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ORIGINS OF SOLAR SYSTEM DUST BEYOND JUPITER

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ABSTRACT

The measurements of cosmic interplanetary dust by the instruments on board the *Pioneer 10* and *11* spacecraft contain the dynamical signature of dust generated by Edgeworth-Kuiper belt objects, as well as short-period Oort cloud comets and short-period Jupiter-family comets. While the dust concentration detected between Jupiter and Saturn is mainly due to the cometary components, the dust outside Saturn's orbit is dominated by grains originating from the Edgeworth-Kuiper belt. In order to sustain a dust concentration that accounts for the *Pioneer* measurements, short-period external Jupiter-family comets, on orbits similar to that of comet 29P/Schwassmann-Wachmann 1, have to produce 8×10^4 g s^{-1} of dust grains with sizes between 0.01 and 6 mm. A sustained production rate of 3×10^5 g s^{-1} has to be provided by short-period Oort cloud comets on 1P/Halley-like orbits. The comets cannot, however, account for the dust flux measured outside Saturn's orbit. The measurements there can only be explained by generation of dust grains in the Edgeworth-Kuiper belt by mutual collisions of the source objects and by impacts of interstellar dust grains onto the objects' surfaces. These processes have to release in total 5×10^7 g s^{-1} of dust from the Edgeworth-Kuiper belt objects in order to account for the amount of dust found by *Pioneer* beyond Saturn, making the Edgeworth-Kuiper disk the brightest extended feature of the solar system when observed from afar.

Key words: comets: individual (1P/Halley, 29P/Schwassmann-Wachmann 1) — Kuiper belt — solar system: general

1. INTRODUCTION

Our solar system, as well as other planetary systems, is filled with small solid particles, either interstellar survivors of the formation process or fragments of larger bodies such as asteroids, comets, moons, or planets. Commonly referred to as interplanetary dust, these particles carry information about their sources, by virtue of not only their chemical signature (Brownlee 1985; Kissel et al. 1986), but also the size and shape of their orbits around the Sun. The particles' chemistry, as well as their orbit, can best be gauged in situ, that is, by dust detectors on board interplanetary spacecraft. While the accretion of interplanetary dust particles by Earth's atmosphere allows their mineralogical, chemical, and isotopic analysis in ground-based laboratories after collection by high-flying aircraft, information on their orbit around the Sun is lost after the atmospheric entry. The orbital properties of solar system dust inside Jupiter's orbit have been extensively studied via in situ measurements (McDonnell & Berg 1975; Grün et al. 1977, 1995a, 1995b; Brownlee et al. 1997). From these measurements, Jupiter-family short-period comets and asteroids have been identified as the dominant dust sources (Liou, Dermott, & Xu 1995; Dermott et al. 1992). In the size regime below 1 μm, a high abundance of interstellar grains is found (Grün et al. 1993). While interstellar impactors can easily be distinguished from detections caused by solar system dust, it is still unclear what the relative contribution of the various interplanetary sources is. Besides this uncertainty, the large number of in situ measurements taken inside Jupiter's orbit led to a consistent picture of the extend and distribution solar system dust cloud there.

The situation beyond Jupiter's orbit is, however, vastly different. So far the only in situ dust detectors ever to fly beyond Jupiter are the dust experiments on board the *Pioneer 10* and *11* spacecraft (Humes 1980).[6] Measurements with the plasma instruments on board *Voyager 1* and *2* seem to indicate a high concentration of micron-sized particles out to 50 AU (Gurnett et al. 1997). The *Voyager* results are however not conclusive, because the plasma instruments were never calibrated to measure dust impacts. From the *Pioneer 10* and *11* measurements, Humes (1980) found that, taken as an ensemble, the particles have to have a constant spatial concentration as function of the distance from the Sun and move on highly eccentric, randomly oriented orbits. In this report, we use the *Pioneer 10* and *11* data to identify the source objects of the particles by modeling the sources' signature in the *Pioneer* data and comparing the measurements with the result of the modeling.

2. IN SITU MEASUREMENTS BEYOND JUPITER BY THE *PIONEER* MISSIONS

The *Pioneer* instruments consist of panels of 234 pressurized cells, mounted on the back of the spacecraft's high-gain antenna. The cells are divided into two separate electronic channels for redundancy; 108 cells are connected to channel 0, and 126 cells are connected to channel 1. Each cell has a cross-sectional area of 2.45×10^{-3} m^2. The instruments register the time when a particle penetrates the thin wall of the cell that encloses the pressurized gas. Before the penetra-

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[6] Since 2000 December 31, the *Cassini* spacecraft has been outside Jupiter's orbit on its way to its final destination, Saturn.

