class, their examples including (1) Ceres, (4) Vesta (shown here), (21) Lutetia and (433) Eros.



Numerous studies are making use of the Gaia reflectance spectra, and I will give a few examples.

Asteroid 'families' result from collisions, some of which are ancient, others being much more recent (e.g. Nesvorný et al., 2002). Collisional fragments can be ejected at moderate velocity (~1 km s^{-1}) and, at least in the main asteroid belt, can remain clustered in orbital space and with similar physical properties.

Bourdelle de Micas et al. (2024) studied 263 fragments of an S-type asteroid recently discovered in the inner main belt, with an age of 4.4 Gyr, and comprising both planetesimals and collisional fragments (Ferrone et al., 2023). The figure below shows six of their breakup candidates. The combination of existing and newly-measured spectra extending to the near infrared, combined with Gaia reflectance spectra below 1 μm (shown here in red), allowed identification of 71 (non-S-type) interlopers, and a final list of 190 S-type members.



The low albedo inner belt C-type (carbonaceous) asteroids, of which there are 11 known families, have been suggested as the sources of the near-Earth asteroids Ryugu (visited by Hayabusa 2 in 2018) and Bennu (by OSIRIS-REx the same year). Delbo et al. (2023) used the Gaia reflectance spectra to characterise these families, showing that the Polana and Eulalia groups can be distinguished in the range 370–500 nm, and that the average spectra of the Eulalia and Polana families are most similar to those of Bennu and Ryugu respectively.

In studies of space weathering, Galluccio et al. (2023) found 21 909 S-type (siliceous or 'stony') asteroids in the Gaia reflectance sample, of which 9225 belong to known families (Nesvorný et al., 2015). Some have ages estimated by backward orbit integration to identify their convergent origin. They showed that the spectral slope increases, and the depth of the 1 μm absorption band decreases, with increasing age (their Fig. 20), which they attribute to the progressive effects of space 'weather'.

The rare inner-belt T-type asteroid (596) Scheila underwent a collision in December 2010 (Ishiguro et al., 2011). Hasegawa et al. (2022) used the Gaia reflectance spectrum (amongst others) to place limits on the effects of surface weathering over a time span of just 10 years.

Andesite is a type of volcanic rock, named after the Andes where it was first identified. The andesitic meteorite Erg Chech 002 was found in the Sahara desert in 2020. With a crystallisation age of 4.565 Gyr, 2.25 Myr after the solar system origin (Barrat et al., 2021), it preserves a record of volcanic events and crust formation in primordial planetesimals, although no asteroid analogue had been identified. Galinier et al. (2023) searched for analogues in the Gaia DR3 reflectance spectra, finding 51 similar main-belt asteroids, and 91 others with the spectrum of a space-weathered analogue. Near-infrared spectra would provide a more definitive association.

The V-type (basaltic) asteroids are also important in understanding planetesimal formation and evolution in the early solar system. Oszkiewicz et al. (2023) identified some 2000 possible V-type asteroids from their Gaia reflectance spectra, increasing the known number by more than a factor three.

Other studies relate to the understanding of small binary asteroids, believed to form through fission induced by Yarkovsky-driven spin-up, depending on their structural strength and therefore composition (Minker & Carry, 2023); to planet-crossing asteroids (Sergeyev et al., 2023); and discovery of the first olivine-dominated A-type asteroid family (Galinier et al., 2024).

The DR3 results give an indication of what is to come. Gaia Data Release 4 will contain more objects, and with twice the temporal coverage than for DR3.