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Measuring Dust Impact Effects in the Interstellar Medium for the 1000 AU Interstellar Probe Mission

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Abstract

The ability to send a space probe beyond the Voyager probes and towards the nearest stars, is contrained by the physics of the interstellar medium and how well we can characterize it in advance which effects our engineering designs. Interstellar dust was first discovered on the Ulysses mission and later confirmed by the Galileo mission to Jupiter. Current estimates suggest dust grain sizes of around 50 μm at 50 AU and an interstellar medium density of around $2.57 \times 10^{-27} g/cc$, with the mean particle mass of order $2 \times 10^{-12} g$ and the largest around $5 \times 10^{-9} g$ with a solid grain density of $3g/cc$. For the 1,000 AU interstellar probe mission, we consider how the properties of interstellar dust particles can measured.

1. Introduction

The Interstellar Probe is a concept under development, led by The Johns Hopkins University Applied Physics Laboratory [1]. It is proposed to send a spacecraft into the solar heliosphere and out into the pristine interstellar medium. The two Voyager spacecraft launched in 1977 have both now left the Solar System, but the interstellar probe proposes to go ten times the distance. As a model payload, and in the absence of a detailed design concept, it is expected that the probe will be similar to the technology used on the New Horizons mission to Pluto, which had a payload mass of 30.4 kg and a payload power of around 30 W. The mission would be launched before the year 2030 and would involve a gravity assist at Jupiter in addition to a Solar Oberth Maneuver in order to achieve the required 100 km/s velocity, which is consistent with the mission goal to reach 1,000 AU within 50 years (20 AU/year).

As the spacecraft travels through the Solar System and eventually out to interstellar space, it is expected that it will encounter dust particles which constitute $\sim$1% of the interstellar medium. It is neccessary to characterize the likely physics environment for the spacecraft. This is especially a concern since some of these particles may be ng in mass and as large as 0.1 μm in size, and so have the potential to deposit significant energy onto any impacting surface. To illustrate, if we assume a 1 ng static dust particle impacting a surface which has a velocity of 100 km/s, it will have a kinetic energy on impact of 0.005 J or $\sim 3.1 \times 10^{10} MeV$.

In this short paper, we describe the expected dust properties and calculate the likely effects on the interstellar probe mission so as to assess whether any shielding would be required at the frontal end. This work is also relevant to the longer-term Breakthrough Initiatives Project Starshot interstellar mission [2], for which this author is also a member.

2. Interstellar Dust

Evidence for gas and dust grain properties comes from the space missions. For example, the Galileo mission measured Dust mass range $10^{-6} - 10^{-7} g$, speed 1-70 km/s, and a mean particle mass of $2 \times 10^{-12} g$. The Ulysses mission measured a mean particle mass of $1 \times 10^{-12} g$. For the Voyager 1 and 2 missions the dust particle size did not exceed $1 \mu m$ at 50 AU.

From what we know today dust particles are typically around $1 - 50 \mu m$ at 50 AU. The latest estimates [3] suggest that the matter density is believed to be around $\rho = 2.57 \times 10^{-27} gcm^{-3}$ and this is similar to modern estimates reported by other authors [4]. The dust is expected to have a typical solid density of around $3gcm^{-3}$ and is mostly silicate with large fractions of carbonaceous material. Some of the largest dust grains may be as large as $5ng$. In general, we can split the interstellar dust grains down into three distributions of particles masses.

Some good knowledge of dust particle sizes came from the recent Stardust mission [5] en route to comet Wild 2 and asteroid 5535 Annefrank. The dust particles were captured in ultra low density aerogel in the Stardust Sample Collection (SCC) instrument, and so far approximately 12 dust particles have been identified of interstellar origin, and these were returned to

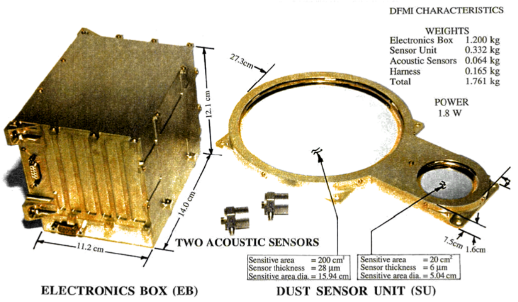

Figure 1: Dust Flux Monitor Instrument (DFMI)

Earth for examination. Table 1 shows some examples of the interstellar dust measurements [6]. Measurements of dust properties were also taken from the Dust Flux Monitor Instrument (DFMI) as shown in Figure 1. It is expected that the 1,000 AU interstellar probe may carry a DFMI for dust property measurements.

Table 1: Examples of Interstellar Dust Candidates from Stardust Mission, with estimated impactor mass, crater diameter and capture speed where known.

Mass (pg)	Diameter (μ m)	Speed (km/s)
3.1 ±0.4	–	«10
4.0 ±0.7	–	«10
3 3	–	>15
–	0.28	>10
–	0.37	5-10
–	0.39	5-10
–	0.46	5-10

3. Erosion Rates

It was shown by [7] that the energy flux into the vehicle has a dependence on the fractional velocity relative to the speed of light $\beta = v/c$, and the matter density of the incoming particle stream, $\rho = nm$ as follows:

$$\phi = \frac{\rho\beta c^3}{(1-\beta^2)^{1/2}} \times \left[\frac{1}{(1-\beta^2)^{1/2}} - 1\right] \quad (1)$$

For the 1,000 AU interstellar probe mission, the spacecraft is travelling a mere 100 km/s (20 AU/Year) so we do not expect any relativistic effects to be significant for such a low speed mission. The ablation rate or mass loss per unit time is derived by [7]:

$$\frac{dm}{dt} = \frac{\eta A_o}{H_s}\frac{\rho\beta c^3}{(1-\beta^2)^{1/2}}\left[\frac{1}{(1-\beta^{1/2})^{1/2}} - 1\right] \quad (2)$$

Where H_s is the latent heat of sublimation, η is the fraction of energy which is transferred from the medium and results in permanent material changes, β is the relativistic velocity factor.

For the model of the interstellar probe we assume a spacecraft cruise velocity of 100 km/s travelling to a distance of 1,000 AU. We assume a circular frontal surface geometry with a radius of 1.05 m, based on the assumption of the New Horizons antenna diameter of 2.1 m. We assume a cylindrical radiating surface geometry, again with a radius of 1.05 m. We calculate erosion rates for shield materials constructed of Li, Be, B, C, Al and estimate the range of mass loss ($\sim 9 \times 10^{-14} - 2 \times 10^{-12} g/s$) and required shielding thickness ($\sim 6 \times 10^{-8} - 1 \times 10^{-6} mm$).

4. Summary and Conclusions

The interstellar probe mission to 1,000 AU will help us to understand the properties of interstellar dust particles. This is important for an improved understanding for the origin of our Solar System but also to help design particle bombardment shields for more ambitious deep space missions of the future which travel over greater distances to the nearest stars.

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