DETECTING INTERPLANETARY AND INTERSTELLAR DUST WITH THE DEBIE SENSOR

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ABSTRACT

ESA's PROBA-1 mission was launched in October 2001 into polar low Earth orbit. Two DEBIE sensors were placed on the spacecraft to monitor the dust and debris flux. The DEBIE sensor utilises two independent detection techniques, and is an active sensor providing real time data. Two sets of wire electrodes, sensitive to impact generated ions and electrons respectively, are mounted in front of a thin aluminium foil (acting as the target plate). On the foil are two piezoelectric devices, which measure the momentum transfer of an impact. If penetration of the foil occurs, there is a third electron plasma detector electrode located behind the foil. The detector is completing its commissioning phase, and we describe how impacting particle masses and speeds, as well as original orbits can be constrained from the flight data.

1. INTRODUCTION

PROBA-1 (PRoject for On-Board Autonomy) was launched in October 2001 as an in-orbit technology demonstration mission. The spacecraft is three axis stabilised in a near polar (inclination ~97.9°), Sun synchronous (the orbit plane maintains an angle ~18.0° with the Sun-Earth line) low Earth orbit (altitude ~600 km). Mounted on the ram and starboard faces of PROBA are two DEBIE (DEBris In-Orbit Evaluator) sensors. The geometry of the orbit means that the detectors will pass through a full range of inclinations, providing data on regions near the poles, where less is known of the debris and meteoroid environment. The heliocentric orientation of the starboard sensor (Sensor Unit 2) is maintained throughout the orbit (see Fig. 1), keeping it pointing in approximately the Earth apex of motion direction. This is an ideal geometry for the detection of interplanetary and interstellar dust at 1AU, giving interplanetary and interstellar fluxes modulated over a yearly cycle, with the debris contribution modulated on an orbital cycle. The figure shows an approximation of the interstellar dust influx direction, using the value for the ecliptic longitude and latitude respectively as: $\lambda = 259° \pm 20°$, $\beta = 8° \pm 10°$ [1]. The orientation of the ram sensor (Sensor Unit 1) will change with respect to the Sun during each orbit and is more suited to the detection of debris, giving interplanetary and debris fluxes modulated on an orbital cycle.

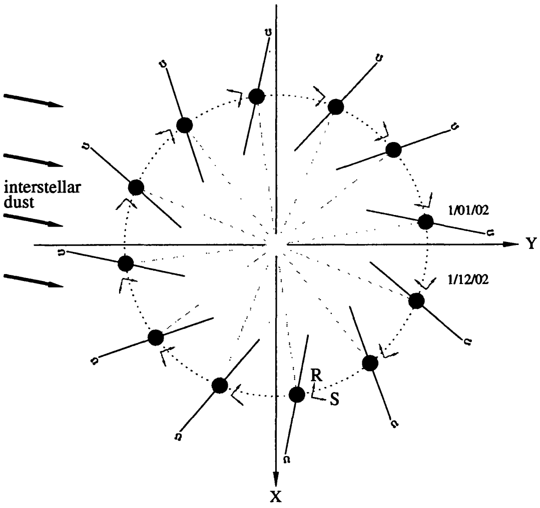

Fig. 1. DEBIE sensor deployment. The heliocentric position of the Earth is shown on the first day of every month for 2002 (viewed from above). The pointing direction of DEBIE (R is ram, S is starboard) is shown at the northernmost point of its orbit by the small arrows. The ascending node Ω is shown. The X-axis points to the first point of Aries.

2. THE DEBIE SENSOR

DEBIE was developed by Patria Finavitec and Uni-Space Kent as a low cost low resource instrument, suited for flight on virtually any spacecraft [2, 3].