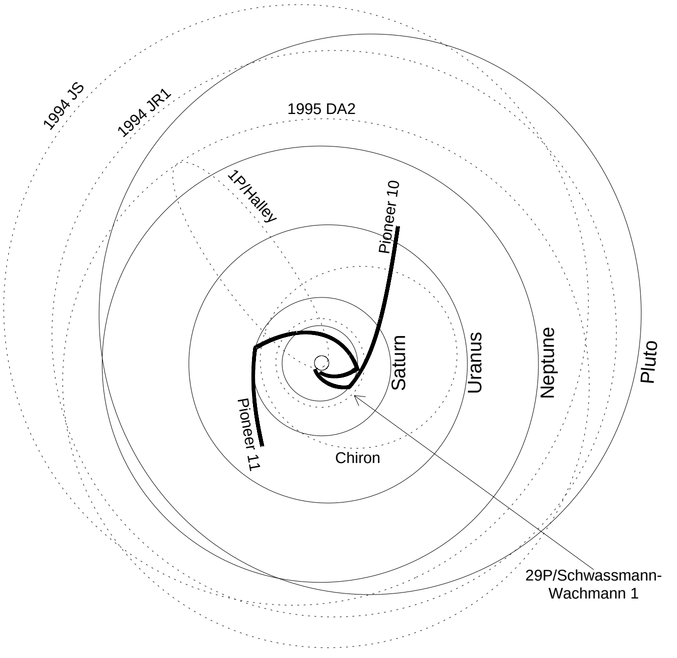

FIG. 1.—Overview of the orbits of the *Pioneer* spacecraft (*thick solid lines*) and potential dust source objects (*dotted lines*). The orbits of the planets Earth, Jupiter, Saturn, Uranus, Neptune, and Pluto are shown as thin solid lines. As representatives of the dust sources comets 1P/Halley and 29P/Schwassmann-Wachmann 1, the Centaur object 2060 Chiron and the Trans-Neptunian objects 1994 JS, 1994 JR_1, and 1995 DA_2 are shown.

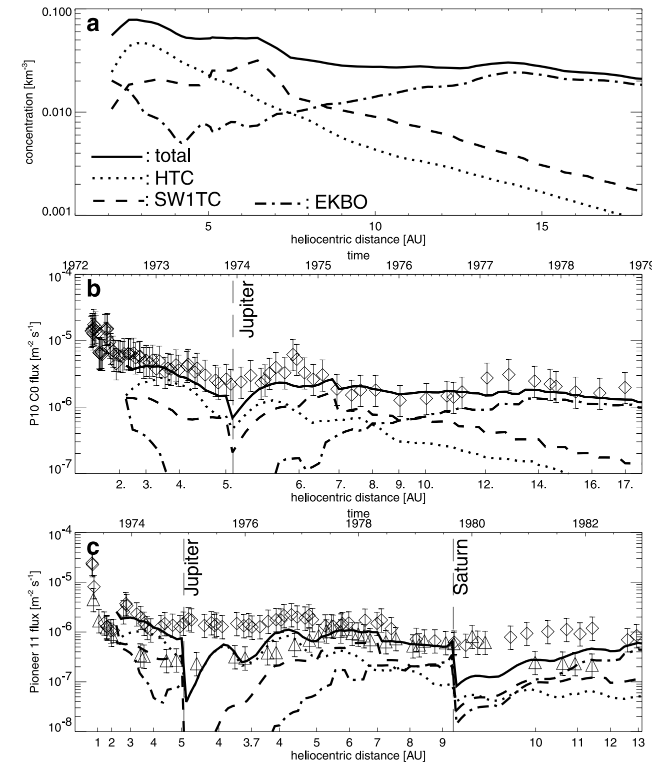

FIG. 2.—Radial profiles of the distribution of interplanetary dust in the outer solar system. (*a*) Concentration of dust particles from 1P/Halley-type comets ("HTC"), comets of the 29P/Schwassmann-Wachmann 1 type ("SW1TC"), and Edgeworth-Kuiper belt objects ("EKBO") that is needed to account for the *Pioneer 10* measurements. (*b*) Comparison of the calculated radial flux signatures of the various sources with the penetration fluxes measured by *Pioneer 10* (*diamonds;* error bars indicate 1 σ errors). Particles from HTCs contribute mainly inside Jupiter's orbit, SW1TC particles between 6 and 7 AU, and particles from EKBOs dominate outside 10 AU. (*c*) Profile of the penetration flux of the *Pioneer 11* dust instrument (*diamonds*, channel 0 data; *triangles*, channel 1 data). The profile is very flat as a result of the triple passage of *Pioneer 11* through the 4–5 AU region.

