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A new analysis of Galileo dust data near Jupiter

R.H. Soja [a,b,*], D.P. Hamilton [c], N. Altobelli [a]

[a] European Space Astronomy Centre, European Space Agency, Madrid, Spain
[b] Institute of Space Systems, University of Stuttgart, Germany
[c] Department of Astronomy, University of Maryland, College Park, MD, USA

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ABSTRACT

The Galileo Dust Detection System (DDS) detected a population of micron-sized grains in and amongst the orbits of Io, Europa, Ganymede and Callisto. Previous studies, using roughly 50% of the data now available, concluded that the dominant sources for the impacts were magnetospherically captured interplanetary particles largely on retrograde orbits (Colwell et al., 1998b; Thiessenhusen et al., 2000) and impact-generated ejecta from the Galilean satellites (Krüger et al., 1999b; Krivov et al., 2002a). Here we revisit the problem with the full data set and broaden our consideration to include four additional source populations: debris from the outer satellites, interplanetary and interstellar grains and particles accelerated outwards from Io and the jovian rings. We develop a model of detectable orbits at each Galileo position and we find that about 10% of the impact data require non-circular orbits with eccentricities greater than 0.1. In addition, ~3% of impacts require orbital solutions with eccentricities in excess of 0.7. Using the spatial distribution of particles, we are able to exclude, as dominant sources, all the additional source populations except for outer satellite particles. A study of DDS directional information demonstrates that none of the six standard sources fit the data well and thus a combination of sources is necessary. There are insufficient data to uniquely identify the relative strengths of the various contributions. However, we find an excess of large particles that is consistent with retrograde trajectories.

1. Introduction

Studies of dust populations within the Jovian system contribute to our understanding of dynamical behaviour, impact hazards, and the erosion and contamination of satellite and ring surfaces. The Galileo Dust Detection System (DDS) provided the best look at the dust environment outside of the main Jovian ring system, though a small amount of additional data was obtained from Pioneer 10 and 11 missions (Humes, 1980; Zeehandelaar and Hamilton, 2007). The Galileo mission was a NASA mission designed to study all aspects of the Jovian system. It completed 34 revolutions of Jupiter between 1996 and 2003, when the mission ended with the steering of the spacecraft into the Jovian atmosphere.

Galileo largely avoided the region within 9 Jupiter radii (R_J) of the planet in order to protect the spacecraft from the intense radiation environment. Beyond 9 R_J, Galileo detected a number of dust populations, including streams of very small and fast dust emanating from volcanism on Io (Grün et al., 1996a; Graps et al., 2000) (detected first by the Ulysses Dust Detector Grün et al., 1993), impact ejecta forming dust clouds around the Galilean satellites (Krüger et al., 1999b, 2003), and a number of impacts at the outskirts of the Jovian system consistent with ejecta from outer satellites (Krivov et al., 2002b). In the final part of the mission, the DDS also directly sampled particles in Jupiter's gossamer rings (Krüger et al., 2009). Furthermore, a distribution of micron-sized grains was found in the Galilean satellite region (~9–30 R_J) (Grün et al., 1996b, 1997).

Grün et al. (1998) and Colwell et al. (1998a) showed that a fraction of this latter population is inconsistent with prograde near-circular impacts. Further work suggested that these micron-sized grains consist of (1) a prograde population that could be mainly explained by impact ejecta from Galilean satellites (Krivov et al., 2002a); and (2) a retrograde population (Thiessenhusen et al., 2000) which may represent magnetospheric capture of interplanetary and interstellar dust particles focused by the strong Jovian magnetosphere (Colwell et al., 1998a,b).

These authors used DDS data from 1996–1999 (Thiessenhusen et al., 2000) and 1996–2001 (Krivov et al., 2002a). Because acquisition of data continued after 2001, these studies use only ~50%–90% of the complete data set and, accordingly, a reanalysis is warranted (Krüger et al., 2010). We also consider additional four dust sources that may contribute to this data, testing populations that are known to exist in the Jovian system, but which have not been unambiguously identified within the Galilean satellite region.

