A LOCAL SOURCE FOR THE PIONEER 10 AND 11 CIRCUMJOVIAN DUST DETECTIONS

Dara B. Zeehandelaar and Douglas P. Hamilton

Astronomy Department, University of Maryland, College Park MD 20740, USA, dara@astro.umd.edu

ABSTRACT

We investigate dust grains orbiting a planet and interacting with its satellite system. The grains are subject to the gravitational force of Jupiter and its four Galilean satellites, the electromagnetic force from the rotating planetary magnetic field, and solar radiation pressure. We generate clouds of 5-μm grains launched perpendicular to the surfaces of the Galilean satellites at each of their respective escape velocities. This collisional ejecta moves initially along planar, near-circular orbits but is often perturbed to orbits with high inclinations and eccentricities. Collisions with not only the satellite of origin but also with the other moons and even Jupiter can then occur. These perturbed grains suggest a possible circumjovian origin for the detections by the Pioneer 10 and 11 meteoroid experiments, which recorded dust well out of the Jovian equatorial plane.

1. INTRODUCTION

In-situ measurements of dust particles in the outer Solar system can give insight into sources of both interplanetary and circumplanetary debris. The first two spacecraft to explore the outer Solar System, Pioneers 10 and 11, carried dust detectors sensitive to the impacts of relatively large grains. Much work has gone into analyzing the detections in interplanetary space (for example, 1; 2; 3; 4), but the spacecraft also sensed particles near Jupiter. The origin of this circumplanetary debris has never been fully explained (5; 6; 7; 8; 9; 10) and hence merits renewed scrutiny. While the Pioneer results have been largely superseded by the wealth of dust data returned by the sophisticated Galileo dust detector that orbited Jupiter from 1995 through 2003 (11; 12; 13), the Pioneer data are still of interest because i) the spacecraft trajectories were significantly out of Jupiter's equatorial plane, ii) the instruments had large collecting areas, and iii) the data set is extremely simple, consisting of only 14 impacts!

The Pioneer 10 and 11 micrometeoroid detection experiments consisted of gas-filled pressurized cells mounted on the leading surface of each spacecraft's antenna; when the wall of one of these 234 cells was punctured by a hypervelocity impact, the gas escaped and the onboard detector registered the resulting loss of pressure (8). The instruments on the two spacecraft were similar except that the container walls on Pioneer 10 were 25-μm thick and sensitive to particles of mass $\sim 10^{-9}$g and those on Pioneer 11 were 50-μm thick and sensitive to particles of mass $\sim 10^{-8}$g for impact velocities typical in interplanetary space. The 234 cells were separated into two channels in order to provide redundancy for the experiment, but otherwise there was no information about which particular cell was triggered (7). One channel on Pioneer 10 failed, giving the spacecraft an effective sensor area of 0.27m^2 (5), and evidence from numerical meteoroid models supports a partial failure of some of Pioneer 11's impact sensors as well (the data do not pass the redundancy test for the original ratio of cells in each channel—see 14). Nevertheless, the detectors did register 14 dust grains near Jupiter, 11 of which were significantly out of Jupiter's equatorial plane (6; unpublished Humes data in 15). Despite instrument failures and observational inconsistencies, however, the data are believed to be reliable because detection rates matched predicted or previously observed flux densities (4). In this paper, we investigate the hypothesis that the grains measured near Jupiter, initially attributed to gravitationally focused interplanetary material (7), may instead originate from impact debris from the Galilean satellites and subsequently scattered to high latitudes.

