Meteoritics & Planetary Science 37, 1491–1505 (2002)
Available online at http://www.uark.edu/meteor

Opportunities for the stratospheric collection of dust from short-period comets

SCOTT MESSENGER

Laboratory for Space Sciences and Physics Department, Washington University, St. Louis, Missouri 63130, USA
Author's e-mail address: dbunny@wuphys.wustl.edu

(Received 2002 April 29; accepted in revised form 2002 July 10)

Abstract–We have identified four comets which have produced low-velocity Earth-crossing dust streams within the past century: 7P/Pons–Winnecke, 26P/Grigg–Skjellerup, 73P/Schwassmann–Wachmann 3, and 103P/Hartley 2. These comets have had the rare characteristics of low eccentricity, low inclination orbits with nodes very close to 1 AU. Dust from these comets is directly injected into Earth-crossing orbits by radiation pressure, unlike the great majority of interplanetary dust particles collected in the stratosphere which spend millennia in space prior to Earth-encounter. Complete dust streams from these comets form within a few decades, and appreciable amounts of dust are accreted by the Earth each year regardless of the positions of the parent comets. Dust from these comets could be collected in the stratosphere and identified by its short space exposure age, as indicated by low abundances of implanted solar-wind noble gases and/or lack of solar flare tracks. Dust from Grigg–Skjellerup probably has the highest concentration at Earth orbit. We estimate that the proportion of dust from this comet will reach at least several percent of the background interplanetary dust flux in the >40 μm size range during April 23–24 of 2003.

INTRODUCTION

For more than two decades NASA has routinely collected interplanetary dust particles (IDPs) in the stratosphere (Sandford, 1987). The particles are collected by inertial impact onto silicone oil-coated plates mounted under the wings of high-altitude aircraft. Most IDPs found on the collectors have diameters ranging from 5 to 40 μm and exhibit a wide range of morphologies and porosities. IDPs are a diverse assemblage of materials with chemical, mineralogical, and isotopic characteristics that generally distinguish them from meteorites (Bradley *et al.*, 1988; Bradley, 1988). Indeed, some IDPs probably represent our only samples of comets. The recent discoveries of preserved molecular cloud materials (Messenger, 2000) and abundant interstellar silicates (Messenger *et al.*, 2002) in IDPs have emphasized the fact that some IDPs are fundamentally more primitive materials than meteorites, and have raised the importance of better understanding their origins.

The fact that IDPs and meteorites have generally different sources is due in part to differences in the dynamical mechanisms that deliver meteorites and IDPs to Earth. Most meteorites likely originate from regions of the asteroid belt that have mean-motion resonances with Jupiter (*e.g.*, Wetherill, 1985). In contrast, IDPs can come from any dust-producing object, as Poynting–Robertson (P-R) light-drag results in the orbital decay of all less than centimeter-sized bodies.

Owing to their complex dynamical histories it has not yet been possible to unambiguously determine the source of any given IDP. Most efforts have focused on identifying probable asteroidal or cometary debris. Many authors have attempted to infer parent-body origins of IDPs on the basis of their composition or structure. Bradley and Brownlee (1986) suggested that cometary grains could be identified by their extremely weak, porous structure since such properties are characteristic of cometary meteors. Sandford (1991) has argued for a cometary origin for anhydrous IDPs based on comparison of laboratory infrared spectra obtained from individual IDPs with a spectrum taken from comet Halley, and "by process of elimination" suggested that hydrated IDPs have an asteroidal origin. The identification of tochilinite in an IDP was used to link it with type CM carbonaceous chondrites (Bradley and Brownlee, 1991). Reflectance spectroscopy of IDPs has been used to infer relationships with meteorite and asteroid classes (Bradley *et al.*, 1996). Thomas *et al.* (1993) suggested that bulk C abundance could be used as a means to distinguish between particles of cometary (high C) and asteroidal (low C) origin. Rietmeijer and Mackinnon (1987) argued for a cometary origin of most IDPs because of their extremely fine-grained, diverse mineralogy. While plausible, these arguments are inconclusive, given that the collected meteorites are an incomplete sampling of the asteroid belt, and *bona fide* cometary material has yet to be studied in detail.

Prelude preprint MS#4825

The most promising means of distinguishing asteroidal from cometary dust particles is to establish their pre-Earth encounter orbital characteristics. Even after thousands of years of orbital evolution, cometary and asteroidal dust particles *by and large* have distinctly different orbits (Flynn, 1989a; Jackson and Zook, 1992). Most asteroidal particles have low eccentricity (e) ~0.1 and low inclination (i) orbits, while cometary particles typically have eccentricities exceeding ~0.4, and a wider range of inclinations. The higher average e and i of cometary dust particles result in higher Earth encounter velocities and consequently stronger atmospheric entry heating than that experienced by asteroidal dust particles. As first suggested by Flynn (1989a), it might be possible to distinguish between cometary and asteroidal dust by the peak temperature that the particles experience upon atmospheric entry. The effects of atmospheric entry heating are evident among many IDPs, resulting in the formation of distinct magnetite rims, dehydration of phyllosilicates, loss of volatile elements, formation of vesicles in carbonaceous material, annealing and melting of silicates and sulfides, and the erasure of solar flare tracks (Sandford and Bradley, 1989).

The most accurate atmospheric entry heating thermometer is based on the temperature-dependent release of solar wind-implanted He, developed by Nier and Schlutter (1992, 1993). Using this technique, Joswiak *et al.* (2000, and references therein) have performed a systematic examination of 42 IDPs for their thermal histories, estimating atmospheric entry velocities with Love and Brownlee's (1991) atmospheric entry heating model. The particles studied so far have calculated entry velocities ranging from 10.2 to 26 km/s, with the "high-velocity" subset (>18 km/s) classified as cometary and the "low-velocity" subset (<14 km/s) classified as asteroidal in origin. Systematic differences in composition and structure are apparent between the two groups, but significant overlaps remain (Joswiak *et al.*, 2000). It is unclear whether the overlaps reflect real compositional similarities between some asteroids and comets or are the result of inherent uncertainty in the technique. For example, it is possible that some high-velocity cometary particles were identified among the "slow" subset of IDPs because they entered the atmosphere at low angles. Conversely, some low-velocity asteroidal particles may have been identified among the "fast" subset of cometary particles because they had high entry angles.

Orbital evolution of IDPs during millennia in space introduces additional complexities. For instance, Kortenkamp and Dermott (1998) and Liou and Zook (1996) have shown that dust particles from Jupiter family comets can become trapped in mean-motion resonances with Jupiter for thousands of years while P-R drag gradually lowers their eccentricities. As much as two-thirds of the cometary dust accreted by the Earth may have been once trapped in jovian resonances. Conversely, some low eccentricity dust particles can have their eccentricities raised by passing through secular resonances or becoming trapped in mean motion resonances with the Earth (Grogan, 2001; S. Kortenkamp, pers. comm.). Of course, planetary encounters can also strongly affect a dust particle's orbit. Virtually all particles accreted by the Earth have had their eccentricities and aphelia greatly reduced by P-R and solar wind drag, with typical space residence times of 10^3 to 10^5 years.

In order to identify dust from *specific* parent bodies, we are forced to consider only those particles very recently released into space. Because these "fresh dust" particles have not undergone significant orbital evolution, their orbits provide strong constraints on their possible parent objects. Fresh dust particles could be identified from their low abundances of solar noble gases and lack of solar flare tracks in appropriate minerals, as discussed in more detail below. While the Earth likely encounters hundreds of dust streams annually (as evidenced by meteor studies: Cook, 1973; Sekanina, 1976), only a handful of these are young and have sufficiently low encounter velocities to be collected and identified.

We have investigated the possible formation of Earth-crossing dust streams by *all* cometary apparitions over the past century as listed in the *Catalogue of Cometary Orbits* (Marsden and Williams, 1999). Nearly all comets fail to meet two fundamental requirements: the comet must have a node within ~0.1 AU of the Earth's orbit, and the eccentricity and inclination must be low enough that the Earth-encounter velocity of the dust is below 25 km/s. Below we discuss the details of the dust stream models for the four comets which meet these basic criteria.

FORMATION OF DUST STREAMS

Over ~10^3 years and longer timescales, P-R drag dominates the orbital evolution of dust particles in the solar system. The instantaneous changes in the aphelion (a) and eccentricity (e) due to P-R drag were shown by Wyatt and Whipple (1950) to be:

$$\frac{da}{dt} = -\Gamma \frac{(2+3e^2)}{a(1-e^2)^{3/2}}$$

and

$$\frac{de}{dt} = -\Gamma \frac{5e}{2a^2(1-e^2)^{1/2}}$$

where $\Gamma = 7.1 \times 10^{-8}/d\rho$ AU^2 year^{-1} and d is the particle diameter and ρ is its density. For a 25 μm diameter particle with density 1 g/cm^3 released from a short-period comet, the relative changes in a and e are <1% over one century. Consequently, the initial orbital elements of young dust streams can be determined solely by the elements of the parent comet, while taking into account the effects of radiation pressure, ejection velocity, and the location of the comet when the particles are released.

Dust particles ejected from a comet or asteroid are immediately affected by solar radiation pressure. Solar radiation exerts the force

$$F_r = \frac{S_0 a Q_{pr}}{r^2 c} \hat{r}$$

on particles of cross-sectional area a, at distance r from the Sun, where S_0 is the solar radiation flux, c is the velocity of light, and Q_{pr} is the radiation pressure "efficiency factor" (Gustafson, 1994, and references therein). Since solar radiation pressure is a $1/r^2$ radial force, it can be thought of as an effective reduction in the solar gravitational force, which also has a $1/r^2$ radial dependence. The ratio of the radiation pressure force to the gravitational force is given by $\beta = CQ_{pr}d\rho$, where d is the diameter of the grain, ρ is its density, and C is a proportionality constant. For dust particles >10 μm, β is roughly proportional to d^{-1} for a given ρ (Gustafson, 1994).

