Icarus 252 (2015) 22–31

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Meteoroid impacts onto asteroids: A competitor for Yarkovsky and YORP

Paul A. Wiegert *

Department of Physics and Astronomy, The University of Western Ontario, London, Canada
Center for Planetary Science and Exploration, The University of Western Ontario, London, Canada

ARTICLE INFO

Article history:
Received 14 July 2014
Revised 2 December 2014
Accepted 18 December 2014
Available online 8 January 2015

Keywords:
Near-Earth objects
Asteroids, dynamics
Asteroids, rotation
Celestial mechanics
Impact processes
Meteorites
Meteors

ABSTRACT

The impact of a meteoroid onto an asteroid transfers linear and angular momentum to the larger body, which may affect its orbit and its rotational state. Here we show that the meteoroid environment of our Solar System can have an effect on small asteroids that is comparable to the Yarkovsky and Yarkovsky–O'Keefe–Radzievskii–Paddack (YORP) effects under certain conditions.

The momentum content of the meteoroids themselves is expected to generate an effect much smaller than that of the Yarkovsky effect. However, momentum transport by ejecta may increase the net effective force by one order of magnitude for iron or regolith surfaces, and two orders of magnitude for impacts into bare rock surfaces. The result is sensitive to the extrapolation of laboratory microcratering experiment results to real meteoroid-asteroid collisions and needs further study. If this extrapolation holds, then meteoroid impacts are more important to the dynamics of small rocky asteroids than had previously been considered.

Asteroids orbiting on prograde orbits near the Earth encounter an anisotropic meteoroid environment, including a population of particles on retrograde orbits generally accepted to be material from long-period comets spiralling inwards under Poynting–Robertson drag. High relative speed (60 km s^{-1}) impacts by meteoroids provide a small effective drag force that decreases asteroid semimajor axes and which is independent of their rotation pole. If small asteroids are bare instead of regolith covered, as is perhaps to be expected given their rapid rotation rates (Harris, A.W., Pravec, P. [2006]. In: Daniela, L., Sylvio Ferraz, M., Angel, F.J. (Eds.), Asteroids, Comets, Meteors. IAU Symposium, vol. 229, pp. 439–447), this effect may exceed the instantaneous Yarkovsky drift at sizes near and below one meter. Since one meter objects are the most abundant meteorite droppers at the Earth, the delivery of these important objects may be controlled by drag against the meteoroid environment.

The rate of reorientation of asteroid spins is also substantially increased when momentum transport by ejecta is included. This has an indirect effect on the net Yarkovsky drift, particularly the diurnal variant, as the sign of the drift it creates depends on its rotational state. The net drift of an asteroid towards a resonance under the diurnal Yarkovsky effect can be slowed by more frequent pole reorientations or induced tumbling. This may make the effect of the meteoroid environment more important than the Yarkovsky effect at sizes even above one meter.

Meteoroid impacts also affect asteroid spins at a level comparable to that of YORP at sizes smaller than tens of meters. Here the effect comes primarily from a small number of impacts by centimeter size particles. We conclude that recent measurements of the YORP effect have probably not been compromised, because of the targets' large sizes and because they are known or likely to be regolith-covered rather than bare rock. However, the effect of impacts increases sharply with decreasing size, and will likely become important for asteroids smaller than a few tens of meters in radius.

1. Introduction

The study of the delivery of meteorites to Earth was much advanced by the revival of the notion that the uneven re-radiation of incident sunlight could affect the orbits of small asteroids. Known as the Yarkovsky effect, this phenomenon results when temperature differences on an asteroid's surface result in it reradiating energy (and hence momentum) asymmetrically. The Yarkovsky effect has been widely discussed elsewhere (the reader is directed to Rubincam (1998) and Farinella et al. (1998) for excellent reviews). It is of interest here because it is one of few dynamical effects acting in the main asteroid belt which create a

* Address: Department of Physics and Astronomy, The University of Western Ontario, London, Canada. Fax: +1 519 661 2033.

E-mail address: pwiegert@uwo.ca

http://dx.doi.org/10.1016/j.icarus.2014.12.022
0019-1035/

net trend in the semimajor axis a of an asteroid's orbit. If such a change in a moves the body into a mean-motion or other resonance, its orbit may be dramatically changed as a result. Resonances can eject asteroids from the asteroid belt and play a key role in the delivery of meteorites to Earth. Thus the Yarkovsky effect, while itself creating only a small change in asteroid orbits, is nonetheless crucial in moving meteorite parent bodies from the asteroid belt to near-Earth space. The importance of the Yarkovsky effect leads one to consider whether or not other small effects might have important roles in the evolution of small asteroids. Here we consider the effect of momentum transfer via meteoroid impacts and show that it can compete with the Yarkovsky effect (and its cousin, the Yarkovsky–O'Keefe–Radzievskii–Paddack or YORP effect) under certain conditions.

In Section 2 we will introduce the meteoroid environment near the Earth. In Section 3, the dynamical effects of meteoroid impacts on small asteroids, and in particular the role of momentum transport by ejecta, will be discussed and comparisons drawn with the Yarkovsky effect. Section 4 extends the discussion to the YORP effect, Section 5 considers radiation pressure and rates of erosion and conclusions are drawn in Section 6.

2. Meteoroid environment at Earth

Most of the mass accreted by the Earth is in small particles, at least over short times. Larger individual asteroid impacts may dominate the overall mass input to the Earth (Rabinowitz, 1993; Rabinowitz et al., 1993) on million year timescales but they are not relevant here. Love and Brownlee (1993) determined that meteoroids with mass $m \approx 1.5 \times 10^{-8}$ kg corresponding to a radius $r = 220$ μm at a density $\rho_p = 2500$ kg m^{-3} dominate the meteoroid flux at Earth. Earlier studies such as those of Grün et al. (1985) found similar values though with total fluxes somewhat (2–3 times) lower.

