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Dust streams from comet Shoemaker-Levy 9?

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Abstract. In 1991 and 1992, the dust detector onboard the Ulysses spacecraft detected several dust streams apparently originating from the jovian system. The timing and measured speeds of the final two dust streams are compatible with dust from comet Shoemaker-Levy 9's (SL9) disruption in 1992. Our further investigations of stream characteristics and dust acceleration mechanisms, however, shed some doubt that two of the eleven dust streams are of SL9 origin. In July 1994 when SL9 impacts Jupiter, the Galileo spacecraft will be about 3500 jovian radii away from the planet. Submicron-sized dust released into, and accelerated by, the jovian magnetosphere during this event may reach Galileo and impact its dust detector between September and November 1994. We also discuss the possibility of directly sampling dust from SL9 during Galileo's orbital tour.

Introduction

Two unusual planetary phenomena were observed in the vicinity of Jupiter during the course of 1992. First, streams of submicron-sized dust particles were recorded by the Ulysses spacecraft for a one-year period around its Jupiter flyby date of 8 February 1992 (*Grün et al.*, 1992, 1993; *Baguhl et al.*, 1993). The flight direction of the stream particles is compatible with a source within the jovian system. Second, comet P/Shoemaker-Levy 9 (SL9) was tidally disrupted during its own close flyby of Jupiter on 8 July 1992. The "comet" currently consists of a train of several kilometer-sized fragments, dust trails (or wings) preceding and following the larger fragments, and an extended dust sheet of micron-sized particles (*Scotti 1993*; *Sekanina et. al.* 1994). In this paper we investigate a potential relation between these two seperate events. We also discuss the possibility of directly sampling dust from SL9 during Galileo's orbital tour commencing in 1996.

Comet SL9 broke into more than 20 large fragments during a flyby only 1.6 R_J off Jupiter's center. The fragments and the associated dust sheet are bound to Jupiter with an orbital period of about 2 years - for a more detailed description of the observations see *Sekanina et al.* (1994). The orbital elements for the midpoint of the fragment train relative to the jovian equatorial plane are given in Table 1. The differences in the two sets of elements are caused by the gravitational perturbation from the Sun, which is quite strong due to the large cometary apojove of about 700 R_J. As a result of this perturbation, all of the kilometer-sized fragments will impact Jupiter's atmosphere during a 6 day period in July 1994. Particles larger than a few hundred microns in the following trail will also strike Jupiter, but some larger particles in the leading trail as well as the bulk of the particles smaller than 100 μm will survive their 1994 encounter with the planet.

1992 Ulysses dust streams

In this section we investigate the possibility that two of the dust streams detected by Ulysses in late 1992 were caused by SL9. Fig. 1 shows the impact rates observed by Ulysses around the time of the Jupiter flyby and *Baguhl et al.* (1993) summarize the relevant features of the eleven dust streams detected to date. They find that the measured mean mass of the approximately 500 stream particles is $2.0^{+4.0}_{-1.3} \cdot 10^{-15}$ g, and that their mean impact speed is 34 km/s ±10 km/s. *Horanyi et al.* (1993a) proposed and *Hamilton* and *Burns* (1993) and *Horanyi et al.* (1993b) further described a mechanism by which such submicron-sized dust particles are expelled at high speed from the jovian magnetosphere. *Horanyi et al.* (1993a,b) assume that the dust emanates from volcanoes on Jupiter's moon Io while *Hamilton* and *Burns* (1993) suggest that they originate from Jupiter's gossamer ring.

We consider three different possible mechanisms for the production of sub-micron sized cometary dust: 1) impact of gossamer ring particles onto the nucleus of SL9 during its 1992 flight through the jovian ring, 2) production of dust during tidal disruption (presumably at or near pericenter), and 3) production of dust during later times from the exposure of fresh cometary ice. Tidal disruption of SL9 occurred on day 190-1992 at which time Ulysses was about 2500R_J away from Jupiter.

