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An improved model for interplanetary dust fluxes in the outer Solar System

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A R T I C L E I N F O

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A B S T R A C T

We present an improved model for interplanetary dust grain fluxes in the outer Solar System constrained by in situ dust density observations. A dynamical dust grain tracing code is used to establish relative dust grain densities and three-dimensional velocity distributions in the outer Solar System for four main sources of dust grains: Jupiter-family comets, Halley-type comets, Oort-Cloud comets, and Edgeworth-Kuiper Belt objects. Model densities are constrained by in situ dust measurements by the *New Horizons* Student Dust Counter, the *Pioneer* 10 meteoroid detector, and the *Galileo* Dust Detection System (DDS). The model predicts that Jupiter-family comet grains dominate the interplanetary dust grain mass flux inside approximately 10 AU, Oort-Cloud cometary grains may dominate between 10 and 25 AU, and Edgeworth-Kuiper Belt grains are dominant outside 25 AU. The model also predicts that while the total interplanetary mass flux at Jupiter roughly matches that inferred by the analysis of the *Galileo* DDS measurements, mass fluxes to Saturn, Uranus, and Neptune are at least one order-of-magnitude lower than that predicted by extrapolations of dust grain flux models from 1 AU. Finally, we compare the model predictions of interplanetary dust oxygen influx to the giant planet atmospheres with various observational and photochemical constraints and generally find good agreement, with the exception of Jupiter, which suggests the possibility of additional chemical pathways for exogenous oxygen in Jupiter's atmosphere.

1. Introduction

Interplanetary dust grains pervade the Solar System and are an important driver of several physical processes. These include, for example, the production of tenuous rings and dusty exospheres around planetary satellites (e.g., Thiessenhusen et al., 2002; Verbiscer et al., 2009; Hedman et al., 2009; Poppe and Horányi, 2011), the spatial and compositional evolution of Saturn's main planetary ring system (Durisen et al., 1989; Cuzzi and Estrada, 1998; Estrada et al., 2015), the possible injection of meteoric metal ions into the magnetospheres of the giant planets (Christon et al., 2015), and the alteration of neutral chemistry and ion densities in the atmospheres of the giant planets and Titan through meteoric ablation (e.g., Moses, 1992; Feuchtgruber et al., 1997, 1999; Moses et al., 2000; Moses and Bass, 2000; Molina-Cuberos et al., 2001). The interplanetary dust grain environment in the inner Solar System has been the subject of extensive modeling (e.g., Grün et al., 1985; Divine, 1993; Kortenkamp and Dermott, 1998; Dikarev et al., 2005; Nesvorný et al., 2010), in situ flux measurements (Dietzel et al., 1973; Love and Brownlee, 1993; Hillier et al., 2007; St. Cyr et al., 2009; Poppe et al., 2011), and remote sensing observations (Leinert, 1975; Hauser et al., 1984; Hahn et al., 2002; Janches and ReVelle, 2005; Janches et al., 2006). Additionally, it has been recently shown from a comparison of dynamical modeling and observations by the *Infrared Astronomical Satellite* (IRAS) that for the inner Solar System, interplanetary dust is mainly supplied by Jupiter-family comets, with small additional contributions from asteroids and Oort-Cloud comets (Nesvorný et al., 2010).

The picture for the outer Solar System, however, is not as clear. Extending from approximately 35 to 50 AU, the Edgeworth-Kuiper Belt (EKB) is thought to be the main source of interplanetary dust grains in the outer Solar System, with some cometary contribution(s) as well (Landgraf et al., 2002). EKB grains, produced through either mutual EKB object collisions and interstellar/interplanetary dust bombardment (Stern, 1996; Yamamoto and Mukai, 1998; Poppe, 2015), diffuse throughout the EKB region and the outer Solar System as they are subjected to a variety of forces, including, but not limited to, solar and planetary gravitation, solar wind and Poynting–Robertson drag, and stellar radiation pressure (Burns et al., 1979; Gustafson, 1994; Horányi, 1996). As dust grains spiral in from the EKB region under the influence of Poynting–Robertson

