Dust Measurements in the Outer Solar System

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Abstract. Dust measurements in the outer solar system are reviewed. Only the plasma wave instrument on board Voyagers 1 and 2 recorded impacts in the Edgeworth-Kuiper belt (EKB). Pioneers 10 and 11 measured a constant dust flux of 10-micron-sized particles out to 20 AU. Dust detectors on board Ulysses and Galileo uniquely identified micron-sized interstellar grains passing through the planetary system. Impacts of interstellar dust grains onto big EKB objects generate at least about a ton per second of micron-sized secondaries that are dispersed by Poynting-Robertson effect and Lorentz force. We conclude that impacts of interstellar particles are also responsible for the loss of dust grains at the inner edge of the EKB. While new dust measurements in the EKB are in an early planning stage, several missions (Cassini and STARDUST) are en route to analyze interstellar dust in much more detail.

1 Introduction

The detection of an infrared excess at main sequence stars started a renewed interest in the outer extensions of our own solar system dust cloud. Especially, the observation of a dust disk around β-Pictoris stimulated comparisons with the zodiacal cloud. Whereas the observed β-Pictoris disk extends from a few 10 to several 100 AU distance from the central star, the zodiacal cloud has been observed only out to a few AU from the Sun [9]. The zodiacal light photometer onboard Pioneer 10 observed zodiacal light out to about 3.3 AU from the Sun where it vanished into the background. The infrared satellites IRAS and COBE observed dust outside the Earth’s orbit. Asteroidal dust bands [17] where comprised of two components: a hot (~300 K) component of nearby (~1 AU) dust and a warm (~200 K) component that corresponds to dust in the asteroid belt. Cold dust (<100 K) corresponds to interstellar dust beyond the solar system near the galactic plane.

Detection of Edgeworth-Kuiper belt objects (EKO) of up to a few 100 km diameter confirmed the existence of objects outside the planetary region in the distance range where the disk around β-Pictoris has been found. Such objects had been theoretically predicted in order to explain the frequency of occurrence of short period comets and from models of the evolution of a disk of planetesimals in the outer solar system. About 30 objects have been found to date outside about 30 AU from the Sun [11]. Theories predict an extension of kilometer-sized objects out to 3,000 AU from the Sun. Because of mutual
collisions and because of their interactions with the environment, generation of dust has been predicted \[^{22}\] in the Edgeworth-Kuiper belt (EKB).

It is obviously very difficult to recognize faint extensions of a dust cloud when the observer sits inside the dense parts of this cloud, therefore, previous attempts to detect these portions of the zodiacal cloud by astronomical means failed. In the next section we review in-situ spacecraft measurements that pertain to dust in the outer solar system. Ironically, so far, the best evidence for dust in the outer solar system comes from measurements inside Jupiter’s distance.

In section 3 we review our knowledge about interstellar dust in the local interstellar medium. After a discussion of dynamical effects of and consequences on dust in the EKB (section 4) we conclude in section 5 by a review of future attempts and plans to get more information about dust in the outer solar system.

2 Spacecraft Observations

Four spacecraft carried dust detectors beyond the asteroid belt: the early Pioneers 10 and 11 \[^{10}\] and recently the Galileo and Ulysses \[^{4}\] spaceprobes. Figure 1 shows trajectories of spacecraft beyond Jupiter’s orbit. The two Voyager spacecraft did not carry specific dust detectors. However, during the passage of Voyager 2 through the newly discovered G-ring in Saturn’s ring system it was recognized that the plasma wave instrument onboard was able

**Fig. 1.** Dust measurements in the outer solar system. Trajectories of space spacecraft beyond Jupiter’s orbit are shown in projection onto the ecliptic plane. Heavy lines indicate regions where dust measurements have been reported by the investigators \[^{10}\] \[^{8}\]
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3 Interstellar Dust Characteristics

Clearly identified interstellar grains range from $10^{-15}$ g to above $10^{-11}$ g (see Figure 2) with a maximum at about $10^{-13}$ g. The deficiency of small grain...
masses is not solely introduced by the detection threshold of the instrument but indicates a depletion of small interstellar grains in the heliosphere. Estimates of the filtering of 0.1 micron-sized and smaller electrically charged grains in the heliospheric bow shock region [2] and in the heliosphere itself [13] show that these small particles are strongly impeded from entering the planetary system by the interaction with the ambient magnetic field.