Radiation pressure causes an increase in the aphelia, perihelia, and eccentricity of dust particles' orbits relative to their parent bodies. Neglecting ejection velocity, the modified semimajor axis and eccentricity are given by

$$a' = \frac{a(1-\beta)(1-e)}{(1-e-2\beta)}$$

and

$$e' = \frac{(e+\beta)}{(1-\beta)}$$

where (a and e) and (a' and e') are the original and modified semimajor axis and eccentricity, respectively (Kresak, 1976). The distances of the ascending and descending nodes from the Sun increase as well, though the orbital inclination and solar longitudes of the nodes remains basically unchanged (see Fig. 1). So long as the radiation pressure force is less than the solar gravitational force, radiation pressure *does not* cause the dust

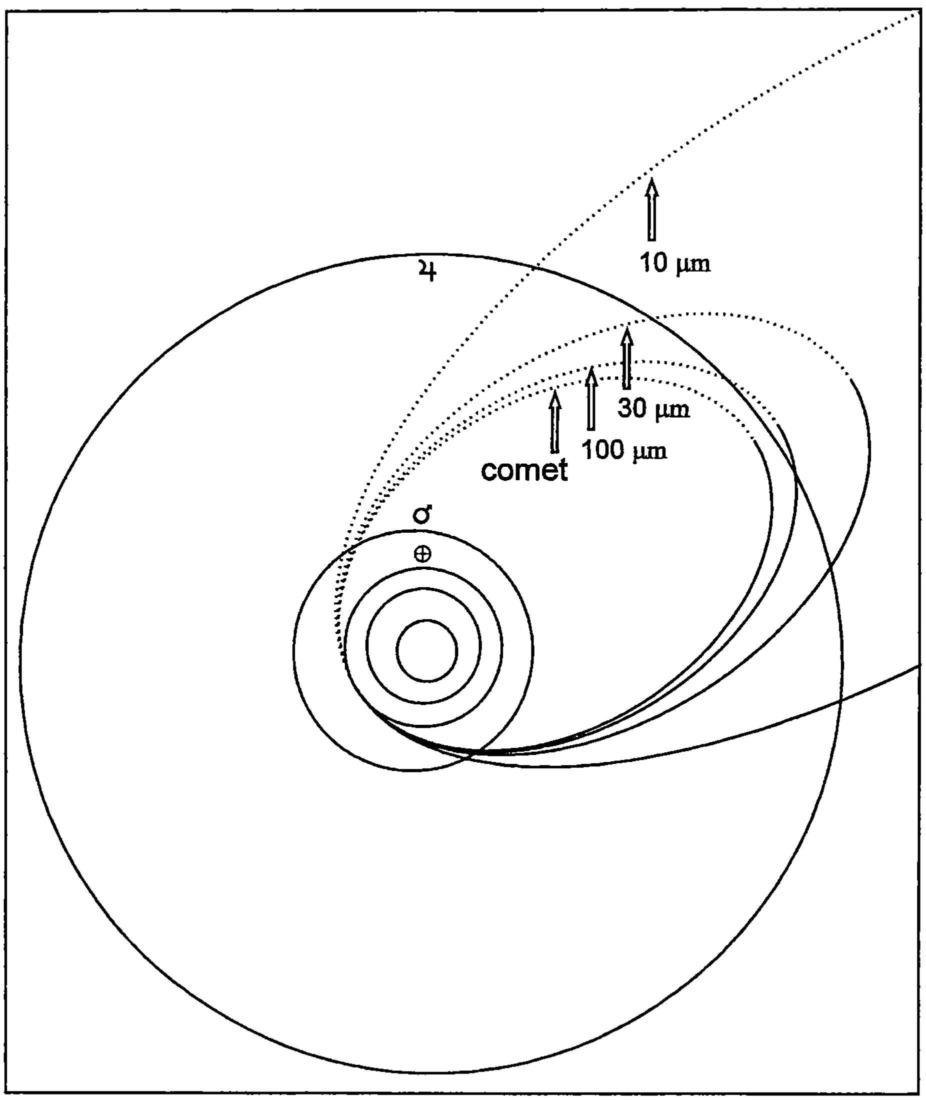

FIG. 1. Illustration of radiation pressure-modified orbits of 10, 30, and 100 μm dust particles (ρ = 1 g cm^{-3}) released at perihelion from a comet, neglecting ejection velocity. The solid portions of the orbits are above the ecliptic plane and the dashed portions are below. Note that the solar longitudes of the nodes are unaffected by radiation pressure. The planetary symbols denote the orbits of Earth, Mars, and Jupiter.

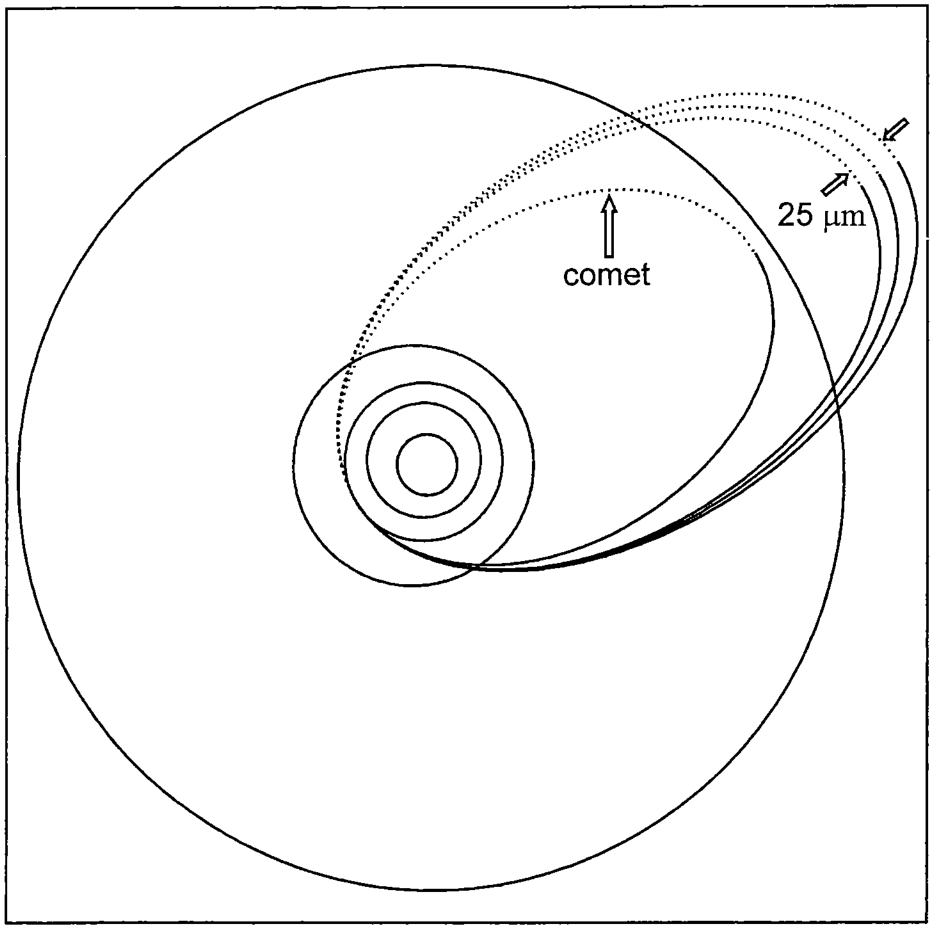

FIG. 2. Illustration of the relative importance of radiation pressure and ejection velocity for a 25 μm diameter dust particle of density 1 g cm^{-3} released at perihelion. The three orbits shown for the dust particle denote radiation pressure without ejection velocity (middle), radiation pressure with particle ejected in the direction of the comet's motion at 100 m/s (outer), and radiation pressure with particle ejected in the direction opposite the comet's motion at 100 m/s. Although ejection velocity decreases with grain size it has a larger affect on the modified orbits of the largest grains than radiation pressure (Fig. 1).

particles' orbits to evolve, but it does have a large affect on their initial orbits.

The ejection velocity from the comet also has an important, but (for grains <100 μm) generally much smaller affect on the dust particles' orbits. Dust is thought to be released at initially low velocities from the cometary nucleus by ice sublimation, but becomes entrained in the expanding coma gas, reaching terminal velocity at a distance of roughly ten nuclear radii (Crifo, 1991). The ejection velocity is determined primarily by the mass loss rate (of the active surface area) and is inversely proportional to the square root of the diameter and density of a given particle. The ejection velocity also increases as comets approach the Sun as $\sim 1/r$ because of the increasing mass loss rate (Whipple, 1951). For 20 μm diameter dust grains, the typical terminal ejection velocity ranges from ~30 to 150 m/s for mass loss rates of 1×10^{-6} and 2×10^{-5} g/cm^2/s, respectively (Hanner, 1984). An example of the relative importance of radiation pressure and ejection velocity is shown in Fig. 2.

The combined effects of radiation pressure and ejection velocity on small particles are sufficient to form a complete dust stream within a few orbits of a short-period comet. The formation of a (small particle) dust stream occurs relatively rapidly because the initial dispersion of radiation pressure-modified a and e results in a wide range of orbital periods. The practical importance of this is that the amount of dust encountered by the Earth in a given year becomes relatively insensitive to the position of the parent comet within a few decades.

EARTH-CROSSING DUST STREAMS

The dust streams are modeled here by releasing test particles along each comet's orbit assuming a $1/r^2$ dependence on the cometary mass loss rate. Test particles are given a density of 1 g/cm^3 and range in size from 20 to 100 μm in diameter. The value of β for each particle was calculated by assuming its optical properties were similar to those of "astronomical silicates" as determined by Draine and Lee (1984). The test particles are modeled as spheres, although the true shapes of IDPs are commonly irregular. Irregular particles have higher surface areas in comparison to spherical grains with equivalent mass and density, and thus have somewhat higher β values. Higher β values also result from lowering a particles diameter or density. The particles are released hemispherically with an axis directed toward the Sun (Fulle *et al.*, 1993). The size-frequency distributions, mass loss rates, and ejection velocities of dust from each of the comets are taken from the literature. Planetary perturbations, P-R drag, and solar-wind drag are not considered here because of the very short duration that the particles have been in space. While certainly some particles may have their orbits strongly affected by Jupiter, the majority will be essentially unaffected over such a short timescale.