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The detector geometry is such that the sensor has a large opening angle (effectively a flat plate), increasing the sampling rate of the environment. The detection area of the sensor is 10 cm x 10 cm. Two independent detection techniques allow particle masses and speeds to be better constrained. Two sets of wire electrodes, (PL1e and PL1i) sensitive to impact generated ions and electrons respectively, are mounted in front of a thin (6 μm) aluminium foil acting as a target plate. The signals from the plasma channels are proportional to $m^\alpha v^\beta$ where α ~1 and β is between 3 and 4. Mounted on the foil are two piezoelectric sensors, (PZT1 and PZT2) which measure the momentum of an impact (α ~1 and β ~1). Since the foil is thin, particles can penetrate it and there is a further electron plasma detector mounted behind the foil (α ~1, β is between 3 and 4). The momentum is constrained from the energy needed to penetrate. The rise time of the PL1e channel is measured. Since there is a relationship between plasma signal rise time and velocity [4], independent of the mass of the dust particle, a crude determination of impact speed (to within a factor of ~2) can be made if the speed is below ~ 20 km s^{-1}. Coincidence of the signals gives confidence of a reliable event. For those events with detection on more than one sensor a combination of the signals further constrains the mass and impact speed. Fig. 2 shows the overlapping region where coincidence can be used, and the detectable mass and velocity ranges.

3. ANALYSIS OF DATA

DEBIE has been in operation for a considerable time during the commissioning phase. Although the optimum configuration has not yet been achieved a number of events have been detected with high confidence. Fig. 3 shows a non-penetrating event which occurred on the 25^{th} November 2001 on Sensor Unit 1 (ram pointing). The lines represent the mass and velocity solutions for each signal — combining the five channels provides a solution at the intersection of the lines. Current calibration leads to consistent solutions within a factor of two of the impact speed being 23 km s^{-1} and the mass being 2×10^{-15} kg. The time of impact is known to within one second, and so the position of PROBA-1 and the pointing direction of DEBIE can be accurately calculated. The orbit of the impacting particle can then be constrained from the position and velocity [5]. Since DEBIE has a large viewing angle and the speed is only known to a factor of two, there are a large range of possible orbits which could produce the observed detection.

Fig. 4 shows the interface for software which uses the detector geometry to determine the possible origin of impacting particles. The viewing direction of the detector is defined by the time (of day, and day of year) and the detector geometry. The time defines the spacecraft position, and the detector pointing direction and impact speed define the impact velocity. By stepping through all the pointing directions from

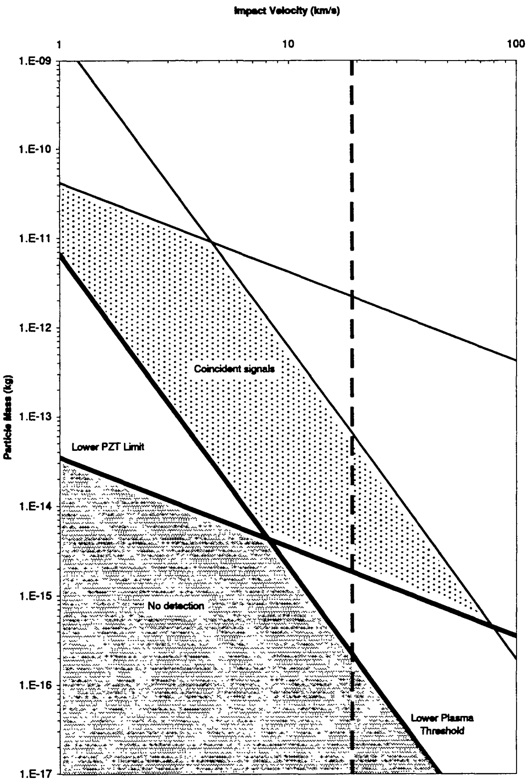


Fig. 2. Detectable mass and velocity ranges for DEBIE. Particles in the checked are undetectable. The dotted region shows where coincident signal combinations can be used to derive unique values for mass and velocity. Coincident signals exist above this region, but one or more sensor signals will be saturated. The thin lines show the saturation levels for each sensor. The vertical dashed line indicates the limit below which the electron rise time can be used to estimate impactor speed. Above this limit an event can only be classed "fast" from the rise time.