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[*] Corresponding author at: Institute of Space Systems, University of Stuttgart, Germany. Tel.: +49 711 685 65860.
E-mail address: soja@irs.uni-stuttgart.de (R.H. Soja).

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These additional sources are (3) material from outer Jovian satellites (Krivov et al., 2002b), (4) particles escaping from Jupiter's gossamer rings (Hamilton and Burns, 1993; Hamilton and Krüger, 2008), and (5) focused interplanetary or (6) interstellar particles traversing near-Jupiter space. All additional sources predict primarily radial orbits which may be required by the data. Here we investigate whether the observed distributions of particles are consistent with the expected distributions for each of the six sources identified above. Due to the lack of constraints on the direction of observed particles, it is not expected that we will be able to uniquely identify the source for individual particles. Rather, we aim to place statistical constraints on how various populations contribute to the dataset as a whole.

2. Galileo DDS

The Galileo DDS is an impact ionisation detector that can detect dust particles when they vaporise on contact with the detector target and produce a plasma cloud. The plasma particles are detected by up to three charge detectors (ion charge, electron charge, and channeltron). While the electron and ion charges are used to estimate the particle speed and mass, the channeltron detection only assists with impact identification (Grün et al., 1995). Dust accelerator tests for different projectile materials were used to calibrate the impact speed as functions of the ion and electron risetimes t_I and t_E, which can be used to produce ion and electron speed measurements v_{t_I} and v_{t_E} (Göller and Grün, 1989). The impact speed is taken as a geometric mean of these measurements: $v = \sqrt{v_{t_I} v_{t_E}}$. Calibration curves are used also to relate the impact speed v to the ratio of charge to mass Q_I/m_{Q_I} and Q_E/m_{Q_E}. The measured mass is then the geometric mean: $m = \sqrt{m_{Q_I} m_{Q_E}}$. This calibration can be approximated by

$$Q_I \propto m^{\alpha} v^{\beta} \tag{1}$$

where $\alpha \approx 1$ and $1.5 \le \beta \le 5.5$ for the calibrated speed range $2 \le v \le 70\ \mathrm{km\ s^{-1}}$ (an average of $\beta \sim 3.5$ is often assumed) (Grün et al., 1995). In practice, speed and mass measurements have large uncertainties, but the ion charge amplitude Q_I is more robust. Individual velocity measurements are typically accurate to a factor of 2, and mass values to a factor of 10. Impact velocity vectors are constrained by the 140° opening angle of the detector (although wall impacts can increase this angle, see below). Further instrument details are given in Grun et al. (1992, 1995).

Galileo DDS impacts are described by two characteristic classes. The 'charge class number' CLN describes the number of independent charge signals registered for that event. Charge classes 0 and 1 are noise within the inner Jovian system (but real impacts outside $\sim 50\ R_J$); while charge classes 2 and 3 register real dust impacts everywhere. We use a denoised data set including all $CLN \ge 2$ impacts that are expected to represent dust impacts (Krüger et al., 1999a, 2005. Previous work has demonstrated that the sensitive area (and thus the effective opening angle) of the detector for $CLN = 3$ impacts may be smaller than for $CLN = 2$ impacts (Krüger et al., 1999a). However, this is only demonstrated fully for tiny $AR = 1$ impacts (corresponding to Jovian dust streams) and thus we utilise all $CLN \ge 2$ data and the full sensor field of view. In Section 5 we also use the full data set including all DDS 'events' (all CLN classes), with the understanding that inwards of $\sim 30 R_J$ those with $CLN < 2$ are noise events.

