241. Asteroid masses

IN MY RECENT review of scientific results from Gaia (Perryman, 2025), I mentioned that *'Asteroid masses are known for a dozen or so main belt asteroids, determined from their orbit evolution as a result of gravitational perturbations during close approaches with other minor bodies. While no such results are yet available from the Gaia astrometry, it is expected that masses for more than a hundred will be obtained by this method.'*

I had missed a number of relevant papers, an omission kindly pointed out by Dr Fan Li of the Purple Mountain Observatory, and which this essay aims to rectify!

THE DETERMINATION of asteroid masses from mutual orbit perturbations can exploit asteroid–asteroid and asteroid–planet perturbations, as well as the motion of asteroid satellites (e.g. Siltala & Granvik, 2017; Fienga et al., 2020) and, in specific circumstances, asteroid–spacecraft perturbations (e.g. Park et al., 2020). A distinct approach for low-mass objects is from the Yarkovsky effect (essay 181), in which solar radiation and re-radiated thermal emission contribute a force tangential to the orbital motion (Chesley et al., 2003).

Masses combined with sizes yield the body's bulk density, an important constraint on its internal structure and composition (e.g. Podlewska-Gaca et al., 2020).

Orbit perturbations from close asteroid–asteroid encounters was applied to the data from Hipparcos, which observed 48 minor planets between 1989–93 with single epoch accuracies 10–100 mas. Estimates were derived for (20) Massalia ($2.42 \pm 0.41 \times 10^{-12} M_\odot$), from its close encounters with (44) Nysa and (4) Vesta (Bange, 1998); and (1) Ceres ($4.759 \pm 0.023 \times 10^{-10} M_\odot$), from its perturbations on 9 other asteroids (Viateau & Rapaport, 1998).

THE PRESENT STATUS of Gaia's solar system astrometry is given by David et al. (2023). For the 157 000 asteroids in the 34-month Gaia DR3 solution, their 'Focused Product Release' study used the 66-month time interval being used for DR4 (essay 159). The 100 00 objects best observed have an average of around 30 ± 10 visibility periods or epochs, with along-scan accuracies better than 1 mas for $G < 18$ mag, degrading to ~10 mas at $G \simeq 20$.

AN ESSENTIAL STARTING POINT for all of these dynamical studies are the solar system (DE) ephemeris models developed at JPL (e.g. Folkner et al., 2014; Park et al., 2021), or the INPOP models developed at IMCCE, Paris. INPOP19a, for example, considers the Earth–Moon barycentre with the seven other planets, the dwarf planet Pluto, 343 asteroids, and the ten most massive trans–Neptunian objects. Its construction also led to the mass determination for 103 asteroids, deduced from their perturbations on the orbits of the inner planets, in particular Mars and Earth (Fienga et al., 2019).

ESTIMATES OF THE improvements expected with Gaia were made in the early pre-launch study phases. The goal is to obtain the mass of (smaller) target asteroids using all (massive) perturbers simultaneously, based on an analysis of the observed minus calculated positions through a reconstruction of the six orbital elements, or state vector, for each object (Mouret et al., 2007; Mouret et al., 2008). They showed that it should be possible to derive more than 100 asteroid masses, 42 with better than 10% precision. They also considered the possible contribution of ground-based observations for specific close approaches. Further studies using Gaia DR2, including a list of the most promising encounters, were given by Murray (2023).

In most of these mutual encounters, the smaller target asteroids are not massive enough to significantly affect the orbit of the more massive perturber. For an encounter between two massive asteroids, the masses must be estimated simultaneously (e.g. Baer & Chesley, 2017). Indeed, these authors concluded that future Gaia studies should search for such possible gravitational 'couplings', and account for their effects.

Detailed numerical methods, not restricted to Gaia data, for example using Markov-chain Monte Carlo (MCMC) algorithms, have been variously described (e.g. Siltala & Granvik, 2017). These include application to (1) Ceres and (4) Vesta observed by the Dawn mission (launched in 2007), and to (16) Psyche, the target of NASA's Psyche mission, launched in 2023 (e.g. Siltala & Granvik, 2020; Siltala & Granvik, 2021).

WITH THE AVAILABILITY of Gaia DR2, various studies have considered asteroid masses and have targeted mass determinations. In the initial analysis and orbit fitting using the DR2 data alone, Spoto et al. (2018) used the JPL DE431 planetary ephemeris for the orbits and masses of the planets (Folkner et al., 2014). They included 16 massive perturbers in their dynamical model.

SUBSEQUENT STUDIES using Gaia DR2 included a detailed consideration of the sensitivity of the orbital adjustment of 14 099 asteroids on the chosen planetary ephemeris (Deram et al., 2022).