At these sizes, the meteoroid environment of the Earth is asymmetric. This is partly because of the Earth's motion around the Sun: our planet tends to get hit more on the leading side than the trailing side. However the asymmetry also originates in part from a heterogeneous distribution of particle orbits. Studies of the *sporadic* meteors (that is, those meteors distinct from *meteor showers*) show concentrations of meteoroid orbits towards the direction of the Earth's motion around the Sun (e.g. Stohl, 1986; Brown and Jones, 1995; Chau et al., 2007; Campbell-Brown, 2008) and many others). When displayed in a co-moving reference frame centered on the apex of the Earth's way, a number of concentrations of impinging orbits are discerned. Here we will be most interested in those known as the north and south apex sporadic meteor sources.

Meteoroids arriving at Earth from these apex sources have relative velocities peaking at 60 km s^{-1} (Jones and Brown, 1993; Chau et al., 2007). These particles are on approximately circular retrograde orbits. Attributed to long-period and Halley-family cometary debris that has decayed onto low-eccentricity orbits through Poynting–Robertson drag, these particles constitute the dominant momentum and kinetic energy flux in near-Earth space. Because they arrive from the direction of the Earth's motion, they hit our planet essentially head-on and provide a small but consistent tangential drag force on any body (such as an asteroid) on a similar orbit. Though the meteoroid environment at the asteroid belt is not well known, it is reasonable to assume that it is similar to that at Earth and will also produce a net drag on asteroidal bodies.

The fraction of retrograde meteoroids arriving at Earth has been measured but there are still uncertainties. Radial scatter meteor radars (often called "High Power Large Aperture" or HPLA radars) typically see a larger fraction of apex meteors (>80%) (e.g. Sato et al., 2000; Hunt et al., 2004; Janches et al., 2003; Chau and Woodman, 2004) while transverse scatter (or "meteor patrol") radars, typically see a smaller fraction (~50%) (e.g. Taylor, 1995; Galligan and Baggaley, 2004) as do video meteor systems (Campbell-Brown and Braid, 2011). This effect can be attributed to the different instrumental sensitivities (Wiegert et al., 2009) at different particle sizes and speeds; however here for simplicity we will assume that the apex meteoroids constitute a fraction $s = 50\%$ of the meteoroid population at these sizes. The magnitude of the effect of this idealized meteoroid environment on a target asteroid will be calculated first at Earth. For simplicity we will ignore the helion and anti-helion sources, whose strengths are similar to each other and whose impact effects tend to cancel each other out. The meteoroid complex as a whole should be considered carefully in a more detailed study but this is beyond the scope of this work, where we simply show the order of magnitude of the effects.

If the meteoroid flux at the Earth is dominated by the apex source as studies of the sporadic meteors would suggest, then taking the (cumulative) flux from Fig. 3 of Love and Brownlee (1993), where their differential flux peaks ($m \approx 1.5 \times 10^{-8}$ kg) we get $n \approx 3 \times 10^{-8}$ m^{-2} s^{-1} where n is the flux of particles per square meter per second, and m is the particle mass. Given these conditions, a one-meter radius asteroid on a circular orbit near the Earth sees roughly three impacts per year, and each of impactor carries $\sim 10^{-12}$ of the momentum of the target. We will consider their cumulative effect to be a small effective drag on the target asteroid.

3. Effective drag due to meteoroid impacts

The impact of a small meteoroid onto an asteroid surface transfers kinetic energy and momentum to the larger body. Using the impulse approximation, the force F exerted on the asteroid as a result of a momentum gain Δp during a time Δt is $F = \Delta p/\Delta t$. The fraction η of the incoming momentum received by the target is unity in the case of a completely inelastic collision, and could be as high as two in the case of an elastic collision. However, high-velocity impacts are highly inelastic and we will adopt $\eta \approx 1$.

The acceleration $f_a = F/M$ imparted to an assumed spherical asteroid of mass M, density ρ_a and radius R being impacted head-on by the apex meteoroid population as described earlier would be

$$f_a = \frac{snm\upsilon\pi R^2}{\frac{4}{3}\pi\rho_a R^3} = \frac{3snm\upsilon}{4R\rho_a} \tag{1}$$

where υ is the relative velocity.

Lagrange's planetary equations e.g. Roy (1978) can be used to calculate the resulting change in semimajor axis a for an asteroid with zero eccentricity and inclination that is subject to a tangential acceleration such as that of Eq. (1)

$$\dot{a} \approx -\frac{2f_a}{n'} = -\frac{3snm\upsilon a^{3/2}}{2\sqrt{GM_\odot}R\rho_a} \tag{2}$$

where $n' = \sqrt{GM_\odot/a^3}$ is the asteroid's mean motion. For an $R = 1$ m target asteroid at 1 AU, the apex meteoroid environment produces a decrease in semimajor axis of

$$\dot{a} \approx -6.1 \times 10^{-6}\left(\frac{s}{0.5}\right)\left(\frac{R}{1\ \text{m}}\right)^{-1}\left(\frac{\rho_a}{3500\ \text{kg m}^{-3}}\right)^{-1} \text{AU Myr}^{-1} \tag{3}$$

This effective drag force is much lower than that of the Yarkovsky effect in its different variants, by factors of several up to 100 (e.g. Fig. 1 of Farinella et al. (1998)).