Each impact is also classified by its ion charge signal Q_I into six 'amplitude ranges' (AR), each corresponding to approximately one order of magnitude in impact charge. AR=1 consists mostly of small Jovian stream particles (Grün et al., 1996a), while larger particles are found in $AR = 2$ to $AR = 6$. Particles detected in a higher impact charge class must have either a higher mass or a higher speed (or both) than those particles in a lower class (see Eq. (1)).

Three instrumental effects that can affect interpretation of the results are noise; electronics ageing and incomplete data transmission. The first is understood, and affects the smallest impacts most strongly. It is largely a result of the radiation environment of the Jovian system. As described above, class 1 and 0 are assumed to be noise in the jovian environment, although they are real impacts outside $\sim 50\ R_J$. Krüger et al. (1999a) describe how noise events can be reliably removed from class 2 impacts. Class 3 impacts are usually noise free.

Electronics ageing as a result of the Jovian radiation environment increases with time and affects the classification of individual particles. As an illustration, no $AR = 5$ or $AR = 6$ impacts are observed in 2000–2003 as a result of this degradation (although very few were observed before these dates). This effect is difficult to quantify, but will be considered qualitatively in our analysis.

Full data from all impact events was not transmitted to Earth as a result of Galileo's low transmission capabilities. However, information was retained on the full number of impacts in order to assess the completeness of the data. This varies strongly depending on the time period and AR class: for $CLN = 3$ particles, from 1996–1999 $AR > 1$ is almost fully transmitted; from 2000 to 2003, transmission rates for $AR = 2, 3$ and 4 are $\sim 84\%$, $\sim 70\%$ and $\sim 47\%$ respectively. Over all years the transmission rates for $AR = 2, 3$ and 4 are $\sim 94\%$, $\sim 91\%$ and $\sim 65\%$ for $CLN = 3$, and $\sim 23\%$, $\sim 46\%$ and $\sim 23\%$ for $CLN = 2$.

In addition, it is possible for impacts on the side wall to register as events. This can increase the apparent field of view of the instrument, and decrease the number density. This has been studied for interstellar particles (Altobelli et al., 2004) and Gossamer ring particles (Krüger et al., 2009). For Galileo, it was found that perhaps 27% of impacts could be wall impacts (Willis et al., 2005). This affect our ability to assign particles to different populations, because the incoming particle direction uncertainty is increased.

2.1. Dust detector geometry

The Galileo spacecraft has a spin axis that, in general, points in the anti-Earth direction. The DDS is mounted at an angle of 60° from the spin axis (Krüger et al., 1999a). The rotation angle *ROT* describes the position of the detector with respect to the spin axis, and is approximately 0 in the direction of ecliptic north. The direction of increasing rotation angle is opposite to the spin direction of Galileo (Grün et al., 1995). This ROT angle is described further in Thiessenhusen et al. (2000); Krivov et al. (2002b), and in particular by their Fig. 2 and 1 respectively. We refer the reader there for a comprehensive view.

The sensitive area of the detector has a maximum of $0.1\ \mathrm{m}^2$ and is a decreasing function of angle from the sensor axis, such that 50% of all particles from a theoretical isotropic distribution impact within 32° of the sensor axis, with an average angle of 36° (Grün et al., 1992). The sensitive area is non-zero for particles that have angles of impact with the sensor axis of less than 70°. However, the sensitive area is increased by the presence of wall impacts, with impacts having non-zero sensitive area up to an impact angle of 90° (Altobelli et al., 2004). We use a sensitive area inclusive of this effect, as given in Fig. 6 of (Altobelli et al., 2004).

The relative velocity of Galileo also affects the probability of detecting a given orbit. Thus, we use an 'effective sensitive area' that accounts for the relative motion of Galileo. As defined in Altobelli et al. (2005), this provides the detector area required to register the same impact rate as in the jovicentric inertial frame, and is given by

$$A_{eff}(V_{imp}, \phi, t) = \frac{|V_{imp}|}{|V_d|} A(\phi, t) \tag{2}$$