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Release of meteoroids from asteroids by Earth's tides

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Abstract. The orbital evolution of particles released from the surface of a rubble-pile body by Earth's tides during flyby within the Roche limit is studied. Test particles initially placed on the surface leave the surface and escape the parent body. Released particles remain in a relative small cloud for about 500 years and spread evenly along the orbit of the parent asteroid during next several hundred years. Their orbital elements exhibit very small dispersion in the mentioned time frame.

Key words: tides – asteroid – meteoroid stream

1. Introduction

The motivation for this work was the fall of the Neuschwanstein meteorite on April 6, 2002 observed by the European Fireball Network. The analysis of photographic records has shown (Spurný *et al.*, 2003) that the heliocentric orbit of the object is practically identical to the orbit of the well-known Příbram meteorite, which was photographed 43 years earlier. The different meteoritic types, Příbram being an H5 ordinary chondrite (Ceplecha, 1961) with cosmic-ray exposure age 12 Myr (Stauffer and Urey, 1962) and Neuschwanstein an EL6 enstatite chondrite with cosmic-ray exposure age 48 Myr (Bischoff and Zipfel, 2003; Zipfel *et al.*, 2003), make their common origin very problematic. Spurný *et al.* (2003) suggested the existence of a heterogeneous stream in the Příbram orbit. Moreover, there is evidence of material movement near the surface of the well-known asteroid Itokawa (Miyamoto *et al.*, 2007 a, 2007 b). In this way, boulders on the surface of the parent asteroid are differentially exposed by cosmic rays. This effect might be responsible for different cosmic-ray exposure ages of potential meteoroids in an asteroidal stream.

Kornoš *et al.* (2008) have shown a similar orbital evolution of both meteorites at least for 5000 years in the past, which supports the possible existence of a meteoroid stream in the orbit of Příbram. Furthermore, the observation of the fireball "Malacky" with the orbit similar to Příbram (Spurný, 2008) increases the expectancy of meteoroid stream existence. On the other hand, the origin of such a stream is still an open question. Pauls and Gladman (2005) showed that the occurrence of pairs as close as Příbram and Neuschwanstein is consistent with a random probability.

The idea of meteoroid showers associated with asteroids was proposed in the past, first time suggested by Olivier (1925) and Hoffmeister (1937). The existence of asteroidal-meteoritic streams was published by Halliday *et al.* (1990). Generally, several mechanisms of meteoroids' release from asteroids were suggested and one of them could be the Earth's tides during close NEA approaches. This scenario offers low relative velocities of meteoroids with respect to the parent asteroid and, at the same time, their orbits are close to the Earth's orbit. Thus the potential meteor shower might be observable from the Earth. The frequency of such approaches (inside the Roche limit of the solid Earth body $\sim 2R_{\otimes}$) by potential parent objects of size of $\sim$ 300 meters is one per 25 000 years according to the population distribution of NEAs by Ivanov (2006). Pauls and Gladman (2005) showed that the decoherence time of possible streams in orbits of well-known meteorite falls (Innisfree, Peekskill, and Příbram) is about 50 000 years and more depending on the orbit type. Thus, by Pauls and Gladman, an extremely recent breakup of the parent body would be required.

In this paper, we model the orbital evolution of particles released from the surface of an Itokawa-like asteroid (a rubble-pile body significantly covered by unbound pebbles and rocks) by Earth's tides during the asteroid flyby within the Roche limit.

2. Model

The complex models of tidal disruption of an asteroid were presented in several papers, e.g. Bottke *et al.* (1997, 1998), Richardson *et al.* (1998), Sharma *et al.* (2006), Holsapple and Michel (2008). Following mentioned results a fragile rubble pile asteroid with weak internal cohesion starts to deform into a rotational ellipsoid shape when getting close to the Roche limit of the Earth. Afterwards the differential gravitational tidal force from the Earth overcomes the gravity of the asteroid and its surface layers at the ends of the longest axis start to separate from the body. Even the most part of the asteroid survives the close approach at the cost of resurfacing and shape elongation, it easily loses a significant number of unbound surface or near-surface pebbles, rocks and boulders.

Our analysis incorporates the parent body of meteoroids as a rubble-pile asteroid with no tensile strength and with the mass and the longest axis same as for asteroid Itokawa (Abe *et al.*, 2006). According to previously mentioned papers we assume that our model asteroid will undergo through tidal elongation up to 700 m in the longest axis.

We gradually put 100 test particles onto the surface of the asteroid in the plane of motion while the asteroid was moving inside the Roche limit. In the constant time intervals a pair of particles was set in the line of centers of the Earth and the asteroid, giving two particles on the opposite sites of the asteroid.

