

Io as a Source of the Jovian Dust Streams

A. L. Graps*, E. Grün*, H. Svedhem†, H. Krüger*,
M. Horányi††, A. Heck*, S. Lammers*

*Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany.

† European Space Research and Technology Centre, 2200 AG Noordwijk, The Netherlands.

†† Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO 80309.

FINAL revised version: 10 March 2000

Ever since the discovery of the Jovian dust streams by the Ulysses spacecraft dust detector in 1992^{1,2}, space scientists have wondered about the streams' origin. Before and since the Galileo spacecraft's arrival in the Jupiter system in December 1995, we recorded more dust stream measurements^{3,4,5} this time with Galileo's dust detector instrument, which is a twin to Ulysses' dust instrument. Researchers narrowed the dust streams' origin to be in the Jovian system², with the possible sources being Jupiter's main ring⁶, Jupiter's gossamer ring⁷, comet Shoemaker-Levy 9⁸, or Io. All but Jupiter's gossamer ring and Io have been ruled out^{4,9,10,11,12,13,14}. Here, from periodicities in the dust impact signal, we argue that the dominant source of the Jovian dust streams is Io.

The Jovian dust stream population detected in the inner satellite region by the Galileo dust instrument (DDS) can be seen in the data's highly variable (over periods of \sim hours), submicrometre-sized particle impact rates. Using a Lomb-Scargle periodogram¹⁵, we have transformed, from the time domain into the frequency domain, the first two years, 1996-1997, of Galileo DDS impact rate data in orbit around Jupiter. Eight peaks are prominent in Fig. 1 in the frequency range 0 to 6 cycles day⁻¹. We interpret these frequency peaks based on the following description of our physical system (Fig. 2).

Io, with its \sim 42 hour rotation period, provides material from its volcanic plumes (up to \sim 460 km in height¹⁶). Material escapes Io at an approximate rate of 1 ton sec⁻¹¹⁷, via a multistep process involving Io's atmosphere and the local plasma environment¹⁸. If charged high enough, some material can be swept up by Jupiter's magnetic field, which orbits with Jupiter with a \sim 10 hour rotation period^{19,20}.

Galileo's and Io's orbits lie very nearly (within 1°) in Jupiter's equatorial plane. Owing to a 10° tilt between Jupiter's rotational and magnetic axis, Io and Galileo pierce Jupiter's magnetic equatorial plane twice each orbit. Since charged dust couples to Jupiter's magnetic field, which co-rotates with Jupiter (frequency 2.4 day⁻¹), Jupiter then modulates the rate at which Io source dust particles (frequency 0.6 day⁻¹) can be detected. Galileo's dust detector records these charged particles when Jupiter's warped dust sheet passes over its position, which occurs *on average* twice per Jupiter rotation (4.8 day⁻¹).

We interpret the frequency peaks seen in Fig. 1 to be the result of Io's frequency of rotation, Jupiter's magnetic field frequency of rotation, and an interaction between these two frequencies called amplitude modulation (AM). The simplest case of AM is a sinusoid modulating the amplitude of a carrier signal, which is itself a sinusoid. Then the carrier signal is broken down in frequency space into several sinusoidal oscillations: $x \approx \sin(\omega_0 t) + \sin(\omega_0 t) \sin(\Omega t)$, which can be converted to sums of frequencies using a trigonometric identity for sine products. The result is a signature in frequency space that displays a carrier frequency: ω_0 with side frequencies ("modulation products"): $(\omega_0 + \Omega)$ and $(\omega_0 - \Omega)$. Jupiter's modulation of Io's frequency signal can be seen as sidelobes around Jupiter's rotation frequency ($\Omega = 2.4$ day⁻¹), with the pattern repeated at the first harmonic of Jupiter's rotation frequency (4.8 day⁻¹).

The presence of Io's rotation frequency argues that Io is a localized source of charged dust particles because charged dust from diffuse sources would couple to Jupiter's magnetic field and appear in frequency space with Jupiter's rotation frequency and its harmonics. A confirmation of Io's role as a localized charged dust source arises through the modulation effects.