The dust models were run on a 2 Ghz desktop personal computer using custom software written in interactive data language (IDL). Because planetary perturbations and P-R drag were neglected, the positions of the dust particles on a given date could be determined by solving Kepler's equation: $M = E - e\sin(E)$, where M is the mean anomaly, e is the eccentricity and E is the eccentric anomaly.

Our aim is to determine the average number of particles encountered by the Earth each year from a given comet. The accretion rate of dust from the comets is a product of the capture cross-section, the encounter velocity, and the spatial density of dust near the Earth. The cross-section for capture by the Earth is larger than the geometrical cross-section because of gravitational focusing, strongly favoring particles with low Earth-encounter velocities (Flynn, 1989b). The effective cross-section is given by:

$$\sigma = \pi R_E^2 \left[1 + \left(\frac{V_E}{V_D} \right)^2 \right]$$

where R_E is the Earth's radius, V_E is the Earth escape velocity (11.2 km/s), and V_D is the geocentric velocity of the dust particle prior to gravitational infall.

26P/Grigg–Skjellerup

Comet 26P/Grigg–Skjellerup (GS) was first observed in 1902 by Grigg, but Kresak (1986) later associated GS with a comet observed in 1808. Prior to 1961 its orbit was always at least 0.08 AU from the Earth's orbit. Following a close encounter with Jupiter in 1964, GS was perturbed into a very close encounter with Earth's orbit. For seven successive apparitions (1967–1997), the ascending node of GS ranged from 0.003 to 0.016 AU from Earth's orbit. Comet GS' orbit was significantly perturbed during another close encounter with Jupiter in 1999, and is no longer an Earth-crossing comet. The complete duration of this Earth-crossing dust stream's formation thus covers a well-defined period of just three decades.

As the secondary target of the GIOTTO mission, GS was subjected to several careful studies of its activity and the characteristics of its dust emission. In this paper we take values of the size-dependent dust mass loss rate from Fulle *et al.* (1993), and scale the activity for other apparitions using the data compiled by Markovich and Markovich (2000). The more easily quantified OH loss rate of GS is an order of magnitude lower than most other active comets, and is estimated as 200× lower than comet Halley (Osip *et al.*, 1992).

The dust model for GS followed the evolution of ~600 000 dust particles through the year 2007. As shown in Fig. 3, a dust stream is completely formed within two decades and begins to approach uniform density after 40 years. A moderate change in the orbit of GS during the 1987 apparition led to the formation of a second, distinct dust trail as shown in Fig. 4.

Since 1973 the amount of dust accreted by the Earth from GS has varied by more than an order of magnitude, peaking in 1987 and 1999 (see Fig. 5). In the near future, the highest fluxes will occur over the period 2003–2005. In Fig. 6 we compare size-dependent dust fluxes for these years with the overall IDP flux determined by Love and Brownlee (1993) from impacts on the long duration exposure facility (LDEF) spacecraft. Although the total accumulation of GS dust is not expected to vary significantly during these 3 years, the dust collected in 2003 will be dominated by large particles, reaching 5–10% of the background IDP flux *above the Earth's atmosphere* in the 40–100 μm size range. This is not the expected relative abundance of GS dust (among the IDP population) in the stratosphere, which is also dependent on the survival and settling rates of the various sources of dust. Of course, the relative abundance of the total stratospheric IDPs population may also vary as a result of the observed episodic changes in the concentration of the more abundant terrestrial background, which includes volcanic dust, industrial pollutants and solid rocket fuel exhaust.

Despite their significant range in a and e (see Fig. 3), most GS dust particles have Earth-encounter velocities near 15 km/s, corresponding to atmospheric entry velocities of 18.5–19 km/s. This velocity is near the lower limit of cometary dust particles accreted by the Earth, and is slightly above the estimated average entry velocity of collected IDPs (Joswiak *et al.*, 2000).

GS is no longer an Earth-crossing comet and is not expected to be for the next century (Kondrat'eva, 1996). It is likely that the strength of the GS dust stream will only decrease over time, as orbital evolution and the influence of Jupiter act to disperse this dust stream with no further opportunities for replenishing it.

7P/Pons–Winnecke

Comet Pons–Winnecke was discovered by Pons in 1819. Since that time its perihelion distance has gradually migrated outward, from initially well inside the Earth's orbit (~0.77 AU) to more than 1.25 AU today. During the period 1909–1927, Pons–Winnecke's orbit was within 0.03 AU of the Earth's, and

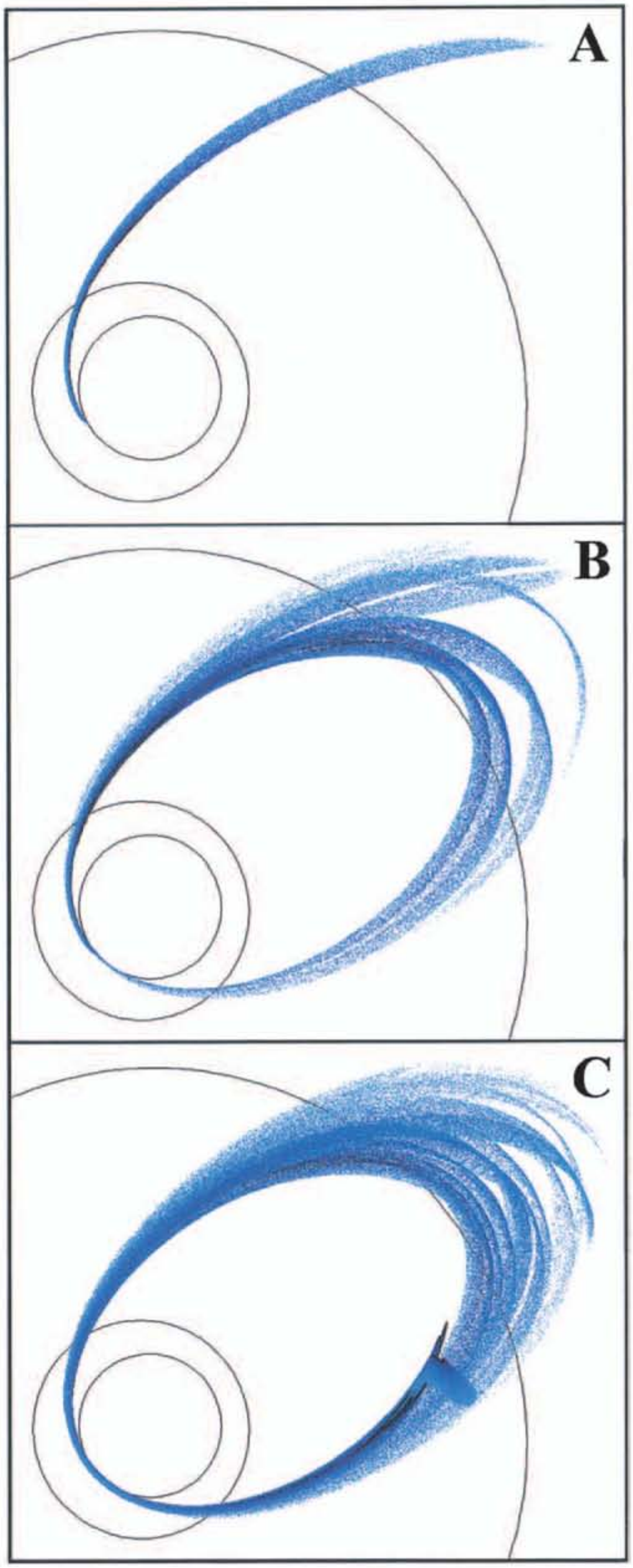

FIG. 3. Evolution of the dust stream formed from comet 23P/Grigg–Skjellerup (GS) since 1967. We show three snapshots of the stream's evolution (top) first return of the stream to perihelion in 1972, (middle) the most significant accretion coinciding with a near encounter with GS in 1987, and (bottom) the fully formed stream as it appears in April 2004. The particles are color coded where the smallest grains (20 μm) are light blue and the largest particles (100 μm) are dark blue.

in 1927 passed within 6×10^6 km of the Earth (Sekanina and Yeomans, 1984).

The fact that Pons–Winnecke's nearest passes by Earth's orbit occurred early in the previous century complicates accurately assessing the dust loss rate during those apparitions. Sekanina (1989) has carefully re-assessed observations from the 1927 passage and derived a peak OH production rate of $10^{28.1}$ mol s^{-1} during late May of that year. In comparison, the reported OH loss rate of comet GS in 1982 is an order of magnitude lower (Osip *et al.*, 1992). Herein we assume that the gas/dust mass loss rate of these two comets was similar near perihelion for the purposes of estimating the density of the Pons–Winnecke dust stream.

The dust model for Pons–Winnecke followed the orbits of 500 000 dust particles generated in the four apparitions between 1909 and 1927. The Earth passes through this dust stream on July 2 over the period of roughly 1 day. Dust grains in this stream have typical atmospheric entry velocities of 18 km/s. We estimate that the Earth accretes roughly twice that accreted from comet GS in the years 2003, 2004, and 2006, with as much as 4× the flux in 2005. However, because this dust stream is nearly one century old, it is likely to have been significantly affected by perturbations from Jupiter. These perturbations will tend to disperse the stream, inhibiting our ability to accurately predict the terrestrial accretion rate. Despite the fact that the first-order flux estimates from this comet significantly exceed those of GS, this is probably a less ideal candidate because of the age of the dust stream.