Then each particle is traced from its initial distance of 350 m from the center of the asteroid. In the first stage we examined the motion of the particle in the geocentric coordinates of Earth – asteroid – particle in a classical three-body problem (the Earth, the asteroid and a particle of negligible mass). The motion of the asteroid was approximated by hyperbolic motion with respect to the center of the Earth and the numerical integration solved the motion of each particle from its entry to the Roche limit to the 100 000 km distance from the center of the Earth. When particles reached the 100 000 km distance the second stage started. We transformed the position vectors and velocity vectors into the cartesian heliocentric ecliptic coordinate system and the further motion was computed by direct integration of particles' equations of motion including gravitational influences of all planets. The Earth and the Moon were considered as two independent objects. The integration was done for 1000 years to the future.

3. Results

When analyzing the motion of test particles released by tides from the asteroid we used two types of orbits of the parent body that cross the Earth's Roche limit: the orbit of meteorite Příbram (a=2.40 AU, e=0.67, i=10.5°, Apollo type) which had to be slightly modified in the mean anomaly to miss the center of the Earth in about 13 000 km. Secondly, we analysed the orbit of asteroid 2004 FU162 (a=0.83 AU, e=0.4, i=4.1°, Aten type) that passed 0.000086 AU (= 13 000 km) from the center of the Earth on March 31.65, 2004 (*MPEC 2004-Q22*). This body has the absolute magnitude (H=28.7) corresponding to 5-10 m in diameter. Given its small size, we assume this body is a monolith and therefore it could not be a source of meteoroids.

Table 1. The maximum escape velocity and relative distance of the particle from the parent asteroid when the asteroid reaches the 100 000 km distance from the Earth. Parent asteroid disintegration is taken into account (whole or half of the parent body mass survives).

mass	1.0		0.5	
orbit type	escape velocity	distance	escape velocity	distance
2004 FU162	10 cm s^{-1}	795 m	11 cm s^{-1}	975 m
Příbram	6 cm s^{-1}	430 m	7 cm s^{-1}	550 m

During the approach to the Earth the model particles start to leave the surface of the parent asteroid but fall back after a short time. We define the Roche limit for our purpose (RL_a) as a distance from the center of the Earth such that the particle did not fall back onto the asteroid surface. For 2004 FU162

