247. Tumbling asteroids

I HAVE COVERED some of Gaia's studies of solar system bodies in five previous essays: the orbits of 157 000 asteroids (essay 159); inferences on their composition from reflectance spectra (essay 180); masses derived from orbit deflections as a result of close asteroid–asteroid encounters (essay 241); the Yarkovsky effect (essay 181); and the YORP effect (essay 182). These have made use of either DR3, or the Focused Product Release, covering the same data interval as the future DR4.

THE YARKOVSKY AND YORP EFFECTS are higher-order effects of solar radiation on the dynamics of rotating bodies, and they enter the study that I focus on here. In the former, delayed thermal emission leads to a component of force tangential to the orbital motion, modifying its orbit, incrementally over millions of years. The orbital changes can be measured for some smaller objects using high-accuracy astrometry (essay 181).

Asteroids are irregular in shape, and have rotation periods of order days, much shorter than their orbital periods. The YORP effect describes the secular change in a body's rotation state which results from averaging the solar radiation torques over its spin and orbital periods (e.g. Rubincam, 2000; Vokrouhlický et al., 2003). The asteroid's slowly-changing rotation period can be determined from long-term multi-epoch photometry, and the YORP effect has been inferred for some dozen asteroids (Durech et al., 2024, and references).

As I described further in essay 182, there is also *indirect* evidence for its role in the orbital evolution of asteroids over long periods, most prominently in the clustering of the directions of rotation axes in asteroid families (e.g. Vokrouhlický & Čapek, 2002; Bottke et al., 2006; Vokrouhlický et al., 2006).

Extreme YORP-driven spin-up may also explain asteroid fragmentation (Paddack, 1969; Paddack & Rhee, 1975; Veras & Scheeres, 2020), including the observed breakup of asteroid P/2013 R3 (Jewitt et al., 2014). It may also be important in the formation of binary asteroids (Walsh et al., 2008), and asteroid pairs with very similar orbits (Vokrouhlický & Nesvorný, 2008).

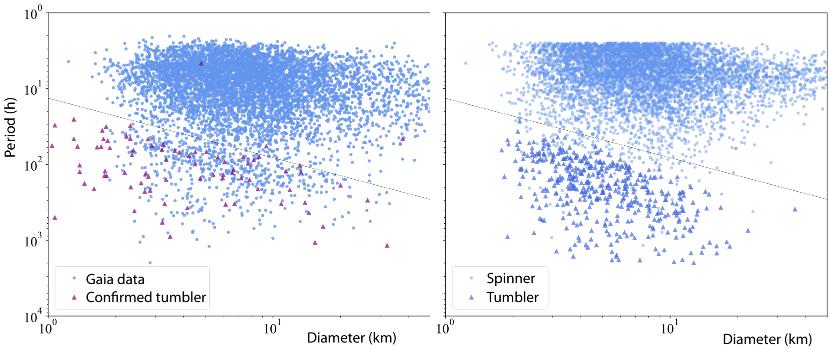
MORE generally, multi-colour photometry provides an important tool in understanding the surface reflectance of solar system bodies, providing detailed insights into their composition, their association with impact-driven asteroid 'families', and the effects of radiation and charged particles, or 'space weather'.

Photometric effects must also be taken into account in high-accuracy astrometry, where irregular surface structure, varying albedo, and changing illumination phase, can lead to measurable differences between the object's photocentre and its barycentre.

As well as providing their rotation periods, multi-epoch photometry can also reveal their rotation axes. In some of the first large-scale studies, Harris & Burns (1979) found that the distribution of rotation rates was in good agreement with a three-dimensional Maxwellian form, inferred to have arisen from a collisionally evolved system, and with their rotation axes appearing to be randomly oriented in space.

Later observations showed a more complex dependency, including an excess of slow rotators (with spin periods above ~1 d) amongst the smaller asteroids (e.g. Dermott et al., 1984; Binzel et al., 1989; Fulchignoni et al., 1995; Harris, 2002). Subsequent observations also revealed an excess of fast rotators, with spin periods $\lesssim 3$ hr (e.g. Pravec & Harris, 2000), modeled as due to spin-up by the YORP effect torque (Pravec et al., 2008). One broad conclusion was that asteroids larger than a few hundred meters are mostly loosely bound, gravity-dominated aggregates ('rubble piles'), while monoliths may be abundant among smaller objects.

