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The Contribution of Kuiper Belt Dust Grains to the Inner Solar System

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Abstract. The recent discovery of the so-called Kuiper belt objects has prompted the idea that these objects produce dust grains that may contribute significantly to the interplanetary dust population at 1 AU. We have completed a numerical study of the orbital evolution of dust grains, of diameters 1 to 9 μm, that originate in the region of the Kuiper belt. Our results show that about 80% of the grains are ejected from the Solar System by the giant planets while the remaining 20% of the grains evolve all the way to the Sun. Surprisingly, these dust grains have small orbital eccentricities and inclinations when they cross the orbit of the Earth. This makes them behave more like asteroidal than cometary-type dust particles. This also enhances their chances to be captured by the Earth and makes them a possible source of the collected interplanetary dust particles (IDPs); in particular, they represent a possible source that brings primitive/organic materials from the outer Solar System to the Earth.

When collisions with interstellar dust grains are considered, however, Kuiper belt dust grains larger than about 9 μm appear likely to be collisionally shattered before they can evolve to the inner part of the Solar System. Therefore, Kuiper belt dust grains may not, as they are expected to be small, contribute significantly to the zodiacal light.

1. Introduction

Since the discovery of the first trans-Neptunian object and the still ongoing discoveries of such objects (e.g., Jewitt and Luu 1995), it has been proposed that micron-sized dust particles produced from these so-called "Kuiper belt objects" may contribute significantly to the interplanetary dust population that constitutes the zodiacal cloud (e.g., Flynn 1994). They may also be an important source of the interplanetary dust particles (IDPs) collected in the stratosphere by high altitude airplanes. The fact that the meteoroid detectors on board Pioneer 10 and 11 recorded impacts at a nearly constant rate up to 18 AU from the Sun (Humes 1980) also suggests a possible dust grain source in the outer Solar System.

However, three key questions must be answered before we can estimate the contribution of Kuiper belt (KB) dust grains to the interplanetary meteoritic complex: (1) What is the dust production rate in the region of the Kuiper belt? (2) Can those grains evolve all the way to the inner part of the Solar System? and (3) What is the collisional lifetime of those dust grains when interstellar dust particles are considered? Question 1 requires the knowledge of the, in addition to the total population of objects in the Kuiper belt, for example, size distribution, composition, and strength, etc. of the Kuiper belt objects. Based on the study by Jewitt and Luu (1995), there are ~35,000 objects with diameters larger than 100 km between 30 AU and 50 AU. Recent observations from the Hubble Space Telescope also suggest that there are more than 2 x 10^8 Halley-sized objects in the Kuiper belt (Cochran *et al.* 1995). Although these numbers do not predict the exact dust production rate, this population is, in principle, capable of producing a large amount of dust (for comparison, there are only about 250 main belt asteroids with diameters larger than 100 km). Based on that, our objectives are to answer the second and third questions with direct numerical integrations of the orbital evolution of dust grains and to apply a simple collision model based on the best available data on the flux of interstellar dust grains. In our numerical calculations, we simulate the actual orbital evolution of the dust grains by including the gravitational perturbations due to the Sun, 7 planets (Mercury and Pluto are not included), radiation pressure, Poynting-Robertson (PR) drag, and solar wind drag. We do similar calculations for dust grains ranging from 1 to 9 μm in diameter.

2. Results

Due to PR and solar wind drag, dust grains will spiral toward the Sun once they are released from their large parent bodies. This motion leads dust grains to pass by planets as well as to encounter numerous mean motion resonances (MMRs) associated with planets. Based on our results, trapping into exterior MMRs with Neptune and, to a lesser extent, Uranus dominates the orbital evolution of these dust grains. Large grains tend to have longer trapping lifetimes. Gravitational scattering by Saturn or Jupiter usually controls their final fate. Approximately 80% of the 80 dust grains evaluated in our numerical calculations eventually were scattered out of the Solar System before reaching the inner part of the Solar System. The remaining 20% of the dust grains were able to pass by Saturn and Jupiter and completed their journeys all the way to the Sun. The evolution in semimajor axis, eccentricity, and inclination of one of the 2 μm dust grains is shown in Fig. 1.