Several Galileo spacecraft orbital characteristics can be identified in the frequency-transformed data, as well. For each orbit, the dust detector receives more dust impacts while in the inner Jovian system than while in the outer Jovian system, which results in a gradual rise and fall in the number of dust impacts. In frequency space, such a "hump" manifests itself as a low-frequency event close to the origin at Galileo's orbital frequency. Also for each orbit, because Galileo and Io, as the "observer" and the "source," are traveling towards and away from each other, doppler effects shift the signal to higher and lower frequencies; however we don't see the long periods due to the detector's field-of-view. Instead, we see Io's orbital

frequency doppler-shifted to shorter periods by roughly 1-2 hours, depending on the dust streams' reference speed, and we believe that this doppler smearing results in the asymmetry of the Io frequency peak, seen in Fig. 1.

We can immediately perform two simple calculations to investigate Io's role as a source of the dust streams: 1) we can find where is Io physically located at the time of a source particle's dynamical trajectory, and, 2) we can find the amount of dust needed from Io, in order to explain the dust measurements. For our first calculation, using 1996-1998 dust impact rate data, we found that Io was usually physically located within 50° longitude of the origin of the particle's model trajectory. For our second calculation, if we assumed a wedge-shaped emission pattern of dust stream particles detected by Galileo, a 2 gr cm^{-3} particle density, a 10 nm particle radius, a 0.0235 m^2 detector sensitivity, an 11° to 45° wedge originating at Jupiter, a $30 R_J$ (where $R_J = 7.1 \times 10^4 \text{ km}$, the radius of Jupiter) distance between Galileo and Jupiter, and an average DDS rate of 0.2 to 30 particles min^{-1} from the larger 1996-1999 DDS impact rate dataset, then we found that the total mass rate was 10.0 gr s^{-1} to 10.0 kg s^{-1} . The periodogram peaks gave us a rough indication of the lower bound of the fraction of dust from Io, if we summed under the Io peak and the modulation sidelobes (primary and first harmonic). That fraction amounted to 60% of the total mass rate, or 6.0 gr s^{-1} to 6.0 kg s^{-1} . The remaining mass fraction could come from Io or elsewhere, but it has lost Io's frequency signature.

In Horányi et al.¹², it was demonstrated that the dynamical requirements for the gossamer ring to be a *direct* source of the Jovian dust streams were that the initial particle size distribution be within a narrow size range, and that the charged dust particles gain enough energy to break through the cold plasma torus, which is located slightly inside of the orbit of Io. The size range required was 50–100 nm, because smaller particles than this would be bent away from the equatorial plane, and not be able to reach Ulysses and Galileo on approach, and larger particles than this would move inward due to Poynting-Robertson drag. Note that this size range is in disagreement with the 5–10 nm sized particles required in order for Ulysses to detect the dust streams¹⁵ in interplanetary space.

Now let us examine the possibility of the gossamer ring or some other non-Io material being an *indirect* source of the Jovian dust streams, with Io modulating this non-Io source material. For this case, some of the same above dynamical constraints apply. In order for this scenario to succeed, three intermediate conditions would have to be satisfied. 1) The material would first need to be transported from their source region to the plasma torus via some diffusion mechanism, yet unidentified, 2) the grains in the right size range would have to be stored in the plasma torus, with their influx rate and their assumed loss balanced in order to maintain the grains' influx and storage in the torus, and finally, 3) Io would have to be able to significantly alter the torus plasma environment to change the 'storage conditions' to 'ejection conditions'. This lat-

ter condition is not an easy feat. Io's material injection rate of about 1 ton s^{-1} into the torus, while seeming very large, is a very small mass compared to the total of 10^5 - 10^6 tons in the torus itself. Therefore, the effect of Io on the torus is very tiny and the probability of any dust stored in the torus picking up this effect is negligible. We believe that any of these three conditions individually *might* be possible (however unlikely), but together they form a compelling argument against Io's ability to modulate non-Io source dust material.

Therefore, we are left with the much simpler explanation that Io itself is the source of the Jovian dust streams. For this scenario to succeed, we need simply the intermediate condition that a small fraction (less than 1%) of the 1 ton s^{-1} material in the form of 10 nm particles to escape, either directly by entrainment in the plumes, or as condensates from the expanding, rapidly-cooling, escaping gas.

