Evolution of Cometary Dust Particles to the Orbit of the Earth: Particle Size, Shape, and Mutual Collisions

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Abstract

In this study, we numerically investigated the orbital evolution of cometary dust particles, with special consideration of the initial size–frequency distribution (SFD) and different evolutionary tracks according to the initial orbit and particle shape. We found that close encounters with planets (mostly Jupiter) are the dominating factor determining the orbital evolution of dust particles. Therefore, the lifetimes of cometary dust particles (∼250,000 yr) are shorter than the Poynting–Robertson lifetime, and only a small fraction of large cometary dust particles can be transferred into orbits with small semimajor axes. The exceptions are dust particles from 2P/Encke and, potentially, active asteroids that have little interaction with Jupiter. We also found that the effects of dust shape, mass density, and SFD were not critical in the total mass supply rate to the interplanetary dust particle (IDP) cloud complex when these quantities are confined by observations of zodiacal light brightness and SFD around the Earth’s orbit. When we incorporate a population of fluffy aggregates discovered in the Earth’s stratosphere and the coma of 67P/Churyumov–Gerasimenko within the initial ejection, the initial SFD measured at the comae of comets (67P and 81P/Wild 2) can produce the observed SFD around the Earth’s orbit. Considering the above effects, we derived the probability of mutual collisions among dust particles within the IDP cloud for the first time in a direct manner via numerical simulation and concluded that mutual collisions can mostly be ignored.

Key words: comets: general – interplanetary medium – planets and satellites: dynamical evolution and stability – zodiacal dust

1. Introduction

During the first half of the 20th century, it became evident that dust particles ejected from objects in the solar system that are not the Sun itself are scattered in interplanetary space and are therefore observed as zodiacal light (by reflecting sunlight) and meteors (through encounters with the Earth) (Fechtig et al. 2001 and references therein). At the same time, it was found that, because of the Poynting–Robertson (P–R) effect and drag from the solar wind, those particles are falling to the Sun on a timescale shorter than ∼10^7 yr, which is ≈2–3 orders of magnitude less than the age of the solar system (Mann et al. 2006). Therefore, recent or continuous dust sources are required to explain the existence of the interplanetary dust particle (IDP) cloud complex at the current epoch. For the source of the IDPs, Nesvorný et al. (2010) argued that approximately 90% of them originate from comets by connecting the vertical brightness profiles of observed mid-infrared zodiacal light with those of their numerical models. Yang & Ishiguro (2015) came to a similar conclusion (i.e., >90% from comets) through a comparison between the observed optical properties (i.e., albedo and optical spectral gradient) of zodiacal light and those of different kinds of minor bodies in the solar system. In contrast, there are studies that have suggested a non-negligible fraction of asteroidal particles in the IDP cloud. Ipavtov et al. (2008) examined the Doppler shifts of zodiacal light’s Mg I Fraunhofer line and contrived an IDP cloud model that consisted of 30%–50% of asteroidal particles. Kawara et al. (2017) analyzed the UV–optical spectrum of zodiacal light taken with the Hubble Space Telescope and insisted that the spectrum is similar to that of C-type asteroids.

Under these circumstances, Nesvorný et al. (2011) reproduced the observed orbital distribution of helion meteors from dust ejected from Jupiter family comets (JFCs). However, as Ueda et al. (2017) indicated, recent in situ measurements by Rosetta at the coma of 67P/Churyumov–Gerasimenko (Fulle et al. 2015, 2016b; Rotundi et al. 2015; Agarwal et al. 2016; Bentley et al. 2016; Hilchenbach et al. 2016; Mannel et al. 2016; Merouane et al. 2016) suggested that the initial dust density and size–frequency distribution (SFD) are different from those in Nesvorný et al. (2011)’s initial conditions. Furthermore, the in situ measurements from the Giotto mission (Fulle et al. 1995) and Stardust mission (Green et al. 2004, 2007) as well as IR observation (Vaubaillon & Reach 2010) unanimously determined an SFD similar to that determined by the Rosetta mission, even though the authors studied different comets (1P/Halley, 81P/Wild 2, and 73P/Schwassmann–Wachmann 3). Therefore, a careful treatment or explanation of these initial conditions is required to further confirm the cometary origin of IDPs. In this work, we investigated this question by introducing fluffy aggregates discovered in the Earth’s stratosphere (Bradley 2003) and the coma of 67P/Churyumov–Gerasimenko (Fulle et al. 2015; Bentley et al. 2016; Mannel et al. 2016).

The total mass budget of the IDP cloud complex is also an important factor in characterizing the various physical processes because the budget is determined by a balance of all the processes that supply and remove dust in the solar system. Nesvorný et al. (2011) estimated the total mass ejection rate to the IDP cloud complex as 10^{5}–10^{7} kg s^{-1}. In this work, we revisited this budget with modified initial conditions.

Regarding the sink, it has been considered that catastrophic mutual collisions would be the dominant mechanism in
breaking IDPs in the size range $>200 \mu m$ (Dohnanyi 1978; Grün et al. 1985; Steel & Elford 1986). Whereas these studies were targeted at IDPs on fixed circular orbits, their results were considered in previous dynamical research into IDPs on eccentric cometary orbits (Wiegert et al. 2009; Nesvorný et al. 2011; Pokorný et al. 2014). However, even though these authors did not pursue the reason, recent studies have reported that their results can be explained better when the actual collisional lifetime is longer than that of Grün et al. (1985) (Nesvorný et al. 2011; Jenniskens et al. 2016, for example). Under this circumstance, Soja et al. (2016) calculated the collisional lifetime of IDPs on fixed eccentric orbits, and reported it to be longer than that of Grün et al. (1985). Therefore, it is time to investigate the probability of mutual collisions in more realistic situations—IDPs on orbits that are initially eccentric and evolving under planetary perturbation and radiational acceleration.

In this study, we numerically examined the evolution of dust particles ejected from cometary nuclei. Through this work, we tested a wide variety of initial conditions, namely orbits, dust shape, density, and the SFD. We investigated different evolutionary tracks according to initial orbits and ratios of cross section to mass for dust particles. Then, we searched for valid combinations of dust particles with different particle shape, density, and initial SFD values, considering the in situ measurements by the spacecraft. The required mass budgets of the IDP cloud complex were derived for valid cases. Finally, we estimated the probability of mutual collisions among dust particles. Note that this is the first attempt to connect the dust SFD of cometary comae with the SFD around the Earth. This work is also the first attempt to derive the probability of mutual collisions in a direct manner via numerical simulation. The description of our methodology is presented in Section 2. In Section 3.1, we examine different evolutionary tracks under different initial conditions: particles ejected from JFCs or 2P/Encke-like objects, and particles with small or large ratios of radiative acceleration to gravitational acceleration. In Section 3.2, we show the possible combinations of evolutionary tracks under different initial conditions, including particles that are compact or fluffy, particles with high or low particle densities, and different forms of initial SFD. We show the expected mass supply rate for the possible combinations in Section 3.3. We estimate the probability of mutual collisions among IDPs with respect to the source orbits, particle sizes, and particle shape in Section 3.4. In Section 4, we consider relative contribution from different initial orbits, particle size, and particle shape to the zodiacal light brightness and density near the Earth’s orbit along with the total mass supply rate.