tion, the gas acts as an insulator between two electrodes, and as it escapes into the vacuum of space, the electrodes discharge and the resulting electrical signal is registered as a penetration event. The sensitivity of the instrument, that is, the minimum impact mass and velocity that cause a penetration, is determined by the thickness of the cell walls. On the *Pioneer 10* experiment, walls of 25 μm were used, and on *Pioneer 11* the cell walls were 50 μm thick. At a typical impact velocity of 20 km s^{-1}, the *Pioneer 10* cells are penetrated by particles with an equivalent diameter larger than 10 μm, and the *Pioneer 11* cells are penetrated by 21 μm particles (Humes et al. 1974).[7] The surfaces of the *Pioneer* instruments always point nearly opposite to the high-gain antenna, away from Earth. Beyond Jupiter, this means the instruments are oriented mainly away from the Sun with an effective field of view of 1.6π sr (240° opening angle). The *Pioneer 10* instrument took measurements from the launch on 1972 March 2 until it failed on 1980 May 10 as a result of the low temperatures, 18 AU from the Sun (for the geometry of the spacecraft trajectories, see Fig. 1). *Pioneer 11* performed dust measurements from launch on 1973 April 5 until it was switched off 1983 September 25.

The *Pioneer* dust instruments successfully detected 225 penetrations altogether; however, they did not work flawlessly. On *Pioneer 10* one channel failed completely, and on *Pioneer 11* an unexplained discrepancy between the rate of penetrations measured by each channel was observed. The flux measured by one channel of the *Pioneer 11* instrument is consistently higher than the flux measured by the other. Because the angular sensitivity of both channels is identical, this discrepancy can only be due to a malfunction of one of the channels. Despite these inconsistencies, we consider the *Pioneer* dust data to be reliable for the following reasons: (1) the rate of detected events increased sharply during the flybys of Jupiter and Saturn, which is not expected for random noise, and (2) the flux densities measured by *Pioneer 10* and *11* at 1 AU are in accord with measurements by *Explorer 23*, an Earth-orbiting spacecraft that was equipped with similar instruments (Humes 1976). The discrepancy between the *Pioneer 11* channels can be explained by either the loss of cells on one of the channels during the launch of the spacecraft, or by electronic noise in one of the channels. Figures 2*a* and 2*b* show the interplanetary penetration flux[8] on the *Pioneer* dust instruments as a function of time and distance from the Sun. After launch, the dust flux measured by *Pioneer 10* was 2×10^{-5} m^{-2} s^{-2}, continuously decreasing with heliocentric distance to 3×10^{-6} m^{-2} s^{-1} at Jupiter distance. After passing Jupiter's orbit, the flux measured by *Pioneer 10* stayed almost constant. Because of the lower abundance of large grains, the fluxes measured by the less sensitive *Pioneer 11* instrument were smaller, but they draw

[7] Assuming a grain mass density of 1 g cm^{-3}.

[8] Penetrations per unit area and time, sliding mean over four penetration events; penetrations during the flybys of the planets have been removed.

a similar picture: decreasing flux from Earth to Jupiter, and an almost constant flux outside Jupiter's orbit.