The consequence of dust grains being trapped in exterior MMRs with Neptune (or with Uranus) is the formation of dust rings like the ring of dust of asteroidal origin near the Earth's orbit (Jackson and Zook 1989, Dermott *et al.* 1994). Because of their large eccentricities, these rings spread out over quite large ranges, approximately from 20 to 40 AU. With their large distances from the Sun and Earth, it is highly unlikely that these rings are telescopically detectable.

The KB dust grains that do enter the inner Solar System (inside Jupiter) have small eccentricities and inclinations when they cross the orbit of the Earth. The low eccentricities and inclinations of the Earth-approaching KB dust grains mean they are more likely to be captured by the Earth and to survive atmospheric entry than cometary dust grains.

Based on measurements of the flux of interstellar dust grains near the orbit of Jupiter by Ulysses (Grün *et al.* 1993) and under the simple assumption that this flux does not vary with time and distance from the Sun, we estimate the collisional destruction of KB dust grains due to interstellar dust grains. The results show that KB dust grains larger than (and including) about 9 μm are likely to be collisionally shattered before they can evolve toward the inner part of the Solar System.

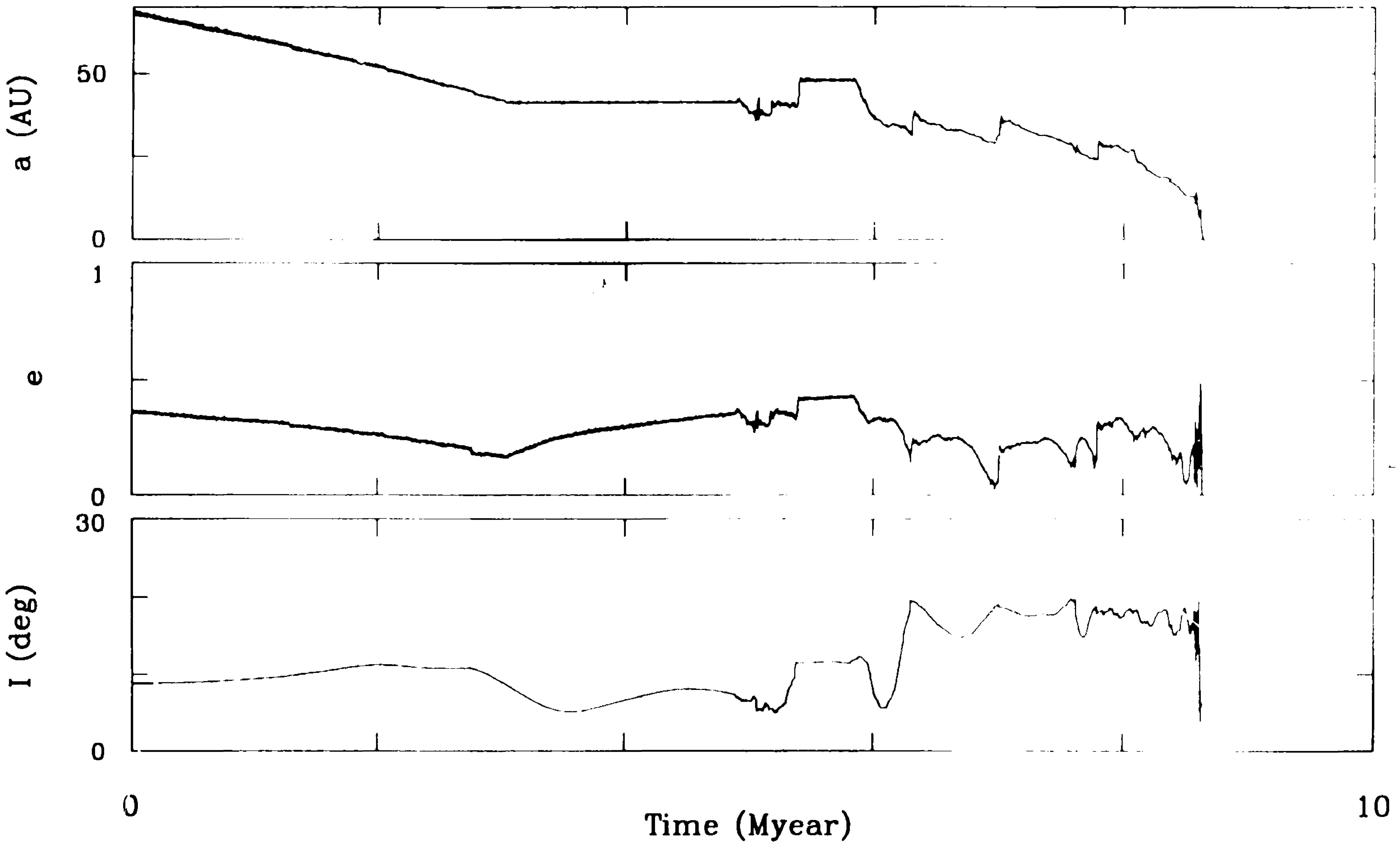

Figure 1. Orbital evolution of a 2 μm KB dust grain. It was trapped in the 9:5 MMR with Neptune (at 41.4AU) for about 1.9 million years and in the 9:4 MMR with Neptune (at 48.0AU) for about 0.4 million years. After the grain escaped the last resonance, it was able to pass by all the planets and complete its journey to the Sun. Even with the large variations in eccentricity and inclination during its evolution, this dust grain finally had a small eccentricity (0.2) and inclination (6°) when it crossed the orbit of the Earth.

3. Discussion

Comets and asteroids have long been considered the two major sources that deposit dust particles into interplanetary space which, in turn, gives rise to the zodiacal light. From *in situ* spacecraft experiments, it has been shown that the main contribution to the zodiacal light is from particles that range from 20 to 200 μm in diameter (Grün *et al.* 1985). On the other hand, from the Infrared Astronomical Satellite (IRAS) observations at 25 μm wavelength and from dynamical modeling, it was shown that 9 μm diameter dust grains from comets and asteroids best fit the observational shape of the zodiacal light as a function of ecliptic longitudes (Liou *et al.