PHOTOMETRIC SIMULATIONS performed in Gaia's pre-launch study phase by Cellino et al. (2006) demonstrated that Gaia's light-curves at different (spin-axis/observer) aspect angles, would allow direct derivation of the object's spin axis, or pole, as obtained in previous ground-based observations (e.g. Magnusson et al., 1989). Cellino et al. (2006) estimated that Gaia would provide the poles, sidereal periods and axial ratios for some 10 000 main belt asteroids.



Zhao et al. (2025)

In essay 182, I described one of the first major photometric studies of asteroids making use of the Gaia DR3 data, spanning a time interval of 34 months.

Durech & Hanuš (2023) computed the illumination geometry for each observation, and used light-curve inversion to find the best-fit physical model. This was parameterised by the rotation period, the spin axis direction, and a low-resolution convex shape. For ∼8600 objects (out of 150 000 in DR3), the data coverage was sufficient to determine their rotation rate and spin-axis direction, together with a low-resolution shape model.

They confirmed previous findings, but with their much larger sample, viz. (i) small asteroids have poles clustered towards the ecliptic poles, attributed to the YORP effect; (ii) Yarkovsky migration depends on the spin orientation; and (iii) members of asteroid families have a sense of rotation correlated with their semi-major axis: over the age of the family, orbits have evolved (due to the Yarkovsky effect), with prograde rotators drifting to larger semi-major axes, and *vice verse*.

But there were other unexplained features. One is a size-dependent gap in the period–diameter diagram, which separates the slow rotators, $P \gtrsim 4$ d, from the faster rotators, $P \lesssim 2-3$ d (Durech & Hanuš, 2023, Fig. 6), also seen in the figures above.

A related problem concerns the 'tumbling' asteroids, i.e. those rotating in a non-principal axis state. The goal here is to understand how they got into this tumbling state. And what physics explains their distribution in the period–diameter diagram.

Nearly all tumblers are known to be slow rotators (Harris, 1994; Pravec et al., 2005). The consensus has been that they have been driven to slow rotation, and entered into a tumbling rotation state, through the YORP effect (Vokrouhlický et al., 2007; Cicalò & Scheeres, 2010; Breiter et al., 2011; Breiter & Murawiecka, 2015).

Incidentally, the first interstellar object Oumuamua appears to be a tumbler (Fraser et al., 2018), although in this case perhaps the result of a major collision in the distant past (Drahus et al., 2018; Katz, 2018), or the result of a long succession of much smaller impacts with interstellar medium particles along its path (Zhou, 2020).

More recent Gaia studies provide a more complete explanation for the occurrence, distribution, and spin properties of the tumblers. Specifically, Zhou et al. (2025) used the same DR3 data as Durech & Hanuš (2023) to develop a more complete model of the underlying physics. Their model of rotational evolution takes into account not only the YORP effect, but also collisional excitation and internal friction damping.

They found that tumbling can be initiated either by the YORP torque spinning down the asteroid to a quasi-static rotational state, or by a non-destructive collision. These slow tumblers in turn evolve either into a stable tumbling state with fixed period, or a completely chaotic state, depending on the initial orientation and on the asteroid shape. For the chaotic rotators, the YORP effect is largely ineffective, since the effects of the radiation torque are averaged out over very long time periods.

In their model of the long-term evolution, the YORP torque is reset numerous times after collisions due to the 'crater-induced' YORP effect, and its extreme sensitivity to small-scale topography (Statler, 2009; Bottke et al., 2015; Zhou et al., 2022; Zhou & Michel, 2024). As a result, the tumblers experience random interchanges between the tumbling states both with or without a fixed period, evolving slowly in the long-period region.

In summary, their model suggests that the slowly evolving tumblers are the origin of the excess of slow rotators, and it predicts that most slow rotators are tumbling. It successfully reproduces the observed period–diameter diagram (above left) using their model simulations (above right).

The transition to the tumbling state actually constrains the product of the body's rigidity, μ, and quality factor, Q (related to its viscosity) to $\mu Q \sim 4 \times 10^9$ Pa. This number, two orders of magnitude smaller than that assumed for monolithic boulders, implies that rubble pile asteroids could have a porous structure or a thick regolith layer, and undergo stronger tidal effects.

Zhou et al. (2025) also provide some supplementary videos, which I also link here: their Video 1 shows the rotational evolution with time, and their Video 2 shows how the description of the gap between tumblers and non-tumblers converges as a result of machine learning.