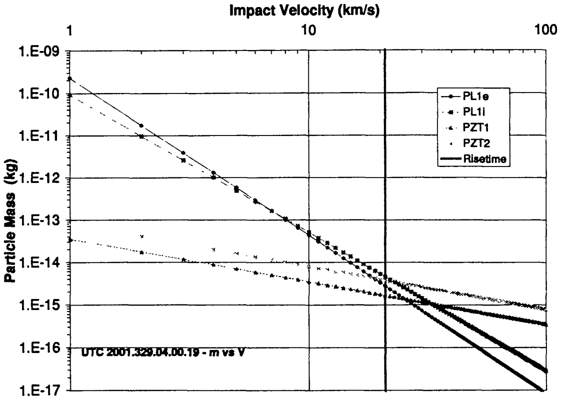
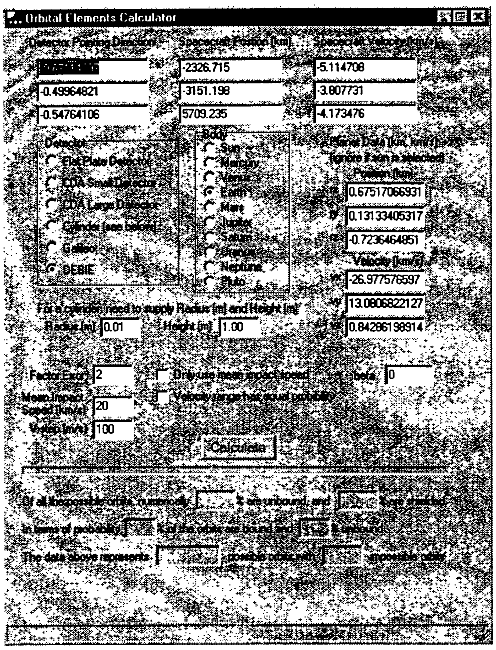


Fig. 3. Event on 25^{th} November 2001 04:00:19 UTC — Combining the plasma, piezoelectric and rise time solutions suggests a velocity of 23 km s^{-1}, for a mass 2×10^{-15} kg both to within a factor of two.



Detector Pointing Direction	Spacecraft Position (km)	Spacecraft Velocity (km/s)
[illegible]	-2326.715	-5.114708
-0.49964821	-3151.198	-3.807731
-0.54764106	5709.235	-4.173476

Detector
○ Flat Plate Detector
○ CDA Small Detector
○ CDA Large Detector
○ Cylinder (see below)
○ Galileo
● DEBIE

Body
○ Sun
○ Mercury
○ Venus
● Earth
○ Mars
○ Jupiter
○ Saturn
○ Uranus
○ Neptune
○ Pluto

Planet Data (km, km/s)
(ignore if sun is selected)
Position (km)
x 0.67517066931
y 0.13133405317
z -0.7236464851
Velocity (km/s)
vx -26.977576597
vy 13.0806822127
vz 0.84286198914

For a cylinder need to supply Radius (m) and Height (m)
Radius (m) 0.01 Height (m) 1.00

Factor Excr: 2
☐ Only use mean impact speed
beta 0
☐ Velocity range has equal probability
Mean Impact Speed (km/s) 20
Vstep (m/s) 100

Of all the possible orbits, numerically % are unbound, and % are shielded
In terms of probability % of the orbits are bound and % unbound
The data above represents possible orbits with impossible orbits

Fig. 4. Orbital Elements Calculator — the program derives all possible orbital elements and their probability for any detector geometry in any orbit (heliocentric and planetocentric).

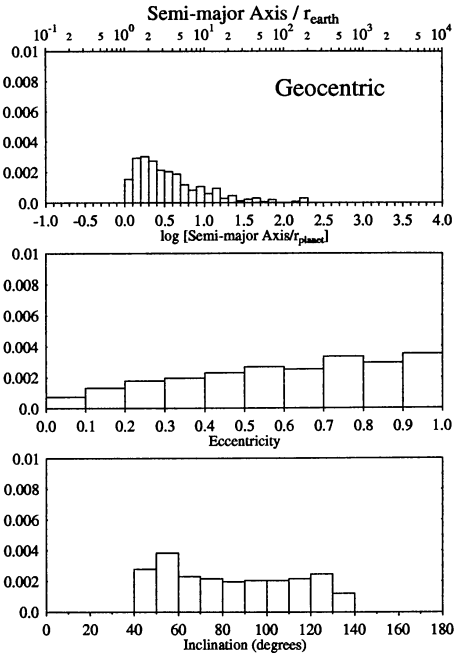


Fig. 5. Geocentric orbital distribution for an impact on DEBIE 25/11/01. The graphs show the semi major axis, eccentricity and inclination vs. probability for all geocentric orbits. The area under the curve represents the total probability of the geocentric orbits, which in this case is ~ 1% of all possible solutions.

which the detector can be hit (effectively a cone) and a range of impact speeds, a range of impact velocity vectors are derived. An impact velocity is converted to a geocentric velocity vector, from which the orbital elements can be calculated. If the speed is such that the particle is unbound to the planet, a heliocentric orbit is calculated and should the particle become unbound to the Sun, then an interstellar influx direction can be derived. The probability of each individual orbit is calculated, based on the area of the detector viewable at specific impact angles, the solid angle interval and the speed, where a Gaussian distribution is used with the mean speed being most probable, and speeds outside the factor of X boundary having zero probability.