* 1995). Regardless of the discrepancy between these two results, it appears that KB dust grains probably do not contribute significantly to the zodiacal light simply because any grains larger than (and including) about 9 μm are likely to be destroyed by collisions before they evolve toward the inner part of the Solar System. However, this is based on our collision model which assumes an uniform and stable interstellar dust flux. In reality the interstellar dust flux is certain to vary as the Solar System moves around our galaxy. There may also be a short term variation due to the solar cycle (Gustafson and Misconi 1979). It is possible that at a time when the Solar System passes through a lower density interstellar dust cloud, KB dust grains larger than 9 μm may be able to evolve all the way toward the Sun and be a significant part of the zodiacal light.

IDPs collected by high altitude aircraft from the stratosphere contain several distinctive types of primitive materials (e.g., Bradley *et al.* 1988, Clemett *et al.* 1993). These IDPs range from 1 to 50 μm in diameter. They could be a source for bringing the first organic materials to the Earth and contribute to the origin of life. Again, asteroids and comets are thought to be the two major sources for these IDPs. However, based on our study, KB dust grains with diameters around 1 to about (but less than) 9 μm could be a significant portion of the small collected IDPs.

Is it possible to distinguish KB dust grains from other dust grains in the collected IDPs? If so, we could analyze them and learn more about material composition in the Kuiper belt, hence increasing our knowledge of the early Solar System. From a dynamical point of view, KB dust grains are just like asteroidal dust grains, with similar eccentricities and inclinations when they cross the orbit of the Earth. This implies that the atmospheric entry heating is similar for both types of grains. The major difference between KB and asteroid dust grains is their space exposure time. The measurement of the solar flare track densities (e.g., Bradley et al. 1984) may show a difference between them. KB dust grains should have a much higher track density than asteroidal dust grains. This suggests that among small collected IDPs, those with the highest solar flare track density may come from the Kuiper belt.

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