PHYSICS OF INTERPLANETARY AND INTERSTELLAR DUST

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Abstract. Observations of dust in the solar system and in the diffuse interstellar medium are summarized. New measurements of interstellar dust in the heliosphere extend our knowledge about micron-sized and bigger particles in the local interstellar medium. Interplanetary grains extend from submicron- to meter-sized meteoroids. The main destructive effect in the solar system are mutual collisions which provide an effective source for smaller particles. In the diffuse interstellar medium sputtering is believed to be the dominant destructive effect on submicron-sized grains. However, an effective supply mechanism for these grains is presently unknown. The dominant transport mechanisms in the solar system is the Poynting-Robertson effect which sweeps meteoroids bigger than about one micron in size towards the sun. Smaller particles are driven out of the solar system by radiation pressure and electromagnetic interaction with the interplanetary magnetic field. In the diffuse interstellar medium coupling of charged interstellar grains to large-scale magnetic fields seem to dominate frictional coupling of dust to the interstellar gas.

1. Introduction

Dust in interplanetary space has various appearances and can be detected and analyzed by a number of techniques. Comprehensive surveys of radio meteor orbits observed by the Harvard-Smithsonian radar have been published by Southworth and Sekanina (1973). Interplanetary dust particles collected in the atmosphere give cosmochemical information (composition and structure, Brownlee, 1985 and Bradley, 1988). The size distribution of dust at $1AU$ distance from the sun is documented in lunar microcrater records (Grün et al., 1985a). Zodiacal light observations form the Earth and from spacecraft (Leinert and Grün, 1990, Levasseur-Regourd, 1980) demonstrate the spatial distribution of dust in the inner solar system. Dust in the asteroid belt has been identified by its thermal emission (Hauser, 1984). Measurements of dust particles by in situ detectors on interplanetary spaceprobes give evidence of new populations of dust (e.g. interstellar dust and dust emitted from the Jovian system, Grün et al. 1993, Baguhl et al., 1995) which are not easily observed at the Earth's distance.

Gravity of the sun dominates all forces on bigger than micron-sized interplanetary meteoroids. Smaller dust particles are increasingly more affected by solar radiation pressure which can exceed gravity for dust particles below $1\mu m$ in size. For tenth micron-sized dust grains electromagnetic interaction

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with the interplanetary magnetic field exceeds gravity by more than a factor 10. Mutual collisions among meteoroids determine the life-time of bigger than tenth millimeter-sized grains and generate smaller particles by fragmentation. Smaller grains are transported towards the sun by the Poynting-Robertson effect where they evaporate.

Little is known about dust in the diffuse interstellar medium which surrounds the solar system. Dust is observed in the diffuse interstellar medium by extinction of star light (Mathis, 1993) and by absorption features in stellar spectra (Jenniskens and Desert, 1993). Scattering of light by dust in the vicinity of near-by stars and thermal emission from interstellar cirrus (Low et al., 1984) give direct evidence of dust in the diffuse interstellar medium. Polarization measurements of interstellar extinction indicates the existence of elongated dust grains which are aligned by large-scale interstellar magnetic fields (Whittet, 1992).

In interstellar space the effects which need to be understood are interactions with: the radiation field, the ambient plasma, energetic particles, the magnetic field, the interstellar gas and grains. Sputtering by energetic particles in a high temperature plasma and mutual collisions are the main loss processes of interstellar grains. Gas drag and magnetic drag of charged dust particles are the dominant dynamic effects in the diffuse interstellar medium.

In-situ dust measurements in the heliosphere open a new window of information about the local interstellar medium. Micron-sized interstellar dust particles have been identified by the Ulysses and Galileo dust instruments inside the orbit of Jupiter (Grün et al., 1994, Baguhl et al., 1995). There are indications that even bigger interstellar grains pass through the solar system. Pioneer 10/11 detected a flux of particles approximately a few microns in size (Humes, 1980) from the opposite hemisphere than the local interstellar gas flux. Recent radio meteor observations indicate a population of extremely fast ($> 100 km/s$) meteor particles of obviously interstellar origin (Taylor et al., 1996). All these new observations should eventually lead to the determination of the physical and chemical properties and the size distribution of local interstellar dust.