2. PHYSICAL AND NUMERICAL MODEL

To simulate the behavior of particles in the Jovian system, we numerically integrate the orbits of dust grains using the Bulirsch-Stoer option of the dust integration code dI, described originally in (16). The code integrates Newton's equations directly and includes electromagnetic and higher-order gravitational forces from the planet as well as solar radiation pressure. To this original code, we have added the gravity from orbiting satellites and a sophisticated satellite collision algorithm in order to obtain pre-

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cise orbital integration during close approaches and to accurately register physical collisions. When a particle is far from a satellite, large time steps are sufficient to follow the orbit accurately; however, near a satellite smaller steps are required to clearly resolve the encounter. We created a close-approach zone around each satellite, with a radius of either 1/100 of the satellite's apocenter distance or 10 times the satellite's radius, whichever is larger (the former criterion avoids close-approach zones that are trivially small for very small satellites). Once within the close-approach radius, the integrator automatically shifts to the Runge-Kutta method which, although more computationally expensive, takes smaller steps and more cleanly resolves the encounter. Furthermore, within the close-approach zone each step is automatically calculated to higher fractional accuracy. For the simulations discussed here, we require convergence to at least one part in 10^{11} (we performed accuracy tests that demonstrated that a fractional accuracy of 10^{9} was adequate for our application). Once outside the near-satellite zone, the integration method reverts to the faster Bulirsch-Stoer algorithm. Our testing showed that the implementation of this close-approach algorithm is able to adequately represent both gravitational scattering and physical collisions for satellites with sizes ranging from Adrastea (radius∼10km) to Ganymede (radius∼2600km).

To create a first approximation to the debris ejected over time by an ensemble of small impactors, we generated a spherical cloud of radially-launched dust grains around each of the Galilean satellites using software to calculate the position and velocity initial conditions for each individual particle. We placed a grain at each of the intersection points of a latitude-longitude grid drawn on the satellite surface. This introduces a bias toward polar impacts, when instead we should actually be accounting for the fact that the leading satellite hemispheres produce most ejected material. In addition, a satellite's size and proximity to Jupiter should also affect its source strength. We can correct for these biases, but for now we wish to only to map out where ejected particles can go, and so our grid approximation is sufficient. Grains were launched at the 2-body escape speed of their source satellite $\sqrt{2GM_{sat}/R_{sat}}$, where G is the gravitational constant, M_{sat} is the satellite's mass, and R_{sat} is its radius; these initial velocities are consistent with the work of (17), who found that the peak in the velocity distribution of the number of escaping fragments generated by an impact event occurs at a value comparable to the escape velocity of the target. The Pioneer 10 detector measured grains at high inclinations (at Jovian latitudes between 10° and 20°) within 20 Jovian radii (R_J = 71492 km), and thus we choose to model 5-μm dust grains ($\sim 10^{-9}$g) which, at velocities typical of orbits near Jupiter (the orbital velocity of Io is ∼17km/s), are large enough to have penetrated the Pioneer 10 cells.

We subjected the grains to Jovian gravity, including both the monopole and quadrupolar terms, satellite gravity, solar radiation pressure, and the electromagnetic force. We put our four simulated satellites, Io, Europa, Ganymede, and Callisto, on circular coplanar orbits around Jupiter, and we gave the planet its 3.12° obliquity and an orbital eccentricity of 0.048. We ignored solar gravity and gravitational interactions between satellites, and adopted a constant equilibrium value of the electrostatic surface potential of Φ = +5 V (18, Figure 3). Finally, we ran orbital simulations and compiled statistics in order to determine how broadly 5-μm grains from the Galilean satellites spread, both radially and vertically.

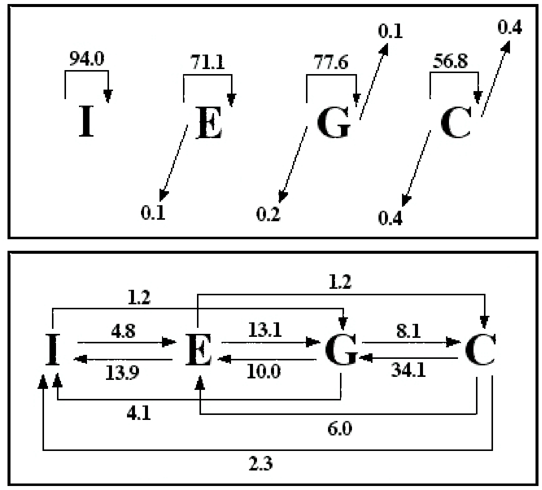

Figure 1. Transfer statistics for 5-μm dust grains. Io, Europa, Ganymede, and Callisto are shown in each panel. Transfer efficiencies are given as percentages of the total number of grains that eventually recollide with a satellite or with Jupiter, or escape the Jovian system (numbers do not include grains that remain in orbit at the conclusion of the simulation or grains that immediately recollide with their satellite of origin). The top panel represents grains that recollide with their source satellite, hit Jupiter (arrows to lower left), or escape the Jovian system (arrows to upper right). The lower panel tallies transfers among satellites; transitions toward and away from Jupiter are drawn in the lower and upper half of the figure, respectively.