73P/Schwassmann–Wachmann 3

Comet Schwassmann–Wachmann 3 (SW3) was discovered in 1930, but was not observed again until 1979. For the first apparition, Sekanina (1989) derived a water production rate (10^{28} mol s^{-1}) nearly identical to that of Pons–Winnecke in its 1927 passage. Subsequently, SW3 has been among the least active comets, until it fragmented into five large pieces in 1995 following a major outburst (Crovisier *et al.*, 1996; Kadota *et al.*, 2000; Scotti *et al.*, 1996). At that time, the OH production rate increased by an order of magnitude for a period of several months (Sanzovo *et al.*, 2001) reaching an unusually high level for a Jupiter-family comet. Part of the sustained activity may have been due to the gradual sublimation of meter-sized fragments released during the disruption, which would have lifetimes on the order of weeks (Chen and Jewitt, 1994).

Because the enhanced activity during the 1995 apparition is substantially higher than that reported for earlier passages, we will focus only on this apparition in modeling the SW3 dust stream. As the SW3 activity did not follow the usual heliocentric power law, we explicitly define the mass loss rate

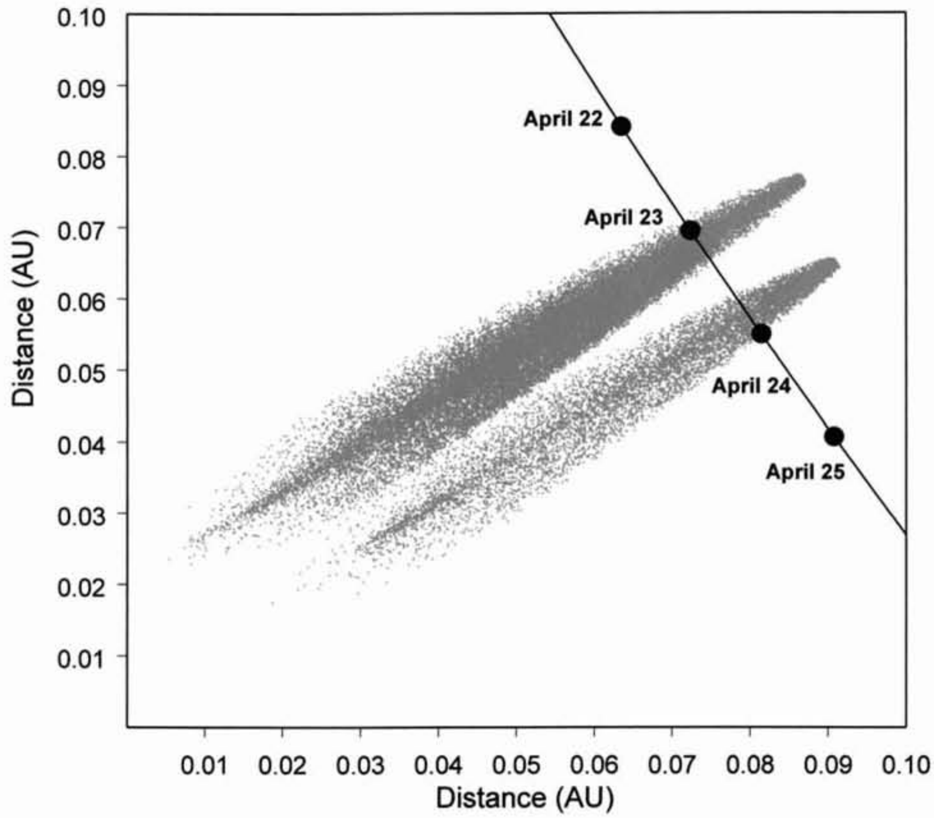

FIG. 4. Cross-section of the 23P/Grigg–Skjellerup (GS) dust trail in the ecliptic plane with the positions of Earth's orbit on April 22–25 indicated. A moderate change in the orbit of GS in 1987 resulted in the formation of a second, distinct trail which the Earth passes through near April 24.

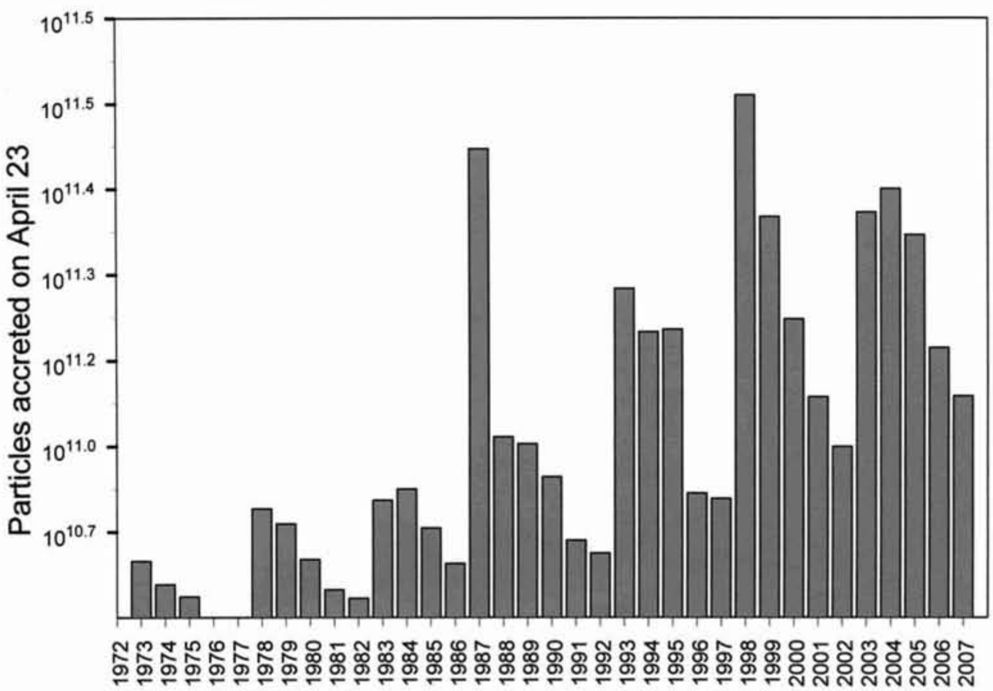

FIG. 5. Relative density of the 23P/Grigg–Skjellerup dust stream at Earth orbit each year on the week of April 23 from 1972 through 2007. The strongest peaks occurred in 1987 and 1998 with the most significant remaining accretions occurring in 2003–2005. As the stream evolves the density near Earth orbit generally increases over time, with the fluctuations from year to year diminishing.

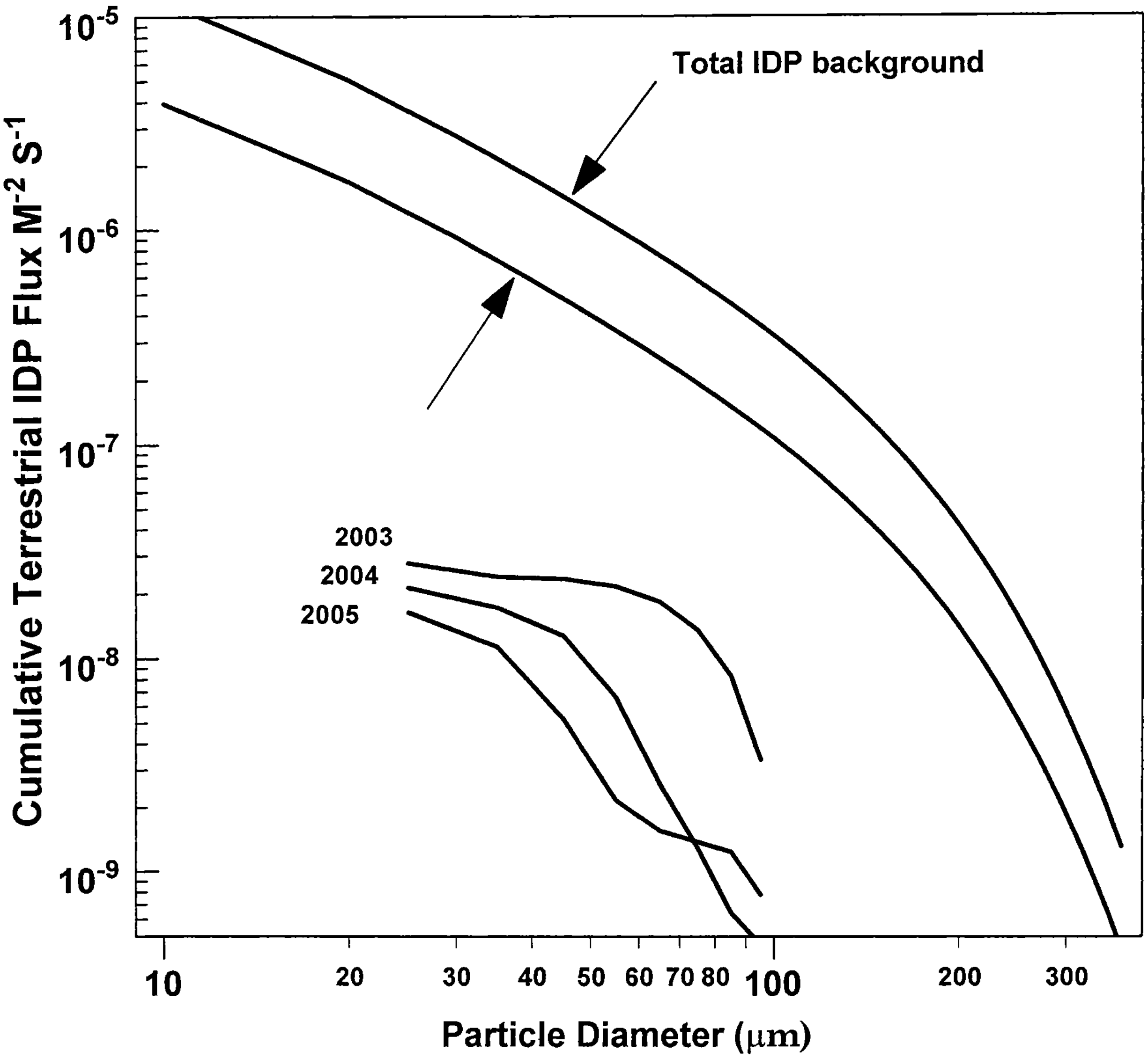

FIG. 6. Comparison of the expected size-dependent cumulative flux of dust from comet 23P/Grigg–Skjellerup (GS) on the Earth on April 23–24 of 2003–2005 with the upper and lower limits to the flux measured by Love and Brownlee (1993). The flux from GS is highest in 2003, especially in the >40 μm size range.

month by month from August 1995 through January 1996, assuming a dust/gas ratio of 1 (following Lisse *et al.*, 1998; Jewitt and Matthews, 1999).

