CHARGING EFFECTS ON COSMIC DUST

Ingrid Mann[(1,2)]

(1) Institut fuer Planetologie, Westfaelische Wilhelms - Universitaet Wilhelm - Klemm - Str. 10, 48149 Muenster, Germany, Email: imann@uni-muenster.de
(2) ESA Space Science Department ESTEC SCI-SO PO Bus 299, 2200AG Noordwijk, The Netherlands

ABSTRACT

We discuss the surface charging of cosmic dust in the interplanetary medium. The charging of particles depends on their size and material composition as well as on the surrounding plasma and radiation. The time scales for dust particles to attain their equilibrium surface charge are small compared to typical lifetimes of dust in the solar system and small particles are sufficiently highly charged so that their motion is influenced by Lorentz force. The discussed effects, however are not accessible to remote astronomical observations, but rather to local in situ measurements. Although we see a severe influence of the charging on the motion of dust particles, the conditions of a "dusty plasma" do not apply.

1. INTRODUCTION

The interaction of dust particles with the cosmic plasma environment leads to the accumulation of surface charge on the grains. This paper will discuss the charging effects of cosmic dust, where our knowledge is largely based on model assumptions. We first give an overview of the dust and plasma conditions in the interplanetary medium and the different charging effects. Estimates of the surface charge allow for a comparison of the different forces that are acting on the grains. Two examples how surface charging affects the distribution of dust in the interplanetary medium will be discussed. For one, the distribution of small dust particles in the solar corona varies with the solar magnetic field. A second application that gained some importance recently is the entry of interstellar dust into the solar system.

2. DUST AS A COMPONENT OF THE INTERPLANETARY MEDIUM

Dust particles in the solar system are predominantly produced by the activity of comets and the collision evolution of asteroids and smaller metereoritic bodies. Their motion is mainly determined by solar gravity.

Table1: Parameters of dust and solar wind at 1 AU

	Solar Wind	**Cosmic Dust**
Mass Density	10^{-23} g·cm^{-3}	10^{-22} g·cm^{-3}
Number Density	~ 7 cm^{-3}	~ 10^{-10} cm^{-3}
Velocity	450 km/s radial	20 km/s azim.
Radial Motion	~ 4 days Sun to Earth	~ 10^5 years Earth to Sun
Temperature	~ 10^5 K plasma temperature	~ 280 K bulk temperature
Flux Density	$3\cdot10^{-8}$cm^{-2} s^{-1}	$3\cdot10^{-5}$cm^{-2} s^{-1}
Mass Flux	$6\cdot10^{-16}$g cm^{-2}s^{-1}	$2\cdot10^{-16}$gcm^{-2} s^{-1}
Lifetime (Coll.)	10^5 -10^6 s	10^{11} -10^{13} s
Gyration Radius	80 km (protons)	100 - 5000 AE

The parameters of this solar system dust cloud have to be compared to its surrounding medium which is mainly given by the solar wind plasma (see table 1). While the mass density of the dust particles near 1 AU is almost of the same order of magnitude as the mass density of the solar wind particles, its number density is much smaller. Further components of the interplanetary medium are interstellar neutral gas particles as well as cosmic ray particles. They are implemented in the surface layers and cause surface processing by sputtering. As well as the trails of high energy cosmic rays were identified in interplanetary dust particles collected in the stratosphere.

The lifetime of particles is limited by mutual catastrophic collisions, the Poynting Robertson effect, dust erosion and sublimation in the vicinity of the sun. Mutual collisions take place with relative velocities of the orders of km/s and cause the destruction of dust particles and the formation of a cascade of particles of smaller sizes. The orbits of the fragments remain similar to those of the initial dust particles - aside from the eccentricity and semi-major axis that increase if the fragments are more influenced by radiation pressure than the initial particles. The lifetime of particles with sizes beyond about 100 micron are limited by collision and are beyond 10^4 years. Catastrophic mutual collisions may also change the size distribution of particles in the dust cloud [1]. The lifetime against collision increases for smaller particles, where the Poynting Robertson lifetime is the limiting parameter: The tangential component of the solar radiation pressure force in the frame of the moving dust particle leads to a slight deceleration of particles (Poynting - Robertson effect) so that the Keplerian orbits are superimposed with a drift toward the Sun on time scales of 10^4 to 10^6 years. Finally particles can reach temperatures close to 2000 K in the vicinity of the sun and sublimate.

