ARTICLE IN PRESS

Icarus xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Icarus

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

Interplanetary dust influx to the Pluto–Charon system

Andrew R. Poppe

Space Sciences Laboratory, 7 Gauss Way, University of California at Berkeley, Berkeley, CA 94720, USA

ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Interplanetary dust
Pluto
Kuiper Belt

ABSTRACT

The influx of interplanetary dust grains (IDPs) to the Pluto–Charon system is expected to drive several physical processes, including the formation of tenuous dusty rings and/or exospheres, the deposition of neutral material in Pluto's atmosphere through ablation, the annealing of surface ices, and the exchange of ejecta between Pluto and its satellites. The characteristics of these physical mechanisms are dependent on the total incoming mass, velocity, variability, and composition of interplanetary dust grains; however, our knowledge of the IDP environment in the Edgeworth-Kuiper Belt has, until recently, remained rather limited. Newly-reported measurements by the New Horizons Student Dust Counter combined with previous Pioneer 10 meteoroid measurements and a dynamical IDP tracing model have improved the characterization of the IDP environment in the outer Solar System, including at Pluto–Charon. Here we report on this modeling and data comparison effort, including a discussion of the IDP influx to Pluto and its moons, and the implications thereof.

1. Introduction

All objects in the Solar System are subject to a flux of sub-micron to millimeter sized dust grains and knowledge of this influx is critical for understanding several physical processes in the Pluto–Charon system. For example, interplanetary dust flux should drive the production of tenuous dusty rings or exospheres. Modeling efforts have shown that ejecta from Pluto's smaller satellites (Nix and Hydra, as well as the newly-discovered Kerberos and Styx) dominates the equilibrium density of grains within the Pluto–Charon system (Thiessenhusen et al., 2002; Poppe and Horányi, 2011; Pires dos Santos et al., 2013); however, estimates of the expected geometric optical depth of such rings diverge over several orders of magnitude. Observational searches for any rings through either direct backscattering or stellar occultation have yielded no detections and have correspondingly placed an upper limit for the optical depth of approximately 6×10^{-6} at the orbit of Hydra (Steffl and Stern, 2007). Characterizing the interplanetary dust influx to the Pluto system will allow for more accurate calculations of any putative ring densities and optical depths. The presence of impact ejecta within the Pluto–Charon system will contribute to ejecta transfer amongst Pluto and its satellites, mainly from the smaller satellites to larger (Stern, 2009; Poppe and Horányi, 2011), which may be a process by which the albedos and colors of Pluto's satellites may evolve to a self-similar state. Interplanetary dust bombardment may anneal water ice on the surfaces of Charon and the smaller satellites, helping to explain the presence of crystalline water ice in the outer Solar System where it is energetically disfavored over amorphous water ice (Porter et al., 2010). Finally, interplanetary dust bombardment may contribute to other processes not yet considered for the Pluto–Charon system, including the production of neutral exospheres via impact vaporization similar to the Moon and Mercury (Verani et al., 1998; Stern, 1999), the deposition of external material in Pluto's atmosphere via ablation and its subsequent photochemical consequences (Krasnopolsky and Cruikshank, 1999; Krasnopolsky, 2012), and impact gardening of surfaces in the Pluto–Charon system (Papike et al., 1982; Lucey et al., 2006).

At the Pluto–Charon system, the interplanetary dust distribution is dominated by grains produced from the Edgeworth-Kuiper Belt (EKB) itself through both mutual collisions and bombardment of EKB objects by interstellar grains (Stern, 1996; Yamamoto and Mukai, 1998), with a small contribution from cometary sources (Landgraf et al., 2002); however, given the historically limited in situ dust density measurements outside the orbit of Jupiter, dust fluxes in the outer Solar System have often been estimated by using the well-characterized flux at 1 AU (Grün et al., 1985) and extrapolating outwards. Since the Grün et al. (1985) model applies to asteroidal and cometary dust produced within the orbit of Jupiter, it does not necessarily represent the dust complex in the outer Solar System, where the sources and dynamics of IDPs are quite different. Recently reported measurements of dust densities in the outer Solar System by the Student Dust Counter (Horányi et al., 2008; Poppe et al., 2010) onboard the New Horizons mission to Pluto (Stern, 2008), when combined with previous Pioneer 10 meteoroid detector measurements (Humes, 1980) and a dynamical model (Han et al., 2011), are now constraining the interplanetary dust density and velocity distributions in the outer Solar System, from which dust influx distributions can be calculated.

