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Trapping and dynamical evolution of interplanetary dust particles in Earth's quasi-satellite resonance

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ABSTRACT

We used numerical simulations to model the orbital evolution of interplanetary dust particles (IDPs) evolving inward past Earth's orbit under the influence of radiation pressure, Poynting–Robertson light drag (PR drag), solar wind drag, and gravitational perturbations from the planets. A series of β values (where β is the ratio of the force from radiation pressure to that of central gravity) were used ranging from 0.0025 up to 0.02. Assuming a composition consistent with astronomical silicate and a particle density of 2.5 g cm^{-3} these β values correspond to dust particle diameters ranging from 200 μm down to 25 μm. As the dust particle orbits decay past 1 AU between 4% (for $\beta = 0.02$, or 25 μm) and 40% (for $\beta = 0.0025$, or 200 μm) of the population became trapped in 1:1 co-orbital resonance with Earth. In addition to traditional horseshoe type co-orbitals, we found about a quarter of the co-orbital IDPs became trapped as so-called quasi-satellites. Quasi-satellite IDPs always remain relatively near to Earth (within 0.1–0.3 AU, or 10–30 Hill radii, R_H) and undergo two close-encounters with Earth each year. While resonant perturbations from Earth halt the decay in semi-major axis of quasi-satellite IDPs their orbital eccentricities continue to decrease under the influence of PR drag and solar wind drag, forcing the IDPs onto more Earth-like orbits. This has dramatic consequences for the relative velocity and distance of closest approach between Earth and the quasi-satellite IDPs. After 10^4–10^5 years in the quasi-satellite resonance dust particles are typically less than $10R_H$ from Earth and consistently coming within about $3R_H$. In the late stages of evolution, as the dust particles are escaping the 1:1 resonance, quasi-satellite IDPs can have deep close-encounters with Earth significantly below R_H. Removing the effects of Earth's gravitational acceleration reveals that encounter velocities (i.e., velocities "at infinity") between quasi-satellite IDPs and Earth during these close-encounters are just a few hundred meters per second or slower, well below the average values of 2–4 km s^{-1} for non-resonant Earth-crossing IDPs with similar initial orbits. These low encounter velocities lead to a factor of 10–100 increase in Earth's gravitationally enhanced impact cross-section (σ_{grav}) for quasi-satellite IDPs compared to similar non-resonant IDPs. The enhancement in σ_{grav} between quasi-satellite IDPs and cometary Earth-crossing IDPs is even more pronounced, favoring accretion of quasi-satellite dust particles by a factor of 100–3000 over the cometary IDPs. This suggests that quasi-satellite dust particles may dominate the flux of large (25–200 μm) IDPs entering Earth's atmosphere. Furthermore, because quasi-satellite trapping is known to be directly correlated with the host planet's orbital eccentricity the accretion of quasi-satellite dust likely ebbs and flows on 10^5 year time scales synchronized with Earth's orbital evolution.

1. Introduction

Over a century ago Brown (1911) and Jackson (1913) demonstrated the existence of a peculiar class of 1:1 mean–motion resonance. They showed that in addition to tadpole and horseshoe orbits associated with the Lagrangian equilibrium points, objects could also be trapped in 1:1 resonance very close to a planet, far from any Lagrangian points. Brown and Jackson populated their resonance with theoretical objects that were originally dubbed "remote retrograde satellites" because of their apparent orbital behavior with respect to the shepherding planet. Today these objects are referred to as "quasi-satellites" to avoid ambiguity with the true retrograde satellites of the giant planets.

Discussion of the quasi-satellite resonance is often omitted from traditional dynamics textbooks (e.g., Murray and Dermott, 1999) and only recently were the first real objects found. These are near-Earth asteroids trapped in Earth's quasi-satellite resonance (Connors et al., 2002, 2004; Wiegert et al., 2005; Wajer, 2010). In the decade since the first objects were recognized, dynamicists have identified additional quasi-satellites hosted by the planets Venus (Mikkola et al., 2004), Jupiter (Kinoshita and

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Nakai, 2007), Saturn (Gallardo, 2006), and Neptune (de la Fuente Marcos and de la Fuente Marcos, 2012a) as well as the minor planets (1) Ceres, (4) Vesta (Christou and Wiegert, 2012), and (134340) Pluto (de la Fuente Marcos and de la Fuente Marcos, 2012b).

There is one orbital characteristic that is unique to the quasi-satellite resonance compared to all other mean–motion resonances, including other classes of the 1:1 co-orbital resonance. In other mean–motion resonances the two objects in resonance are generally prevented from having relatively close approaches with each other. Quasi-satellites behave quite differently. In fact, quasi-satellites always remain relatively near to their host planet. The orbital characteristics of quasi-satellites are illustrated in Fig. 1 using two idealized quasi-satellites of Earth.

In Fig. 1 we use two different reference frames, one rotating with the same average motion of Earth (Fig. 1A) and the other a non-rotating Earth-centered frame (Fig. 1B). In Fig. 1A objects with the same mean–motion as the rotating frame, but with non-zero orbital eccentricity, trace out elliptical paths. Earth follows the black elliptical path while the quasi-satellites (in 1:1 mean–motion resonance with Earth) follow the green and red paths (or light and dark gray, respectively, in a black and white rendering). The quasi-satellites in Fig. 1A have the appearance of moving around Earth in a direction opposite Earth's rotation but at a significantly farther distance compared to true satellites, thus the "remote" or "distant" retrograde satellite nomenclature used by early theorists.