About 40 minutes before its closest approach to Jupiter, comet SL9 crossed the jovian ring plane at a distance of 1.97R_J heading north. This is just 0.16R_J outside of the main jovian ring and in the densest part of the gossamer ring, a very tenuous sheet of material with

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Table 1. Jovicentric osculating orbital elements of SL9

perijove time	1992 July 8.02	1994 July 21.22
eccentricity	0.9959	0.9987
perijove distance (km)	112820	35722
inclination	63.36	75.80
longitude of ascending node	116.17	136.37
argument of perijove	53.12	46.80

Elements are given for the midpoint of the nuclear train, after *Sekanina et al.* (1994), epoch at perijove. In this coordinate system, longitudes are measured from the ascending node of Jupiter's orbital plane on its equatorial plane which is about 140° from the vernal equinox.

a normal optical depth of a few times 10^{-7} (*Showalter et al.*, 1985). The comet nucleus passed through the ring with a velocity of 41 km/s relative to a circularly orbiting particle and probably struck a few hundred grams of micron-sized dust. The ejecta from these energetic impacts amount to a few tons of micron- and submicron-sized dust that initially travels with the comet. This amount of material is insignificant, both in comparison to that currently seen in SL9's dust sheet and relative to that produced hourly in the gossamer ring by impacts of interplanetary micrometeoroids. It may be important, however, that the dust particles produced by SL9 move on initially comet-like orbits. Furthermore, the comet may have struck some centimeter- to meter-sized parent bodies that are likely to reside in the ring, in which case a correspondingly greater amount of ejecta would have been produced. The comet then proceeded inward and upward to a radial distance of $1.57 R_J$ where tidal disruption occurred. Tidal forces alone probably do not produce much fine dust, but friction among fragments and mutual low velocity collisions are viable mechanisms. Violent sublimation of volatiles, previously buried deep in the cold interior of the comet, probably accounts for most of the subsequent dust production. Fragments from the breakup then descended beneath the equatorial plane at a distance of $7.83 R_J$, and continued traveling away from the planet until mid 1993.

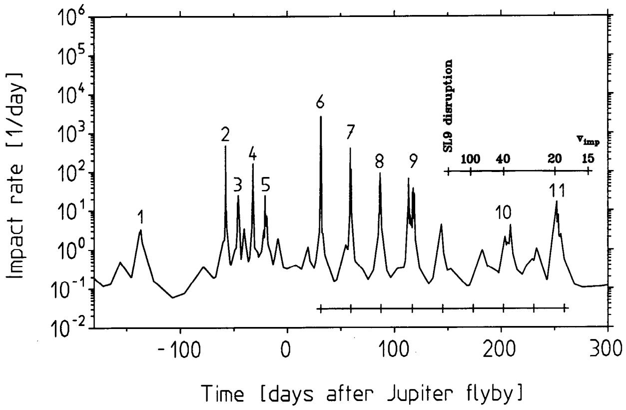

Figure 1. Impact rate of small dust particles (m < $2.5 \cdot 10^{-14}$ g) observed by the Ulysses dust detector. A sliding mean of 3 impacts was applied. The upper inset scale shows the impact speed v_{imp} which is necessary for dust particles produced at breakup of the comet to reach Ulysses. The lower inset scale marks times of streams extrapolated from the stream period and the midpoints of streams 6 to 9. Since the period varies by ±1 day, the extrapolated positions of streams 10 and 11 may be in error by up to ±5 days.

Modeling allows us to estimate particle sizes which are ejected by electromagnetic interactions with the jovian magnetosphere. We followed the charging and dynamics of various grains released during or shortly after the cometary disruption (*Horanyi et al.*, 1993a, b) and show the velocity of grains that escape Jupiter in Fig. 2. Particles larger than 0.1 μm ($m \sim 4 \cdot 10^{-15}$ g) are slower than the measured speeds of streams 10 and 11 while those smaller than 0.01 μm ($m \sim 4 \cdot 10^{-18}$ g) are much faster. Grains in the 0.05 to 0.1 μm size range ($\sim 5 \cdot 10^{-16}$ g to $\sim 4 \cdot 10^{-15}$ g mass range) have speeds similar to those measured by Ulysses. Of course, the interplanetary magnetic field has to be oriented correctly to get these particles to Ulysses. Future detailed modeling is needed to verify whether these particles really can reach the spacecraft.

Only the two dust streams occurring after the SL9 breakup (streams 10 and 11) could have originated from the SL9 disruption (Fig. 1); the particles in these streams have masses and speeds that are similar to the averages given above. Figure 1 also contains a scale of velocities at which dust particles would strike Ulysses, assuming that they were released at Jupiter during SL9's disruption and traveled along straight-line