2. Methodology

2.1. Numerical Integration

In our model, we ejected hypothetical dust particles from the orbits of selected “actual” comets. We considered nine different values of $\beta$, the ratio of the solar radiative acceleration to the solar gravitational acceleration: $\beta = 0.57, 0.285, 0.114, 0.057, 0.0114, 0.0057, 0.00285, 0.00114$, and $0.00057$. When spherical particles with a density of $0.8 \text{ g cm}^{-3}$ are assumed, these $\beta$ values are equivalent to diameters of 2.5, 5, 12.5, 25, 125, 250, 500, 1250, and $2500 \mu m$ (Burns et al. 1979). Details of the source selection and dust ejection will be explained in the subsections below. All dust particles were ejected at the same epoch, a Julian date of 2457054.5 (A.D. 2015 February 1, 0:00) for convenience in our simulation. Planetary ephemerides for each epoch were calculated with an $N$-body simulation using the initial data in Chambers (1999). During the numerical calculation of the orbital evolution of dust particles, we accounted for the Sun and eight planets as massive objects that exert gravitational accelerations and ignored the gravitational effects of other objects. In addition, radiative acceleration, including P–R drag due to solar radiation, was considered, while such effects due to other sources were ignored because of their weakness. Solar radiation was treated as constant over time. The effect of drag from the solar wind is assumed to be equal to $30\%$ of the P–R drag (Burns et al. 1979). We employed a numerical integrator applying the RADAU15 algorithm (Everhart 1985), originally coted by Chambers (1999, MERCURY 6.2), and modified by Jeong (2014) to take into account the effects of radiation. Dust particles were excluded from the calculation when their heliocentric distance became larger than 80 au or smaller than 0.05 au. The initial integration time step was 3.6525 days, and the variable time step was chosen to achieve an accuracy of at least $|\Delta E/E| \leq 10^{-12}$ in energy during a single step. We stopped integrations after 2 million years, when most dust particles were excluded from the numerical integration by the above conditions.

2.2. Source Population

According to previous research (Tancredi et al. 2006; Snodgrass et al. 2011), even though JFCs have not been completely surveyed, it is suggested that the distribution of known JFCs is not observationally biased, and therefore the SFDs of all known JFCs and those of JFCs with small perihelion distances are statistically the same (Fernández et al. 2013), implying that known JFCs can statistically represent the whole population. Therefore, supposing that JFCs are the main source of the IDP cloud complex, we began our simulation from existing cometary nuclei. Furthermore, we assumed that number of comets has been constant over a few million years, as we explain in Section 2.4. This approach of source selection is basically similar to but slightly different from the idea in Wiegert et al. (2009). The difference in source selection between Wiegert et al. (2009) and this work is threefold. First, they assumed that the whole asteroid population in their model ejects a small number of dust particles as a result of mutual collisions, whereas we considered that active asteroids (rather than the entire population) eject dust particles. Second, we considered small dust particles with a large cross section to mass ratio (i.e., $\beta > 0.057$), which were not considered in Wiegert et al. (2009). Lastly, we included three times as many comets as Wiegert et al. (2009) did. We chose the source comets from the JPL Horizons comet list as of 2015 January 23 (http://ssd.jpl.nasa.gov/dot/ELEMENTS.COMET).

Among the 3321 comets in the list, we chose periodic comets with eccentricity $e < 1$ and excluded fragments to avoid duplication from dust particles from the same comets. In total, we chose 1049 comets for consideration. We classified these comets into JFCs, Encke-type comets (ETCs), Chiron-type comets (CTCs), and Halley-type comets (HTCs) following the criteria in Levison (1996). HTCs were further divided into two classes: one with semimajor axis $a$ larger than that of Jupiter, $a_j$ (HTC-1), and the other with $a \leq a_j$ (HTC-2). ETCs
were further categorized into two classes: one case having a Tisserand parameter with respect to Jupiter of $T_J < 3.01$ (ETC-1), the other with $T_J \geq 3.01$ (ETC-2). In our simulation, dust particles from ETC-1 experienced close encounters with Jupiter and had similar evolutionary tracks to dust particles from JFCs. Dust particles from ETC-2 are less influenced by close encounters with Jupiter. Note that this criterion is different from the working definition of active asteroids (AAs), that is, $T_J \geq 3.08$ (Jewitt et al. 2015), because our concern is not the orbital similarity with asteroids but the dynamical interaction with Jupiter. The orbit of 2P/Encke is largely different from those of AAs (occasionally referred to as main-belt comets) in that 2P/Encke has a large eccentricity and a short perihelion distance. However, dust particles from 2P/Encke are less susceptible to a close encounter with Jupiter than those from JFCs, similar to AAs. For this reason, both 2P/Encke and AAs are categorized into the same group (ETC-2) in our definition.

In orbital element space, we constructed 17 step bins for semimajor axis $a$ (0.0–0.5, 0.5–1.0, 1.0–1.5, 1.5–2.0, 2.0–2.5, 2.5–3.0, 3.0–3.5, 3.5–4.0, 4.0–4.5, 4.5–5.0, 5.0–7.0, 7.0–9.0, 9.0–14.0, 14.0–19.0, 19.0–24.0, 24.0–30.0, 30.0–40.0 in au), 5 bins for eccentricity $e$ (0.0–0.2, 0.2–0.4, 0.4–0.6, 0.6–0.8, 0.8–1.0), and 6 bins for inclination $i$ (0°–30°, 30°–60°, 60°–90°, 90°–120°, 120°–150°, 150°–180°), and counted the number of cometary orbits within each bin three-dimensionally. With this choice of bins, each box includes 0 to 63 cometary orbits. In each box, we chose sample comets as representative of the whole population of the given orbital class and performed the numerical calculation with their orbital elements. To eliminate sampling bias and reduce computational load, we chose multiple samples in a box if the number of orbits in a box is larger than 5.5% of the total number of JFCs, ETC-1s, ETC-2s, and HTC-2s. With this assumption, we implied that dust ejected from other comets in the box should experience orbital evolution similar to that of representative comets. Table 1 shows the list of selected comets included in the calculation and their weighting factor $w_i$, which is the number of comets whose dust particles are assumed to have similar evolution to the particles from the listed comets. Later in Section 2.4, when we made clones of cometary dust particles, the number of clones was determined to be proportional to $w_i$. The orbital elements of selected comets, 64 JFCs, 45 HTC-1s, 2 HTC-2s, 3 ETC-1s, 6 ETC-2s, and 6 CTCs are listed in Table 1 along with their $w_i$ values.

As mentioned above, we assumed that our sample of JFCs, HTC-2s, ETC-1s, and ETC-2s is free from discovery bias and used the data in making the IDP cloud complex model in Section 2.4. CTCs and HTC-1s were not included in the model but are referred to for comparison. The orbital distribution of these comets is shown in Figure 1. As a comparison (see Tables 2 and 3), we also performed a numerical simulation of asteroidal dust particles. We tested a simple situation in which one dust particle per $\beta$ value was ejected from the largest 1933 asteroids (>15 km in diameter), considering that these large asteroids are completely detected.

