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Near Earth Asteroids with measurable Yarkovsky effect

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ABSTRACT

We seek evidence of the Yarkovsky effect among Near Earth Asteroids (NEAs) by measuring the Yarkovsky-related orbital drift from the orbital fit. To prevent the occurrence of unreliable detections we employ a high precision dynamical model, including the Newtonian attraction of 16 massive asteroids and the planetary relativistic terms, and a suitable astrometric data treatment. We find 21 NEAs whose orbital fits show a measurable orbital drift with a signal to noise ratio (SNR) greater than 3. The best determination is for asteroid (101955) 1999 RQ_{36}, with an SNR $\sim$ 200. In some cases it is possible to constrain physical quantities otherwise unknown. Furthermore, the distribution of the detected orbital drifts shows an excess of retrograde rotators that can be connected to the delivery mechanism from the most important NEA feeding resonances and allows us to infer the obliquity distribution of NEAs. We discuss the implications of the Yarkovsky effect for impact predictions. In particular, for asteroid (29075) 1950 DA our results favor a retrograde rotation, which may have implications for the 2880 impact threat.

1. Introduction

It is well known that nongravitational forces should be considered as important as collisions and gravitational perturbations for the overall understanding of asteroid evolution (Bottke et al., 2006). The most important nongravitational perturbation is the Yarkovsky effect, which is due to radiative recoil of anisotropic thermal emission and causes asteroids to undergo a secular semimajor axis drift da/dt. Typical values of da/dt for sub-kilometer NEAs are 10^{-4}–10^{-3} au/Myr (Vokrouhlický et al., 2000).

The Yarkovsky acceleration depends on several physical quantities such as spin state, size, mass, shape, and thermal properties (Vokrouhlický, 1999). Furthermore, Rozitis and Green (2012) show that surface roughness also plays an important role by enhancing the Yarkovsky related semimajor axis drift by as much as tens of per cent. Though no complete physical characterization is typically available to compute the Yarkovsky acceleration based on a thermophysical model, the orbital drift may be detectable from an astrometric dataset. As a matter of fact, purely gravitational dynamics could result in an unsatisfactory orbital fit to the observational data. This is especially true when extremely accurate observations are available, e.g., radar observations, or when the observational dataset spans a long time interval thus allowing the orbital drift to accumulate and become detectable.

Until recently, the Yarkovsky effect has been measured directly only in three cases, (6489) Golevka (Chesley et al., 2003), (152563) 1992 BF (Vokrouhlický et al., 2008), and recently for (101955) 1999 RQ_{36} (Chesley et al., 2012). For both Golevka and 1999 RQ_{36} the Yarkovsky perturbation must be included to fit accurate radar observations spanning three apparitions. For 1992 BF the Yarkovsky effect is needed to link four precovery observations of 1953. Furthermore, in the case of 1999 RQ_{36} the available physical characterization, along with the estimate of the Yarkovsky effect, allows the estimate of the asteroid's bulk density.

Nugent et al. (2012b) find 54 detections of semimajor axis drift by performing a search for semimajor axis drift among NEAs similar to the one presented in this paper. However, there are differences in the observational data treatment, in the modeling, and in the selection filters. A description of the differences and a comparison of the results is provided in Section 3.2. Nugent et al. (2012a) use WISE-derived geometric albedos and diameters to predict orbital drifts for 540 NEAs. Even if none of these objects has an observational record that allows one to measure the predicted orbital drift, the authors list upcoming observing opportunities that may reveal the Yarkovsky signal.

The Yarkovsky effect plays an important role for orbital predictions such as those concerning Earth impacts. In particular, when an asteroid has an exceptionally well constrained orbit, the Yarkovsky effect may become the principal source of uncertainty. Milani et al. (2009) show how the size of the semimajor axis drift along with its uncertainty modifies impact predictions for the next century for 1999 RQ_{36}. The cumulative impact probability is

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approximately 10^{-3}, while a Yarkovsky-free propagation would rule out any impact event. Chesley et al. (2012) improve the da/dt estimate by means of September 2011 Arecibo radar measurements and find a cumulative impact probability approximately 4×10^{-4}. Another remarkable case is (99942) Apophis. Though only a marginal da/dt estimate is available, Giorgini et al. (2008) and Chesley et al. (2009) prove that the occurrence of an impact in 2036 is decisively driven by the magnitude of the Yarkovsky effect. In the longer term, Giorgini et al. (2002) show that an impact between asteroid (29075) 1950 DA and the Earth in 2880 depends on the accelerations arising from thermal re-radiation of solar energy absorbed by the asteroid.

2. Methodology

2.1. Yarkovsky modeling and determination

The Yarkovsky effect depends on typically unknown physical quantities. As the primary manifestation is a semimajor axis drift, we seek a formulation depending on a single parameter to be determined simultaneously with the orbital elements from the observational dataset. To bypass the need of physical characterization we used a comet-like model (Marsden et al., 1973) for transverse acceleration $a_t = A_2\, g(r)$, where g is a suitable function of the heliocentric distance r and A_2 is an unknown parameter.