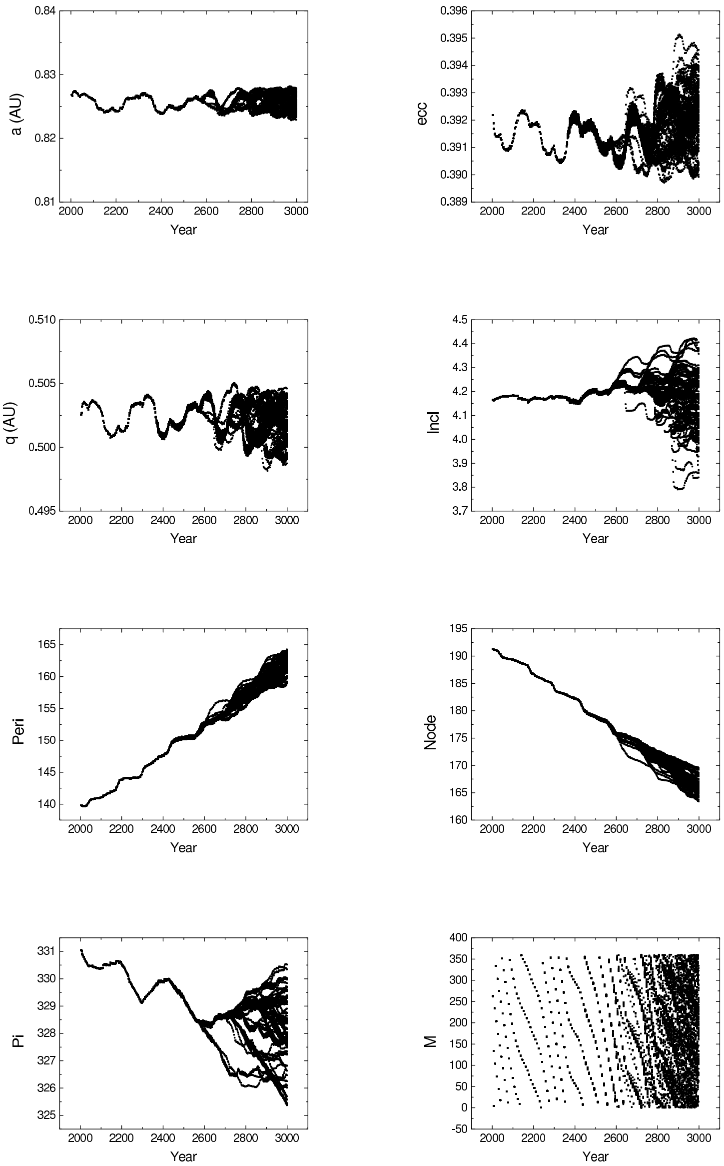

Figure 1. The orbital evolution of modeled particles released by Earth's tides over 1000 years; a - semimajor axis, ecc - eccentricity, q - perihelion distance, $Incl$ - inclination, $Peri$ - argument of perihelion, $Node$ - longitude of the ascending node, Pi - longitude of perihelion, M - mean anomaly.

we found $RL_a = 22\,280$ km and the asteroid was traveling 50 minutes inside this limit. The Příbram-like asteroid travels 13 minutes inside its $RL_a = 14\,700$ km. Obviously, the fly-by time depends on the approach geometry and the relative velocity of the asteroid to the Earth. For our model orbits we set the approach epochs to the real approach time of 2004 FU162 and fall time of Příbram, April 7, 1959. Adequate velocities in perigee were 13.4 km s^{-1} for 2004 FU162 and 19.2 km s^{-1} for Příbram, respectively.

Particles that definitely left 2004 FU162 surface reached escape velocities in range of 5-10 cm s^{-1} and in the geocentric distance of asteroid 100 000 km leaving particles were $\sim$ hundreds of meters away from the parent body (Table 1). We also considered a possible mass loss of the parent body that could theoretically change the behavior of leaving particle motion. Though the model took two possibilities into account (after the perigee the whole parent asteroid survives or the half of the mass survives), the parent body mass loss had minimum influence on particle motion and particle cloud diffusion. The particle gains the maximum escape velocity when leaving the parent body before the perigee.

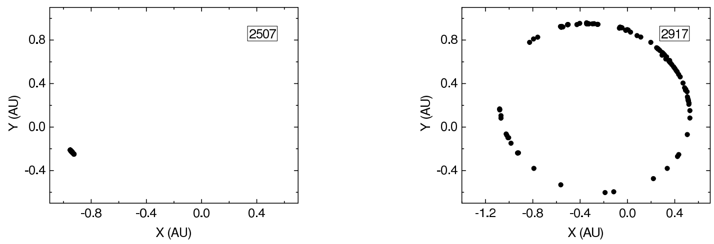

Figure 2. The spread of modeled particles in years 2507 and 2917, respectively. Projection onto the ecliptic plane (x, y).

The motion of a cloud of 100 escaping particles was examined through its motion during next 1000 years. In the first 500 years the orbital evolution of all particles is practically identical with no significant spread. Figure 1 shows the evolution of orbital elements of particles that left the parent body of half the mass of Itokawa on a 2004 FU162-like orbit. In this case the particles obtained maximum escape velocities and their spread in orbital elements at the end of integration was widest as well. The nature of orbital elements evolution of particles derived from a Příbram-like orbit is similar, but with smaller spread.

Figure 2 shows the cloud of test particles projected onto the ecliptic plane. The spread of the particles demonstrates that during first few hundred years the particles remain in one packet and later disperse around the orbit of the parent body.

4. Conclusions

The gravitational tidal influence of the Earth on potential meteoroids originating from approaching asteroids is very small even during the close approach. On the other hand, the escape velocity of a pebble, rock or a boulder from a small asteroid is only several $\mathrm{cm\,s^{-1}}$. We found that the escape velocity of a particle lying on the asteroid surface and its possible independent motion depends on the geometry of the parent body fly-by of the Earth. Although the different geocentric velocity allows the approaching asteroids to stay longer or shorter inside the Roche limit where the particle release is possible, our simulation showed that particles left from two different geocentric orbits obtained very similar escape velocities. That is why we suppose that the meteoroid streams from parent bodies on different orbits will behave similar in order of stream dispersion and evolution. Even a simple model of meteoroid particles production by tidal disruption of asteroids shows that the orbital evolution of particles is stable at least for the first 1000 years. Released particles stay in a relative small cloud for about 500 years and spread evenly along the orbit of the parent asteroid during next several hundred years. Their orbital elements exhibit a very small dispersion in the mentioned time frame.

Accordingly, we expect similar meteoroid stream behavior of a possible asteroidal origin. If there is observed such kind of the stream, our model might be useful for interpretation of asteroidal stream origin.

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