The major sources determine the distribution of orbits in the dust cloud which are similar to the parentbodies. Asteroids are in orbits with inclinations < 30º and eccentricity < 0.1. Short period comets are in orbits with inclinations < 40º and eccentricity < 0.4. For long period comets, inclinations may range from 0 to 180º. The deceleration of particles reduces the semimajor axis and eccentricity of orbits and leads to an increase of dust number density with decreasing solar distance [2]. Perturbations, for instance due to the presence of planets randomise the other orbital elements, argument of the perihelion and of the ascending node so that the overall distribution of dust in the solar system appears to be rotationally symmetric to an axis through the solar pole. The symmetry plane of the dust cloud is close to, but not identical with the invariable plane of the solar system.

Aside from gravity the acting forces are the solar radiation pressure force, the solar wind drag, and the Lorentz force. While the influence of the solar wind drag is usually negligible, both, the Lorentz force and the radiation pressure force become increasingly important for small dust particles.

3. CHARGING OF COSMIC DUST

The charging of cosmic dust particles is caused by sticking of low energy electrons and ions of the surrounding plasma, induced secondary electron emission, thermionic emission and photoelectric emission due to solar and interstellar radiation (see Fig.1). Draine and Salpeter [3] carried out a detailed study of the charging of dust grains in a hot plasma with temperatures of the order of 10^4 to 10^9 K to apply to dust in cosmic, interstellar environments. Plasma density and temperature, the relative velocity of the dust and the plasma, the solar radiation and finally the physical properties of the dust grains determine their charging rates. Mukai [4] calculated the surface charge of dust particles in the solar system and showed that in the interplanetary medium this is predominantly determined by photoelectric emission due to solar radiation.

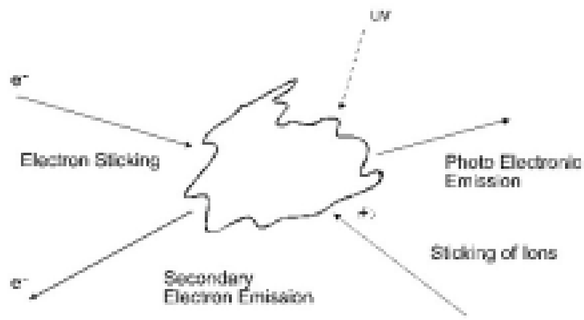

Fig.1. Charging Mechanisms

For small dust particles that reach high positive values of the surface potential the field emission of positive ions can cause a significant mass loss and lead to the destruction of particles [3]. It has however been shown to be not the case for dust particles in the interplanetary medium [5]. Since especially the secondary electron yield depends on the material composition of particles, the surface charge of dust also depends on the dust composition. Different conditions apply for local plasma environments, such as for instance in planetary magnetospheres. The charging process in a dense plasma is determined by the plasma parameters rather than by the radiation environment. Particular cases of dust plasma interaction are discussed for instance [6,7] for the Saturnian ring system, the environment of comets and the Jovian environment. We here will concentrate on discussing the surface charge and its consequences for dust in the interplanetary medium.

4. CONSEQUENCES OF DUST CHARGES

Dust particles in the interplanetary medium attain their equilibrium surface charge within a time span of *10s* to $10^5 s$. The time for one orbital revolution in comparison is of the order of $10^7 s$ *at 1AU* and the change of the distance from the sun is negligible over that time. As bulk velocity, number density and temperature of solar wind particles vary in time the surface charge of dust particles may vary by up to 20 percent [5]. The time to reach the equilibrium surface charge decreases with increasing size of particles and is approximately proportional to a^{-1} where a is the radius of the dust particle and slightly depends on the material composition. The characteristic time increases with distance from the sun.

It should be noted that typical parameters of dust in the overall interplanetary medium do not fulfil the conditions of a "dusty plasma" [6,8] where the charged dust particles act as a further "heavy" plasma component. Dust particles in the interplanetary medium can be considered as isolated screened grains that do not participate in the collective behaviour of the plasma particles. Rather than a "dusty plasma" they may be described as "dust in a plasma".