### 2.3. Dust Ejection

We ejected dust particles from the orbits of the above actual cometary nuclei by using the following methods. At first, the orbits of comets at the epoch $t_0 = JD 2457054.5$ were numerically calculated from the orbital elements of the JPL.
| Name                      | Orbital Type | q (au) | e | i (deg) | w (°) |
|--------------------------|--------------|--------|---|---------|-------|
| P/2002 T5 (LINEAR)       | JFC          | 3.93   | 0.437 | 30.9    | 3     |
| C/2003 E1 (NEAT)         | JFC          | 3.24   | 0.764 | 33.5    | 1     |
| P/2004 A1 (LONEOS)       | JFC          | 5.46   | 0.308 | 10.6    | 7     |
| P/2004 V3 (Siding Spring)| JFC          | 3.94   | 0.446 | 50.5    | 2     |
| C/2007 S2 (Lemmon)       | JFC          | 5.56   | 0.557 | 16.9    | 2     |
| C/2008 E1 (Catalina)     | JFC          | 4.83   | 0.548 | 35.0    | 1     |
| P/2008 O3 (Boattini)     | JFC          | 2.50   | 0.695 | 32.3    | 2     |
| P/2010 H2 (Vales)        | JFC          | 3.11   | 0.193 | 14.3    | 1     |
| P/2010 H5 (Scotii)       | JFC          | 6.03   | 0.156 | 14.1    | 1     |
| C/2011 KP36 (Spacewatch) | JFC          | 4.88   | 0.873 | 19.0    | 1     |
| P/2012 C3 (PANSTARRS)    | JFC          | 3.62   | 0.626 | 9.19    | 9     |
| C/2012 Q1 (Kowalski)     | JFC          | 9.48   | 0.637 | 45.2    | 1     |
| P/2012 US27 (Siding Spring)| JFC         | 1.82   | 0.649 | 39.3    | 1     |
| C/2012 X2 (PANSTARRS)    | JFC          | 4.75   | 0.771 | 34.1    | 1     |
| P/2013 EW90 (Tenagra)    | JFC          | 3.30   | 0.196 | 31.8    | 1     |
| 2003EH1                   | JFC          | 1.19   | 0.618 | 70.8    | 1     |
| 74P/Smirnova–Chernykh     | ETC-1        | 3.54   | 0.149 | 6.65    | 5     |
| 87P/Bus                   | ETC-1        | 2.10   | 0.389 | 2.60    | 8     |
| 94P/Russell 4            | ETC-1        | 2.23   | 0.364 | 6.18    | 6     |
| 2P/Encke                 | ETC-2        | 0.336  | 0.848 | 11.8    | 1     |
| 233P/La Sagra            | ETC-2        | 1.79   | 0.409 | 11.3    | 5     |
| 259P/Garradd             | ETC-2        | 1.79   | 0.342 | 15.9    | 1     |
| 311P/PANSTARRS           | ETC-2        | 1.94   | 0.115 | 4.97    | 2     |
| 324P/La Sagra            | ETC-2        | 2.62   | 0.154 | 21.4    | 1     |
| 331P/Gibbs               | ETC-2        | 2.88   | 0.0414| 9.74    | 1     |
| 39P/Opherma              | CTC          | 5.47   | 0.246 | 1.94    | 2     |
| 165P/LINEAR              | CTC          | 6.83   | 0.622 | 15.9    | 1     |
| 166P/NEAT                | CTC          | 8.56   | 0.383 | 15.4    | 2     |
| 167P/CINEOS              | CTC          | 11.8   | 0.270 | 19.1    | 1     |
| P/2005 S2 (Skiff)        | CTC          | 6.40   | 0.197 | 3.14    | 2     |
| C/2013 C2 (Tenagra)      | CTC          | 9.13   | 0.429 | 21.3    | 2     |
| 1P/Halley                | HTC-1        | 0.586  | 0.967 | 162.    | 1     |
| 5P/Tuttle                | HTC-1        | 1.03   | 0.820 | 55.0    | 1     |
| 12P/Pons–Brooks          | HTC-1        | 0.774  | 0.955 | 74.2    | 2     |
| 13P/Olbers               | HTC-1        | 1.18   | 0.930 | 44.6    | 4     |
| 23P/Brosen–Metcalf       | HTC-1        | 0.479  | 0.972 | 19.3    | 2     |
| 27P/Crommelin           | HTC-1        | 0.748  | 0.919 | 29.0    | 4     |
| 35P/Herschel–Rigollet    | HTC-1        | 0.748  | 0.974 | 64.2    | 5     |
| 55P/Tempel–Tuttle        | HTC-1        | 0.976  | 0.906 | 162.    | 2     |
| 109P/Swift–Tuttle        | HTC-1        | 0.960  | 0.963 | 113.    | 1     |
| 122P/de Vico             | HTC-1        | 0.659  | 0.963 | 85.4    | 2     |
| 126P/IRAS                | HTC-1        | 1.72   | 0.696 | 45.8    | 1     |
| 161P/Hartley–IRAS        | HTC-1        | 1.27   | 0.835 | 95.7    | 1     |
| 177P/Barnard             | HTC-1        | 1.11   | 0.955 | 31.2    | 3     |
| 262P/McNaught–Rusell     | HTC-1        | 1.28   | 0.815 | 29.1    | 1     |
| 273P/Pons–Gambart        | HTC-1        | 0.810  | 0.975 | 136.    | 2     |
| C/1855 L1 (Donati)       | HTC-1        | 0.568  | 0.986 | 157.    | 1     |
| C/1857 O1 (Peters)       | HTC-1        | 0.747  | 0.980 | 32.8    | 3     |
| C/1906 V1 (Thiele)       | HTC-1        | 1.21   | 0.949 | 56.0    | 2     |
| C/1921 H1 (Dubiego)      | HTC-1        | 1.10   | 0.848 | 22.1    | 1     |

Notes.

* Orbital types of comets (see Section 2.2).
* Perihelion distance.
* Eccentricity.
* Inclination.
* Initial weighting factor (see Section 2.2).

Horizons comet lists. Then, five orbital elements of the comets were fixed, except for anomalies. All dust particles were ejected simultaneously at the epoch on the orbits of comets with randomized true anomalies. We ejected 100 dust particles per given size per cometary orbit for particles with $\beta \geq 0.00285$ and 50 for particles with $\beta \leq 0.0014$.

When we distributed the true anomalies, we made the number density of ejected dust particles becomes a function of...
Figure 1. Distributions of orbital elements of all comets with semimajor axes shorter than 40 au, discovered before 2015 January 23. Large filled circles are comets included in our numerical integration, and small crosses are comets that are not included.

Table 2
Proportion of Dust Particles with $a \leq 1$ au from Different Source Populations and $\beta$ Values (%)

| $\beta$ | 0.57 | 0.285 | 0.114 | 0.057 | 0.0114 | 0.0057 | 0.00285 | 0.00114 | 0.00057 |
|---------|------|-------|-------|-------|--------|--------|---------|--------|--------|
| JFC     | 0.025| 4.3   | 41    | 45    | 30     | 25     | 16      | 5.6    | 2.9    |
| ETC-1   | 0.0  | 9.8   | 47    | 30    | 19     | 12     | 6.9     | 2.6    | 0.84   |
| ETC-2   | 0.0  | 25    | 73    | 77    | 97     | 99     | 100     | 100    | 97     |
| HTC-1   | 0.0  | 0.22  | 3.2   | 13    | 19     | 12     | 5.5     | 1.4    | 0.16   |
| HTC-2   | 0.0  | 0.0   | 0.0   | 0.0   | 0.83   | 1.0    | 0.0     | 0.33   | 0.0    |
| CTC     | 0.0  | 0.30  | 7.2   | 12    | 8.1    | 5.2    | 3.1     | 0.80   | 0.0    |
| Asteroids | 0.052| 35    | 86    | 94    | 97     | 96     | 87      | 6.5    |        |