3. SOURCES OF DUST BEYOND JUPITER

What are the sources of the particles that penetrated the cells of the *Pioneer* dust instruments? The interstellar dust stream that was discovered by the dust instrument on board *Ulysses* causes an approximately constant dust concentration around the Sun, which potentially explains the constant penetration rate of the *Pioneer* instrument. However, from extrapolation of the flux-mass distribution of interstellar dust measured by *Ulysses* to the *Pioneer 10* threshold mass, it follows that less than 10^{-8} m^{-2} s^{-1} interstellar penetrations of *Pioneer 10* cells can be expected (Landgraf et al. 2000), less than 1% of the measured flux. We are thus left with interplanetary particles as the cause for the penetrations detected by the *Pioneer* dust experiments. Since the abundance of interplanetary particles decreases steeply with their size (Grün et al. 1985), we can assume that the penetrations were caused mainly by particles with sizes just above the detection threshold of the instruments, that is, with diameters on the order of 10 μm. Particles in this size regime move approximately on Keplerian orbits, because their dynamics are dominated by solar gravity. Over long timescales, the orbits evolve under Poynting-Robertson (P-R) and solar wind drag. This drag force is caused by the relativistic aberration of the sunlight and solar wind particles (Burns, Lamy, & Soter 1979). The effect of P-R and solar wind drag is to remove energy from a particle's orbit, causing a slow inward-directed spiral motion. The aphelion of the source object of a particle must therefore be equal to or larger than the particle's distance from the Sun. Consequently, the sources of the constant flux of particles measured by *Pioneer* outside Jupiter must lie beyond Jupiter's orbit.

We distinguish three dynamical families that we consider as potential dust sources: 1P/Halley-type comets (HTCs; short-period Oort cloud comets), comets of the 29P/Schwassmann-Wachmann 1 type (SW1TCs; short-period Jupiter-family comets with perihelia close to Jupiter's orbit), and Edgeworth-Kuiper belt objects (EKBOs). Both 1P/Halley and 29P/Schwassmann Wachmann 1 have been reported to be prolific sources of dust (Kissel et al. 1986; Fulle 1992) as they disintegrate because of solar heating. For EKBOs, the release of dust has been proposed to be the result of mutual collisions (Backman, Dasgupta, & Stencel 1995; Stern 1996) and impacts by interstellar particles (Yamamoto & Mukai 1998). Another potential source of dust outside Jupiter is the Centaur objects, which orbit the Sun between Saturn and Uranus. They are however not considered strong sources, because their number is too small to cause frequent collisions, and dust particles released by them are likely to be ejected from the solar system as a result of their highly eccentric orbits, which cross the orbits of several giant planets. They are also too far from the Sun to exhibit strong cometary activity (Brown & Luu 1998). The dynamical families of source objects described above are defined by their interaction with the major planets. A comet is considered an HTC if its perihelion is inside Jupiter's, its aphelion outside Neptune's orbit, and its inclination between 160° and 180°. SW1TCs have their perihelia close to Jupiter's orbit, eccentricities below 0.1, and inclinations below 10°. Finally, members of the EKBO family have perihelia beyond Neptune, eccentricities below 0.1, and inclinations below 20°, which includes classical as well as scattered members of the Edgeworth-Kuiper belt (Brown 2001).

4. DUST DISTRIBUTION BY ORBITAL EVOLUTION

What is the signature of particles from HTCs, SW1TCs, and EKBOs in the *Pioneer* data? The particles' equilibrium distribution in the solar system is determined by their initial orbit after they have been released from the source object,[9] and by their orbital evolution under P-R and solar wind drag, as well as under gravitational perturbations by the planets. The effect of a planet's gravity on the grains is strongest when the orbital period of the planet and the particle have an integer ratio, that is, when the particle is in a mean motion resonance (MMR) with the planet. An MMR is described by the ratio $p:q$, where q is the number of orbits the particle completes in the time the planet orbits the Sun p times. The effect of exterior MMRs, for which $p > q$, on the spatial distribution and orbits of dust particles in the solar system has been predicted (Jackson & Zook 1989) and observed (Dermott et al. 1994). When a particle is in an exterior MMR, its sunward motion is temporarily halted because the energy loss due to P-R and solar wind drag is compensated by the resonant interaction with the planet's gravitational field. But then the eccentricity of the particle's orbit increases until a close encounter with the resonant planet or a neighboring planet ejects the particle from the resonance. Depending on the planet's mass and the proximity of other strong perturbers, the exterior MMRs cause a circumsolar dust ring to form. The equilibrium distribution is achieved when the dust production by the sources is equalized by the particle sinks, which are evaporation close to the Sun and ejection from the solar system by close encounters with the giant planets, mainly Jupiter and Saturn. Because of the long timescales of orbital evolution, the equilibrium distribution is reached after 10^5 to 10^6 yr.[10] This means that not a single comet, the lifetime of which is typically 10^3 to 10^4 yr, but only a whole class of comets with similar orbital characteristics can sustain an equilibrium distribution. Particles originating from HTCs have been found (Liou, Zook, & Jackson 1999) to mainly occupy $p:1$ MMRs with Jupiter, where p ranges from 2 to 12. When they leave the Jupiter resonances, they continue sunward until they evaporate. Unlike HTC particles, dust particles released by SW1TCs are not concentrated in exterior Jupiter MMRs. This is caused by their unstable initial orbits, which bring them close to Jupiter within the first few centuries after their release from the parent comet. Jupiter perturbs SW1TC particles out to Neptune's orbit, with the maximum spatial concentration at 5 to 6 AU. Particles originating from EKBOs approach the planets' orbits from the outside and consequently are found mainly in the 2 : 1, 3 : 2, or 4 : 3 resonance with Neptune (Liou & Zook 1999). After they are ejected from the exterior Neptune MMRs, they continue to spiral toward the Jupiter-Saturn region, where 80% of them are ejected from the solar system by close encounters with one of the giant planets. The other 20% continue to spiral sunward, whereupon they evaporate at a solar distance that