Table 2. Specific forces on dust at 1 AU

mass	**radius**	**F_{grav}/m**	**F_{rad}/m**	**F_L/m**
[kg]	[μm]	[N·kg^{-1}]	[N·kg^{-1}]	[N·kg^{-1}]
10^{-17}	0.1	10^{-3}	10^{-2}	10^{-2}
10^{-14}	1.0	10^{-3}	10^{-3}	10^{-4}
10^{-11}	10	10^{-3}	10^{-4}	10^{-6}
10^{-8}	100	10^{-3}	10^{-5}	10^{-8}

The effect that the surface charge has on the dynamics of dust grains in a magnetic field depends on the charge to mass ratio of grains. The charge being proportional to the surface area of grains and the mass being proportional to the volume in the case of compact grains, especially small grains are influenced by the surface charge. The estimated specific forces F/m for dust particles of radii 0.1 to 100 μm are listed in table 1. The estimate shows solar gravity force, F_{grav} solar radiation pressure force, F_{rad} and Lorentz force F_L, for particles in interplanetary space at 1 AU that attained equilibrium surface charge.

5. DUST IN THE SOLAR CORONA

Dust in the solar vicinity attains a higher electric surface charge as a result of the increasing photon flux and secondary electron emission caused by the impact of solar wind particles. Also the solar magnetic field and as a result the Lorentz force increases. Particles experience a fluctuation of their orbital inclination so that the dust cloud in comparison to the initial distribution extends to higher latitudes [9,10]. If the influence of the Lorentz force becomes stronger then particles can be deflected into random orbits. The solar radiation pressure influences the motion of small dust particles as a competing effect [11]. While the Lorentz force acts perpendicular to the magnetic field and to the dust velocity, the solar radiation acts radially away from the sun. The main, radial component of the radiation pressure (in the frame of the moving particle) counteracts solar gravity, so that the particles move in a reduced gravitational field as long as the radiation pressure does not exceed gravity.

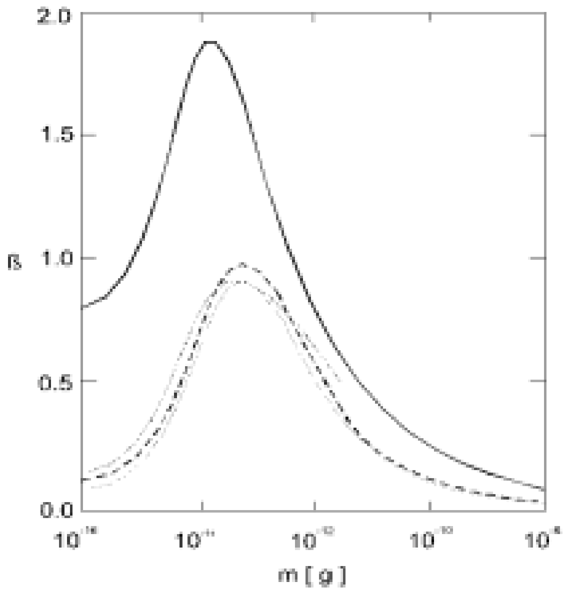

Figure 2: The ratio $\beta = F_{rad}/F_{grav}$ for dust models

The radiation pressure depends on the light scattering properties of the dust and therefore on size, structure and material composition [12] as shown in Fig. 2. The solar radiation pressure F_{rad} is given as the ratio $\beta = F_{rad} / F_{grav}$ where F_{grav} is the solar gravity force. Shown are the values for highly absorbing cometary grains (solid line), moderately absorbing cometary grains (dotted line), asteroidal grains (dashed line) and interstellar grains of core-mantle structure (dash-dotted line). The radiation pressure increases with decreasing mass of grains to about 10^{17} Kg and then drops down for smaller particles. For all models, except for strongly absorbing dust particles, radiation pressure and gravity are about equal at maximum.

When the sizes of particles are diminished either by sublimation or by collisional destruction in the inner solar system, then the radiation pressure force increases. The interplay of sublimation and increasing radiation pressure for diminished size of dust particles can lead to the formation of dust rings [13]. Radiation pressure can also lead to the formation of beta meteorites that are ejected from the corona in hyperbolic orbits [14]. The distribution of dust near the sun and the dust ring formation was studied in detail for absorbing and refractory particles [15, 16] of porous and compact structure. Carbon and silicate are used as examples for refractive and absorbing material. Fig. 3 shows then evolution of dust particles near the Sun under the influence of radiation pressure and sublimation. Solid lines denote the decrease in size with distance from the sun for refractory grains, dotted lines for absorbing grains.