Table 3
Proportion of Dust Particles that Remain in the Solar System after 2 Million Years of Integration (%)

| $\beta$ | 0.57 | 0.285 | 0.114 | 0.057 | 0.0114 | 0.0057 | 0.00285 | 0.00114 | 0.00057 |
|---------|------|-------|-------|-------|--------|--------|---------|--------|--------|
| JFC     | 0.0  | 0.0   | 0.0   | 0.025 | 0.75   | 1.1    | 1.6     | 1.8    | 2.6    |
| ETC-1   | 0.0  | 0.0   | 0.0   | 0.0   | 2.4    | 0.89   | 1.9     | 2.6    | 3.8    |
| ETC-2   | 0.0  | 0.0   | 0.0   | 0.0   | 0.0    | 0.0    | 0.0     | 0.0    | 0.0    |
| HTC-1   | 0.0  | 0.0   | 0.0   | 0.0   | 0.099  | 1.6    | 2.3     | 4.0    | 4.7    |
| HTC-2   | 0.0  | 0.0   | 0.0   | 0.0   | 0.0    | 0.0    | 0.0     | 0.0    | 0.0    |
| CTC     | 0.0  | 0.0   | 0.80  | 3.3   | 8.7    | 8.2    | 9.8     | 7.6    | 10     |
| Asteroids | 0.0  | 0.0   | 0.0   | 0.10  | 0.16   | 0.0    | 0.21    | 6.8    | 84     |
heliocentric distance which reflects the observed change in the dust ejection efficiency (Ishiguro et al. 2007; Mazzotta Epifani et al. 2009; Hanayama et al. 2012). Where $N(r_h)$ denotes the initial number density of ejected particles on the given cometary orbit in cm$^{-3}$, and $r_h$ denotes the heliocentric distance in au, we distributed the particles as

$$N(r_h) \propto r_h^{-3.0},$$ (1)

The directions of ejection are randomly distributed over the sunlit hemisphere following an uniform probability distribution, and the speeds of ejection are given as a function of $\beta$ and $r_h$ (Ishiguro et al. 2007; Hanayama et al. 2012), hence the ejection speed $v_e(r_h)$ are given by

$$v_e(r_h) = 200[\text{m s}^{-1}] \beta^{0.5} r_h^{-0.5}.\quad (2)$$

Although we assumed a relatively realistic situation in ejecting dust particles compared to the cases with zero ejection velocity, numerically, the added ejection velocities function as a kind of cloning process because they are small compared to the orbital velocities. Likewise, even though we ejected dust particles simultaneously at different positions on the cometary orbits instead of at the exact position of nuclei at the epoch, this approach is dynamically the same as changing the anomaly without changing other orbital elements, and therefore this method works as if it were a cloning process.

The initial orbital elements of ejected dust particles were calculated after the ejection velocities were added to the orbital velocities, taking account of the change of orbital elements due to radiative acceleration.

2.4. IDP Complex Modeling

We assumed that all of the above cometary nuclei eject dust particles at the same rate when we calculate the average over single revolutions. We also assumed that all nuclei eject dust particles with same shape and SFD once we fixed these parameters. Under these assumptions, the ratio between initial dust masses JFCs:HTC-2:ETC-1:ETC-2 is 486:6:19:11.

We constructed an IDP distribution covering different ages of particles for given $\beta$ values using the following methods. First, we recorded the positions and velocities of dust particles every 100 yr and cloned $1000 \times w_1$ particles from each individual dust particle. We set the number of the clones to be proportional to the parameter $w_1$. During the cloning process, we kept three orbital elements (i.e., the semimajor axes, eccentricities, and inclinations) constant and randomized their arguments of perihelion, longitudes of ascending node, and mean anomalies for each clone. Consequently, we made snapshots composed of clones with single $\beta$ values and from the same class of cometary population every 100 yr. Assuming a steady state (i.e., that dust ejections have occurred constantly over 2 million years), we regarded dust particle records after a given time of integration from the current epoch as records from possible ejections at the same amount of time before the current epoch. This assumption is similar to that made in previous works such as Wiegert et al. (2009). Finally, the snapshots were added together, constructing an IDP distribution covering the full dynamical evolution from sources to sinks.

Using the above information from our numerical calculation, we validated the initial conditions of dust ejection via following methods. Whenever the initial conditions about dust particle shape, mass density, and initial SFD were given, the resulting IDP cloud complex models were derived. We constructed a three-dimensional grid in Cartesian coordinates. Grids of size 0.1 au $\times$ 0.1 au $\times$ 0.1 au were constructed throughout interplanetary space, and the number of dust particles of a given $\beta$ value within a single grid was counted. The results for different $\beta$ values were weighted by the given initial conditions (see Section 3.2). As a next step, we derived the cumulative number, cross section, and mass distribution of IDPs in the grid box, assuming a piecewise exponential SFD within every single grid box. Then, after summing the numbers from different source populations, the resulting SFDs around the Earth’s orbit were normalized at $\beta = 0.00285$ and compared with the observational SFD in Grün et al. (1985), which was obtained through the Pegasus and HEOS-2 missions and widely applied as the reference SFD model. We examined the ratio between our normalized SFD and the observed one between $\beta = 0.00057$ and $\beta = 0.114$ and we treated the given initial conditions as valid if the ratio in SFD is between 0.5 and 2 for every $\beta$ value. For such cases, we derived a goodness of fit as the averaged absolute value of the logarithm of the ratios.

Finally, the total IDP cloud complex model was scaled to match the observed zodiacal light brightness in the antisolar direction (i.e., gegenschein) (Leinert et al. 1998; Ishiguro et al. 2013). As we mentioned in Section 2.1, we limited the largest dust size to $\beta = 0.00057$. This cutoff is expected to have negligible effects on the total cross section but may exert a considerable influence on the total mass according to the initial conditions. Therefore, we tabulated the total mass supply in two cases, namely up to $\beta \geq 0.00114$ and $\beta \geq 0.00057$, along with validated initial conditions.

3. Results

3.1. Orbital Evolution of Dust Particles According to Different Populations and Sizes

In this work, the sinks of dust particles were determined by close encounters with planets for most cases. We will explain the role of close encounters, which concurs with previous research. Dust particles ejected from comets fall toward the Sun because of P–R drag if the Sun’s gravity and radiation are the only two factors affecting their orbits. P–R drag continuously reduces $a$ and $e$ of the dust particles. The effects of resonances with planets (i.e., the mean motion and secular resonances) do not themselves change sinks of dust particles significantly because the resonances change $e$ rather than $a$. Note that the lifetime of dust particles may be changed by resonances, which would increase it temporarily by trapping them. In contrast, close encounters with planets, mainly Jupiter, can completely change the orbits of dust particles and usually prevent their falling toward the Sun. As a consequence of close encounters, $a$ may decrease or increase, and any $e$ value may occur from a circular orbit to a hyperbolic orbit. Dust particles ejected from the JFCs are prone to close encounters with Jupiter because the initial orbits of their source comets intersect or are close to the Jovian orbit and their velocities relative to Jupiter are low.

Smaller dust particles have higher chances of avoiding close encounters than larger particles because they fall toward the Sun faster via P–R drag and therefore spend less time in the region where the Jovian gravity is critical. Figure 2 shows the lifetime of dust particles under radiative acceleration. For
comparison, we construct the lifetime in the case where there are no planetary perturbations. Because P–R drift is slow for large particles, the lifetime of particles that are larger than 100 μm is determined by close encounters, not by P–R drift. Therefore, the lifetimes of large dust particles are similar to those of their parent bodies, ~100,000–300,000 yr (~100,000 yr as a weighted median, ~250,000 yr as a weighted average) (Levison & Duncan 1994, 1997). Note that the lifetime with planetary perturbation included the effects of resonances. The resonances may increase the lifetime of dust particles by temporarily trapping them, especially for particles that have evolved into the inner solar system.

