181. The Yarkovsky effect

THE YARKOVSKY EFFECT is an important phenomenon in solar system dynamics. It appears in discussions of the astrometry and photometry of the small solar system objects which are part of Gaia's global observing programme (essays 64 and 159). I touched on it in my previous essay on the reflectance spectra of more than 60 000 objects released as part of Gaia DR3 (essay 180).

Here, I will say more about the effect, why it is important, and how Gaia is contributing to its understanding.

THE ORBITS of all solar system bodies are controlled by gravitational forces, and in particular by the Sun. Today's state-of-the-art positions and velocities of the Sun, Earth, Moon, and planets (INPOP10e prepared by the Observatoire de Paris, and DE430 by Caltech's JPL) are based on a numerically integrated dynamical model which, for DE430, also includes the perturbative effects of 343 asteroids, viz. 90% of the mass of the main belt.

Solar radiation also affects an object's orbital motion. Solar radiation *pressure*, imparted by photon momentum, and quantified by Petr Lebedev in 1899, is a tiny force, but one with a large cumulative effect over long periods of time, affecting the motion of small solar system bodies (including spacecraft such as Gaia!).

The Poynting–Robertson effect, described by J. H. Poynting in 1903 and H. P. Robertson in 1937, only affects particles smaller than about 1 mm. A particle's motion around the Sun, combined vectorially with the velocity of the incident radiation (as in stellar aberration), results in the particle losing angular momentum and, for small particle sizes, spiralling inwards towards the Sun.

The Yarkovsky effect is a force acting on a *rotating* body, was described by Polish engineer Ivan Yarkovsky in 1901, and by Ernst Öpik in 1951 (see Beekman, 2005). It results from the re-radiated thermal emission, which carries momentum, lagging behind the incident radiation in time, thus (perhaps non-intuitively) contributing a component of force tangent to the orbital motion.

The Yarkovsky–O'Keefe–Radzievskii–Paddack/YORP is a second-order effect, mainly affecting the body's spin. I will look at its importance for Gaia in essay 182.

THE MAGNITUDE of the Yarkovsky effect is dependent on the orbit size and eccentricity, and on its mass, size, shape, spin and composition (e.g. Bottke et al., 2006). But qualitatively, the Yarkovsky force is in the direction of orbital motion for a prograde rotator, causing the semi-major axis to increase steadily. Conversely, a retrograde rotator spirals inwards, with the Yarkovsky and Poynting–Robertson 'drags' working together.

Models supplement the standard dynamical model with solar radiation pressure as an extra radial force, A_1, and a transverse 'Yarkovsky' force, A_2, both inversely proportional to the heliocentric radius. Coefficients are determined by a model fit to the observations (Vokrouhlický, 1999; Farnocchia et al., 2013; Vokrouhlický et al., 2015a; Del Vigna et al., 2018; Fenucci et al., 2024).

For an object 100–1000 m in size, the effect is all-but-negligible even over many years, but it is relentless: over millions of years an object can be transported from the asteroid belt to the inner solar system. As a result, though tiny and difficult to detect, it is important in understanding various aspects of solar system dynamics.

FIRST observational confirmation of the Yarkovsky effect came from radar tracking of the half-kilometer size asteroid (6489) Golevka, from Arecibo, between 1991–2003 (Chesley et al., 2003). Over that time, and as predicted qualitatively by Vokrouhlický et al. (2000), it was 15 km from the position predicted from gravitational interactions with other solar system bodies alone.

Chesley et al. (2003) estimated a Yarkovsky force of 0.25 N, and acceleration 10^{-12} m s^{-2}. The accompanying press release described this as the *'equivalent of one ounce of thrust pushing against a 0.5 km, 210 million-ton tumbling "mountain".'*

The use of radar tracking in this context is noteworthy because, pre-Gaia, it was the most powerful technique for determining a 'nearby' asteroid's orbit.

The second detection was the 400-m diameter asteroid (152563) 1992 BF from astrometric measurements over 50 years, including precovery observations from 1953 (Chesley et al., 2006; Vokrouhlický et al., 2008).

THE YARKOVSKY EFFECT complicates orbit determination for near-Earth asteroids, occasionally frustrating their identification (e.g. Vokrouhlický et al., 2008), and affects the prediction of near-Earth approaches and impact probabilities (e.g. Giorgini et al., 2002; Milani et al., 2009; Vokrouhlický et al., 2015b).

But it also appears to play a much deeper role in solar system dynamics. It could explain the origin of high-eccentricity meteorites (Peterson, 1976; Afonso et al., 1995), and perhaps NEOs more generally, by delivering main belt asteroids up to 20 km in size into Earth-crossing orbits (Morbidelli & Vokrouhlický, 2003).