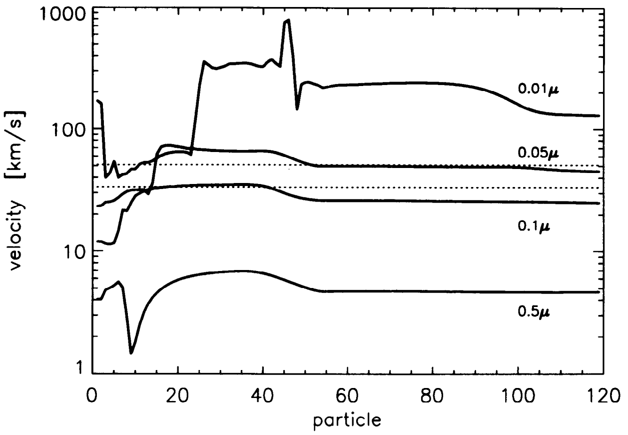

Figure 2. Speeds relative to Jupiter of grains released every 6 minutes for a 12 hour period after breakup of SL9. The 12 hours correspond to the time required for the comet fragments to traverse the dense inner part of the jovian magnetosphere. The particles themselves were initially placed in randomly selected positions within an 8 km radius sphere centered on the cometary midpoint, with zero relative velocity. Grains are numbered chronologically; those released near pericenter are on the left and those released about 12 hours later are on the right. The dotted lines mark the 34 and the 52 km/sec speeds of the Ulysses streams 10 and 11 relative to Jupiter.

trajectories to Ulysses. The calculated impact speed of particles in stream 10 would be about 38 km/s (i.e. 52 km/s relative to Jupiter) whereas that of stream 11 grains would be about 20 km/s (34 km/s). These calculated speeds are not inconsistent with the measured mean impact speed due to the factor of two uncertainty in the latter, but the difference is still disturbing. Both the *Hamilton* and *Burns* (1993) and *Horanyi et al.* (1993a,b) models predict that if the particles in streams 10 and 11 have similar masses, they should also have similar impact velocities.

In this section we have described a scenario in which material released around the time of SL9's 1992 breakup may account for one or both of the streams sensed by Ulysses after that time. This thesis seems promising at first. Measured stream masses and velocities are consistent (although marginally) with a SL9 source, and stream activity seems to pick up after a lull (Fig. 1), perhaps indicating the influence of a new source. We also demonstrated that the ejection mechanism is feasible. The fact that stream parameters in the final two streams are similar to those in the earlier streams, however, makes it difficult to discount an Io or gossamer ring source. We conclude that some of the particles in streams 10 and 11 are probably of cometary origin, but refrain from claiming that these cometary grains are in the majority. More detailed modeling is clearly necessary.

Galileo's 1994 opportunity

In July 1994 when the fragments of SL9 return to strike Jupiter, some of the particles smaller than about a millimeter in radius avoid collision with the planet. Particles with radii greater than 20 μm cross the jovian equatorial plane within $50R_J$ of Jupiter over a two to three month period beginning in late May 1994; some pass through the main jovian ring, some through the gossamer ring, and some near the Galilean satellites. A small fraction of these particles strike the moons and parent bodies within the rings, creating micron and submicron particles on initially circular jovicentric orbits. Sub-micron dust created outside of synchronous orbit ($2.25R_J$) is ejected from the jovian system at high velocities in dust streams like those detected by Ulysses.

The largest error in predicting the amount of dust produced by impacts with the jovian rings and moons arises in estimating the amount of SL9 dust in the dynamically-important 20 to 1000 μm size range; here we adopt *Sekanina et al.* (1994)'s estimate of a few tons. Because the probability of a SL9 dust grain colliding with a large Jupiter-orbiting object is so low ($\leq 10^{-6}$ in the main ring), the amount of material produced in this way is minimal, even after accounting for the fact that the mass of collisional ejecta exceeds the impactor mass by a factor of $\sim 10^4$.

A second way to produce dust is for SL9 particles to encounter micron-sized ring particles; the resulting ejecta continue along the original cometary particle's orbit modified by the appropriate electromagnetic forces. These collisions are more common than those with large objects (probability $\sim 10^{-2}$ in the main ring) but again, the amount of material produced is minimal. Further tidal disruptions of kilometer-sized fragments and the impact of these bodies into Jupiter are not efficient sources of dust since particles so produced will almost certainly be caught in Jupiter's atmosphere. All of these estimates predict significantly less dust production in 1994 than in 1992.

At the time of the SL9 impact into Jupiter, Galileo will be $3450R_J$ from Jupiter approaching the planet at a relative speed of only 4.7 km/s. If dust streams are generated by comet SL9 and their speed is in the range from 20 to 40 km/s, they could reach Galileo between 60 and 120 days after the collision, i.e. between September and November 1994. In October 1994, Galileo will be near the ecliptic plane and about $3000R_J$ away from Jupiter. Because of this location, the *Hamilton* and *Burns* (1993) model suggests that a symmetric solar magnetic field profile is necessary for the streams to be detected by Galileo (cf. their figs. 2b and 3b). Although the estimate of the amount of material in SL9's dust sheet suggests that dust streams of cometary origin will be weak, there are many uncertainties and hence such streams should be sought. We note that, by analogy with the Ulysses observations, "normal" stream activity may also commence at about this time. This will limit our ability to uniquely identify dust streams from SL9.