We measured the fraction of dust particles transferred into the inner solar system (a ≤ 1 au) for different populations with different sizes (Table 2). The probability of successful transfer to an orbit with a semimajor axis smaller than 1 au will be selectively higher for dust particles meeting the following two conditions: dust particles ejected from objects with aphelion distances shorter than the semimajor axis of Jupiter and which are free from close encounters with Jupiter, ETC-2s, and asteroids; and dust particles that are small. We checked that the dust particles that are not transferred to the inner solar system within 2 million years of integration time satisfy one of the following conditions: they are trapped in the Trojan region; or β < 0.00114 and they are free from planetary encounter and thus still under P–R decay. The latter case includes dust particles ejected from AAs and asteroids, and we performed 5 million years of integration for these particles to complete the process of dust particle evolution. The proportions of dust particles surviving after 2 million years of integration are summarized in Table 3.

3.2. Dust Particle Shape, Density, and SFD

In previous subsection, we explained the different evolutionary tracks between the particles with different β values. From now on, we will connect the dust SFD measured around the Earth’s orbit with that measured around cometary comae. According to measurements from the Rosetta mission, the dust SFD at the coma of 67P/Churyumov–Gerasimenko changed over time, but it appears that there are at least two bending points in the SFD that can thus be approximated by a doubly broken power-law function. The bending points were determined at ~10^{-6} and ~10^{-4} g for most cases except for the region around perihelion (Rotundi et al. 2015; Agarwal et al. 2016; Fulle et al. 2016b; Hilchenbach et al. 2016; Merouane et al. 2016). The power-law exponents α for differential mass distributions dn ∝ m^{-α}dm varied between ~1.75 and 2.05 for the smallest masses, ~0.97 and 1.67 for intermediate masses (~1.9 right after perihelion), and approximately ~2.0 for the largest masses. The results from the Stardust mission (Green et al. 2004, 2007); Giotto mission (Fulle et al. 1995), and IR observation (Vauberion & Reach 2010) coincided with this point. This distribution is different from that measured around the Earth’s orbit by the Pegasus and HEROS-2 missions (Grün et al. 1985), but the difference itself is understandable when we consider the content of the previous subsection.

As explained before, what we actually calculated were orbital evolutionary tracks as a function of initial orbits and β values. In this subsection, we first converted β to particle mass assuming the particle shape and density. Next, we found the expected initial dust SFD that can explain the measured SFD around the Earth’s orbit. Finally, we compared the expected initial dust SFD with the measured one and derived assumptions that can match the two SFDs.

Cometary dust particles have been conventionally approximated as having a compact structure and a spherical shape. For compact particles, a low mass density of 0.8 g cm^{-3} was derived from modeling porous icy dust via the Rosetta measurements (Fulle et al. 2016a), but a relatively wide density range of 1.9 ± 1.1 g cm^{-3} was measured during the Rosetta mission by direct comparison between cross section and impact momenta assuming particle shape (Rotundi et al. 2015). We thus tested three different values of particle mass density, namely 0.8, 1.9, and 3.0 g cm^{-3} (Rotundi et al. 2015; Fulle et al. 2016a).
Despite the conventional treatment of IDPs as compact spherical particles, large fluffy aggregates (larger than hundreds of micrometers in diameter) were recently found around 67P/Churyumov–Gerasimenko via the observations of the Rosetta spacecraft (Fulle et al. 2015; Bentley et al. 2016; Mannel et al. 2016). Although the detailed physical properties such as the structures and/or porosity of the fluffy aggregates are not well investigated, it is likely that these fluffy aggregates have mass densities as low as 0.001 g cm$^{-3}$ (Fulle et al. 2015), and fractal dimensions were estimated to be 1.87 (Fulle et al. 2015; Mannel et al. 2016). Under these conditions, the ratio of cross section to mass of the aggregates is expected to be constant regardless of aggregate mass, or at least to exhibit only insignificant changes, unlike compact particles (Mukai et al. 1992; Skorov et al. 2016). We are not sure about the exact cause of the shallow SFD between $10^{-6}$ and $10^{-4}$ g, but we conjecture that the fluffy aggregates that were discovered by the Rosetta mission (Fulle et al. 2015; Bentley et al. 2016; Mannel et al. 2016) are responsible for this shallow SFD slope. The time of the change in the fluffy aggregate ratio coincides with a change in SFD around perihelion (Della Corte et al. 2015, 2016), and the size of large fragments from fluffy aggregates matches the particle size of the smaller bending point in the SFD (Hilchenbach et al. 2016; Merouane et al. 2016).

As the first trial, we employed the initial SFD of compact spherical dust particles with a single power law. Where $dn$ is the differential number density of dust particles of mass $m$, the initial SFD is written as $dn \propto m^{-\alpha} dm$. We tested different $\alpha$ values with intervals of 1/12. In this model, we cannot validate any initial parameters that yield less than twice the difference between observations and expectations; therefore, we tabulated the initial parameters that yield results that differ by less than a factor of five from the observation. The derived power index, $\alpha$, is summarized in Table 4. We also show the results of the fitting in Figure 3 along with other cases. We present the ratio between our best-fit SFD and that of Grün et al. (1985) in Figure 4.

Second, we employed compact spherical dust particles having a broken power-law initial SFD, namely $dn \propto m^{-\alpha_1} dm$ for $m \leq m_1$, and $dn \propto m^{-\alpha_2} dm$ for $m \geq m_1$. When fitting the data, we varied $m_1$ between five discrete $\beta$ values included in the numerical integration. The derived initial parameters are tabulated in Table 5.

Table 4

| $\rho$ (g cm$^{-3}$) | $\alpha$ | $dn_{\text{total}}/dt$ (t$^{-1}$)$^b$ | $dm_{\text{total}}/dt$ (g cm$^{-2}$ t$^{-1}$)$^c$ | Goodness of Fitd |
|---------------------|----------|-------------------------------------|-----------------------------------|-----------------|
| 0.8                 | 2.000–2.167 | 39–45                               | 35–43                             | 0.22–0.32       |
| 1.9                 | 1.917–2.000 | 39–44                               | ~35                               | 0.27            |
| 3.0                 | 1.833–2.000 | 44–53                               | 35–37                             | 0.25–0.27       |

Notes.

$^a$ $dn \propto m^{-\alpha} dm$.

$^b$ Total mass supply rate into the IDP cloud complex for particles with $\beta > 0.00057$.

$^c$ Total mass supply rate into the IDP cloud complex for particles with $\beta > 0.00114$.

$^d$ Average of absolute values of log of ratio between our model and observed model (Grün et al. 1985).

Third, we tested the case of a doubly broken power-law SFD with compact spherical dust particles. The SFD was assumed in the form $dn \propto m^{-\alpha_1} dm$ for $m \leq m_1$, $dn \propto m^{-\alpha_2} dm$ for $m_1 \leq m \leq m_2$, and $dn \propto m^{-\alpha_3} dm$ for $m_2 \leq m$. In this case, we assumed $\alpha_1 > \alpha_2$, $\alpha_3 > \alpha_2$, and limited parameters as in the previous case. The results are tabulated in Table 6.

The next model is composed of both compact spherical particles and fluffy aggregates. We assumed that the fluffy aggregates have constant $\beta$ values regardless of mass (Mukai et al. 1992; Skorov et al. 2016). The SFD of compact spherical particles was assumed to be $dn \propto m^{-\alpha_1} dm$ for $m \leq m_1$, and $dn \propto m^{-\alpha_3} dm$ for $m \geq m_1$. Then we assumed the total SFD of fluffy aggregates and compact spherical particles between masses of $m_1$ and $m_2$ to $dn \propto m^{-\alpha} dm$. The results are presented in Table 7.

