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Nanodust released in interplanetary collisions

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ABSTRACT

The lifecycle of near-Earth objects (NEOs) involves a collisional cascade that produces ever smaller debris ending with nanoscale particles which are removed from the solar system by radiation pressure and electromagnetic effects. It has been proposed that the nanodust clouds released in collisions perturb the background interplanetary magnetic field and create the interplanetary field enhancements (IFEs). Assuming that this IFE formation scenario is actually operating, we calculate the interplanetary collision rate, estimate the total debris mass carried by nanodust, and compare the collision rate with the IFE rate. We find that to release the same amount of nanodust, the collision rate is comparable to the observed IFE rate. Besides quantitatively testing the association between the collisions evolving large objects and giant solar wind structures, such a study can be extended to ranges of smaller scales and to investigate the source of moderate and small solar wind perturbations.

1. Introduction

By June 1 2017, more than 16,000 near-Earth objects (NEOs) have been discovered (https://cneos.jpl.nasa.gov/stats/size.html), and the number of NEOs is expected to increase dramatically as the size of the NEOs decreases (Johnson, 2014).

As Fig. 1 shows, collisional cascade is involved in the lifecycle of the NEOs. It grinds up the NEOs to smaller and smaller debris. The dynamics of the debris are governed by different effects, depending on the debris' sizes. For particles larger than a micrometer in diameter, they will spiral into the Sun under the Poynting-Robertson effect; while the nanoscale particles can be picked up via electromagnetic forces.

The debris released in collisions generally constitutes a large amount in a relatively short time and limited space. Therefore, instead of picking up the nanodust individually, the solar wind interacts with a cloud of nanodust coherently. Such interactions could perturb the background interplanetary magnetic field (IMF) significantly and create a unique magnetic structure called an interplanetary field enhancement (IFE).

IFEs are characterized by a cusp-shaped enhancement in the field strength and strong central current sheets (Russell et al., 1983). It has been proposed that the former signature is caused by the pileup of the magnetic field in the upstream region of the dust cloud, transferring momentum from the solar wind to push the dust away from the Sun (Lai et al., 2013; Lai et al., 2015). Lai et al., (2015) explained the latter signature as the twist of the magnetic field due to the existence of heavy charged particles (Jia et al., 2012). Statistical studies also reveal that solar wind is slowed down in the upstream region of the dust cloud (Lai et al., 2013).

IFEs as collisional signatures have been used to identify co-orbiting objects of known NEOs (Russell et al., 1984; Lai et al., 2017). Those co-orbitals may be generated in early collisions and are still subject to continuous collisions. This new survey technique is powerful as it is sensitive to small objects which are otherwise "invisible" to a traditional terrestrial-based optical telescope. In addition, most of the interplanetary spacecraft are equipped with magnetometers, and their data can be used in such a technique.

Although early studies have already qualitatively tested the relation between IFEs and collisions, the quantitative comparison between the IFE rate and collision rate is still elusive. To further test this IFE formation scenario, we compare an estimated interplanetary collision rate to the IFE rate in this paper. In Section 2, we review the statistical properties of IFEs detected at 1AU, including their annual rate, scale and the mass of related dust clouds. In Section 3, we introduce our model calculating the interplanetary collision rate and compare the modeled results with IFE observations. Section 4 summarizes this study.

2. IFE properties

One-Hz magnetic field data from the Advanced Composition Explorer (ACE) (Smith et al., 1998) are used to survey the IFEs at 1AU. We use the same IFE selection criteria (Lai et al., 2013; Lai et al., 2014; Lai et al., 2017): (1) the magnetic field enhancement $\frac{B_{max}-B_{amb}}{B_{amb}}$ is at least 25%; (2)

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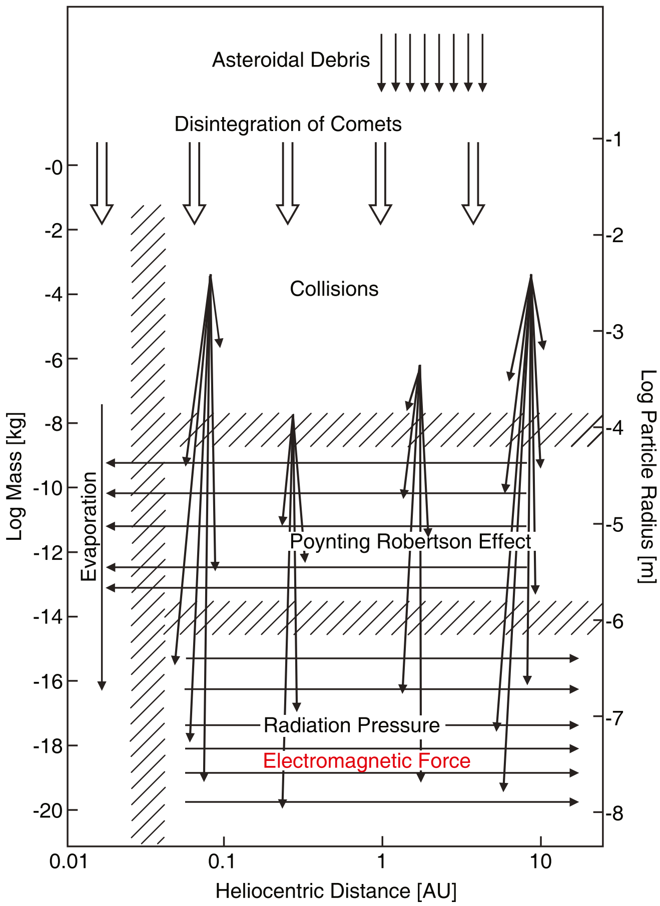

Fig. 1. The collisional cascade that grinds meteoroids and asteroids into dust, which falls into the Sun or is blown out of the solar system (after Grün et al., 1985).

the influence period (see Fig. 2) of the IFEs is at least 10 min; (3) no smooth rotation is shown in the magnetic field during the event. An example of moderately large IFEs is shown in Fig. 2.