The mass density of interstellar grains detected by Galileo and Ulysses is displayed in Figure 3. Below about $10^{-13}$ g it shows a strong deficiency of small grains due to heliospheric filtering. Above about $10^{-12}$ g a flat distribution is suggested (corresponding to a slope of -4 of a differential size distribution). The total mass density of the observed grains is $7 \cdot 10^{-27}$ g cm$^{-3}$.

The upper limit ($10^{-9}$ g) of the mass distribution is not well determined: if we extend the flat distribution to bigger masses, about $1.5 \cdot 10^{-27}$ g cm$^{-3}$ per logarithmic mass interval has to be added.

Even bigger radar meteor particles ($m \geq 10^{-7}$ g) have been found [19] to enter the Earth’s atmosphere with speeds above 100 km s$^{-1}$. These speeds are well above the escape speed from the solar system which confirms their interstellar origin. Big interstellar meteors arrive from a broad range of directions and are not collimated to the interstellar gas direction as smaller particles are. At present the total mass flux of big interstellar meteor particles is not known. Therefore, an extrapolation from the Ulysses observations up to $10^{-7}$ g has a large uncertainty.

Frisch et al. [2] summarize properties of the local interstellar cloud (LIC, Table 1). If the total hydrogen density is complemented by helium (with a number density ratio $n_\text{He}/n_\text{H} = 0.1$) the total gas mass density in the LIC is about $7 \cdot 10^{-25}$ g cm$^{-3}$. The canonical gas-to-dust mass ratio of 100 (from “cosmic abundance” considerations) compares favorable with the observed values. However, several modifications of the dust mass density in the LIC are suggested. Firstly, small ”classic” astronomical interstellar grains may
Fig. 3. Mass density of interstellar dust. Measurements by Galileo and Ulysses in the inner heliosphere are compared with "classic" astronomical grains expected to be present in the local interstellar medium as well. The astronomical grains are represented by the MRN distribution [15] corresponding to a total hydrogen density of $0.3\,\text{cm}^{-3}$. Additional mass densities need to be added to the interstellar grains detected by Galileo and Ulysses. Mathis, Rumpel and Nordsieck (MRN, [15]) represent these particles by a power law with exponent -3.5 in the radius range from 5 to 250 nm. Figure 3 shows this distribution by a dashed line. A mass density of $5 \times 10^{-27} \,\text{g cm}^{-3}$ has to be added if these small particles are present in the LIC - which we will assume in the further discussion. Secondly, supernova shocks passing through the interstellar medium process interstellar grains by shattering and evaporation, i.e. part of the grain material is put into the gas phase and shows up as absorption lines in the spectra of nearby stars. Refractory elements like Mg, Si, Ca, and Fe have been identified. Therefore, the total content of heavy elements in the LIC is further increased. Both the mere existence of big interstellar grains ($> 10^{-13} \,\text{g}$) and the total mass of interstellar grains in the LIC have important consequences for the understanding of the interstellar medium. Big grains couple to the interstellar gas over much longer lengths scales than the small "classic" interstellar grains, both by friction and by gyro-motion imposed by the interstellar magnetic field. Grains in the diffuse interstellar medium are electrically charged by the competing effects of electron collection from the ambient medium and the photo-effect of the far UV radiation field. The so charged dust grains couple to the magnetic field.
Table 1. Characteristics of the local interstellar cloud (LIC, after [2]). Both hydrogen number densities (neutral \( n_{\text{H}^0} \), and ionized \( n_{\text{H}^+} \)) are given

| Item               | Value   |
|--------------------|---------|
| \( n_{\text{H}^0} \) | 0.22 cm\(^{-3}\) |
| \( n_{\text{H}^+} \) | 0.1 cm\(^{-3}\) |
| Temperature        | 6,900 K |
| Magnetic Field     | 0.15 to 0.6 nT |

which itself is strongly coupled to the ionized component of the interstellar medium. A simple comparison shows that the electromagnetic coupling length is several orders of magnitude shorter than the frictional length scale for LIC conditions. However, for particles with masses \( > 10^{-12} \) g the gyro radius exceeds the dimension of the LIC and, therefore, these particles are not expected to move with the LIC gas. \( 10^{-7} \) g particles could travel more than 100 pc through the diffuse interstellar medium (at LIC conditions) with little effect. This mechanism provides the basis for any heterogeneity in the gas-to-dust mass ratio. Locally there may be significant variations in the gas-to-dust mass ratio and hence deviations from the "cosmic abundance" which has to be preserved only on the average over large regions of space.