For a given A_2 we estimate semimajor axis drift by means of Gauss' perturbative equations:

$$\dot{a} = \frac{2a\sqrt{1-e^2}}{nr} A_2 g(r) \tag{1}$$

where a is the semimajor axis, e is the eccentricity and n is the mean motion. By averaging we obtain

$$\bar{\dot{a}} = \frac{a\sqrt{1-e^2}A_2}{\pi}\int_0^T \frac{g(r)}{r}\,dt = \frac{A_2}{\pi n a}\int_0^{2\pi} r g(r) df \tag{2}$$

where T is the orbital period and f is the true anomaly. Let us now assume $g(r) = (r_0/r)^d$, where r_0 is a normalizing parameter, e.g., we use $r_0 = 1$ au. In this case the semimajor axis drift is

$$\bar{\dot{a}} = \frac{A_2(1-e^2)}{\pi n}\left(\frac{r_0}{p}\right)^d \int_0^{2\pi}(1+e\cos f)^{d-1}\,df \tag{3}$$

By Taylor expansion, we have

$$\int_0^{2\pi}(1+e\cos f)^{d-1}\,df = \sum_{k=0}^{\infty}\binom{d-1}{k} e^k \int_0^{2\pi}\cos^k f\,df \tag{4}$$

The odd powers of the cosine average out, so we obtain

$$\bar{\dot{a}} = \frac{2A_2(1-e^2)}{n}\left(\frac{r_0}{p}\right)^d J(e,d) \tag{5}$$

where

$$J(e,d) = \sum_{k=0}^{\infty}\alpha_k e^{2k}, \quad \alpha_k = \binom{d-1}{2k}\binom{2k}{k}\frac{1}{2^{2k}} \tag{6}$$

The ratio

$$\frac{\alpha_{k+1}}{\alpha_k} = \left(1-\frac{d+1}{2k+2}\right)\left(1-\frac{d}{2k+2}\right) \tag{7}$$

is smaller than 1 for $d > 0$ and k large enough. Therefore, α_k are bounded and $J(e,d)$ is convergent for any $e < 1$. Eq. (7) can be used to recursively compute α_k starting from $\alpha_0 = 1$. For integer d the series J is a finite sum that can be computed analytically, e.g., $J(e,2) = 1$ and $J(e,3) = 1 + 0.5e^2$.

For a fixed d we have a transverse acceleration $a_t = A_2(r_0/r)^d$. To determine A_2 we used a 7-dimensional differential corrector: starting from the observational dataset we simultaneously determine a best-fitting solution for both the orbital elements and A_2 along with an associated covariance matrix C describing the uncertainty of the nominal solution. The marginal uncertainty of A_2 is obtained from C: $\sigma_{A_2} = \sqrt{c_{77}}$, where c_{ij} is the generic element of C. This uncertainty is then mapped to the uncertainty of the semimajor axis drift by means of Eq. (5).

The proper value of d is not easily determined. From Vokrouhlický (1998), we have

$$a_t \simeq \frac{4(1-A)}{9}\Phi(r) f(\Theta)\cos\gamma, \quad f(\Theta) = \frac{0.5\Theta}{1+\Theta+0.5\Theta^2} \tag{8}$$

for the Yarkovsky diurnal component (which is typically dominant), where A is the Bond albedo, Θ is the thermal parameter, γ is the obliquity, and $\Phi(r)$ is the standard radiation force factor, which is inversely proportional to the bulk density ρ, the diameter D, and r^2. The thermal parameter Θ is related to the thermal inertia Γ by means of the following equation

$$\Theta = \frac{\Gamma}{\varepsilon\sigma T_*^3}\sqrt{\frac{2\pi}{P}} \tag{9}$$

where ε is the emissivity, σ is the Boltzmann's constant, T_* is the subsolar temperature, and P is the rotation period. In this paper we use $d = 2$ to match the level of absorbed solar radiation. Then, from Eq. (8) we have that

$$A_2 \simeq \frac{4(1-A)}{9}\Phi(1\text{ au}) f(\Theta)\cos\gamma \tag{10}$$

However, as $T_* \propto r^{-0.5}$ we have that $\Theta \propto r^{1.5}$, therefore the best value of d depends on the object's thermal properties:

- for $\Theta \gg 1$ we obtain $f \propto r^{-1.5}$, which gives $d = 3.5$;
- for $\Theta \ll 1$ we obtain $f \propto r^{1.5}$, which gives $d = 0.5$.

These are limit cases, the true d is always going to be between them. As a matter of fact, it turns out that most NEAs, whose rotation period is not excessively large and whose surface thermal inertia is not excessively small or large, have typically values of Θ near unity or only slightly larger, and we can thus expect d values in the range 2–3. As an example, Chesley et al. (2012) show that for 1999 RQ_{36} the best match to the Yarkovsky perturbation computed by using a linear heat diffusion model is $d = 2.75$.

What matters to us is that da/dt does not critically depend on the chosen value of d. As an example for asteroid 1999 RQ_{36} we have that $da/dt = (-18.99 \pm 0.10) \times 10^{-4}$ au/Myr for $d = 2$ and $da/dt = (-19.02 \pm 0.10) \times 10^{-4}$ au/Myr for $d = 3$. Another example is Golevka, for which we obtain $da/dt = (-6.62 \pm 0.64) \times 10^{-4}$ au/Myr for $d = 2$ and $da/dt = (-6.87 \pm 0.66) \times 10^{-4}$ au/Myr for $d = 3$. In both cases the difference in da/dt due to the different values assumed for d is well within one standard deviation.

2.2. Dynamical model

To consistently detect the Yarkovsky effect we need to account for the other accelerations down to the same order of magnitude. For a sub-kilometer NEA, typical values of a_t range from 10^{-15} to 10^{-13} au/d^2.

Our N-body model includes the Newtonian accelerations of the Sun, eight planets, the Moon, and Pluto that are based on JPL's DE405 planetary ephemerides (Standish, 2000). Furthermore, we added the contribution of 16 massive asteroids, as listed in Table 1.

We used a relativistic force model including the contribution of the Sun, the planets, and the Moon. Namely, we used the Einstein–Infeld–Hoffman (EIH) approximation as described in Moyer (2003) or Will (1993). As already noted in Chesley et al. (2012),