In total, 103 IFEs are identified from 1998 to 2011. Since the IFEs generally move at nearly the solar wind speed (e.g., Russell et al., 2010; Lai et al., 2015), the radial scale of the IFEs is defined as the product of the solar wind speed and the event duration. Here the solar wind speed is measured by solar wind electron proton alpha monitor (SWEPAM) on ACE (McComas et al., 1998). Fig. 3a shows the IFE annual rate binned by the radial scale.

To estimate the mass of the dust cloud contained in the IFEs, Lai et al., (2014) calculate the gradient force on the IFEs by integrating the pressure difference over the IFE cross section, which is proportional to the square of the radial scale. Lai et al., (2015) confirm that this force is consistent with the solar wind slowdown. By balancing the pressure gradient force with the solar gravity, the mass contained in the IFEs is estimated (e.g., Lai et al., 2014; Lai et al., 2017). We use the same technique here, and the mass distribution is shown in Fig. 3b. We note that the IFE rate is a non-monotonic function of the mass. Due to the selection criteria, we might have undercounted the very weak and small IFEs, as shown in the left-most bar in Fig. 3b. In addition, there are few very large IFEs. Therefore, the right-most bars in Fig. 3a and b have less statistical accuracy.

3. Collision model and results

3.1. Interplanetary collision model

As calculated by Grün et al., (1985), the impactors (the smaller objects in these binary collisions) can disrupt targets (the larger objects in the collisions) 10^6 times larger than themselves in mass when the collisional speed is tens of kilometers per second. Thus we must investigate the interplanetary objects over a wide range of masses. Below we modify the influx model given by Ceplecha (1992) to obtain the interplanetary flux model at 1AU.

Ceplecha (1992) employed observations in different mass ranges and reconstructed the flux of the interplanetary objects from 10^{-20}kg to 10^{15}kg coming to the entire surface of the Earth. To convert this influx model to a more general interplanetary flux model, we scale Ceplecha's model so that it matches the lunar flux model (Grün et al., 1985) from 10^{-20}kg to 10^{-10}kg, as shown in Fig. 4a. The differential spatial number density at 1AU is then $\frac{dN(m,r_0)}{d(\log_{10}m)} = \frac{dF(m,r_0)}{d(\log_{10}m)}\frac{k}{V(r_0)}$. Here F is the cumulative flux, N is the cumulative spatial density, r_0 is 1AU and $k = 4$ in the case of an isotropic flux. $V(r)$ is the average collisional velocity and $V(r) = V_0\left(\frac{r}{r_0}\right)^{0.5}$ with $V_0 = 20\mathrm{km/s}$ (Grün et al., 1985). Inside 1AU, we assume that the number density of the interplanetary bodies is $\left(\frac{r}{r_0}\right)^{-1.5}$ (Leinert et al., 1978).

Here we consider catastrophic collisions only, which are defined in situations when the largest fragment contains at most 50% of the target's mass. Such collisions are expected to produce nanoscale dust most efficiently. Catastrophic collisions happen when the mass ratio between the target (m_1) and the impactor (m_2) satisfies $\frac{m_1}{m_2} \le T$, where T is a function of the collisional speed and the material properties of the targets. We use the same model as Grün's $T(r) = T_0\left(\frac{r}{r_0}\right)^{-1}$, where $T_0 = 9.76\times10^2 S_c^{-0.45}\left(\frac{m_1}{\rho_1}\times10^6\right)^{0.075} v_0^2$. For a crystalline rock target, $S_c = 3\mathrm{kbar}$ and $\rho_1 = 2.5\times10^3\mathrm{kg}$. Fig. 4b shows estimated T_0 as a function of the target mass at 1AU. We can see that when the collisional velocity is 20 km/s, T is generally larger than 10^4 and can reach 10^6 when the mass of the target is larger than 5.13×10^5kg.

The collisional cross section can be expressed as $\sigma(m_1,m_2) = \pi\left(\frac{3}{4\pi\rho}\right)^{\frac{2}{3}}\left(m_1^{\frac{1}{3}} + m_2^{\frac{1}{3}}\right)^2$ and the rate of catastrophic collisions of a target (m_1) by impactors (m_2) in the range $m_1/T \le m_2 < M_\infty$ is given by

$$-\int_{m_1/T}^{M_\infty}\sigma(m_1,m_2)k\frac{dF(m_2,r)}{d(\log_{10}m_2)}d(\log_{10}m_2). \quad (1)$$

In a unit volume, the collision rate between targets (m_1) and impactors (m_2) is thus

$$\frac{dN(m_1,r)}{d(\log_{10}m_1)}\int_{m_1/T}^{M_\infty}\sigma(m_1,m_2)k\frac{dF(m_2,r)}{d(\log_{10}m_2)}d(\log_{10}m_2).$$

Here M_∞ is set to be 10^{15}kg and the negative sign in (1) is due to the definition of cumulative flux.

After collision, the mass of the targets and impactors is carried by the debris. To get the debris distribution, we extrapolate the experimental results of Fujiwara et al., (1977) to small debris regions and assume that the mass distribution of the fragments can be approximated by a power law (Grün et al., 1985)

$$\frac{dG(m,m_1,m_2)}{d(\log_{10}m)} = c_1 m^{-\eta}.$$

Here $\eta = 0.83$ and c_1 can be calculated from the conservation of mass

$$\int_0^{m_L} m\frac{dG(m,m_1,m_2)}{d(\log_{10}m)}d(\log_{10}m) = m_1.$$

The mass of the largest fragment m_L is found to be