The best-fit initial SFD of the previous paragraph has bending points at smaller mass than the SFD measured at cometary comae, and slopes steeper than measurements in the range 0.000114 < $\beta$ < 0.0057 (Table 7). As a final model, we applied the SFD with the same functional form as that in the above model but we fixed $m_1$ and $m_2$ around the observed values. Then, $\alpha_1$, $\alpha_2$, and $\alpha_3$ will be near the observed values, especially when the density of compact particles is higher than 1.9 g cm$^{-3}$. In these cases, the ratio between our estimation and the model of Grün et al. (1985) worsened by a factor of three for some sizes. However, our model using this observed value of input parameters is still not far from the SFD observed in the Earth’s orbit as presented in Table 8 and Figures 3 and 4.

As presented in Figure 4 and Tables 4–8, different dust ejection conditions for dust particle shape and density can be validated with the appropriate initial SFD. It is noteworthy that the dust ejection conditions measured around 67P/Churyumov–Gerasimenko and 81P/Wild 2 concur with dust particle measurements around the Earth’s orbit when we assume the existence of fluffy aggregates in the discovered size range. We consider that the various dust environments measured around cometary nuclei are in accordance with our knowledge about the IDP cloud complex and its cometary origin, and that the target comets of space missions (i.e., IP, 67P, and 81P) are not extraordinary but may represent ordinary dust ejections from comets.

3.3. Mass Supply Rate to the IDP Cloud Complex

By scaling our model SFD by the observed gegenschein brightness, we calculated the expected mass supply rate to the IDP cloud complex. As presented in Tables 4–8 and Figure 5, the total dust supply rate does not vary greatly according to dust particle shape, density, and the initial SFD when the latter is confined by the observed SFD around the Earth’s orbit. The required dust supply rate for particles with $\beta > 0.00057$ was 39–45 t s$^{-1}$ for model 1, 29–41 t s$^{-1}$ for model 2, 31–49 t s$^{-1}$ for model 3, 32–41 t s$^{-1}$ for model 4, and 32–43 t s$^{-1}$ for model 5. We thus find that the different SFD models in this research do not significantly change the mass supply rate. This value is roughly consistent with but slightly larger than the estimation of Nesvorný et al. (2011) of 1.6–25 t s$^{-1}$. When we consider that our derived SFD is shallower than that of Nesvorný et al. (2011), we believe that this difference is understandable.

Even though we did not include dust particles larger than $\beta = 0.00057$, we expect that this omission will not critically change our conclusion because the mass
supply rates for $\beta \geq 0.00114$ and $\beta \geq 0.00057$ are not significantly different from each other, as shown in Tables 4–8.

3.4. Mutual Collisions

Collisional probabilities of the objects in the solar system have been investigated since the pioneering works by Opik.
Table 5
Best-fit Parameters and Expected Mass Supply Rate for the SFD Model 2a

| ρ (g cm⁻³) | m₁ (g)      | m₂ (g)      | α₁    | α₂    | α₃    | dm_total/dt (t⁻¹)b | dm_total/dt (t⁻¹)c | Goodness of Fitd |
|------------|-------------|-------------|-------|-------|-------|--------------------|--------------------|------------------|
| 0.8        | 6.5 × 10⁻⁹  | 8.2 × 10⁻⁷  | 2.000 | 2.333 | ~34   | ~34                | 30–35              | 0.09–0.15        |
| 0.8        | 6.5 × 10⁻⁶  | 8.2 × 10⁻⁷  | 2.000 | 2.333 | ~34   | ~34                | 30–35              | 0.09–0.15        |
| 1.9        | 1.4 × 10⁻⁶  | 1.833–1.833 | 2.167 | ~29   | ~29   | 0.18               | 0.11–0.16          |
| 1.9        | 1.2 × 10⁻⁴  | 1.833–1.833 | 2.167 | ~29   | ~29   | 0.18               | 0.11–0.16          |
| 3.0        | 5.8 × 10⁻⁸  | 1.833–1.833 | 2.167 | ~29   | ~29   | 0.18               | 0.11–0.16          |
| 3.0        | 4.7 × 10⁻⁷  | 1.750–1.833 | 2.000 | 2.167 | 36–42 | 33–35              | 0.06–0.16          |

Notes.

a: $dn \propto m^{-α} dm$ for $m \leq m_c$, and $dn \propto m^{-α} dm$ for $m \geq m_c$.
b: Total mass supply rate into the IDP cloud complex for particles with $β > 0.00057$.
c: Total mass supply rate into the IDP cloud complex for particles with $β > 0.00114$.
d: Average of absolute values of log of ratio between our model and observed model (Grün et al. 1985).

Table 6
Best-fit Parameters and Expected Mass Supply Rate for the SFD Model 3a

| ρ (g cm⁻³) | m₁ (g)      | m₂ (g)      | α₁    | α₂    | α₃    | dm_total/dt (t⁻¹)b | dm_total/dt (t⁻¹)c | Goodness of Fitd |
|------------|-------------|-------------|-------|-------|-------|--------------------|--------------------|------------------|
| 0.8        | 6.5 × 10⁻⁹  | 8.2 × 10⁻⁷  | 2.000 | 2.333 | ~34   | ~34                | 30–35              | 0.10–0.19        |
| 1.9        | 6.5 × 10⁻⁶  | 8.2 × 10⁻⁷  | 2.000 | 2.333 | ~34   | ~34                | 30–35              | 0.10–0.19        |
| 3.0        | 5.8 × 10⁻⁸  | 4.7 × 10⁻⁷  | 2.000 | 2.167 | 36–42 | 33–35              | 0.06–0.16          |

Notes.

a: $dn \propto m^{-α} dm$ for $m \leq m_c$, $dn \propto m^{-α} dm$ for $m_1 \leq m \leq m_2$, and $dn \propto m^{-α} dm$ for $m \leq m$.
b: Total mass supply rate into the IDP cloud complex for particles with $β > 0.00057$.
c: Total mass supply rate into the IDP cloud complex for particles with $β > 0.00114$.
d: Average of absolute values of log of ratio between our model and observed model (Grün et al. 1985).

Table 7
Best-fit Parameters, Expected Mass Supply Rate, and Contribution of Fluffy Particles in Zodiacal Light for the SFD Model 4a

| ρ (g cm⁻³) | m₁ (g)      | m₂ (g)      | α₁    | α₂    | α₃    | dm_compl/dt (t⁻¹)b | ZL_dial/ZL (t⁻¹)c | Goodness of Fitd |
|------------|-------------|-------------|-------|-------|-------|--------------------|--------------------|------------------|
| 0.8        | 8.2 × 10⁻⁷  | 6.5 × 10⁻⁶  | 2.000 | 2.333 | 32–35 | 0.05–0.2           | 0.005              | 0.12–0.18        |
| 1.9        | 1.5 × 10⁻⁷  | 1.2 × 10⁻⁶  | 2.000 | 2.333 | 32–35 | 0.05–0.2           | 0.005              | 0.10–0.14        |
| 3.0        | 5.8 × 10⁻⁸  | 4.7 × 10⁻⁷  | 2.000 | 2.167 | 36–41 | 0.1–0.3            | 0.007              | 0.10–0.17        |

Notes.

a: Explanations of functional form in text.
b: Total mass supply rate into the IDP cloud complex for compact particles.
c: Total mass supply rate into the IDP cloud complex for fluffy aggregates.
d: Fraction of gegenschein brightness contributed by fluffy aggregates.
e: Fraction of mass of fluffy aggregates around the Earth’s orbit.
f: Average of absolute values of log of ratio between our model and observed model (Grün et al. 1985).