E-mail address: poppe@ssl.berkeley.edu

0019-1035/$ - see front matter © 2014 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.icarus.2013.12.029

Please cite this article in press as: Poppe, A.R. Interplanetary dust influx to the Pluto–Charon system. Icarus (2014), http://dx.doi.org/10.1016/j.icarus.2013.12.029

In this paper, we calculate the magnitude and variability of the interplanetary dust influx to the Pluto–Charon system using a dynamical dust tracing model and in situ dust density measurements by the Pioneer 10 and New Horizons spacecraft. Section 2 describes the dust model and Section 3 presents the influx calculations to the Pluto–Charon system. Finally, we discuss implications and conclude in Sections 4 and 5, respectively.

2. Interplanetary dust model

In order to calculate the interplanetary dust flux to the Pluto–Charon system, we use the results of a dynamical dust grain tracing model described in detail in Han et al. (2011). This code models the behavior of dust grains originating from the Edgeworth-Kuiper Belt for a discrete collection of grain sizes in the range of 0.5–50 μm. Grains are launched with initial conditions corresponding to known EKB sub-populations, namely, classical, scattered, and resonant objects (Kavelaars et al., 2009), although we note that recently reported investigations into the orbital structure of the EKB may affect these results by refining the estimates of the number and distribution of various sub-populations (e.g., Petit et al., 2011; Gladman et al., 2012). Each grain is subject to variety of forces, including solar and outer planetary gravitation, solar radiation pressure, Poynting–Robertson drag, and the electromagnetic interaction with the interplanetary magnetic field (Burns et al., 1979; Gustafson, 1994). All grains are modeled as silicates with density $\rho = 2.5$ g cm^{-3}, although, we note that dust grains with other compositions (i.e., icy or carbonaceous) may exist due to the extensive diversity of surface compositions amongst EKB objects (Brown, 2012). Individual grains are followed until they either reach the far inner Solar System (defined as inside 0.1 AU) or are ejected from the Solar System. The dust grain state vector data are routinely printed out, from which statistical equilibrium maps of the three-dimensional dust grain density and velocity distributions at each grain size can be constructed (Liou and Zook, 1999). At this time, we do not consider interplanetary grain–grain collisions, although, previous modeling work has shown that collisions may play a role in modifying size distributions of EKB grains (Kuchner and Stark, 2010). Additionally, collisions between interstellar grains and interplanetary grains may be an efficient mass-loss mechanism and could alter the equilibrium distribution; however, we neglect this effect presently but identify the inclusion of interstellar grain impacts as a future task. Fig. 1 shows the relative density of 10 μm EKB-generated grains in (a) the ecliptic plane for the Neptune-rotated frame and (b) in the vertical plane where the dust density has been azimuthally averaged. Mean-motion resonances dominate the behavior of dust grains outside the orbit of Neptune, yielding the complex density structure both radially and azimuthally. The character of these structures depends on the dust parent bodies (EKB classical, scattered or resonant objects) as well as the dust grain size and composition. In general, larger grains and/or dynamically colder grains have longer resonance lifetimes with Neptune and thus, have equilibrium density distributions with a higher degree of structure (Liou and Zook, 1999; Moro-Martín and Malhotra, 2003).