In the following chapters we discuss different processes which affect interplanetary and interstellar dust. We start with a brief description of the sources of dust in interstellar and interplanetary space and continue to discuss life-time and dynamic effects. We describe the basic effects and show their relevance in both scenarios. This review is not considered to be complete in the sense that it describes all processes which affect interplanetary and interstellar dust but it concentrates on the dominant effects which are manifested by observational evidences. With this paper a comparison is attempted between the interplanetary and interstellar environment for the mutual benefit of both fields of study.

2. Sources of dust in interplanetary and interstellar space

Dust in the solar system is characterized by short life times, ($< 10^6$ years). Several effects destroy dust grains and disperse the material in space. Therefore, interplanetary dust must have contemporary sources: bigger objects like meteoroids, comets and asteroids.

Obvious sources of interplanetary dust are comets and asteroids. In the inner solar system comets shed large amounts of dust into interplanetary space. However, it can easily be shown that most of this dust is rapidly lost to interstellar space due to the action of radiation pressure. Bands of increased thermal radiation detected by the IRAS satellite indicate the presence of mm-sized particulates in the asteroid belt. However, in-situ detectors on board of the Pioneer 10 and 11 as well as the Galileo and Ulysses spacecraft did not find significant enhancements of small micron-sized dust in the asteroid belt. Where does interplanetary dust come from? The clue was given by Whipple 1967 and Dohnanyi 1969 who pointed out that cometary and asteroidal matter is efficiently injected into the solar system as bigger (millimeter- to meter-sized) meteoroids which are subsequently ground-up by mutual collisions. Grün et al. (1985a, b) demonstrated how the observed size distribution of meteoroids can be quantitatively explained by this effect.

There is a continuous stochastic stirring of asteroid orbits by the gravitational pull of the planets, especially of Jupiter. Dust in the asteroid belt originates from mutual collisions among asteroids. Small, micron-sized meteoroids produced in such a collision will be immediately removed by solar radiation pressure from their place of origin and will be swept by Poynting-Robertson effect towards the sun.

Comets produce dust and bigger meteoroids by a quite different process: Sublimation of the cometary ices drag particulates embedded within the cometary nucleus into interplanetary space. Most dust visible in the coma and in the tail consists of micron-sized dust particles which leave the solar system on hyperbolic orbits due to the action of radiation pressure. However, we know that also much bigger objects are released from comets. Meter-sized fireballs which hit the Earth's atmosphere demonstrate by their trajectories clearly their cometary origin. Splitting of comets give testimony that substantial fractions of kilometer-sized nuclei are left behind in interplanetary space.

Besides the ejection of dust into interstellar space from our own planetary system there are various other ways of dust formation and injection into the interstellar medium. Most visible stardust is born in stellar outflows especially from cool high luminosity stars (M- and C- giants, and supergiants, Jones and Tielens, 1994). Planetary nebulae, novae and supernovae provide the rest. Carbon and silicate grains and metal oxides like Al_2O_3 have been identified in the outflowing material (see e.g. the review by Dorschner and

Table I
Phases of the diffuse interstellar medium. HI is neutral and HII is ionized hydrogen.

phase	temperature (K)	density ($n(H)/cm^3$)
cold neutral matter	30 – 80	20 – 50 (HI)
warm neutral matter	5000 – 8000	0.1 – 1.0 (HI,HII)
thin hot ionized matter	10^5 – 10^6	10^{-3} – 10^{-2} (HII)

Henning, 1995). However, not all of the heavy elements is condensed in the dust: e.g. much of the carbon is contained in gaseous CO. Refractory carbon phases are amorphous and hydrogenated amorphous graphite and polycyclic aromatic hydrocarbon (PAH, Allamandola et al., 1987). PAHs range from macro- molecules to nanometer-sized particulates.

The diffuse interstellar medium appears in three distinct phases (McKee and Ostriker, 1977): dusty gas clouds consisting out of a cold neutral core and warm neutral envelopes are embedded in thin hot ionized matter. Typical parameters of the diffuse interstellar medium are summarized in Table I.