The SW3 Earth-crossing dust stream began to form at least as early as 1930, when its perihelia was 1.01 AU. However, given that the comet was so inactive that it escaped re-discovery until 1979, the total mass of the SW3 dust stream prior to 1995 was small in comparison to the amount added during the disruption event. In fact, over a 4 month period SW3 probably released an amount of dust similar to that present in the Earth-crossing GS dust stream. However, with a perihelion of ~0.93 AU SW3 is not nearly so ideally situated in its orbit in comparison to GS for the creation of an Earth-crossing dust stream. At present, the Earth passes through the fringe of the SW3 dust stream, and until 2006 the amount of dust accreted is likely to be negligible. During its next passage (in 2006), SW3 will pass within 12 × 10^6 km of the Earth. It is possible that SW3 will continue to disintegrate, potentially leading to a very significant loading of extremely fresh dust into the atmosphere that year. It is not possible to make any firm predictions about this event other than that the particles will tend to be small (<20 μm, ρ = 1 or larger particles with lower density), and have an atmospheric entry velocity ~21 km/s. The Earth will pass through significant portions of the dust stream created in the 1995 event in 2008–2010, peaking on June 1 of each year. However, given its greater distance from Earth orbit, it is unlikely that this dust stream will be significant in comparison to the GS dust stream.

103P/Hartley 2

Comet 103P/Hartley 2 was discovered by Hartley in 1986. During its first two apparitions its perihelion was 0.95 AU, but a close encounter with Jupiter in 1993 raised it to 1.03 AU for the 1997 apparition. It is expected that the perihelion distance will move slightly farther outward to 1.04 AU for its next return in 2004.

The nuclear radius measurements of Hartley 2 vary from ≥0.6 to ≤5.9 km (A'Hearn *et al.*, 1995; Lowry and Fitzsimmons, 2001). There have been few studies of the activity and dust production of Hartley 2. For the 1998 apparition, Fomenkova *et al.* (1999) derived a dust production rate of 45 kg/s when the heliocentric distance ranged from 1.09 to 1.12 AU. This dust production rate is ~3× lower than that reported for GS.

The Earth passes through the Hartley 2 dust stream on November 9, with the most significant dust accumulations occurring in 1991, 1998, and peaking in 2004. However, owing to the short duration of the streams accumulation, Hartley 2's significant distance from Earth's orbit, and the reportedly lower dust loss rate, the maximum flux in 2004 is 20× lower than that estimated for GS, or ~1 part per thousand of the total IDP flux. Although the Hartley 2 dust stream is far weaker than the GS stream, the typical atmospheric entry velocity for these particles is only 15 km/s. These dust particles are thus among the most pristine cometary dust particles available for terrestrial collection. Unfortunately, the stream is probably simply too faint to distinguish from the background.

SOURCES OF UNCERTAINTY

While we are confident that the Earth passes through these cometary dust streams, a number of critical parameters are poorly constrained, inhibiting an accurate assessment of the amount of dust accreted in a given year. Below we consider the most important sources of uncertainty in parameters relevant to this model.

Mass Loss Rate

These models follow the evolution of dust particles continuously released from their parent comets over periods of decades, but the mass loss estimates rely on a handful of observations. Reported mass loss rates have stated uncertainties of 50%, but the true uncertainties for the particle size range considered here are substantially larger. Total mass loss estimates are further complicated by episodic increases in the activity of some comets and cometary disintegration (*e.g.*, Crovisier *et al.*, 1996), which can temporarily increase the mass loss rate by more than an order of magnitude. The situation is complicated by the fact that we are primarily interested in large (>20 μm) dust particles, which are difficult to observe, and dust loss rates are most often reported for single-sized submicrometer grains. While most of the dust surface area is accounted for by micrometer and submicrometer-sized dust grains, the majority of the mass is in large (>1 mm) grains. Recent infrared and submillimeter observations suggest that optical imaging may underestimate the true dust mass loss rates by more than an order of magnitude for some comets (Jewitt and Matthews, 1999; Lisse *et al.*, 1998). Optical imaging is especially insensitive to large, dark particles such as IDPs. The mass loss rates used here should thus only be considered as a guide in producing rough estimates on the density of the respective dust streams. We have attempted to use conservative estimates of dust loss rates in this paper, neglecting (for instance) the probable contribution of secondary fragmentation of large fragments in the cometary dust trails.

Size-Frequency Distribution

Dust in the size range considered here represents a minor amount of the cometary mass loss, which is usually dominated by approximately millimeter-sized grains. Thus the uncertainty in the size-frequency distribution results in a significant uncertainty in the amount of IDP-sized dust released. The size-frequency distribution is not directly measured, but is an input model parameter used in deconvolving two color images of cometary tails. For the GS model discussed above, the power index used (–3.3; Fulle *et al.*, 1993) indicated that ~2.5% of the dust mass loss was in the 20–100 μm size range. A slightly different value of the power index (–3.2 or –3.4) results in a significantly different relative contribution of small dust (1.6 or 3.8%, respectively). Furthermore, the size-frequency distribution is observed to be extremely variable between different comets and even for the same comet at different heliocentric distances (*e.g.*, Lisse *et al.*, 1998).

Ejection Velocity

The ejection velocity v of dust from a comet is size (s) dependent and is approximated by a power law, where the power law index

$$u = \frac{\partial \log v}{\partial \log s}$$

(Cremonese *et al.*, 1997). The significant uncertainty in this parameter ($-0.5 < u < -0.15$) determined with different tail models, results in significant uncertainty in the ejection velocity. This uncertainty is most important for the largest grains because radiation pressure is not as significant (Fig. 1). While different assumed ejection velocities would result in qualitatively different dust streams, this does not change the basic result that dust streams form quickly. Variation in the ejection velocity could result in somewhat different size-frequency distribution of the dust encountered by the Earth, but this has a relatively minor impact on the overall dust flux.

Effect of Jupiter

Jupiter is well known to have a dominating affect on the orbital evolution of IDPs from short-period comets. This is due to the combination of Jupiter's strong gravitational field and the proximity of cometary dust particles' aphelia to Jupiter's orbit. Cremonese *et al.* (1997) have modeled the evolution of 20–200 μm dust particles from GS, and found that most of the largest grains were prevented from spiraling toward the Sun by perturbations by Jupiter. Nevertheless, the vast majority of the dust particles are essentially unaffected over very short timescales (<100 years), although a minor population is likely to have been removed from the stream. Jupiter has thus had a relatively small affect on the density of GS dust near the Earth.

Atmospheric Settling Time

IDPs decelerate at very high altitudes (85–100 km), impacting a mass of air roughly equivalent to their own mass with ram pressures at least an order of magnitude lower than the estimated crushing strength of cometary meteors (Brownlee, 1985). The particles subsequently settle at speeds of approximately 1–10 cm/s to the collection altitude (15–20 km). To first order, the falling speed at a given altitude can be estimated with Stoke's law, in which the terminal velocity is given as

$$v = \frac{gd^2(\rho_P - \rho_a)}{18\mu}$$

where g is the gravitational acceleration; d is the diameter of the particle; μ is the viscosity; and ρ_P and ρ_a are the densities of the particle and the atmosphere, respectively. Kasten (1968) used a modified Stokes–Cunningham law to calculate the falling speeds of spherical aerosol particles in the atmosphere from 80 to 20 km, providing a first approximation to the stratospheric residence times of IDPs. For a 20 μm spherical grain of density 1 g/cm^3, the settling time to the collection altitude is ~13 days. Larger particles fall much faster, with 40 and 100 μm grains (ρ = 1 g/cm^3) spending about 4 and 1 days, respectively, settling to the collection altitude. This is a simplified view, of course, as there is a large range of measured IDP densities (0.3 to 6.2 g/cm^3; Love *et al.*, 1994). The observed populations of dust particles in the stratosphere are biased toward low-density particles, because their fall speeds are lower. The density of cometary dust particles is probably lower than average IDPs, and their relative abundances are thus likely to be enhanced. Furthermore, the typically rough, irregular shapes of most IDPs are expected to result in lower terminal velocities (Rietmeijer, 1993; Wilson and Huang, 1979), and thus longer stratospheric residence times. Nevertheless, these rough estimates are useful in considering the timing and length of collection flights. There is a clear advantage in collecting large cometary dust particles, because their lower residence times minimize the dilution with the background IDP flux.

Background Flux

The conceptually simple task of measuring the mass flux of interplanetary dust on the Earth has proven to be very difficult in practice. The most recent efforts include measuring the abundance of melted micrometeorites in the South Pole water well (Taylor *et al.*, 1998), radar micrometeor observations (Mathews *et al.*, 2001), and measurements of impacts on spacecraft in low Earth orbit (Love and Brownlee, 1993). The first two methods yield terrestrial mass fluxes an order of magnitude below that of the spacecraft measurements. In this paper we relate the estimated flux of cometary dust streams to that reported by Love and Brownlee (~40 000 tons/year), which has a stated uncertainty of 50%. If the other measurements are correct, the estimated relative abundances of dust from these streams would be 10× higher. Thus it is possible that in the >40 μm size range, GS could contribute more than *half* of the IDP flux accreted by the Earth during April 23–24 of 2003. However, it is difficult to compare theses flux estimates because only the spacecraft measurements were sensitive to particles in the size range of stratospheric IDPs. Both the radar and micrometeorite studies were most sensitive for particles >100 μm in diameter, where there was large discrepancy with the spacecraft observations.