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drag, their motion is often dominated by resonant gravitational interactions with Neptune, which serve to trap grains in mean-motion resonances (MMRs) outside of 30 AU (Liou and Zook, 1997, 1999; Moro-Martín and Malhotra, 2002, 2003), a phenomenon which may be observable in observations of other nascent exozodical disks (e.g., Greaves et al., 1998; Wyatt et al., 1999; Lisse et al., 2007a, 2008, 2009, 2012; Stark and Kuchner, 2008; Moro-Martín et al., 2010). Eventually, the grains break free of these resonances to continue their progression inwards past the outer planets, before either being ejected from the Solar System by one of the planets (usually Jupiter or Saturn) or making their way into the inner Solar System. More recent dynamical models have begun to explore the role that grain–grain collisions have on the equilibrium density, especially in the Edgeworth-Kuiper Belt where Poynting–Robertson decay times are equal to or significantly longer than expected collisional destruction times (Stark and Kuchner, 2009; Kuchner and Stark, 2010; Vitense et al., 2014). Some recent dynamical dust models have used either in situ dust density measurements (i.e., *Pioneer* 10/11 meteoroid detectors and the *New Horizons* Student Dust Counter) or remote sensing observations of zodiacal brightness to constrain the production rates of various interplanetary dust grain sources (Nesvorný et al., 2010; Han et al., 2011).

In light of the fundamental importance of interplanetary dust grain fluxes on various planetary processes in the outer Solar System, the recent developments in the understanding of how grain–grain collisions affect dust grain densities, the availability of both in situ and remote sensing constraints on various sub-populations of the interplanetary dust, and the long-persisting overall uncertainty of outer Solar System dust fluxes, we are motivated to develop a comprehensive model of the interplanetary dust grain environment in the outer Solar System. The model presented here combines the main interplanetary dust grain sources, relevant physics for both dust grain dynamical evolution and collisions, and several in situ constraints on dust densities. Section 2 describes the model, including the parent source bodies and the dynamical evolution of the dust, Section 3 describes the model results and the constraints imposed by available measurements, Section 4 compares the influx of oxygen from interplanetary dust grains to the atmospheres of the outer planets with observational constraints, and Section 5 discusses the results and presents conclusions.

2. Model description

The dust dynamics model is built on that used previously in Han et al. (2011), Poppe and Horányi (2012), and Poppe (2015) with several important enhancements. These include more accurate, observationally-constrained EKB object (EKBO) parent body populations (Petit et al., 2011), modeling of cometary dust grain sources, and the inclusion of a collisional algorithm for Edgeworth-Kuiper Belt dust grains (Stark and Kuchner, 2009; Kuchner and Stark, 2010). Individual dust grains are launched from a collection of parent bodies (see Section 2.1 and Appendix A) and their trajectories are traced using a Bulirsch–Stoer step-size controlled integrator (Press et al., 2007). The equation of motion for an individual dust grain is given by,

$$\ddot{\mathbf{r}}_s = -\frac{GM_\odot}{r_s^3}\mathbf{r_s} - \sum_{i=1}^{4}\frac{GM_i}{r_i^3}\mathbf{r_i} + \frac{1}{m}\mathbf{F_L} + \frac{\pi a_d^2}{mc}SQ_{pr}\left[\left(1-(1+w)\frac{\dot{r}_s}{c}\right)\hat{\mathbf{r}}_\mathbf{s} - (1+w)\frac{\dot{\mathbf{r}}_\mathbf{s}}{c}\right], \tag{1}$$