The sizes of interstellar grains which are observable by astronomical means range from nanometer-sized grains over classic grains ($0.1\mu m$) to very big grains ($10\mu m$) in some interstellar environments. For classic grains a power law $n(s) \propto s^{-3.5}$ is postulated with a sharp cut-off at $s = 0.2\mu m$ (Mathis et al., 1977).

There is indirect evidence that grain growth partially balances grain destruction in the diffuse interstellar medium (Draine, 1990). Observations of interstellar absorption lines (Whittet, 1992, Sofia et al., 1994) show that refractory elements (like e.g. Al, Ca, Fe, Ni, Si, Mg) are underabundant with respect to cosmic abundance (Anders and Grevesse, 1989). Draine (1990) suspects that much of the dust observed in the diffuse interstellar medium was condensed in molecular clouds and not in stellar outflows. Rapid exchange with the diffuse interstellar medium supplied enough dust to balance the losses expected to occur.

The local interstellar medium in the solar neighborhood consists of a local bubble of hot ionized matter with about $50pc$ radius. Embedded in it are clouds of local fluff of warm neutral matter of a few pc dimension. From stellar absorption measurements (Bertin et al., 1993) and in-situ measurements by the Ulysses spacecraft (Witte et al., 1993) we know that the solar system is moving at $26km/s$ through interstellar medium of $7000K$ and density $n(H) = 0.1cm^{-3}$.

3. Grain destruction

MUTUAL COLLISIONS

In interstellar space mutual collisions are not believed to play a major role (Tielens et al., 1994), although fragmentation of bigger interstellar grains could provide an efficient source for the much more abundant smaller dust particles. On the contrary, collisions determine the lifetime of interplanetary meteoroids and they are the main process by which micrometeoroids are generated. It has been recognized since long that meteoroids have a continuous distribution of sizes (and masses) ranging from km-sized asteroids to submicron-sized dust particles. The flux of interplanetary meteoroids is generally given in the form of the cumulative meteoroid flux $F(m)$, which is the number of meteoroids with masses bigger than or equal to mass m which impact $1m^2$ each second. It is related to the differential flux $f(m)$ of particles in the mass range m to $m + dm$

$$F(m) = \int_m^\infty f(\tilde{m})d\tilde{m} \tag{1}$$

In collisions between interplanetary meteoroids the impact speed $v(r)$ is usually high enough to result in fragmentation of one or both particles. We approximate the average impact speed $\langle v(r) \rangle \propto r^{-1/2}$ as given by Kepler's law. In such a collision the smaller projectile always gets destroyed. A catastrophic collision, i.e. fragmentation of both particles, only occurs, if the mass ratio of target and projectile is not too large, i.e. if

$$m_{projectile} \geq \frac{1}{\Gamma(v)} M_{target} \tag{2}$$

where the maximum allowable mass ratio depends on velocity and was found experimentally for basalt to be $G(v) = 500v^2$ (km/s, Fujiwara et al. 1977). This may or may not also be typical for interplanetary particles. If the projectile mass is smaller, the larger particle is eroded by the impact cratering process, a kind of sputtering on a macroscopic scale. Dohnanyi (1970) showed that for the meteoroids of concern to us ($m < 10^{-3}kg$) erosive collisions are much less important than catastrophic collisions, so that we may limit our discussions to the latter case.

The rate of catastrophic collisions $C(m, r)$ of a meteoroid of mass m at heliocentric distance r can now be calculated by adding the probabilities that the meteoroid will encounter during the following second a projectile particle large enough to disrupt the meteoroid. This integral has to be taken over all projectile masses m_p larger than the minimum mass given in eqn. (2):

$$C(m, r) = \int_{m/\Gamma(v(r))}^\infty \sigma \cdot f(m_p, r) dm_p \tag{3}$$

Here $f(m_p, r) = n(m_p, r)\langle v(r)\rangle$ is the flux of particles of mass m at heliocentric distance r. The cross section is taken as the total area inside the circle where the particles touch, $\sigma = \pi(s + s_p)^2$, where s and s_p are the radii of the meteoroid and projectile particles, respectively.