Kuznetsov & Chernetenko (2022) included Gaia DR2 data in their mass estimate for (7348) $1993FJ_{22}$, based on its observed perturbation of asteroid (7562) Kagiroino–Oka during their close approach (1060 km) on 26 March 1993. Their result, $(0.867 \pm 0.243) \times 10^{-14} M_\odot$, was the smallest mass determined by this method at the time.

Siltala & Granvik (2022) also used the mas-level accuracies for the 14 099 asteroids included in Gaia DR2, selecting various combinations of Gaia and/or Earth-based astrometry to determine the impact of Gaia on the mass estimates. For example, using only Gaia data, their value for (367) Amicitia improves on the solution previously published by Spoto et al. (2018), while no solution using Gaia DR2 data alone could be found for (445) Edna, based on its close mutual encounter with (1764) Cogshall. In contrast, a combination of Gaia DR2 and Earth-based astrometry results in significantly reduced uncertainties compared with the less accurate Earth-based astrometry alone.

The few objects for which mass determinations could be derived should, they estimated, be advanced significantly with DR3, allowing for *'a wave of numerous accurate mass estimates for a wide range of asteroids'*.

Simulations of the capabilities of asteroid mass determination using Gaia DR2, in combination with positions expected from planned observations with the Chinese Space Station Telescope (CSST), are detailed by Li et al. (2023b).

THE 22-MONTH SOLUTION for the 14 099 asteroids in Gaia DR2 was duly superseded by the 34-month solution of DR3. This gave astrometry for 158 000 solar system objects, orbits for 154 787, and BP/RP reflectance spectra for 60 518 (Tanga et al., 2023).

Li et al. (2023a) combined the DR3 astrometry with the available ground-based observations to determine the masses of 20 asteroids by means of these asteroid–asteroid encounters, with Gaia DR3 providing *'substantial benefits in terms of improving mass precision'*. For 10 asteroids, a mass precision better than 5% was achieved, with 15 asteroids better than 10%. Combined with diameters from the literature, they derived bulk densities for 20 asteroids.

THE 'Focused Product Release' data set provides a major improvement with respect to Gaia DR3 by making use of the 66-month time interval adopted for DR4.

Farnocchia et al. (2024) used the FPR data to estimate the mass of (16) Psyche from the astrometric solutions for asteroids that came within 0.05 au, yielding $GM = 1.601 \pm 0.017\,\mathrm{km^3\,s^{-2}}$, and a bulk density $4.172 \pm 0.145\,\mathrm{Mg\,m^{-3}}$, compatible with its M-type taxonomic classification. The specific interest in (16) Psyche is that its mass is a critical parameter for determining the altitude to be used for the different Psyche mission phases (Elkins-Tanton et al., 2022). Mass estimates for 38 other asteroids were derived in the process (their Figure 3).

Fuentes-Muñoz et al. (2025) used the FPR data to search for close encounters between all known asteroids and a list of the largest asteroids, finding some 975 000 that may have been perturbed in a measurable way, and 86 000 with an astrometric signal for one or more asteroid masses. They derived 77 asteroid masses with signal-to-noise ratio >10, and 232 asteroid masses with SNR >3, all in the main belt or outer main belt.

GAIA'S FINAL DATA RELEASE, DR5 in around 2030, will yield a much larger number of mass detections as well as a better mass accuracy per event. Also of considerable importance for the future, Gaia's accurate stellar reference frame allows ground-based observatories to place asteroid positions on an inertial coordinate system with systematic errors well below 1 mas.

In particular, the LSST survey, to be conducted with the Vera Rubin Observatory from 2025–2035, will detect and track millions of main belt asteroids. The individual astrometric uncertainties are smaller than for Gaia at Gaia's faint magnitude limit, and the LSST observations will extend some 3 mag deeper, increasing the number of potential tracers by a factor of 100. This will allow mass estimates of several hundred main belt asteroids with uncertainties below 30% (Bernstein et al., 2025).

MUTUAL ENCOUNTERS amongst the main belt asteroids that cannot be predicted from the ephemeredes of larger bodies is a source of stochastic astrometric noise. Bernstein (2025) estimated that the rms azimuthal shift of this noise contribution accumulates to 2–9 km, or 1–5 mas over $t = 10$ yr, increasing as $t^{3/2}$, and affecting inferences from the Gaia astrometry. The LSST survey data is expected to improve the knowledge of the main belt asteroid masses, lowering this uncertainty to 260–400 m, or 140–210 μas.

For full exploitation of Gaia and LSST main belt asteroid data, Bernstein (2025) shows that ephemeris models should include the 10 000 or so largest asteroids as active bodies with free masses. The rms value of deflections from the less massive main belt asteroids would then be reduced to some 17–60 m, or 9–40 μas.