where $\mathbf{r_j}$, $\dot{\mathbf{r}}_\mathbf{j}$, and $\ddot{\mathbf{r}}_\mathbf{j}$ are the position, velocity, and acceleration vectors of the dust grain with respect to the Sun ($j = s$) or the outer planets, Jupiter to Neptune, ($j = i$), $M_\odot$ and M_i are the masses of the Sun and the planets, respectively, $\mathbf{F_L}$ is the Lorentz force, S is the radiation flux density, $Q_{pr} = 1$ is the radiation pressure coefficient (typically valid for $a \gtrsim 0.5$ μm), and $w = 0.35$ is a constant ratio between solar wind drag and Poynting–Robertson drag (Burns et al., 1979; Gustafson, 1994; Liou et al., 1995). The Lorentz force is $\mathbf{F_L} = q(\dot{\mathbf{r}}_\mathbf{s} \times \mathbf{B})$, where q is the grain charge and $\mathbf{B}$ is the interplanetary magnetic field. We use the interplanetary magnetic field model described by Landgraf et al. (2000) and assume a constant electrostatic potential on all grains, $\phi = +5$ V, yielding a size-dependent grain charge, $q = 4\pi\epsilon_o a_d \phi$ (Horányi, 1996). Modeled grain sizes span from 10^{-12} g to 10^{-5} g in half-logarithmic intervals (i.e., $[10^{-12}, 10^{-11.5}, 10^{-11}, \ldots, 10^{-5.5}, 10^{-5}]$ g), which assuming a density of $\rho = 2.5$ g cm^{-3} spans sizes from approximately 0.5 μm to 100 μm. In terms of the ratio of the radiation pressure force to the solar gravitational force, β, the particles range from 0.46 to 0.0023.

2.1. Dust grain sources

The model includes four separate dust grain source populations: Edgeworth-Kuiper Belt objects (EKBOs), Jupiter-family comets (i.e., Levison and Duncan, 1997), Halley-type comets, and Oort-Cloud comets (Oort, 1950; Francis, 2005). Each of these populations contributes dust to the interplanetary medium either through active outgassing or disruptive outbursts in the case of comets or from either mutual collisions (Stern, 1996) and interstellar or interplanetary dust grain bombardment in the case of EKBOs (Yamamoto and Mukai, 1998; Poppe, 2015). An accurate description of the parent body orbital distributions is essential to modeling dust grain equilibria in the Solar System, as dust grains ejected with different initial conditions can yield significantly different spatial and velocity distributions. Table 1 summarizes the main orbital characteristics of each of the dust grain sources, with a full description provided in Appendix A.

Similar to previous models, we must ensure that enough grains are simulated to prevent the spurious dominance of individual grains with relatively long lifetimes due to trapping in MMRs when calculating equilibrium density and velocity distributions (Moro-Martín and Malhotra, 2002). For EKB grains, which are particularly susceptible to capture in MMRs and therefore have longer lifetimes, we ran approximately 2500 grains for each size bin, yielding roughly 37,500 EKB grains in total. For JFC and HTC grains, with relatively shorter dynamical lifetimes, we ran 6000 grains per size bin for each type, for a total of nearly 100,000 grains for both types. For OCC grains, we ran 1200 grains per size, except for the largest three grain sizes (10^{-6}, $10^{-6.5}$, and 10^{-5} g, or equivalently 50, 70, and 100 μm), where we doubled the number of grains (2400 per size bin). The additional grains for these largest sizes were deemed necessary based on inspection of equilibrium densities with only 1200 grains, which suffered from somewhat poor statistics. For all

Table 1
A description of the various dust grain sources used in the model. See Appendix A for a full discussion.

Type	Description
Edgeworth-Kuiper Belt	See Table A.3
Jupiter-family comets	$f(a,e)$ from Levison and Duncan (1997) $dN(i) \propto \sin(i)\exp^{-0.5(i/\sigma_J)^2}$
Halley-type comets	$20 < P < 200$ years, ($7.5 < a < 34$ AU) $0.9 < e < 0.99$ $dN(i) \propto \sin(i)\exp^{-0.5(i/\sigma_H)^2}$
Oort Cloud comets	$1000 < a < 10{,}000$ AU $dN(q) = \{1+\sqrt{q},\ q < 2\text{ AU};\ 2.41(q/2)^{\gamma},\ q > 2\text{ AU}\}$ $dN(i) \propto \sin(i)$