3. TRANSFER STATISTICS AND DISTRIBUTION OF DUST GRAINS

We simulated 8000 dust grains (2000 launched from each satellite) over an integration time of 5000 years, finding that 88% of all grains collide with Jupiter or one of its satellites within 3000 years, and half of the remaining particles collide in the next 2000 years— these decay rates are consistent with theoretical estimates (19). The dust is rapidly scattered to high inclinations and eccentricities, and to distances well outside Callisto's orbit. The high eccentricities attained by the 5-μm dust grains put them on crossing orbits with multiple satellites and allows transfer of material between objects as illustrated in Fig. 1.

We find that most of the 5-μm grains launched from Io

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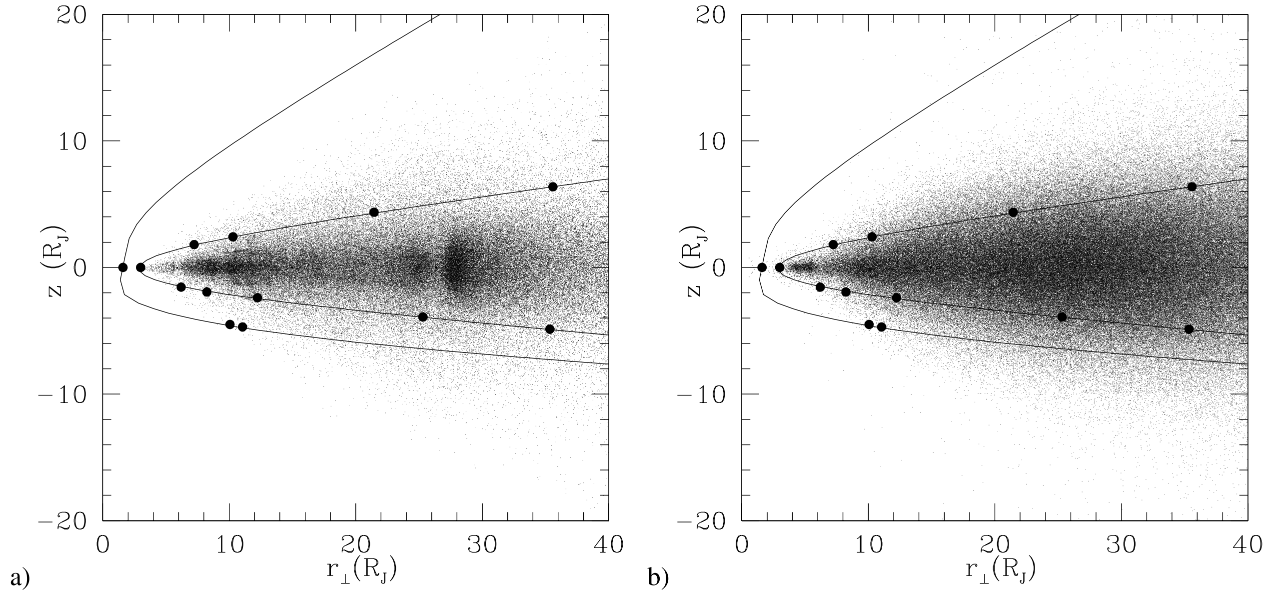