RELATION TO METEOR STREAMS

It is natural to question whether it is possible to collect dust particles from meteor streams. Indeed, there have been attempts over the years to identify meteor remnants on the IDP collection surfaces (Rietmeijer and Jenniskens, 1998), as well as dedicated high-altitude aircraft (Zolensky, pers. comm.) and balloon collections (Noever, 1999). In particular, there has been a significant effort to collect material from the Leonid meteor shower.

Unfortunately, the Leonid shower is among the most spectacular largely because of the very high impact speed of the meteors (71 km/s), which is far higher than the maximum survivable entry velocity (deceleration without melting) of large IDPs. The smallest particles in a meteor stream experience the lowest peak temperatures during atmospheric entry, but in order to associate collected IDPs with specific streams, dust settling rates impose a practical lower limit of ~20 μm. Smaller particles may spend more than 1 month settling to the collection altitude, decreasing their abundance relative to the background. According to models by Love and Brownlee (1991, 1994), the maximum survivable atmospheric entry velocity of a 20 μm IDP of density 1 g/cm^3 is ~26 km/s, although shallower (<45°) entry angles or lower densities (and correspondingly longer settling times) will result in lower peak temperatures. Of the 50 most significant visual meteor streams, only six have entry velocities below this upper limit (Jenniskens, 1994).

Radio meteor studies are far more sensitive than visual observations, especially for low-velocity meteors, as the luminosity of a meteor is roughly proportional to the fourth power of its velocity (Hughes, 1978). In a compilation by Sekanina (1976) 275 streams were detected, including 95 with entry velocities below 26 km/s, and 28 below the entry velocity of GS dust (18.5 km/s). However, with the few exceptions discussed in this paper it is very unlikely that any of these low-velocity streams could be identified among the stratospheric collections because (except for a few hours) their activities are not significantly above background. This underlines the advantage of searching for *fresh* dust streams, because at least in principle these dust particles can be identified even if their abundance is significantly below the background.

Of the four comets discussed here, three have observed meteor showers associated with them: 26P/Grigg–Skjellerup (σ Puppids: Kondrat'eva, 1996; Lindblad, 1987), 73P/Schwassmann–Wachmann 3 (τ Herculids: Drummond, 1981) and 7P/Pons–Winnecke (June Bootids: Drummond, 1981). Comet 103P/Hartley 2 is a dynamically new comet and has not yet produced an observed shower. The significant size difference between a typical meteor particle ($\sim 10^{-4}$ g; Verniani, 1973) and stratospheric IDPs (10^{-10} to 10^{-7} g) prevents us from using meteor stream activity to predict the accretion rate of IDP-sized dust particles from the associated comets. This is because the large meteor particles are essentially unaffected by radiation pressure, and have significantly lower cometary ejection velocities, resulting in much more concentrated streams than those produced by smaller dust particles. Second, owing to their low spread in a and e, meteor stream particles take much longer to spread out along the entire length of the stream, resulting in strong annual variations in activity. This is one of the reasons why predicting the activity of meteor showers has proven to be such a challenge.

LABORATORY ANALYSIS

It will probably be necessary to perform thorough, detailed analyses of many dust particles collected by dedicated missions in order to identify fresh cometary dust particles. Since fresh dust particles are not likely to be abundant (though it is possible given the uncertainties stated above), they can only be recognized by their low space exposure ages. Unfortunately, the sizes of the particles and the need to distinguish between relatively short time scales ($<10^2$ *vs.* $\sim 10^3$ to 10^4 years) do not allow for the use of cosmic-ray spallation age dating methods. However, two other techniques hold promise.

Solar Flare Tracks

Dust particles in the solar system are constantly bombarded by high-energy radiation from the Sun. Iron group nuclei with energies of order 1 MeV/amu or greater (accelerated in solar flares) completely penetrate these dust particles and cause sufficient damage on an atomic scale that a nuclear damage track may be recorded in silicate minerals (Fleischer *et al.*, 1975). Solar flare tracks were first observed in IDPs by Bradley *et al.* (1984), and have since been found to be common within (unmelted) IDPs, occurring in 70% of IDPs with appropriate track-recording minerals, such as olivine and pyroxene (L. Keller, pers. comm.). Most of those IDPs that do not contain tracks have been strongly heated during atmospheric entry, as evidenced by the formation of magnetite rims on their surfaces and the partial decomposition of Fe-bearing minerals (Keller *et al.*, 1996). Since solar flare tracks quickly anneal at temperatures between 500 and 600 °C (Fraundorf *et al.*, 1982), this provides a useful diagnostic for highly heated particles.

Solar flare tracks accumulate at a rate of roughly 3×10^5 to 3×10^7 tracks/cm^2/year at 1 AU (Fraundorf *et al.*, 1980), and are stable over geological timescales. Thus the density of tracks can be used to derive an estimate of the space exposure age, given assumptions about orbital history. Sandford (1986) first proposed using the abundance of solar flare tracks as a means to distinguish cometary from asteroidal dust particles. While most asteroidal dust accreted by the Earth gradually spirals into the inner solar system under the influence of P-R drag from the asteroid belt, cometary dust particles tend to have significantly lower initial perihelia resulting in lower average space residence ages. For particles with the very low space residence ages considered here (<100 years), the expected solar flare track density would be $<2 \times 10^8$ cm^{-2} for GS dust particles (taking into account the fact that the particles' average heliocentric distance is >1 AU). This corresponds to <2 tracks/μm^2, roughly the minimum observable track density for most particles. Most IDPs have track densities consistent with space exposure ages of order 10^4 years (L. Keller, pers. comm.).

There are a number of complications to consider when attempting to measure such low (or nonexistent) track densities. The observation of tracks first of all requires that the particles contain appropriate track recording minerals large enough to provide useful track density constraints. Second, the lack of observed tracks may be due to unfavorable instrumental conditions (*e.g.*, specimen tilt), rather than an actual lack of tracks. Third, as stated above, tracks are quickly annealed when the particles reach ~600 °C. Other independent indications of the temperature history of the particles must be carefully considered before one can conclude the particle was truly devoid of tracks. One possibility is to use the abundance of Zn, which Flynn and Sutton (1992) have shown is lost to varying degrees from IDPs during entry heating. Finally, it is possible that even particles with very low space residence ages will contain track-rich crystals that obtained their tracks in a pre-accretional irradiation episode, either in the solar nebula or in an interstellar environment.

Solar Noble Gases

Small particles in space are continually bathed in the solar wind. With energies in the range of 1 keV/nucleon, solar wind ions penetrate into the surfaces of the particles up to 100 nm depth. Much lower fluxes of higher energy (>10 keV/nucleon) solar energetic particle (SEP) ions penetrate ~1 μm into the grain surfaces. Solar noble gases are present in IDPs in very high abundances, approaching those observed in lunar soil grains. Rajan *et al.* (1977) were the first to measure ^{4}He in a group of IDPs, providing one of the first lines of evidence establishing their extraterrestrial origin. Hudson *et al.* (1981) subsequently measured the heavier noble gases in another bulk measurement of 13 particles. The elemental and isotopic compositions of the noble gases pointed to a combination of solar and planetary components. Techniques have been significantly refined since then, and it is now possible to measure He in individual IDPs. Nier and Schlutter (1990, 1992, 1993) have performed the most extensive studies of He and Ne in IDPs to date. By developing the capability to measure the temperature-dependent release of He in individual particles, they established perhaps the most accurate measure of the temperature history of IDPs.

Dust particles in space at 1 AU have their surfaces saturated with implanted solar wind on a timescale of a few decades. Particles in orbits typical of short-period comets will require ~5× longer to become saturated. The abundance of solar noble gases could, in principle, be used as a chronometer for very short space exposure ages. However, there are a number of complications that will make this potential difficult to exploit. As mentioned above, dust particles entering the atmosphere lose an unknown amount of gas during drag heating. As with solar flare tracks, the lack of observable solar noble gas could simply result from a particle having been highly heated. It will be necessary to include a detailed independent assessment of a particle's heating history before concluding that it was gas-poor prior to atmospheric entry. It is also possible that gas-poor particles found on the IDP collectors were recently part of a larger object which may have been in space for a long period of time. This is certainly the case with cluster IDP fragments, and in such cases it is clearly necessary to analyze several fragments in order to assess the true noble gas abundances. Perhaps the clearest case would be a low, but measurable abundance of solar wind, coupled with several indications that the particle experienced a minimum degree of heating, including the temperature-dependent release of the gas.

Many of these criteria appeared to have been met by particles analyzed by Nier and Schlutter, collected by NASA in June/July of 1991. They found that most of the cluster particles (11 of 12) measured from one collector (L2011) had very low ^{4}He abundances in comparison to typical IDPs. Messenger and Walker (1998) interpreted this as an indication of low space exposure age, and using the dynamical arguments outlined in this paper deduced that a possible source of the particles was comet 73P/Schwassmann–Wachmann 3. Subsequent measurements of many fragments from other clusters from a paired (exposed simultaneously) collector have been unable to reproduce this surprising observation, leaving the original interpretation in doubt (Pepin *et al.*, 2000, 2001). However, since the same (gas-poor) particles have not been re-measured, the possibility remains that those IDPs are indeed gas-poor and hence represent fresh dust. Firmer conclusions will rely on carefully analyzing these and any future samples by noble gas analysis together with appropriate complementary techniques (*e.g.*, search for solar flare tracks).