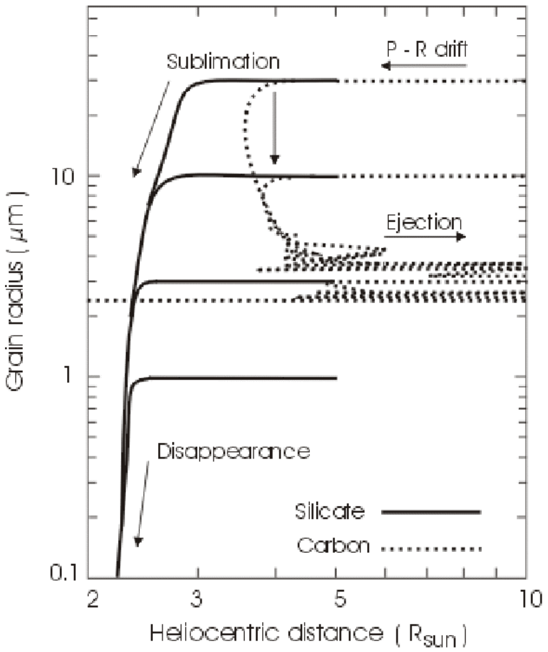

Figure 3: Formation of dust rings and β - meteorites

Refractory grains sublimate inward from about 3 solar radii and sublimation begins for particles of different size at about the same distance from the Sun. The sublimation of absorbing grains begins at larger distances from the sun. As a result of the diminished size radiation pressure increases and pushes the particles out from where they drift inward where sublimation begins again. As a result the particles are drifting inward and outward during their sublimation before the completely sublimate or they are blown away from the vicinity of the sun. The enhancement of the dust number density in the dust rings is smaller than by a factor of 2 over less than 1 solar radius for silicate particles (porous, fluffy) with initial eccentricities < 0.1. The strongest enhancement is seen for 10 µm fluffy carbon particles, but only if the initial orbits are almost circular, that is for orbital eccentricities e = 0.01 and smaller [16].

Aside from radiation pressure also the Lorentz force modifies the dust distribution. Assuming an initial distribution in latitudes 30º below and above the ecliptic plane, dust particles of size 2-5 µm will be distributed to latitudes +/- 50º at 10 R_{sun}. Particles in the size range 0.5 - 2 µm show the strongest variation with the solar magnetic field. They are distributed out to +/- 70º in a weak magnetic field and distributed out to 90º for times of the solar cycle with a strong magnetic field. Smaller silicate particles are randomly distributed at all phases of the solar cycle. Small Carbon dust particles sublimate before their orbits can be randomized. It should be noted that the particles that are influenced by radiation pressure and Lorentz force are relatively small. Their contribution to brightness observations is not sufficient for detecting these effects with remote astronomical observations [17, 18].

6. ENTRY OF INTERSTELLAR DUST

The in - situ study of interstellar dust from spacecraft in the solar system is crucial for the understanding of the physical and chemical evolution of solid material in the interstellar medium. Interstellar dust has been detected in the solar system for instance aboard Ulysses [19]. The experiment detected to a large majority particles, of masses m > 10^{14} Kg, while the majority of smaller interstellar dust particles are missing in the in situ data. In order to determine interstellar dust properties from these measurements, it is essential to understand the conditions under which interstellar dust can enter the solar system

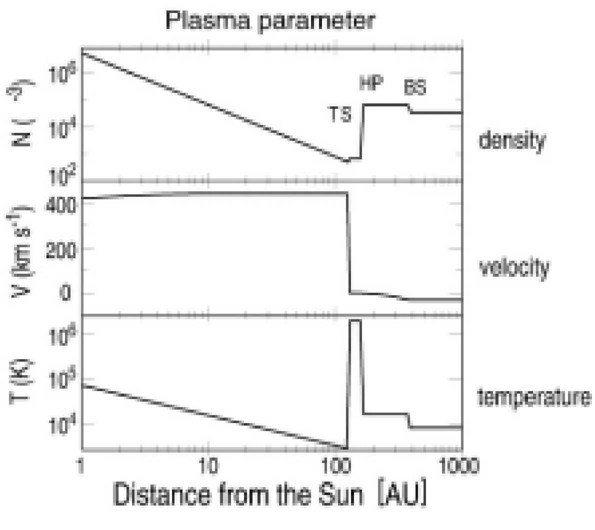

Fig. 4. Plasma parameter in the heliosphere

The motion of the Sun (and the heliosphere) relative to the surrounding local interstellar medium (LISM) causes a stream of interstellar matter into the solar system. Within this "interstellar wind" dust particles may enter the solar system, i.e. the heliosphere. The heliosphere denotes the region around the sun that is filled with the solar wind plasma [20]. It is determined by the interaction of the interstellar medium plasma with the solar wind plasma flow [21]. The plasma conditions are illustrated in Fig. 3: shown are the electron number density, the electron velocity and the temperature as function of the distance from the sun in interstellar upwind direction, i.e. toward the stream of the incoming interstellar wind.