Figure 2. Vertical vs. horizontal distances for a) centimeter-sized and b) 5-μm dust grains launched from the four Galilean satellites and followed for 5000 years or until a collision occurred. Here $r_\perp = \sqrt{x^2 + y^2}$, and x, y, and z are Cartesian coordinates with the origin at Jupiter and z along the planet's spin axis. We overplot the Pioneer 10 and 11 trajectories, which we converted from ecliptic coordinates. The two spacecraft approached Jupiter from the lower right and departed at high latitudes. We also plot dust detections as solid circles along the trajectories; Pioneer 10's single channel recorded ten hits (6) while Pioneer 11, with its thicker cell wall and dual channels, received four hits (Humes data from 15). There is some uncertainty in the exact location of each detection due to the finite time required for gas to leak out of a cell after its wall was penetrated. These uncertainties are about the size of the solid circles. A total of three hits, one per channel, were detected at times consistent with the spacecraft's crossing of the ring plane.

tend to recollide with that satellite. In contrast, only just over half of those originating from Callisto eventually hit Callisto again, with the remainder transferring mostly to Ganymede but also in small numbers to Europa and Io. Grains launched from Europa and Ganymede represent an intermediary result, with approximately 75% recollisions, 10% transfers to exterior satellites, and 15% transfers to interior ones. Additionally, although some transfers can skip over one or even two satellites, very few grains hit Jupiter or escape the Jovian system completely. Somewhat paradoxically, Jupiter receives no material from Io, the innermost Galilean satellite, because radiation pressure, which drives dust grain eccentricities, is a comparably weaker perturbation near the planet. The transfer of material between bodies may cause surface contamination for elements generally assumed to arise locally (e.g., possible delivery of sulfur compounds from Io to Europa). Ultimately, more rigorous models of actual impacts and other geological processes, and a survey of the dynamics of different ejecta sizes, are necessary, but it is clear that at least some surface composition characteristics may have an exogenous origin.

Fig. 2 compares the spatial distributions of 5-μm with cm-sized dust grains that are unaffected by non-gravitational forces. The centimeter-sized particles show less pronounced radial and vertical scatter, and they tend to evolve while maintaining a pericenter or apocenter locked to the orbit of one of the Galilean satellites. The results of this behavior are visible as clumps on either side of the satellites Io ($\sim 6R_J$) and Callisto ($\sim 26R_J$) in Fig. 2a.

The interplay between gravitational and non-gravitational forces enhances both the radial and vertical mobility of dust grains, allowing for the more extended dust distribution seen in Fig. 2b. Non-gravitational forces break this pericenter and apocenter locking seen for cm-sized grains, resulting in a much smoother profile for the 5-μm dust of Fig. 2b. Radiation pressure strongly affects grain orbital eccentricities, which increases moon flyby speeds. This diminishes the importance of gravitational focusing and allows dust grains to avoid collisions significantly longer than macroscopic material. Since high-inclination orbits survive longer against collisions (19), these orbits are favored in the steady state population of the debris torus.

The Pioneer 10 dust detector observations (6) fall well within the realm covered by the simulated 5-μm grains, and even the distribution of larger material fits reasonably well. The two out-of-plane Pioneer 11 data points (15) occur at the most favorable part of the Pioneer 11 trajectory near the inner edge of the dust distribution. At earlier times impact speeds are lower, while later the spacecraft moves to high latitudes where the density of potenial impactors is negligible.

Our study shows that grains larger than 5-μm provide a plausible fit to the Pioneer 10 and 11 dust data set. Due to the change of impact speed with distance from Jupiter, different sized dust grains are able to trigger the detector at different points along the trajectory. The next logical step for this study is to consider more realistic source strengths for the Galilean satellites, and estimate actual number densities for dust grains of several different sizes. Results from the Galileo dust detector, with a sensitive area of 0.1m^2 and over seven years of Jovian measurements, have been investigated by (20; 21). Comparison of both data sets to a single numerical model will be essential to see if a consistent story emerges. In the meantime, a local source for the Pioneer 10 and 11 detections near Jupiter appears very promising.

We dedicate this paper to the memory of Herb Zook, whose initial investigations into this problem were insightful and ahead of their time. This material is based upon work supported by the National Aeronautics and Space Administration under Grant NNG04GM18G issued through the Exobiology Program. We thank Harald Krüger for providing us with the Pioneer trajectories, and Joe Burns, Valeri Dikarev, and an anonymous referee for their useful comments.

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