4 Dust Dynamics in the Edgeworth-Kuiper Belt

Impacts of interstellar grains onto objects in the Edgeworth-Kuiper belt generate dust locally. In order to estimate the amount of dust generated we represent the size distribution of EKOs by a simple power law [18] 
\[
n(s) \, ds = N_0 \, s^{-4} \, ds,
\]
with \( N_0 = 1.3 \times 10^{19} \), i.e. 35,000 objects are in the observed EKO size range of \( 5 \times 10^4 \) m to \( s_{\text{max}} = 1.6 \times 10^5 \) m radius. This distribution has constant mass per equal logarithmic size interval, but most of the cross sectional area is in the smallest objects. Therefore, the size distribution is truncated at \( s_{\text{min}} = 100 \) m. By integrating this size distribution over the full size range we arrive at a total cross section of about \( 4 \times 10^{17} \) m\(^2\).

Impact experiments with micron-sized projectiles into water ice [1] suggest that at \( 26 \) km s\(^{-1}\) impact speed about \( 10^4 \) times the projectile mass is excavated and ejected mostly in form of small particulates. Because of the low gravity of EKOs we assume that most secondary particles are ejected at speeds in excess of the escape speed of 0.1 to 10 m s\(^{-1}\). The interstellar dust mass flux of \( 2 \times 10^{-16} \) g m\(^{-2}\) s\(^{-1}\) generates ejecta particles at a rate of \( 8 \times 10^5 \) g s\(^{-1}\). A more detailed calculation [21] arrives at similar values. About the same amount of micron-sized dust is generated by mutual collisions among EKOs [18], i.e. about 2 tons of dust are generated in the Edgeworth-Kuiper
belt every second. This value has a large uncertainty and is probably a lower limit since much cross sectional area could be in smaller EKOs than previously assumed.

In the absence of big planets the Poynting-Robertson effect is the most important dynamical effect on dust in the EKB. The time $\tau_{pr}$ (years) for a dust grain of radius $s$ (cm) and density $\rho_d$($\text{g cm}^{-3}$) to spiral to the Sun from a circular orbit at distance $r$ (AU) under the Poynting-Robertson effect can be estimated from

$$\tau_{pr} = 7 \cdot 10^6 \frac{s \rho_d}{Q_{pr} r^2}. \quad (1)$$

A 10 µm sized particle with $\rho_d = 2.7 \text{ g cm}^{-3}$ and radiation pressure efficiency $Q_{pr} = 1$ would need about 6.5 Myrs to reach the inner planetary system starting from an initial circular orbit at 50 AU. The radiation pressure efficiency $Q_{pr}$ decreases for particles smaller than the effective wavelength of solar radiation. Liou et al. [14] have shown that during their orbital evolution micron-sized grains are trapped in mean motion resonances with the outer giant planets. The biggest effect comes from resonances with Neptune which prolongs the particle’s residence time inside about 40 AU significantly. Therefore, the Poynting-Robertson life time given in eqn. (1) is only a lower limit for the dynamical life time of EKB dust particles. Liou et al. found that in many cases ($\sim 80 \%$) particles are ejected out of the solar system by passages close to Jupiter before they could reach the region of the inner planets.

There is another force that becomes increasingly important in the outer heliosphere: Lorentz scattering of electrically charged interplanetary grains by solar wind magnetic field fluctuations [16]. Charging of dust particles by the combined solar UV photo-effect and electron capture from solar wind plasma results in a surface potential of about +5 V leading to a charge-to-mass ratio that varies as $s^{-2}$. Carried out by the solar wind plasma (at speeds of 400 to 800 km s$^{-1}$ away from the Sun) the interplanetary magnetic field forms a Parker spiral. The dominant azimuthal component of the magnetic field varies as $1/r$ with heliocentric distance. At 1 AU the Lorentz force is comparable to solar gravitational attraction for particles of $s \sim 0.1$ microns. Therefore, in the EKB at 50 AU, Kepler orbits of even micron-sized particles are strongly affected by the Lorentz force.

Near the solar equatorial plane ($\sim \pm 15^\circ$) the magnetic field changes polarity two to four times per solar rotation period (25.2 d). Above and below this equatorial region (which is roughly centered at the ecliptic plane) a unipolar magnetic field prevails that changes its polarity with the 11-year solar cycle. Both short and long-term magnetic field fluctuations lead to diffusion of grain orbits mostly in inclination [16] but also some outward convection reduces the Poynting-Robertson effect of 10 micron-sized and smaller grains.