In summary, frequency analysis of the Galileo DDS data provides our first direct evidence of an Io dust source. We believe that the Io dust source is predominately Io's volcanoes, rather than impact ejecta from Io, because the dust stream observations show that the particles are submicrometre-sized, and work by Ip²⁰ demonstrate, that the size of the dust particles that can escape from a typical Io volcanic plume is $\leq 0.01 \mu\text{m}$. In addition, work by Krüger, et al.²¹ shows that Io impact ejecta is, by far, not effective enough to be a dominant source of dust for the dust streams.

We see several implications for this discovery.

Dust from Io's volcanoes is a minor dust source compared to collisions of the main belt asteroids and comet activity, nevertheless, it adds to the variety of dust sources in the solar system. At a velocity of $\geq 200 \text{ km s}^{-1}$ ²², the Jovian dust stream particles can also leave the solar system to slightly populate the local interstellar medium.

We can now use dust stream measurements to monitor Io's volcanoes' plume activity. Such measurements are a unique complement to the partial glimpses acquired by Galileo and ground-based image observations because our temporal coverage is more complete (we provide information for each Galileo orbit), and because the dust detector measurements give an estimate of the integrated total amount of volcanic material from Io's (more than 100) volcanoes, e.g. material that escapes from Io, and which then disperses through the Jovian system, painting the other satellite surfaces.

In addition, this discovery lends more support for using dust measurements as a probe for charging effects in the Jovian magnetosphere. The dust from the dust streams is clearly magnetically-controlled dust. Dust particles carry information about charging processes in regions of the Jovian magnetosphere, where information is otherwise sparse or unknown.

And finally, in December 2000, we will have a unique opportunity to measure the elemental composition of the Io dust stream particles, confirming the dust streams origin, by Cassini's Cosmic Dust Analyzer (CDA) simulta-

neously with Galileo Dust Detector System during the Cassini-Jupiter flyby.

References

1. Grün, E., et al. Ulysses dust measurements near Jupiter. *Science* **257**, 1550-1552 (1993a).
2. Grün, E., et al. Discovery of Jovian dust streams and interstellar grains by the Ulysses spacecraft. *Nature* **362**, 428-430 (1993b).
3. Grün, E., et al. Dust measurements during the initial Galileo Jupiter approach and Io encounter. *Science* **274**, 399-401 (1996a).
4. Grün, E., et al. Constraints from Galileo observations on the origin of Jovian dust streams. *Nature* **381**, 395-398 (1996b).
5. Grün, E., et al. Galileo observes electromagnetically coupled dust in the Jovian magnetosphere. *JGR* **103**, No. E9, 20, 011-20, 022 (1998).
6. Showalter, M.R., Burns, J.A., Cuzzi, J.N. & Pollack, J.B. Jupiter's ring system - New results on structure and particle properties. *Icarus* **69**, 458-498 (1987).
7. Showalter, M.R., Burns, J.A., Cuzzi, J.N. & Pollack, J.B. Discovery of Jupiter's 'gossamer' ring. *Nature* **316**, 526-528 (1985).
8. Sekanina, A., Chodas, P.W. & Yeomans, D.K. Tidal disruption and the appearance of periodic comet Shoemaker-Levy 9. *A&A* **289**, 607-636 (1994).
9. Grün, E., et al. Dust streams from comet Shoemaker-Levy 9? *GRL* **21**, 1035-1038 (1994).
10. Hamilton, D., & Burns, J. A. Ejection of dust from Jupiter's gossamer ring. *Nature* **364**, 695-699 (1993).
11. Horányi, M., Morfill, G. & Grün, E. Mechanism for the acceleration and ejection of dust grains from Jupiter's magnetosphere. *Nature* **363**, 144-146 (1993a).
12. Horányi, M., Morfill, G. & Grün, E. The dusty ballerina skirt of Jupiter. *JGR* **98**, 21,245-21,251 (1993b).
13. Horányi, M., Grün, E. & Heck, A. Modeling the Galileo dust measurements at Jupiter. *GRL* **24**, 2175-2178 (1997).
14. Maravilla, D., Flammer, K. R. & Mendis, D. A. On the injection of fine dust from the Jovian magnetosphere. *ApJ* **438**, 968-974 (1995).
15. Scargle, J. D. Studies in astronomical time series II: Statistical aspects of spectral analysis of unevenly spaced data. *ApJ* **263**, 835-853 (1982).
16. McEwen, A.S., et al. Active volcanism on Io as seen by Galileo SSI. *Icarus* **135**, 181-219 (1998).
17. Spencer, J.R. & Schneider, N.M. Io on the eve of the Galileo mission. *Annu. Rev. Earth Planet. Sci.* **24**, 125-190 (1996).
18. McGrath, M. Io and the plasma torus. *Science* **278**, 237-238 (1997).
19. Johnson, T.V., Morfill, G. & Grün, E., Dust in Jupiter's magnetosphere - an Io source. *GRL* **7**, 305-308 (1980).
20. Ip, W. H. The dust halo of Io. *GRL* **24**, 3671-3674 (1996).
21. Krüger, H., Krivov, A. V., Hamilton, D. P. & Grün, E. Discovery of a dust cloud around Ganymede. *Nature* **399**, 558-560 (1999).
22. Zook, H. A., et al. Solar wind magnetic field bending of Jovian dust trajectories. *Science* **274**, 1501-1503 (1996).
23. Dessler, A.J., in *Physics of the Jovian Magnetosphere*, pp. 248 (Cambridge University Press, 1983).