The plasma parameters were derived from numerical models of the heliosphere [22]. While the heliosphere is characterized by gradually decreasing plasma density and temperature in the radially outward flowing solar wind, the radial solar wind velocity drops off steeply at the termination shock (TS). The deflected solar wind plasma forms a region of constant plasma density and high plasma temperature between termination shock and heliopause (HP). Secondary electron emission increases as a result of the increasing plasma temperature in this region and leads to an increasing surface charge [5] which depends as well on the material composition of grains. Hence the entry of interstellar dust in the solar system depends on the size and material composition of grains and on the conditions of the interstellar medium and the solar wind plasma.

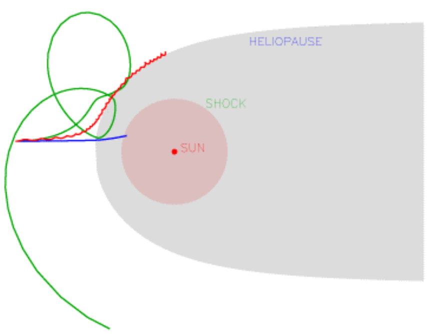

Fig. 5. Dust entry into the heliosphere

If the surface charge of interstellar dust is low, then the orbits of particles are determined by solar gravity force F_{grav} and solar radiation pressure force F_{rad}. The particles initially form a monodirectional stream from the interstellar upstream direction relative to the Sun. Particles with the *ratio* $\beta = F_{rad} / F_{grav} < 1$, are in hyperbolic orbits, with the focus of orbits behind the Sun: the flux is collimated in interstellar downwind direction. Particles for which radiation pressure force exceeds gravity ($\beta > 1$) are repelled in hyperbolic orbits with focus in the interstellar upwind direction.

For small particles the electric surface charge is more important and particles are influenced by the Lorentz force in the interstellar and interplanetary magnetic field. Particles of size 0.01 µm are strongly influenced by the magnetic field and picked up by the plasma flow. They are deflected from entering the heliosphere. Larger grains, of 0.1 µm size, are less significantly influenced by interaction with the plasma and they can enter the heliosphere. The dust entry into the heliosphere is illustrate in Fig. 5 where grey denotes the region of the heliosphere and red the region within the termination shock.

Table 3. : Deflection of interstellar dust

Deflection Mechanism	**Mass Interval**
heliospheric deflection	$m < 10^{-18}$ kg
solar magnetic field deflection	$m < 10^{-17}$ kg
radiation pressure repulsion	$10^{-17}\text{kg} < m < 10^{-15}\text{kg}$
gravitational focusing	$m > 10^{-15}$ kg

The efficiency of the different mechanisms varies with dust structure, size, and material composition. The relevant mass intervals for the deflection mechanisms [23] are listed in Table 3. While the heliospheric deflection and solar magnetic field deflection take place already at the boundaries and in the outer solar system, radiation pressure and gravitational focussing are relevant at distances < 5 AU from the sun. All deflection mechanisms do also depend on the material composition of dust particles.

7. SUMMARY

Charging effects influence the motion and the distribution of small dust particles in the interplanetary medium. Although the influence of the surface charge is very important, the conditions of a "dusty plasma" where collective effects occur do not apply. Small dust particles in the vicinity of the sun are severely influenced by the Lorentz force, but solar radiation pressure force is equally important. The flux of refractory dust particles in the vicinity of the sun is estimated to vary with the solar magnetic field. Absorbing particles can be pushed out from the solar vicinity as a result of radiation pressure. The entry of small interstellar dust into the solar system depends on the surface charge and the resulting deflection at the boundaries of the solar system. In this case radiation pressure is negligible and becomes only important for particles that reach distances < 5 AU from the Sun. Since the charging effects are particularly important for particles at the smaller size end of the cosmic dust spectrum the discussed effects are not accessible to remote astronomical observations and can only be detected with in situ measurements.

8. ACKNOWLEDGEMENT

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