SUMMARY AND CONCLUSIONS

The principal results of this study are that (1) at least four short-period comets have produced low-velocity, Earth-crossing dust streams in the past century, (2) particles in the size range of stratospheric IDPs form a complete dust stream within several decades, and (3) that the flux of dust from comet Grigg–Skjellerup (GS) is sufficiently high that its collection is feasible. The highest flux of GS dust will occur in April 23–24 of 2003, accounting for 5–50% of the total IDP flux on the Earth in the >40 μm size range. These particles will settle to the IDP collection altitude (20 km) in 1–4 days, on average for particles of density 1 g cm^{-3}. Although comet Schwassmann–Wachmann 3 has previously been suspected of being the progenitor of fresh dust particles collected in June/July of 1991, this conclusion is presently uncertain but it is clearly worthy of further study. This comet should be carefully watched during its next return in 2006 because its recent disintegration coupled with a close encounter with Earth could result in a significant flux of cometary dust in that year.

Identifying dust particles from these comets does not rely on them accounting for a majority of the dust in the stratosphere following passage through a dust stream. It should be possible to distinguish rare fresh dust particles from a complex background of IDPs from numerous sources and diverse histories because of their very low space exposure ages, as indicated by a dearth of solar flare tracks and low abundances of solar noble gases. Both of these measurements are sensitive to the temperature history of the particles, necessitating coordinated independent measures of the temperature history of the grains. Some possibilities include the degree of magnetite formation, degree of Zn loss, and the preservation of temperature-sensitive phases.

It is impossible to predict with certainty how much dust will be collected from these sources because of a number of poorly constrained parameters. Among the most important are the cometary dust mass loss rates in the intermediate size rage 20–100 μm and the total IDP flux accreted by the Earth. Further complications are related to the key observations of collected dust particles: solar flare tracks and solar noble gases. It is possible that significant amounts of trapped gases are already present in cometary dust from a pre-accretional implantation. Similarly, some minerals in comets are likely to contain nuclear tracks from pre-accretional irradiation, either in the solar nebula or in an interstellar environment (*e.g.*, Bradley, 1994). The currently active Stardust mission will help to clarify some of these issues when it returns the first direct samples of a comet in 2006, after rendezvousing with comet 81P/Wild 2 in January 2004.

The Stardust mission will result in a great step forward in our understanding of the composition of comets, and will furnish valuable ground truth to studies of IDPs. Because this spacecraft will sample freshly released material, we will have the opportunity to study dust which has not been affected by present-day solar wind, SEP, or solar flares, providing a valuable baseline for fresh dust identification. The Stardust mission has the disadvantage that the material will be collected in aerogel with an impact velocity of 6.2 km/s. Although IDPs collected in the stratosphere impact the Earth's atmosphere at 2–3× this velocity, they decelerate over distances of several kilometers, in comparison to the 1 cm stopping distance in aerogel. Until the next-generation cometary sample return mission occurs (*i.e.*, returning quiescently collected cometary material), stratospherically collected IDPs will be the most pristine samples of cometary dust available. Given the importance and wide-ranging impact of cometary studies, we feel that several dedicated stratospheric collections will yield a high value return for the investment—which is very low in comparison to any space mission. Collecting and identifying fresh dust from a comet in the stratosphere is certainly not an easy task, and success is not guaranteed. However, the imminent passage through the peak of the GS dust stream is likely to be the best opportunity to collect dust from a specific comet in the stratosphere for the foreseeable future.

Acknowledgments–This work greatly benefited from discussions with Steven Kortenkamp, George Flynn, Robert Walker, Lindsay Keller and many others. This research was supported by the NASA Cosmochemistry program.

Editorial handling: D. E. Brownlee

REFERENCES

A'HEARN M. F., SCHLEICHER D. G., FELDMAN P. D., MILLIS R. L. AND THOMSON D. T. (1995) The ensemble properties of comets: Results from narrow band photometry of 85 comets, 1976–1992. *Icarus* **118**, 223–270.

BRADLEY J. P. (1988) Analysis of chondritic interplanetary dust thin-sections. *Geochim. Cosmochim. Acta* **52**, 889–900.

BRADLEY J. P. (1994) Chemically anomalous, preaccretionally irradiated grains in interplanetary dust from comets. *Science* **265**, 925–929.

BRADLEY J. P. AND BROWNLEE D. E. (1986) Cometary particles: Thin sectioning and electron beam analysis. *Science* **231**, 1542–1544.

BRADLEY J. P. AND BROWNLEE D. E. (1991) An interplanetary dust particle linked directly to type CM meteorites and an asteroidal origin. *Science* **251**, 549–552.

BRADLEY J. P., BROWNLEE, D. E. AND FRAUNDORF P. (1984) Discovery of nuclear tracks in interplanetary dust. *Science* **226**, 1432–1434.

BRADLEY J. P., SANDFORD S. A. AND WALKER R. M. (1988) Interplanetary dust particles. In *Meteorites and the Early Solar System* (eds. J. Kerridge and M. S. Matthews), pp. 861–895. Univ. Arizona Press, Tucson, Arizona, USA.

BRADLEY J. P., KELLER L. P., BROWNLEE D. E. AND THOMAS K. L. (1996) Reflectance spectroscopy of interplanetary dust particles. *Meteorit. Planet. Sci.* **31**, 394–402.

BROWNLEE D. E. (1985) Cosmic dust: Collection and research. *Ann. Rev. Earth Planet. Sci.* **13**, 147–173.

CHEN J. AND JEWITT D. (1994) On the rate at which comets split. *Icarus* **108**, 265–271.

COOK A. F. (1973) Working list of meteor streams. In *Evolutionary and Physical Properties of Meteoroids* (eds. C. L. Hemenway, P. M. Millman and A. F. Cook), p. 183. NASA-SP **319**, Washington D.C., USA.

CREMONESE G., FULLE M., MARZARI F. AND VANZANI V. (1997) Orbital evolution of meteoroids from short period comets. *Astron. Astrophys.* **324**, 770–777.

CRIFO J. F. (1991) Hydrodynamic models of the collisional coma. In *Comets in the Post-Halley Era* (eds. R. L. Newburn, Jr., M. Neugebauer and J. Rahe), p. 937–989. Kluwer, Dordrecht, The Netherlands.

CROVISIER J., BOCKLÉE-MORVAN D., GERARD E., RAUER H., BIVER N., COLOM P. AND JORDA L. (1996) What happened to comet 73P/Schwassmann–Wachmann 3? *Astron. Astrophys.* **310**, L17–L20.

DRAINE B. T. AND LEE H. M. (1984) Optical properties of interstellar graphite and silicate grains. *Astrophys. J.* **285**, 89–108.

DRUMMOND J. D. (1981) Earth-orbit-approaching comets and their theoretical meteor radiants. *Icarus* **47**, 500–517.

FLEISCHER R. L., PRICE P. B. AND WALKER R. M. (1975) *Nuclear Tracks in Solids: Principles and Applications.* Univ. California Press, Berkeley, California, USA. 605 pp.

FLYNN G. J. (1989a) Atmospheric entry heating: A criterion to distinguish between asteroidal and cometary sources of interplanetary dust. *Icarus* **77**, 287–310.

FLYNN G. J. (1989b) The near-Earth enhancement of asteroidal over cometary dust. *Proc. Lunar Planet. Sci. Conf.* **20th**, 363–371.

FLYNN G. J. AND SUTTON S. R. (1992) Trace elements in chondritic stratospheric particles: Zinc depletion as a possible indicator of atmospheric entry heating. *Proc. Lunar Planet. Sci. Conf.* **22nd**, 171–184.

FOMENKOVA M., SOKOLOV R., WANG M. AND JONES B. (1999) Dust properties of comets 55P/Tempel–Tuttle and 103P/Hartley 2 (abstract). *Meteorit. Planet. Sci.* **34 (Suppl.)**, A37.

FRAUNDORF P., FLYNN G. J., SHIRCK J. AND WALKER R. M. (1980) Interplanetary dust in the Earth's stratosphere: The question of solar flare tracks. *Proc. Lunar Planet. Sci. Conf.* **11th**, 1235–1249.

FRAUNDORF P., LYONS T. AND SCHUBERT P. (1982) The survival of solar flare tracks in interplanetary dust silicates on deceleration in the Earth's atmosphere. *J. Geophys. Res.* **87**, A409–A412.

FULLE M., MENNELLA V., ROTUNDI A., COLANGELI L., BUSSOLETTI E. AND PASIAN F. (1993) The dust environment of comet P/Grigg–Skjellerup as evidenced from ground-based observations. *Astron. Astrophys.* **276**, 582–588.

GROGAN K., DERMOTT S. F. AND KEHOE T. J. J. (2001) Dynamics of interplanetary dust: Modeling the Zodiacal Cloud (abstract). *Am. Astron. Soc. DDA Meeting* **32**, #01.04.

GUSTAFSON B. A. S. (1994) Physics of zodiacal dust. *Ann. Rev. Earth Planet. Sci.* **22**, 553–595.

HANNER M. S. (1984) A comparison of the dust properties in recent periodic comets. *Adv. Space. Res.* **4**, 189–196.

HUDSON B., FLYNN G. H., FRAUNDORF P., HOHENBERG C. M. AND SHIRCK J. (1981) Noble gases in stratospheric dust particles: Confirmation of extraterrestrial origin. *Science* **211**, 383–386.

HUGHES D. W. (1978) Meteors. In *Cosmic Dust* (ed. J. A. M. McDonnell), pp. 123–185. Wiley, New York, New York, USA.

JACKSON A. A. AND ZOOK H. A. (1992) Orbital evolution of dust particles from comets and asteroids. *Icarus* **97**, 70–84.

JENNISKENS P. (1994) Meteor stream activity I. The annual streams. *Astron. Astrophys.* **287**, 990–1013.

JEWITT D. AND MATTHEWS H. (1999) Particulate mass loss from comet Hale–Bopp. *Astron. J.* **117**, 1056–1062.