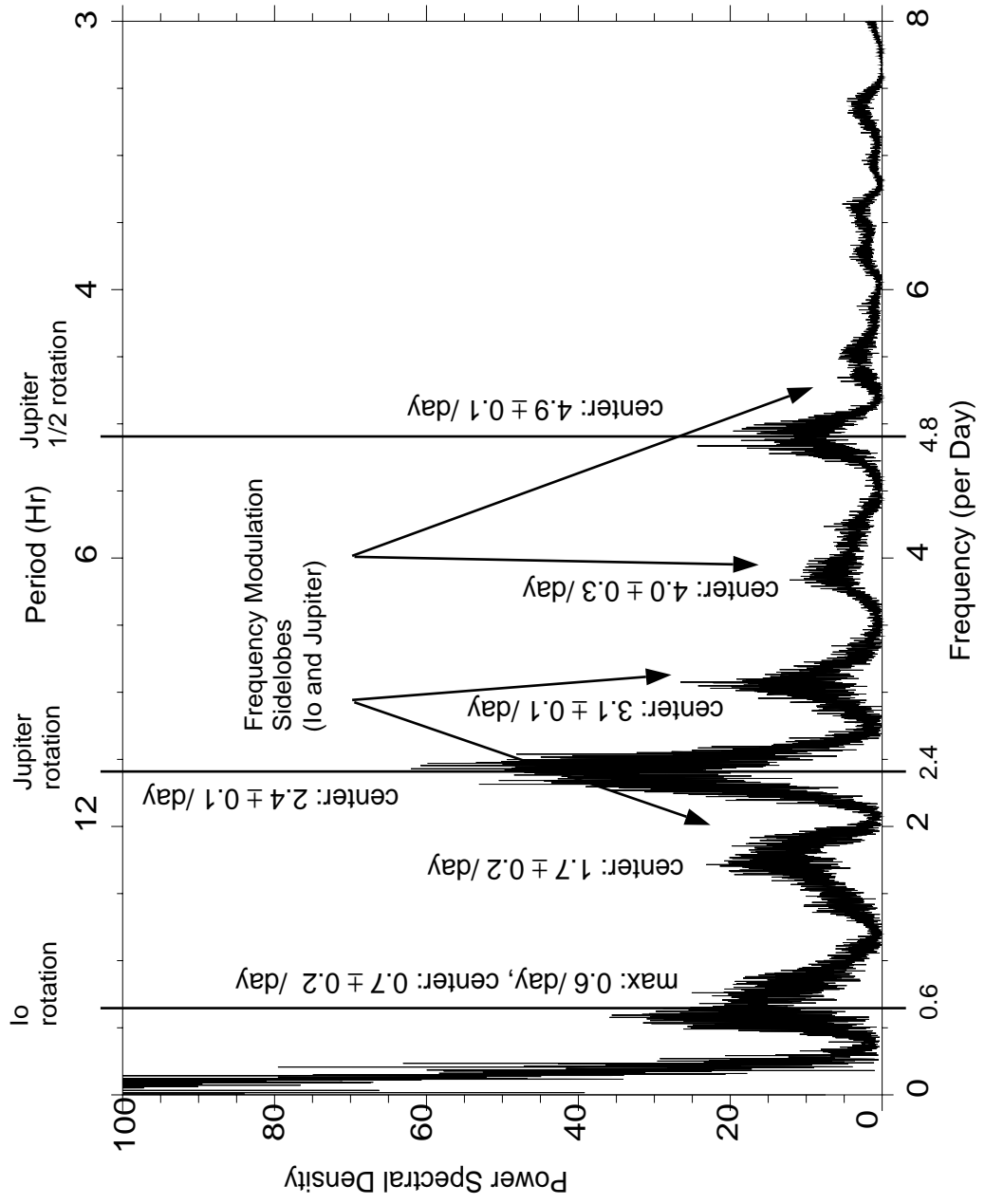
Acknowledgements. We thank the Galileo project at JPL for effective and successful mission operations. We also thank J. A. Burns and an anonymous referee for helpful comments, which significantly improved the paper. This work was supported by Deutsches Zentrum für Luft-und Raumfahrt E.V. (DLR).