Galileo observations in 1996

In this section we discuss the expected dust observations while Galileo is in orbit about Jupiter and study

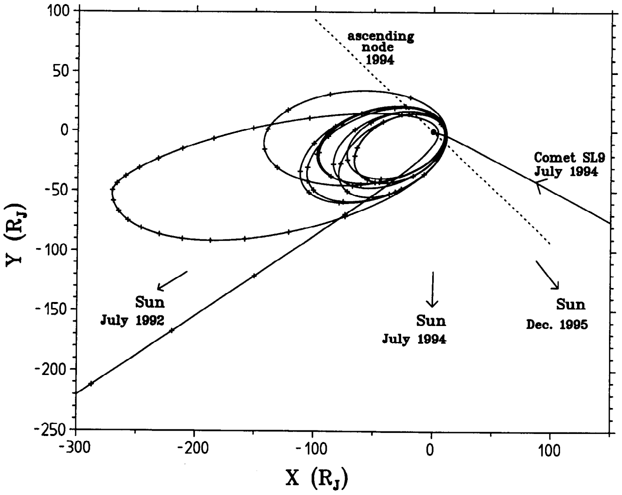

Figure 3. Galileo trajectory. The x-axis points towards the ascending node of Jupiter's equatorial plane on its orbital plane on July 8th, 1992. The Galileo trajectory is projected into the x-y-plane. The tick marks of the trajectory are 10 days apart. Also included is the orbit of comet SL9 and its 1994 nodal line with Jupiter's equatorial plane. Sun directions are also included for the times of perijove of comet SL9 in 1992 and 1994 and for Jupiter orbit insertion of Galileo on December 5th, 1995.

whether it is possible to differentiate between SL9 dust bound to Jupiter and dust from other sources in the jovian magnetosphere. Figure 3 shows the trajectory of Galileo inside a distance of $370R_J$. During initial approach to Jupiter, the dust experiment returns data by instrument memory readouts about twice per week with a few gaps of several weeks duration for engineering tests. This data transmission scheme corresponds roughly to a rate of about 0.02 bits/s. During the first six-month orbit about Jupiter, the spacecraft samples distances out to $370R_J$. Unfortunately, no data from the dust experiment is scheduled to be transmitted during this interesting period because data from the atmospheric entry probe has precedence. For most of the following orbits we expect an instrument data readout rate of about 1 bit/s inside of $50R_J$. At larger distances, occasional instrument memory readouts at an average data rate of 0.01 to 0.02 bits/s are scheduled.

When Galileo approaches Jupiter in late 1995, most of the cometary material in the 20 to 1000 μm size range that avoided collision in 1994 will be far beneath Jupiter's equatorial plane. Of this material, virtually all that is now in the west-southwest trail and tail regions will escape Jupiter into heliocentric space. Very little of the material that remains bound to Jupiter gets within 100 R_J of the planet over the 20 year duration of our numerical simulations. Hence it is unlikely that Galileo will encounter these larger particles in quantity.

The orbits of particles smaller than 20 μm are substantially affected by electromagnetic effects. Using a reasonable plasma model, we find that particles smaller than a few μm in radius will depart the jovian magnetosphere. Since the smallest grains are the most numerous in SL9's particle size distribution (*Sekanina et. al.* 1994), grains that are a few microns in radius are the most likely to be observed. In an accompanying paper *Horanyi* (1994) shows that in about 10 years time these grains may settle into retrograde orbits in a region between 4.5 and $6R_J$ possibly remaining there for 10^3 to 10^4 years.

The Galileo dust instrument provides information on impact positions, directions and speeds. Impacts of large particles (20 to 1000 μm) from SL9 will be rare, but are most likely to occur when Galileo is furthest from Jupiter since these particles rarely venture within 100 R_J of the planet. Impact speeds at 100 R_J are from 5 to 10 km/s, only slightly slower than that expected for focused interplanetary particles. Interstellar particles will have much larger speeds. If 2 μm particles settle down into retrograde orbits, these should strike Galileo at high velocities and from particular directions. The Galileo dust detector should be able to distinguish between these various particle populations due to the expected differences in particle size, velocity, and impact direction.

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