It also drives an additional orbital dispersion of asteroid 'families' beyond the effects of collisions alone, leading to their characteristic V-shape in diagrams of semi-major axis versus absolute magnitude (or $a-1/D$), which is important for their age estimation (e.g. Bottke et al., 2001; Bottke et al., 2002; Milani et al., 2014; Spoto et al., 2015; Milić Žitnik, 2020; Novaković et al., 2022).

As a result of its role in the YORP effect, where it changes the spin rates and axes of the smaller irregular asteroids, it could also explain the large number with very high and very low rotation rates (Rubincam, 2000; Kaasalainen et al., 2007; Lowry et al., 2007).

Finally, NEAs are generally of relatively low mass, and the Yarkovsky effect provides the possibility of mass determinations, providing an important constraint on the body's internal structure and composition (Chesley et al., 2003). This method is distinct from masses derived from mutual orbit perturbations of some of the more massive objects (e.g. Bange, 1998; Viateau & Rapaport, 1998; Mouret et al., 2007; Podlewska-Gaca et al., 2020).

ACCORDING TO Tanga et al. (2023), the JPL Small-Body Database includes measurements of the Yarkovsky effect for 234 asteroids. All are NEOs, for which small objects and accurate orbits dominate. Some estimates predate Gaia (e.g. Greenberg et al., 2020), while others are from Gaia alone or combined with other observations.

EARLY GAIA studies suggested that the effect might be detectable in several tens of NEOs (Tanga et al., 2007; Delbo' et al., 2008; Dziadura et al., 2022), and 64 promising candidates were listed by Mouret & Mignard (2011). Detection models are given by Tsiganis et al. (2012), Desmars (2015), and Fenucci et al. (2024).

Results reported from Gaia are often in combination with other observations, mainly long-term astrometry or radar ranging. Thus Hanuš et al. (2018) used Arecibo and DR2 astrometry of (3200) Phaethon to constrain the secular drift of its orbital semi-major axis, yielding the bulk density assuming that the drift is Yarkovsky dominated. Results are typical of large C-complex asteroids, and support its association with asteroid (2) Pallas, as suggested from their dynamics (Todorović, 2018).

With a target list chosen with prospects for detectability in mind, Greenstreet et al. (2019) used Gaia DR1 with the Las Cumbres ground network to detect the Yarkovsky effect in 18 out of 36 observed asteroids.

Gaia DR3 contains orbits for 154 787 solar system objects. Orbit post-fit residuals have a standard deviation of some 5 milli-arcsec along scan, a factor 100 better than ground-based values. Tanga et al. (2023) identified 447 NEOs in DR3, of which 24 had a previous measurement of the Yarkovsky effect, mostly from radar data.

They discussed two specific cases. For (3200) Phaethon, the parent body of the Geminid meteorite shower, they found a value for the Yarkovsky term when combining ground-based with Gaia DR3 astrometry within 1σ of the JPL Small-Body Database value derived from ground-based astrometry combined with radar observations. For (1620) Geographos they reported a first 3σ detection of the Yarkovsky effect using 5242 ground-based optical observations, 7 radar observations, and 105 observations from Gaia DR3. More generally, combining the accurate astrometry from Gaia DR3 with the existing observations from the Minor Planet Center significantly improves the asteroid orbit, and enhances the detectability of the non-gravitational terms.

Dziadura et al. (2023) used the Minor Planet Center's OrbFit software, along with their complete astrometric data set (which includes all radar and Gaia DR3 data) to derive the orbits of 446 Near-Earth Asteroids (including 93 Potentially Hazardous Asteroids, 54 094 inner main belt asteroids, and various Mars crossing asteroids. They determined a significant and improved Yarkovsky term (and associated bulk densities) for 49 Near-Earth Asteroids, including 10 new detections.

No Yarkovsky acceleration term was detected in the main-belt asteroid study by Dziadura et al. (2023), with a similar non-result for 134 MBA objects observed with the University of Hawai'i 88-inch telescope, supplemented with the observations from the Minor Planet Center, including Gaia DR3 (Hung et al., 2023).

DETECTION DIFFICULTY for main-belt asteroids notwithstanding, one notable asteroid without a measured Yarkovsky term today is (35334) Yarkovsky!

THE FUTURE will see even deeper asteroid surveys, including ESA's Flyeye, the Vera Rubin Observatory, and possibly the space-based NEO Surveyor and NEOMIR, together likely increasing the known asteroids by an order of magnitude (Jones et al., 2018).

While improved Gaia astrometry will come with DR4 in 2025, I believe that the expected orbit improvements already appear in the Focused Product Release reported by David et al. (2023). This covers 66-months of Gaia mission data, compared with the 34 months of DR3. I am not aware of any Yarkovsky studies based on it so far.