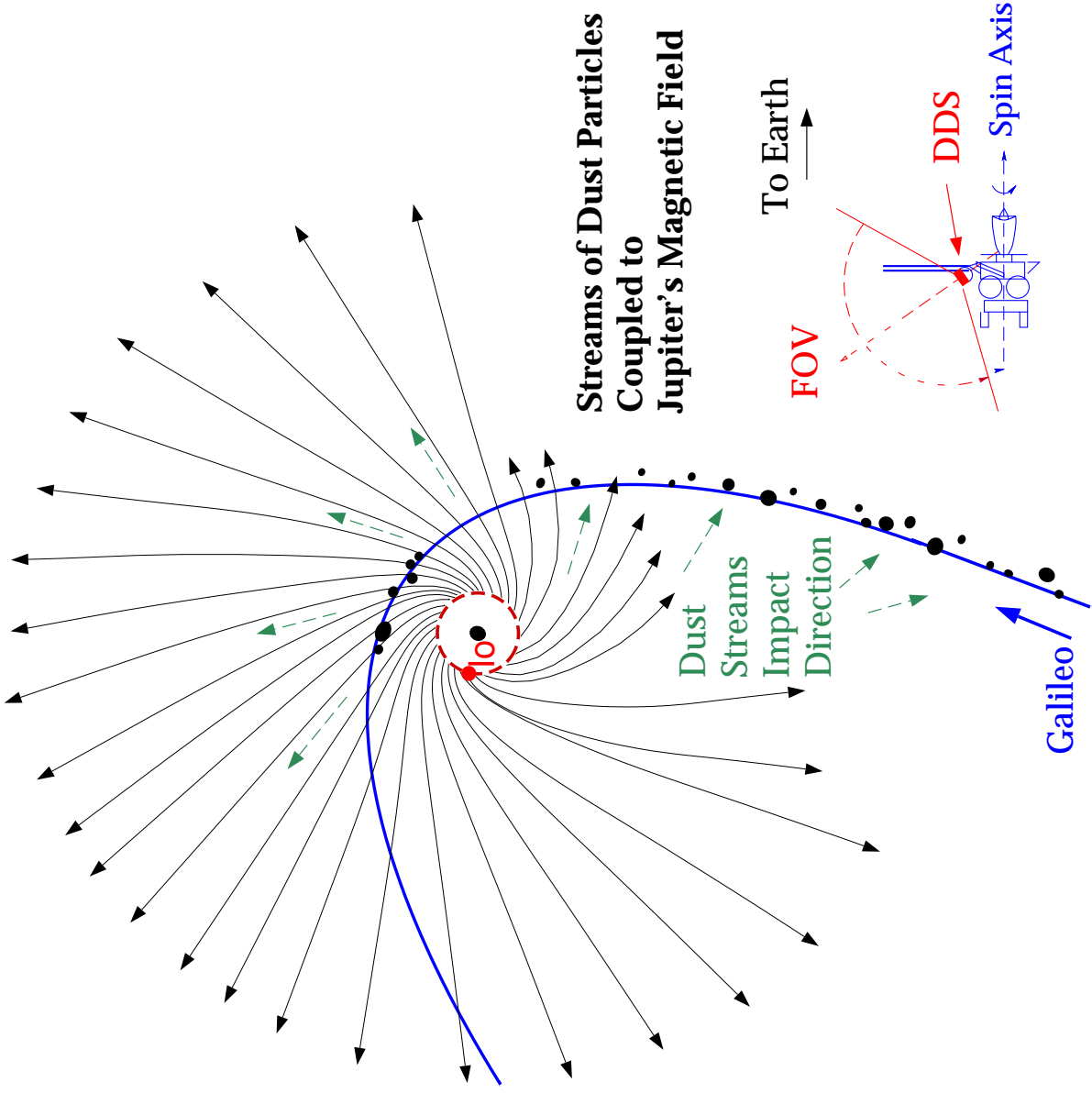
Correspondence and requests for materials should be addressed to Amara.Graps@mpi-hd.mpg.de.