Table 8
Best-fit Parameters, Expected Mass Supply Rate, and Contribution of Fluffy Particles in Zodiacal Light for Model 5a

| ρ (g cm⁻³) | m₁ (g)      | m₂ (g)      | α₁    | α₂    | α₃    | dm_compl/dt (t⁻¹)b | ZL_dial/ZL (t⁻¹)c | Goodness of Fitd |
|------------|-------------|-------------|-------|-------|-------|--------------------|--------------------|------------------|
| 0.8        | 6.5 × 10⁻⁶  | 8.2 × 10⁻⁴  | 2.083 | 2.333 | 34–41 | 0.8–3              | 0.07               | 0.20–0.33        |
| 1.9        | 1.2 × 10⁻⁵  | 1.5 × 10⁻⁴  | 2.083 | 2.333 | 34–41 | 0.8–3              | 0.07               | 0.20–0.33        |
| 3.0        | 3.7 × 10⁻⁵  | 5.8 × 10⁻⁵  | 2.083 | 2.333 | 34–41 | 0.8–3              | 0.07               | 0.20–0.33        |

Notes.

a: Explanations of functional form in text.
b: Total mass supply rate into the IDP cloud complex for compact particles.
c: Total mass supply rate into the IDP cloud complex for fluffy aggregates.
d: Fraction of gegenschein brightness caused by fluffy aggregates.
e: Fraction of mass of fluffy aggregates around the Earth’s orbit.
f: Average of absolute values of log of ratio between our model and observed model (Grün et al. 1985).
The collisional lifetime of IDPs was estimated under the assumption of fixed circular orbits (Dohnanyi 1978; Grün et al. 1985; Steel & Elford 1986). It is noticed that catastrophic collisions among IDPs could be a dominant mechanism for losing IDPs if their sizes are larger than \( \sim 200 \mu m \) (Dohnanyi 1978; Grün et al. 1985; Steel & Elford 1986). Despite the simplified models in these references where IDPs revolve on fixed circular orbits, their estimated values have been considered in recent dynamical studies of cometary dust particles with eccentric orbits (Wiegert et al. 2009; Nesvorný et al. 2011; Pokorný et al. 2014). More recently, Soja et al. (2016) derived the collisional lifetime for

Figure 4. Ratio between our best-fit SFD models and the SFD observed around the Earth’s orbit by Pegasus and HEOS-2 spacecraft. Panel (e) is not from best-fit input parameters but from parameters measured around cometary nuclei by Rosetta and Stardust missions. (f) Goodness of fit indicates the average of absolute values of the log of the ratio between the model with the parameter and the observed model from Grün et al. (1985).
particles on various fixed eccentric orbits, and the lifetime was comparable with the P–R lifetime for 100 μm particles. On another front, the orbital distribution of helion meteors favors a collisional lifetime longer than the estimate of Grün et al. (1985) (Nesvorný et al. 2011). From the observational aspect, Jenniskens et al. (2016) discovered 7 mm meteorites delivered to the Earth that have orbits with low eccentricity, suggesting that such dust particles migrated via P–R drag before collisional breakup. To sum up this bibliographic background, it is required to calculate the collisional lifetime in a more realistic manner, where the orbits of IDPs evolve under planetary perturbations and P–R drag.

As mentioned in Section 3.1, most dust particles from JFCs are kicked out to orbits with large a values and stay for a long time in the outer solar system. Frequently, the particles eventually fall toward the Sun, are kicked out to orbits with large a values, and spend most of their lifetimes in such orbits. Furthermore, the eccentricity of their orbits does not decrease as in the situation with no planets. When we consider these factors along with the dynamical lifetimes of dust particles that are shorter than the P–R timescale, we can expect a lower probability of mutual collision in the IDP cloud complex. In this paper, we treated mutual collisions quantitatively and discussed whether the effect of impact is significant. We did not consider the impact velocity and the consequence of collision, but calculated the probability of collision regardless of impact velocity. We think this choice can simplify the treatments required during calculation.

We calculated the volume swept by a dust particle during orbital evolution. At each epoch, we also calculated the cross-section density on the positions of the dust particle orbit as a function of particle size. By integrating the product of these two values (i.e., the swept volume and the cross-section density), we derived the cross section swept by the dust particle. By dividing the swept cross section by the cross section of the single particle responsible (i.e., the projectile), we derived the contact probability for given epochs. We defined the contact timescale by dividing the dynamical lifetime by the total contact probability, which is the integral of the contact probability over the entire dynamical lifetime.

As we can see in Figure 2, mutual contact between particles with a size ratio that is larger than 1:100 (a mass ratio of one to million) will not happen in the IDP cloud complex. Because we did not consider the impact speed of these contacts, we are not sure how large a projectile is required to break the target dust particle, but it is expected that a projectile 100 times smaller than the target will not destroy it. In addition, we do not know the projectile size that is required to break the fluffy aggregates. The values in Figure 2 are from the case in which fluffy aggregates have the longest dynamical lifetime and the largest size (3 mm diameter), the case in which particles most easily experience collision. When we consider that fluffy aggregates were fragmented by collisions with impact speeds of ~cm s\(^{-1}\) in the COSIMA detector on the Rosetta spacecraft (Hilchenbach et al. 2016), we think contact with a 25 μm projectile would break the 3 mm fluffy aggregates at least partially, but we are not sure about the exact consequences of contact. However, overall, we can see that fluffy aggregates will not experience mutual collisions, especially at sizes smaller than a few millimeters in diameter.

### 4. The Relative Importance of Particles: Source, Size, and Shape

We list the relative contributions to the gegenschein brightness as a function of source and size in Table 9, adopting the case of a compact particle model with a density of 1.9 g cm\(^{-3}\). The difference is not large for other cases. A dominant fraction (>90%) of gegenschein brightness is caused by dust particles from JFCs, the β of which is in the range 0.057–0.00285 (10–200 μm in diameter for ρ = 1.9 g cm\(^{-3}\)). However, when we derived the relative contributions of each source to the dust particles around the orbit of the Earth as a function of size, for particles ≥1 mm, the contribution of ETC-2 dust particles is even larger than that of JFC particles, as shown in Table 10. Typically, dust particles ejected from 2P/Encke have lifetimes of ~100,000 yr, even for the largest ones, requiring about half of their lifetime to reach a < 1 au. Although

![Figure 5](https://via.placeholder.com/150)

**Figure 5.** Total mass supply rate for models with validated initial parameters. The resulting values from all different densities are included.
the past activities of 2P/Encke and similar objects (i.e., ETC-2) are not well known, we found that dust ejected from 2P/Encke will be more important than dust ejected from any other comet, at least for large dust particles in the inner solar system. Additionally, large dust particles ejected from AAs would have a larger contribution to the IDP cloud complex at small heliocentric distances than to the dust supply rate, though further research is needed to survey the dust production rates and the occurrence of AAs. Therefore, when we observe zodiacal light, meteors in the sky, and meteorites on the surface of the Earth, there is the possibility that each observation is of a different type of particle.

We tabulated the following values for compact particles and fluffy aggregates in Tables 7 and 8: mass supply rate, contribution to the gegenschein brightness, and fractional mass around the Earth’s orbit. As measured by Fulle et al. (2015) in the coma of 67P/Churyumov–Gerasimenko, the fluffy aggregates have small relative contributions at the moment of ejection. The contribution of these fluffy aggregates to the zodiacal light brightness is also small, that is, as much as ~1%–20%. Therefore, in our methodology, the total mass supply rate to the IDP cloud complex does not change much with or without fluffy aggregates. However, as shown in Table 8, their contribution may be significantly large in the sense of number density (or mass) near the Earth’s orbit. Therefore, our results suggest that fluffy IDPs discovered in the Earth’s stratosphere, which have similar fractal dimensions to the fluffy aggregates from 67P/Churyumov–Gerasimenko (Katyal et al. 2014), were possibly ejected from comets such as 67P.