This dynamical evolution has to be compared with the collisional life times in the outer solar system. There the dominant flux of micron-sized projectiles is from interstellar grains. Therefore, we calculate the collision rate $C_{coll}$ and the corresponding mean collisional life time $\tau_{coll} = 1/C_{coll}$ for
interstellar grains. We follow a similar calculation for interplanetary grain collisions by Grün et al. [3], especially, we use the same collisional parameters for our calculation. Although the EKB is beyond the planetary region it is still located inside the heliosphere and some filtering of interstellar grains may occur. Therefore, we cut-off the interstellar size distribution at about $10^{-15}$ g.

Figure 4 shows the life times of EKB particles at 50 AU due to collisions with interstellar grains. For comparison we show the pure Poynting-Robertson life times. The life times of 10 micron-sized particles are dominated by collisions with interstellar grains. Considering the prolonged residence time due to Lorentz scattering and mean motion resonances, even smaller EKB grains are destroyed by interstellar dust impacts before they can reach the inner planetary system where they mix-in with zodiacal dust. We conclude that impacts of interstellar particles are not only a major contributor of dust in the EKB but may also be responsible for the loss of dust grains at the inner edge of the EKB. A complication is that the density of the ambient interstellar medium is variable on time scales of $10^5$ to $10^6$ years and extrapolations from the present state cannot be easily made. Impacts of interstellar grains may play an important role for the existence and structure of extended dust sheets like that around β-Pictoris.

Fig. 4. Life times of dust grains at 50 AU from the Sun. Collision life times are calculated for a flux of interstellar projectiles with masses $> 10^{-15}$ g. For comparison life times due to the Poyting-Robertson effect are shown. The Poyting-Robertson life time is calculated for particles on circular orbits starting at 50 AU distance; no planetary resonance effects have been considered.
5 Future Measurements

New measurements of interstellar grains passing through the planetary system are expected from the Cassini and STARDUST missions. Cassini with its Cosmic Dust Analyzer (CDA) was launched in October 1997. It will commence dust measurements at its final Venus flyby in June 1999 and continue to make interplanetary dust measurements until its arrival at Saturn in 2004. The Cassini CDA combines a large area dust detector (0.1 m²) with a mass analyzer for impact generated ions. Thereby, the first medium-resolution ($M/\Delta M \sim 20$ to 50) compositional measurements of interstellar grains will be performed.

The STARDUST Discovery mission will collect samples of cometary coma and interstellar dust and return them to Earth. Several times during its eccentric orbit about the Sun (out to about 3 AU) interstellar dust in addition to dust from Comet Wild 2 will be captured by impact into aerogel and brought back to the Earth in 2006. In addition in-situ detection and high-resolution ($M/\Delta M > 100$) compositional measurements of cometary and interstellar grains will be performed by the Cometary and Interstellar Dust Analyzer (CIDA). Interstellar dust analyses and collections may be possible even in high-Earth orbit (Grün, in preparation).

The currently studied Pluto Kuiper Express mission focuses on the big objects Pluto and Charon and perhaps one EKO, but no dust measurements in the EKB are considered. Missions to the heliospheric boundary and beyond are in their early planning phases and have to take into account dust in the outer solar system at least for hazard studies.

References

1. Eichhorn G., Grün, E. (1993) High velocity impacts of dust particles in low temperature water ice, Planet. Space Sci. 41, 429-433
2. Frisch P., Dorschner J., Greenberg M., Grün E., Landgraf M., Hoppe P., Jones A., Krätschmer W., Linde T., Morfill G. E., Reach W., Svestka J., Witt A., Zank G. (1999) Dust in the local interstellar wind, Astrophys. J. submitted
3. Grün E., Zook H. A., Fechtig H., Giese R. H. (1985) Collisional balance of the meteoritic complex, Icarus 62, 244-272
4. Grün, E., Zook, H. A., Baguhl, M., Balogh, A., Bame, S. J., Fechtig, H., Forsyth, R., Hanner, M. S., Horanyi, M., Kissel, J., Lindblad, B.-A., Linkert, D., Linkert, G., Mann, I., McDonnell, J.A.M., Morfill, G.E., Phillips, J.L., Polanskey, C., Schwehm, G., Siddique, N., Staubach, P., Svestka, J. and Taylor, A., (1993) Discovery of jovian dust streams and interstellar grains by the Ulysses spacecraft, Nature 362, 428-430
5. Grün, E., B E. Gustafson, I. Mann, M. Baguhl, G. E. Morfill, P. Staubach, A. Taylor and H. A. Zook (1994) Interstellar dust in the heliosphere, Astron. Astrophys., 286, 915-924
6. Grün E., P. Staubach, M. Baguhl, S. Dermott, H. Fechtig, B.A. Gustafson, D.P. Hamilton, M.S. Hanner, M. Horanyi, J. Kissel, B.A. Lindblad, D. Linkert, G.
Linkert, I. Mann, J.A.M. McDonnell, G.E. Morfill, C. Polanskey, G. Schwehm, R. Srama and H.A. Zook. (1997) South-North and radial traverses through the zodiacal cloud, Icarus, 129, 270-288.