To provide an absolute measure of the EKB density throughout the Solar System, the model has been compared to both Pioneer 10 and New Horizons Student Dust Counter (SDC) measurements (Humes, 1980; Horányi et al., 2008; Poppe et al., 2010). Since SDC measures grains larger than approximately 0.5 μm while Pioneer 10 measured grains larger than approximately 3.5 μm, both the overall dust production rate from the EKB and the slope of the corresponding mass distribution have been constrained (Han et al., 2011). The dust production mass distribution is assumed to be in a longitudinally-averaged, quasi-steady state equilibrium (based on calculations by Stern (1996) and Yamamoto and Mukai (1998)), that follows a power law given by $d\dot{M}/dm = \dot{M}_o(m/m_o)^{-\alpha/3}$, where $\dot{M}$ is the overall dust production rate, $\dot{M}_o$ is a normalization constant, $m_o = 10^{-11}$ g is a reference grain mass, and $\alpha = 3.02$ is the slope of the mass distribution (Han et al., 2011). The overall mass production rate of dust grains between 0.1 and 10 μm in radius in the EKB was found to be approximately $\dot{M} = 8.9 \times 10^5$ g/s (Han et al., 2011), well within the range estimated theoretically (Stern, 1996; Yamamoto and Mukai, 1998). From these constraints, the density, velocity, and mass distributions of micron-sized EKB grains can be calculated throughout the Solar System.

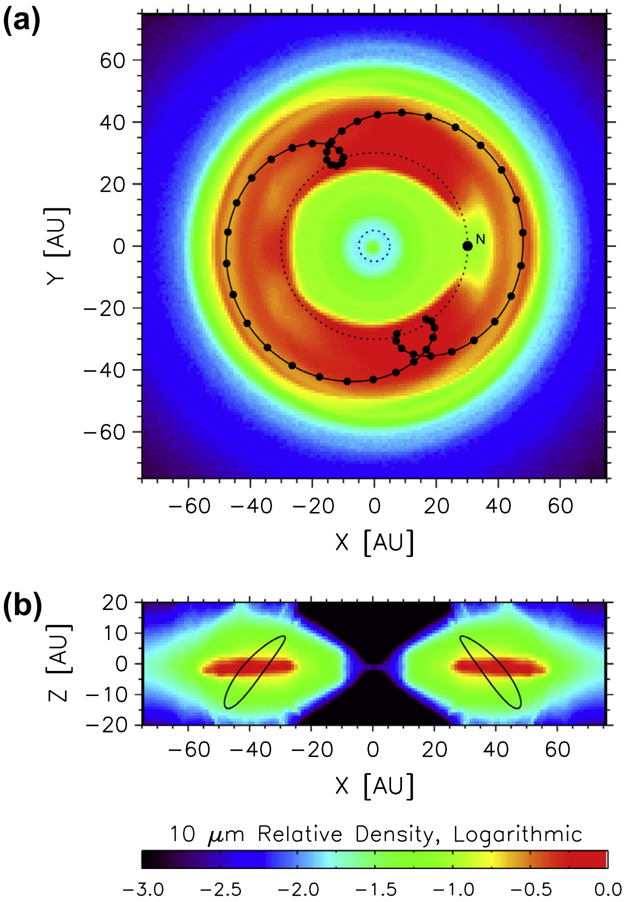

Fig. 1. The equilibrium density of 10 μm Edgeworth-Kuiper Belt grains (a) in the ecliptic, Neptune-rotated frame and (b) in the azimuthally averaged, vertical plane containing the Sun and Neptune. Overplotted on both panels is the orbit of Pluto, also in the Neptune-rotated frame. Additionally, the orbits of Neptune and Jupiter are shown as thin dotted lines.

3. IDP flux to Pluto

Overplotted on both panels of Fig. 1 are projections of the trajectory of the Pluto–Charon system in the Neptune-rotated frame. In Fig. 1(a), where the trajectory is projected onto the ecliptic plane, we see that Pluto (as a Neptune-resonant object itself) orbits through the densest part of the 10 μm EKB grain density. In addition to the variability of the dust density in the ecliptic plane, one must also consider the vertical variation of the EKB dust density above and below the ecliptic plane for the case of the Pluto system. Pluto has an orbital inclination of approximately 17.1° and attains a maximum distance above and below the ecliptic plane of approximately 10 and 15 AU, respectively. The 10 μm EKB dust

Please cite this article in press as: Poppe, A.R. Interplanetary dust influx to the Pluto–Charon system. Icarus (2014), http://dx.doi.org/10.1016/j.icarus.2013.12.029