[9] Or, equivalently, from centimeter-sized fragments that form the source object's trail along its orbit.

[10] For dust particles with sizes on the order of 10 μm.

depends on their composition. Figure 2*a* shows the radial profile of the spatial particle concentration in the solar system for particles from HTCs, SW1TCs, and EKBOs.

We have simulated the *Pioneer 10* and *11* measurements along the spacecrafts' orbits by calculating the flux of dust particles from a given source on the target surface of the dust detector at the spacecraft's location, given its attitude and velocity vector, and the local dust concentration and velocity vector. Figures 2*a* and 2*b* show the predicted and the measured dust fluxes on the *Pioneer 10* and *11* instruments, respectively. Because the average dust production rates of the source objects are unknown, we treated the total amount of dust, that is, the normalization of the radial concentration profile, as a free parameter that was established by a least-squares fit of the predictions to the measured values. On both spacecraft, the penetration flux initially decreased because of the lower dust concentration at larger heliocentric distances. The peak in the penetration flux measured by *Pioneer 10* near the end of 1974, at 6 AU, is well explained with penetrations caused by particles from HTCs and SW1TCs. The peak appears to be even stronger than expected from our calculations. At heliocentric distances of 7 AU and beyond, the constant penetration flux of 2×10^{-6} m^{-2} s^{-1} can be explained only if we include a substantial contribution from EKBO particles. At 18 AU, the flux of EKBO particles dominates the other two sources by an order of magnitude. Because the *Pioneer 11* dust instrument did not provide much data beyond the Jupiter-Saturn region, the signature from EKBO particles is less dominant. Between Jupiter and Saturn, as well as between Saturn's orbit and a heliocentric distance of 11 AU, the contributions from all three sources are comparable.

5. DUST PRODUCTION RATES

The comparison of the measured fluxes with the calculated radial profiles gives us a direct determination of the dust particle production rates. In order to provide the penetration fluxes shown in Figure 2*a*, HTCs have to produce 6×10^{11}, SW1TCs 3×10^{11}, and EKBOs 2×10^{14} dust particles of size 10 μm or larger per second. The production rate in terms of dust mass is given by the integral of the production rate over the grain mass distribution. The integration covers grain masses from the lower sensitivity limit of the *Pioneer 10* instrument of 10^{-9} g to an upper limit of 0.1 g. The lower mass limit of HTC grains is 10^{-7} g, because the high eccentricity of the source object and solar radiation pressure cause them to leave the solar system if they have smaller masses. The upper limit is determined by the requirement that the grains must be distributed by orbital evolution over a large volume in order to contribute to the interplanetary dust flux measured by *Pioneer*. Only grains with masses of less than 0.1 g move away from their parent bodies' orbits on timescales shorter than the age of the solar system. Assuming a generic collision-type grain mass distribution (Dohnanyi 1972), we find dust mass production rates of 3×10^5 g s^{-1} for HTCs, 8×10^4 g s^{-1} for SW1TCs, and 5×10^7 g s^{-1} for EKBOs.

6. DISCUSSION

From in situ measurements (Mazets et al. 1987), as well as remote sensing experiments (Thomas & Keller 1991) close to the comet's perihelion, it was found that 1P/Halley's dust production rate during its active phase was 10^7 g s^{-1}. Keeping in mind that comet 1P/Halley has an active period that covers less than 1% of its orbital period, we find that Halley itself produces on average less than 10^5 g s^{-1}. This means that unless HTCs have been much more active in the past, there must be a significant contribution from other sources, such as short-period Jupiter-family comets, in order to sustain the dust concentration observed by *Pioneer 10* between 2 and 5 AU.