JOSWIAK D. J., BROWNLEE D. E., PEPIN R. O. AND SCHLUTTER D. J. (2000) Characteristics of asteroidal and cometary IDPs obtained from stratospheric collectors: Summary of measured He release temperatures, velocities, and descriptive mineralogy (abstract). *Lunar Planet. Sci.* **31**, #1500, Lunar and Planetary Institute, Houston, Texas, USA (CD-ROM).

KADOTA K., JAEGER M., GALAD A., KOLENY P., HALE A. AND YOSHIDA S. (2000) *IAUC Circ.* #7534.

KASTEN F. (1968) Falling speeds of aerosol particles. *J. Appl. Met.* **7**, 944–947.

KELLER L. P., THOMAS K. L. AND MCKAY D. S. (1996) Mineralogical changes in IDPs resulting from atmospheric entry heating. In *Physics, Chemistry, and Dynamics of Interplanetary Dust* (eds. B. A. Gustafson and M. S. Hanner), p. 295. Proc. IAU Colloq. 150, Astron. Soc. Pacific, Berkeley, California, USA.

KONDRAT'EVA E. D. (1996) Comet Grigg–Skjellerup in the 21th century. *Solar System Res.* **30**, 329–331.

KORTENKAMP S. J. AND DERMOTT S. F. (1998) Accretion of interplanetary dust particles by the Earth. *Icarus* **135**, 469–495.

KRESAK L. (1976) Orbital evolution of the dust streams released from comets. *Bull. Astron. Inst. Czech.* **27**, 35–46.

KRESAK L. (1986) Periodic comet Grigg–Skjellerup. *IAU Circ.* #4234.

LINDBLAD B. A. (1987) The meteor stream associated with comet P/Grigg–Skjellerup. *Astron. Astrophys.* **187**, 931–932.

LIOU J. C. AND ZOOK H. A. (1996) Comets as a source of low eccentricity and low inclination interplanetary dust particles. *Icarus* **123**, 491–502.

LISSE C. M., A'HEARN M. F., HAUSER M. G., KELSALL T., LIEN D. J., MOSELEY S. H., REACH W. T. AND SILVERBERG R. F. (1998) Infrared observations of comets by COBE. *Astrophys. J.* **496**, 971–991.

LOWRY S. C. AND FITZSIMMONS A. (2001) CCD photometry of distant comets. *Astron. Astrophys.* **365**, 204–213.

LOVE S. G. AND BROWNLEE D. E. (1991) Heating and thermal transformation of micrometeoroids entering the Earth's atmosphere. *Icarus* **89**, 26–43.

LOVE S. G. AND BROWNLEE D. E. (1993) A direct measurement of the terrestrial mass accretion rate of cosmic dust. *Science* **262**, 1993.

LOVE S. G. AND BROWNLEE D. E. (1994) Peak atmospheric entry temperatures of micrometeorites. *Meteoritics* **29**, 69–70.

LOVE S. G., JOSWIAK D. J. AND BROWNLEE D. E. (1994) Densities of stratospheric micrometeorites. *Icarus* **111**, 227–236.

MARKOVICH M. Z. AND MARKOVICH N. M. (2000) Photometric characteristics and variations in brightness of periodic comet Grigg–Skjellerup (1902–1987). *Solar System Res.* **34**, 256–261.

MARSDEN B. G. AND WILLIAMS G. V. (1999) *Catalogue of Cometary Orbits*. Minor Planet Center, Cambridge, Massachusetts, USA. 127 pp.

MATHEWS J. D., JANCHES D., MEISEL D. D. AND ZHOU Q-H. (2001) The micrometeoroid mass flux into the upper atmosphere: Arecibo results and a comparison with prior estimates. *Geophys. Res. Lett.* **28**, 1929–1932.

MESSENGER S. (2000) Identification of molecular cloud material in interplanetary dust. *Nature* **404**, 968–971.

MESSENGER S. AND WALKER R. M. (1998) Possible association of isotopically anomalous cluster IDPs with comet Schwassmann–Wachmann 3 (abstract). *Lunar Planet. Sci.* **29**, #1906, Lunar and Planetary Institute, Houston, Texas, USA (CD-ROM).

MESSENGER S., KELLER L. P. AND WALKER R. M. (2002) Discovery of abundant interstellar silicates in cluster IDPs (abstract). *Lunar Planet. Sci.* **33**, #1887, Lunar and Planetary Institute, Houston, Texas, USA (CD-ROM).

NIER A. O. AND SCHLUTTER D. J. (1990) Helium and neon isotopes in stratospheric particles. *Meteoritics* **25**, 263–267.

NIER A. O. AND SCHLUTTER D. J. (1992) Extraction of helium from individual dust particles by step-heating. *Meteoritics* **27**, 166–173.

NIER A. O. AND SCHLUTTER D. J. (1993) The thermal history of interplanetary dust particles collected in the stratosphere. *Meteoritics* **28**, 675–680.

NOEVER D. (1999) Leonids' particle analyses from stratospheric balloon collection on xerogel surfaces. In *The Leonid MAC Workshop* (eds. P. Jenniskens and F. J. M. Rietmeijer), p. 13N. NASA ARC.

OSIP D. J., SCHLEICHER D. G. AND MILLIS R. L. (1992) Comets: Ground-based observations of spacecraft mission candidates. *Icarus* **98**, 115–124.

PEPIN R. O., PALMA R. L. AND SCHLUTTER D. J. (2000) Noble gases in interplanetary dust particles, I: The excess helium-3 problem and estimates of the relative fluxes of solar wind and solar energetic particles in interplanetary space. *Meteorit. Planet. Sci.* **35**, 495–504.

PEPIN R. O., PALMA R. L. AND SCHLUTTER D. J. (2001) Noble gases in interplanetary dust particles, II: Excess helium-3 in cluster particles and modeling constraints on interplanetary dust particle exposures to cosmic-ray irradiation. *Meteorit. Planet. Sci.* **36**, 1515–1534.

RAJAN R. S., BROWNLEE D. E., TOMANDL D., HODGE P. W., FARRAR H. AND BRITTEN R. A. (1977) Detection of ^{4}He in stratospheric particles gives evidence of extraterrestrial origin. *Nature* **267**, 133–134.

RIETMEIJER F. J. M. (1993) The bromine content of micrometeorites: Arguments for stratospheric contamination. *J. Geophys. Res.* **98**, 7409–7414.

RIETMEIJER F. J. M. AND JENNISKENS P. (1998) Recognizing Leonid meteoroids among the collected stratospheric dust. *Earth Moon Planets* **82**, 505–524.

RIETMEIJER F. J. M. AND MACKINNON I. D. R. (1987) Cometary evolution: Clues from chondritic interplanetary dust particles. In *Diversity and Similarity of Comets* (eds. E. J. Rolfe and B. Battrick), pp. 363–367. ESA SP-278, ESTEC, Noordwijk, The Netherlands.

SANDFORD S. A. (1986) Solar flare track densities in interplanetary dust particles: The determination of an asteroidal versus cometary source of the zodiacal dust cloud. *Icarus* **68**, 377–394.

SANDFORD S. A. (1987) The collection and analysis of extraterrestrial dust particles. *Fund. Cosmic Phys.* **12**, 1–73.

SANDFORD S. A. (1991) Constraints on the origin of collected interplanetary dust particles. In *Origin and Evolution of Interplanetary Dust* (eds. A. C. Levasseur-Regourd and H. Hasegawa), pp. 397–404. Kluwer Academic, Japan.

SANDFORD S. A. AND BRADLEY J. P. (1989) Interplanetary dust particles collected in the stratosphere: Observations of atmospheric heating and constraints on their interrelationships and sources. *Icarus* **82**, 146–166.

SANZOVO G. C., DE ALMEIDA A. A., MISRA A., MIGUEL TORRES R., BOICE D. C. AND HUEBNER W. F. (2001) Mass-loss rates, dust particle sizes, nuclear active areas and minimum nuclear radii of target comets for missions STARDUST and CONTOUR. *Mon. Not. R. Astron. Soc.* **326**, 852–868.

SCOTTI J. V., GALLAD A., BONHARDT H., KAUFL H. U., CHEN J., JEWITT D., REINSCH K., STORM J. AND SEKANINA Z. (1996) *IAUC Circ.* #6301.

SEKANINA Z. (1976) Statistical model of meteor streams, IV: A study of radio streams from the synoptic year. *Icarus* **27**, 265–322.

SEKANINA Z. (1989) Nuclei of two Earth-grazing comets of fan-shaped appearance. *Astron. J.* **98**, 2322–2382.

SEKANINA Z. AND YEOMANS D. K. (1984) Close encounters and collisions of comets with the Earth. *Astron. J.* **89**, 154–161.

TAYLOR S., LEVER J. H. AND HARVEY R. P. (1998) Accretion rate of cosmic spherules at the South Pole. *Nature* **392**, 899–903.

THOMAS K. L., KLÖCK W., KELLER L. P., BLANFORD G. E. AND MCKAY D. S. (1993) Analysis of fragments from cluster particles: Carbon abundance, bulk chemistry, and mineralogy (abstract). *Meteoritics* **28**, 448–449.

VERNIANI F. (1973) An analysis of the physical parameters of 5759 faint radio meteors. *J. Geophys. Res.* **78**, 8429–8462.

WETHERILL G. W. (1985) Asteroidal source of ordinary chondrites. *Meteoritics* **20**, 1–22.

WHIPPLE F. L. (1951) A comet model. II. Physical relations for comets and meteors. *Astrophys. J.* **113**, 464–474.

WILSON L. AND HUANG T. C. (1979) The influence of shape on the atmospheric settling velocity of volcanic ash particles. *Earth Planet. Sci. Lett.* **44**, 311–324.

WYATT S. P., JR. AND WHIPPLE F. L. (1950) The Poynting–Robertson effect on meteor orbits. *Astrophys. J.* **111**, 134–141.