The program will work for any detector geometry anywhere in the solar system for a given spacecraft position, spacecraft velocity, detector pointing direction and impact speed. The orbital elements are binned and probabilities summed. Figures 5 to 7 show example output for the event shown in Fig. 3. Fig. 5 shows the orbital distribution for geocentric solutions, representing less than 1% of all the possible orbits (represented by the low impact speed needed for these orbits) — around 17% are heliocentric and the remaining 82% are interstellar. The geocentric orbit distribution shows a wide range of values for the semi major axis, and increasing eccentricity as impact speed increases. The inclination is constrained to 'near' polar orbits. The inclination is determined by the position of the spacecraft and the orbits it can sample. As the impact speed increases the particle becomes unbound to the Earth. Fig. 6 shows results for heliocentric solutions. The semi major axis is only weakly constrained, to between 0.5 and 10 AU with lower semi major axes being more likely. The eccentricity is less constrained, but the inclination plot shows that if the particle is heliocentric, it will be prograde. Faster impact speeds can have an interstellar origin as shown in Fig. 7. This shows all the possible sources of an interstellar particle, and represents the largest probability based on the mean velocity used. The cross hairs show the interstellar gas dust influx direction into the solar system.

4. CONCLUSIONS

Data from the DEBIE sensor are now being available over the internet. Impacts have been identified and preliminary analysis is being performed. The DEBIE sensor is designed as a 'universal flight opportunity' instrument, and future flights are planned using developments of the current DEBIE sensor. The large range of possible orbit solutions in the example shows that DEBIE is not able to constrain individual impactors to specific sources. However, the constraints will provide a useful statistical tool for analysis of a large sample of impacts. The software developed has been applied to Cassini CDA and GORID data to how whether impact sources can be constrained.

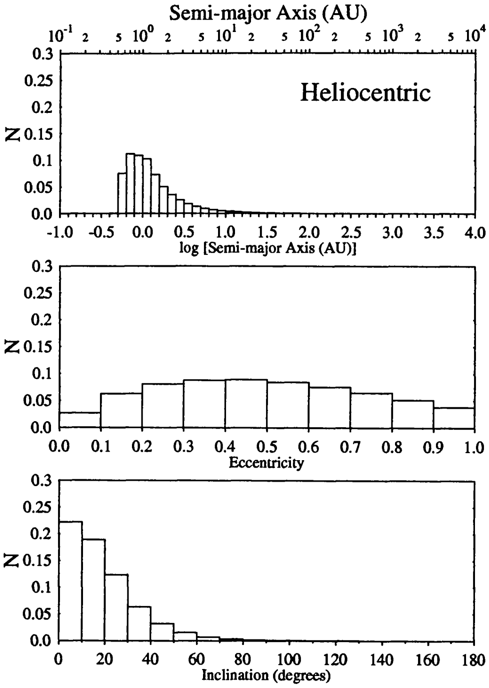


Fig. 6. Orbital distribution for an impact on DEBIE 25/11/01. The graphs show the semi major axis, eccentricity and inclination vs. probability for heliocentric orbits. The heliocentric orbits represent ~ 17% of all possible orbits for this event

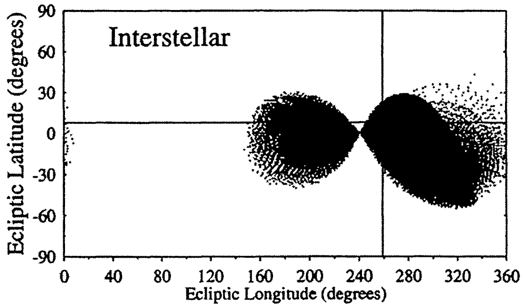


Fig. 7. Origins of interstellar orbits for impact on DEBIE 25/11/01 — the cross hairs show the interstellar dust influx at ecliptic longitude. $\lambda = 259°$ and latitude $\beta = 8°$

5. REFERENCES

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