The measurements by *Pioneer 10* at heliocentric distances larger than 6 AU provide better constraints on the dust production rate of SW1TCs than on the dust production by HTCs. The high penetration flux measured between 6 and 7 AU cannot be explained with a contribution from HTCs or short-period Jupiter-family comets. From the *Pioneer 10* measurements we find that, on average, 8×10^4 g s^{-1} of dust have to be generated by SW1TCs. This is considerably lower than the value of $(6 \pm 3) \times 10^5$ g s^{-1} for the current dust production rate found by Fulle (1992) for 29P/Schwassmann-Wachmann 1 itself. This confirms that, because of the proximity of the strong perturber Jupiter, the dwell time of SW1TCs in their peculiar orbits is small compared with their lifetimes. This also means that 29P/Schwassmann-Wachmann 1 itself is able to provide a major fraction of the solar system dust that is currently found between 6 and 8 AU.

Our calculations show that the interplanetary dust environment outside Saturn is dominated by particles originating from EKBOs, unless there is an unexpected significant contribution from Centaur objects or unknown sources. If there were a significant amount of dust from Centaur objects, its spatial density would decrease steeply with increasing heliocentric distances because of the high eccentricity of the Centaurs' orbits. Such a radial distribution would not explain the nearly constant flux observed by *Pioneer 10* outside Saturn's orbit. In order to fit the *Pioneer 10* detections outside 10 AU, dust has to be produced in the Edgeworth-Kuiper belt at a rate of 5×10^7 g s^{-1}. Because we assume an equilibrium dust distribution, this value represents the average over the typical dust particle lifetime of 10^7 yr. Estimates of the collisional dust production (Stern 1996) that include fragments up to kilometer size give values of 10^9 to 10^{11} g s^{-1}. However, the orbits of these large fragments do not evolve under P-R drag into the 10 to 18 AU region. Translating the collisional production rate into the mass range between 10^{-9} and 0.1 g gives a value between 9×10^5 and 3×10^8 g s^{-1}, depending on the surface properties of EKBOs. In addition to the collisional dust production, the production of particles by impacts of interstellar dust grains onto EKBOs has been found to be between 3×10^5 and 3×10^7 g s^{-1} (Yamamoto & Mukai 1998). Thus, the EKBO dust production rate derived from the *Pioneer 10* measurements is on the high side of the source models, but well within the theoretical uncertainties, which include the size distribution of Edgeworth-Kuiper belt objects, the impactor flux, and the source objects' surface properties.

7. CONCLUSION

The discussion above shows that we have been able to identify a set of observable dust sources for the *Pioneer* dust measurements. Unlike the interpretation by Humes (1980), we have used a set of three dynamical families of source objects. The sum of these sources provides the right spatial and local velocity distribution to explain the penetration fluxes measured by *Pioneer*. We found the calculated signature of the source families in the data to be independent, that is, dominant for different heliocentric distances, so that dust production rates for the individual sources could be derived separately from the data. The data collected by the spacecraft outside Saturn's orbit are especially valuable, because with increasing heliocentric distance the number of possible contributors to the interplanetary dust cloud decreases. The only known source of interplanetary dust outside Saturn is the Edgeworth-Kuiper belt. This gives us the opportunity to unambiguously determine the amount of dust released by the objects of the belt. According to the *Pioneer 10* measurements, the density of interplanetary dust generated by the Edgeworth-Kuiper belt is high enough for this dust cloud to be the second brightest feature of the solar system when observed from afar (Liou & Zook 1999). Thus the Edgeworth-Kuiper belt and the distribution of dust particles it produces can act as a model for detecting other planetary systems around middle-aged main-sequence stars. Interplanetary dust in the region between Jupiter and Saturn gives us information about the dynamical properties of this interesting region. Since a flyby of Jupiter on 2000 December 31, the *Cassini* spacecraft is en route to Saturn, carrying a highly sensitive dust instrument. It will provide data on the mass, velocity, and chemical composition of the smaller sized dust particles.

Sadly, our dear colleague Herbert A. Zook passed away on 2001 March 14. Support by D. H. Humes in various discussions is gratefully acknowledged. M. L. thanks D. P. Hamilton for valuable discussions, and M. Khan for improving the clarity of the manuscript. We also acknowledge the support of the National Space Science Data Center, which provided a copy of the original *Pioneer* data. M. L. was supported by the National Research Council while this work was performed.

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