Figure 1: A Lomb-Scargle periodogram¹⁵ for the first two years, 1996-1997, of Galileo dust impact rate data. We see the following frequencies in this periodogram: 1) A strong peak near the origin, 2) An asymmetric peak: maximum at 0.6 day^{-1} , center at $0.7 \pm 0.2 \text{ day}^{-1}$, 3) An asymmetric peak: center at $1.7 \pm 0.2 \text{ day}^{-1}$, 4) A tall peak: center at $2.4 \pm 0.1 \text{ day}^{-1}$, 5) A peak: center at $3.1 \pm 0.1 \text{ day}^{-1}$, 6) Harmonics of the previous three peaks, and 7) and progressively smaller and less-defined peaks. The vertical solid lines mark Io's and Jupiter's rotational periods (see ref 23), and the arrows point to Jupiter's modulation products with Io straddling Jupiter's frequency. The first harmonic of Jupiter's rotation frequency is visible at ($\omega_1 = 4.8 \text{ day}^{-1}$) and Jupiter's modulation products with Io, which are straddling that first harmonic peak, can be seen, as well. The strong frequency peak near the origin at 1 over Galileo's orbital period is due to the Galileo spacecraft orbital geometry.

Figure 2: Sketch of one of Galileo's orbital trajectories from late-1997 overlaid with trajectory results from a dust stream particles model¹². The Galileo orbital trajectory is indicated with a solid blue line and the dust streams' impact direction is indicated with the dashed green arrows. The DDS instrument is mounted on the spinning portion (rotation angle 0 to 360°) of the spacecraft, its center line offset from the spacecraft spin axis by 60° , and subtending a 140° field-of-view (FOV). The perijove of the spacecraft's orbital ellipse shifts over time, and due to the detector's geometrical orientation, the DDS instrument captures dust stream particles at different locations in its trajectories during the mission. In this sketch from late-1997, the dust stream particles on the approach leg of Galileo's trajectory could enter the dust detector, whereas on the receding leg, the dust streams approach Galileo from outside the detector field-of-view (FOV). Therefore, the DDS instrument (in 1996-1997) captured most of the dust stream particles during the inbound leg of Galileo's orbital trajectory. Since Galileo's orbital speed is $\leq 20 \text{ km s}^{-1}$ and the dust streams' speed is $\geq 200 \text{ km s}^{-1}$ ²², Galileo, to first order, is a stationary observer with respect to the dust streams.

Periodogram: Galileo Dust Detector 1996-1997





**Streams of Dust Particles
Coupled to
Jupiter's Magnetic Field**

To Earth →

FOV

DDS

Spin Axis

Dust
Streams
Impact
Direction

Galileo