7. Gurnett D.A., Grün, E., Gallagher, D., Kurth, W.S., Scarf, F.L. (1983) Micron-sized particles detected near Saturn by the Voyager plasma wave instrument, Icarus 53, 236-254.

8. Gurnett D.A., Ansher, J.A., Kurth W.S., Granroth L.J. (1997) Micron-sized dust particles detected in the outer solar system by the Voyager 1 and 2 plasma wave instruments, Geophys. Res. Lett., 24, 3125-3128

9. Hanner M. S., Sparrow J. G., Weinberg J. L., Beeson D. E. (1976) Pioneer 10 observations of zodiacal light brightness near the ecliptic: Changes with heliocentric distance, In: Lecture Notes in Physics, 48: Interplanetary Dust and Zodiacal Light (H. Elsasser and H. Fechtig, Eds.) Springer-Verlag, New York, pp. 29-35.

10. Humes, D.H. (1980) Results of Pioneer 10 and 11 meteoroid experiments: Interplanetary and near-Saturn, J. Geophys. Res. 85, 5841-5852.

11. Jewitt D., Luu J., Trujillo C. (1998) Large Kuiper belt objects: The Mauna Kea 8K CCD survey, Astron. J. 115, 2125-2135

12. Krüger, H., Grün, E., Landgraf, M., Baguhl, M., Dermott, S., Fechtig, H., Gustafson, B. A., Hamilton, D. P., Hanner, M. S., Horányi, M., Kissel, J., Lindblad, B.-A., Linkert, D., Linkert, G., Mann, I., McDonnell, J. A. M., Morfill, G. E., Polanskey, C., Schwehm, G., Srama, R. and Zook, H. A. (1998) Three years of Ulysses dust data: 1993 to 1995, Planet. Space. Sci. in press

13. Landgraf, M. (1998) Modellierung der Dynamik und Interpretation der In-Situ-Messungen interstellaren Staubes in der lokalen Umgebung des Sonnensystems, PhD Thesis, University of Heidelberg

14. Liou J.C., Zook H.A., Dermott S.F. (1996) Kuiper belt dust grains as a source of interplanetary dust particles, Icarus, 124, 429-440

15. Mathis, J. S., Rumpl, W., Nordsieck, K. H. (1977) The size distribution of interstellar grains, Astrophys. J. 217, 425-433

16. Morfill G. E., Grün, E., Leinert, C. (1986) The Interaction of Solid Particles with the Interplanetary Medium, in The Sun and the Heliosphere in Three Dimensions, R. G. Mardsen, Reidel, Doordrecht, 455-474.

17. Reach, W. T. (1992) Zodiacal emission. III - Dust near the asteroid belt, Astrophys. J. 392, 289-299.

18. Stern S.A. (1996) Signatures of collisions in the Kuiper Disk, Astron. Astrophys. 310, 999-1010

19. Taylor D.A., Baggaley W.J., Steel D.I. (1996) Discovery of interstellar dust entering the Earth’s atmosphere, Nature 380, 323-325

20. Witte M., Rosenbauer H., Banaskiewicz M., Fahr H. (1993) The Ulysses neutral gas experiment: Determination of the velocity and temperature of the neutral interstellar helium, Adv. Space Res. 13, (6)121-(6)130.

21. Yamamoto S., Mukai T. (1998) Dust production by impacts of interstellar dust on Edgeworth-Kuiper Belt objects, Astron. Astrophys. 329, 785-791