5. Summary

In this study, we followed the evolution of dust particles ejected from cometary nuclei, considering different initial orbits, shapes, and SFDs. According to our model, the total mass supply rate from comets to the IDP cloud complex is 29–53 t s⁻¹. We discovered that if we introduce fluffy aggregates, the dust SFD measured in cometary comae can be evolved into the dust SFD measured around the Earth’s orbit. Even though the initial fractional mass of fluffy aggregates is small in the source regions, cometary comae, these aggregates may represent a relatively large fraction of the mass around the Earth’s orbit. Based on our findings above, we conjecture an initial dust SFD and mass supply rate that are different from those in Wiegert et al. (2009) and Nesvorny et al. (2011) without altering their conclusions of the dominant cometary contribution to IDPs, the model of zodiacal light brightness, and the orbital distribution of helion meteoroids.

Furthermore, we identified that large dust particles ejected from JFCs cannot be easily transferred to a small a orbit because of close encounters with Jupiter. Therefore, the contribution from ETC-2s may be high for large dust particles in small a orbits.

Finally, we directly calculated the probability of mutual collisions between dust particles in the IDP cloud complex and concluded that mutual collisions can be ignored. This collisional lifetime is longer (by a factor of 10 or less) than the simplified estimate by Soja et al. (2016), while the dynamical lifetime is more than an order of magnitude shorter than the collisional lifetime in Soja et al. (2016). We conjecture that the discovery of Jenniskens et al. (2016)—large meteorites on low-eccentricity orbits—was possibly caused by fluffy aggregates, which have small eccentricities around the Earth’s orbit, unlike the compact particles from 2P/Encke or JFCs.

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References

Agarwal, J., A’Hearn, M. F., Vincent, J.-B., et al. 2016, MNRAS, 462, S78
Bentley, M. S., Schmied, R., Mannel, T., et al. 2016, Natur, 537, 73
Bradley, J. P. 2003, TdGeo, 1, 689
Burns, J. A., Lamy, P. L., & Soter, S. 1979, Icar, 40, 1
Chambers, J. E. 1999, MNRAS, 304, 793
Della Corte, V., Rotundi, A., Fulle, M., et al. 2015, A&A, 583, A13
Della Corte, V., Rotundi, A., Fulle, M., et al. 2016, MNRAS, 462, S210
Dohnanyi, J. S. 1969, JGR, 74, 2531
Dohnanyi, J. S. 1978, in Cosmic Dust, ed. J. A. M. McDonnell (Chichester, Sussex, England and New York: Wiley-Interscience), 527
Everhart, E. 1985, in Proc. IAU Coll. 83, Dynamics of Comets: Their Origin and Evolution, ed. A. Carusi & G. B. Valsecchi (Dordrecht: Reidel), 185
Fechtig, H., Leinert, C., & Berg, O. E. 2001, in Interplanetary Dust, ed. E. Grun et al. (Berlin: Springer).
Fernández, Y. R., Kelley, M. S., Lamy, P. L., et al. 2013, Icar, 226, 1138
Fulle, M., Colangeli, L., Mennella, V., Rotundi, A., & Bussoletti, E. 1995, A&A, 304, 622
Fulle, M., Della Corte, V., Rotundi, A., et al. 2015, ApJL, 802, L12
Fulle, M., Della Corte, V., Rotundi, A., et al. 2016a, MNRAS, 462, S132
Fulle, M., Marzari, F., Della Corte, V., et al. 2016b, ApJ, 821, 19
Green, S. F., McBride, N., Colwell, M. T. S. H., et al. 2007, in Workshop on Dust in Planetary Systems, ed. H. Krueger & A. Graps (Kauai, Hawaii: ESA), 35
Green, S. F., McDonnell, J. A. M., McBride, N., et al. 2004, JGR, 109, E12S04
Grün, E., Zook, H. A., Fechtig, H., & Giese, R. H. 1985, Icar, 62, 244
Hanayama, H., Ishiguro, M., Watanabe, J.-i., et al. 2012, PASJ, 64, 134
Hilchenbach, M., Kissel, J., Langevin, Y., et al. 2016, ApJL, 816, L32
Ipatov, S. I., Kutyrev, A. S., Madsen, G. J., et al. 2008, Icar, 194, 769
Ishiguro, M., Sarugaku, Y., Ueno, M., et al. 2007, Icar, 189, 169
Ishiguro, M., Yang, H., Usui, F., et al. 2013, ApJL, 767, 75
Jenniskens, P., Nénon, Q., Gural, P. S., et al. 2016, Icar, 266, 384
Jeong, J. 2014, Master’s thesis, Seoul National Univ.
Jewitt, D., Hsieh, H., & Agarwal, J. 2015, in Asteroids IV, ed. P. Michel, F. E. DeMeo, & W. F. Bottke (Tucson, AZ: Univ. of Arizona Press), 221
Katyal, N., Banerjee, V., & Puri, S. 2014, IJQRET, 146, 290
Kawara, K., Matsuoka, Y., Sano, K., et al. 2017, PASJ, 69, 31
Leinert, C., Bowyer, S., Haikala, L. K., et al. 1998, A&AS, 127, 1
Levison, H. F. 1996, in ASP Conf. Ser. 107, Completing the Inventory of the Solar System, ed. T. Rettig & J. M. Hahn (San Francisco, CA: ASP), 173
Levison, H. F., & Duncan, M. J. 1994, Icar, 108, 18
Levison, H. F., & Duncan, M. J. 1997, Icar, 127, 13
Mann, I., Köhler, M., Kimura, H., Ceccobelli, A., & Minato, T. 2006, A&ARv, 13, 159
Mannel, T., Bentley, M. S., Schmied, R., et al. 2016, MNRAS, 462, S304
Mazzotta Epifani, E., Palumbo, P., & Colangeli, L. 2009, A&A, 508, 1031
Merouane, S., Zaprudin, B., Stenzel, O., et al. 2016, A&A, 596, A87
Murakami, T., Ishimoto, H., Kozasa, T., Blum, J., & Greenberg, J. M. 1992, A&A, 262, 315
Nesvorny, D., Janches, D., Vokrouhlický, D., et al. 2011, ApJ, 741, 129
Nesvorny, D., Jenniskens, P., Levison, H. F., et al. 2010, ApJ, 713, 816
Opik, E. J. 1951, PrIAA, 54, 165
Pokorny, P., Vokrouhlický, D., Nesvorny, D., Campbell-Brown, M., & Brown, P. 2014, ApJ, 789, 25
Rotundi, A., Sierks, H., Della Corte, V., et al. 2015, Sci, 347, aaa3905
Skorov, Y., Reshetnyk, V., Lacerda, P., Hartogh, P., & Blum, J. 2016, MNRAS, 461, 3410
Snodgrass, C., Fitzsimmons, A., Lowry, S. C., & Weissman, P. 2011, MNRAS, 414, 458
Soja, R. H., Schwarzkopf, G. J., Sommer, M., et al. 2016, in Int. Meteor Conf. Egmond, ed. A. Roggemans & P. Roggemans (Egmond: IMO), 284

Steel, D. I., & Elford, W. G. 1986, MNRAS, 218, 185
Tancredi, G., Fernández, J. A., Rickman, H., & Licandro, J. 2006, Icar, 182, 527
Ueda, T., Kobayashi, H., Takeuchi, T., et al. 2017, AJ, 153, 232
Vauclairon, J. J., & Reach, W. T. 2010, AJ, 139, 1491
Wiegert, P., Vauclairon, J., & Campbell-Brown, M. 2009, Icar, 201, 295
Yang, H., & Ishiguro, M. 2015, ApJ, 813, 87