Fig. 1B preserves an inertial orientation of the *X*–*Y* axes, meaning that the Sun circulates around Earth but distant stars are fixed. Fig. 1B also uses the Hill radius (Hill, 1878), $R_{\rm H}$, to indicate the distance from Earth where solar gravity and Earth's gravity are approximately equal. If we neglect Earth's small orbital eccentricity, the generalized relation is given as $R_{\rm H} = a_\oplus[m_\oplus/(3M_\odot)]^{1/3}$, where $m_\oplus$ & $a_\oplus$ are Earth's mass and semi-major axis and $M_\odot$ is the Sun's mass. Within $R_{\rm H}$ an object's motion is dominated by Earth with the Sun acting as a perturber, while beyond $R_{\rm H}$ an object's motion is dominated by the Sun with Earth acting as the perturber. All true satellites, even the most distant irregulars, have orbital semi-major axes deep inside their planet's Hill radius. For example, $R_{\rm H}$ for Earth is about 0.01 AU and our Moon orbits at about a quarter of this distance.

In the Earth-centered frame of Fig. 1B the quasi-satellites exhibit both prograde and retrograde behavior, depending on the time scale over which they are being observed. Over the course of one year they move prograde (counter-clockwise) around the double-lobed paths but do not circle Earth. On longer time scales (tens to hundreds of years) these looping paths move retrograde (clockwise) around Earth. Quasi-satellites typically remain well outside the Hill radius but also do not stray beyond about 10–30$R_{\rm H}$.

Although quasi-satellites usually remain at least several Hill radii away from their host planet, when drag forces are involved they can experience close-encounters deep inside the planet's Hill radius. There are several drag forces applicable to Solar System dynamics that can influence quasi-satellites. During the early evolution of the Solar System drag forces acting on planets caused their orbits to migrate. Kortenkamp and Joseph (2011) recently demonstrated that migration of giant planets leads to resonant trapping of quasi-satellites by these planets. The continuing effects of planetary migration can cause a significant fraction of these quasi-satellites to have deep low-velocity close-encounters with their host planets well inside the Hill radius. Quasi-satellite trapping can also occur when the drag force acts on the small bodies rather than on the planets. Kortenkamp (2005) showed that gas drag acting on km-size planetesimals in the early solar nebula can result in significant quasi-satellite trapping by giant planets. In these simulations the continuing action of gas drag acting on primordial quasi-satellites led to; (1) deep close-encounters with the host planet well inside $R_{\rm H}$, (2) capture of quasi-satellites by the host planet as true satellites, and (3) impacts of quasi-satellites with the host planet.

In the contemporary Solar System the planets no longer migrate and the nebular gas has long since dissipated. Nevertheless, other drag forces remain important for the dynamics of small bodies. In this paper we show that micron-size interplanetary dust particles (IDPs) on orbits decaying into the inner Solar System under the influence of Poynting–Robertson light drag and solar wind drag can become trapped in Earth's quasi-satellite resonance. In

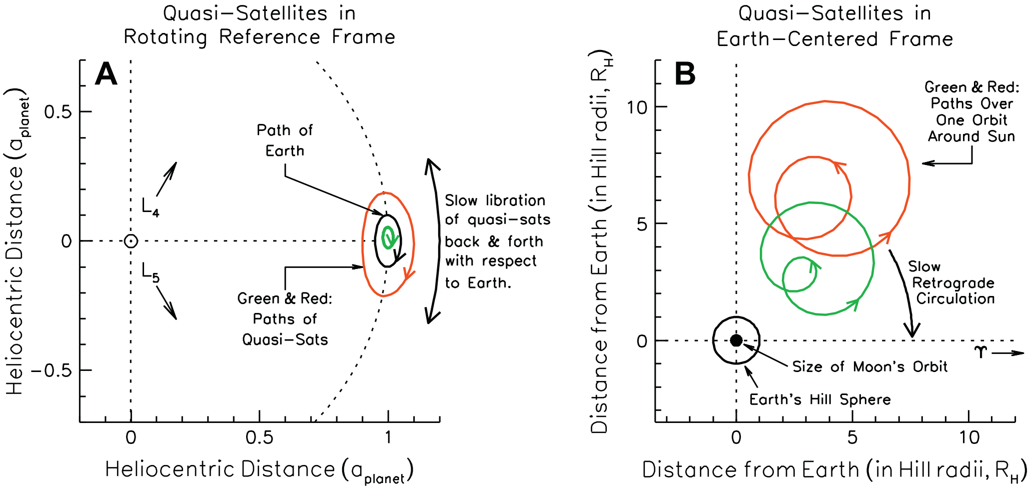

Fig. 1. Panel A is a Sun-centered reference frame rotating with the mean orbital motion of Earth and with axes in units of the semi-major axis (a) of Earth. Panel B is an Earth-centered frame with the inertial orientation of the *X*–*Y* axes preserved (i.e., the *X*-axis is fixed in the direction of the vernal equinox). Panel B uses units of Earth's Hill radius, $R_{\rm H}$ (see text for discussion). Shown are the orbits of Earth and two quasi-satellites, one particle with orbital eccentricity lower than Earth's (green, or light gray) and one with orbital eccentricity higher than Earth's (red, or dark gray). For illustration purposes Earth's eccentricity is set to 0.05, near its maximum value over long time scales. In the rotating frame of A, the orbital eccentricities of Earth and the quasi-satellites cause them to follow elliptical paths. In the geocentric frame of B the quasi-satellites trace out the double-lobed looping paths once each year (note that the quasi-satellites remain in the same quadrant of the sky as seen from Earth for the entire year). Over longer time scales the looping paths followed by the quasi-satellites slowly circulate clockwise around Earth, corresponding to retrograde motion as seen from Earth. Small arrows indicate the direction of motion along each path. In B the filled circle at the origin represents the size of the Moon's orbit and on this scale the period at the end of this sentence is about 10 Earth-diameters in size.