The collisional lifetime for this particle then is defined as the reciprocal of the average collision rate,

$$\tau_C = \frac{1}{C(m, r)} \tag{4}$$

In interplanetary space the lifetime of particles with masses $> 10^{-5}g$ is dominated by collisions. The mass of particles destroyed by collisions is not really lost but reappears in the form of small fragments, constituting a gain of particle in those size ranges. Comparing gains and losses, the net effect of collisions is to produce dust particles ($m < 10^{-5}g$, radii $< 100\mu m$) at the expense of the larger meteoroids (Grün et al., 1985a). This means that at $1AU$ the spatial density of interplanetary dust increases by 10% in 3000 years, at $0.1AU$ even in only 30 years. Most of the interplanetary dust is produced by collisions of larger meteoroids at a rate of about $10t/s$ inside $1AU$, which present a reservoir continually being replenished by disintegration of comets or asteroids. Part of it ($\approx 1t/s$) is lost by evaporation after being driven close to the sun by the Poynting-Robertson effect. The remainder is transformed by collisions to beta-meteoroids ($\approx 9t/s$) which is blown out of the solar system (Grün et al., 1985b).

Sputtering

In the diffuse interstellar medium sputtering is considered to be the main loss process for interstellar dust, whereas, in interplanetary space sputtering plays only a minor role. Sputtering is the process when an individual atom or ion collides with a solid body and removes from it one or more ions or atoms. The sputtering yield $Y(E)$ is the average number of atoms or ions released by impact of a single atom or ion with an energy E. Sputtering yields, especially for lower energy atoms or ions, are rather uncertain, and new laboratory experiments with appropriate targets and projectiles are desirable. Sputtering of dust particles by ions will be investigated in a near future by an experimental set-up for studies of dust electric charging by electrons and ions described in Svestka et al. (1993) and Cermak et al. (1995).

The number of sputtered ions is generally much smaller than the number of atoms. The threshold energy, i.e., the minimum energy of incoming particle required for sputtering, is approximately four times higher than the sublimation energy, e.g., for metals equal 5 to $40eV$ (Barlow, 1978). Most important for sputtering are atoms (or ions) of hydrogen or helium. The abundance of helium is about an order of magnitude smaller than that of hydrogen, but the sputtering yield of helium atoms is about an order of magnitude higher compared to hydrogen. Therefore, relative importance of sputtering by hydrogen and helium atoms is about the same. Sputtering yields of atoms of the CNO group are about an order of magnitude higher compared to helium atoms, but their relative abundance compared to hydrogen is only about 10^{-3} and so they contribute to the total sputtering rate only by about 2.5%.

In a hot gas where plasma particles are moving with thermal velocities we speak about "thermal sputtering". This process may be important for the destruction of particles in a hot gas. In the case of the local interstellar medium, where we find temperatures of $7000K$ to 10^6K and densities of hydrogen atoms 0.1 to $1cm^{-3}$, we can use sputtering rates estimated by Draine and Salpeter (1979). In the local cloud with a temperature not higher than 10^4K, thermal sputtering rates are negligible. Sputtering yields of hydrogen and helium atoms of energies $100eV$ incident on graphite are equal to about 0.01, the yield of oxygen atoms is 0.1. In the case of silicates the yield for hydrogen is equal to 0.01, for helium 0.1, and for oxygen 0.3. In the local bubble with temperature 10^6K and hydrogen number density 0.1 the erosion rates of silicate, graphite and iron grains due to the thermal sputtering are equal to approximately $3 \cdot 10^{-12} cm\ yr^{-1}$. It means that the lifetime of $0.01\mu m$ grains against the thermal sputtering would be about $3 \cdot 10^5$ years, the lifetime of $0.1\mu m$ grains $3 \cdot 10^6$ years. Erosion rates due to thermal sputtering are proportional to the hydrogen density and, therefore, the lifetimes against the sputtering are inversely proportional to the hydrogen density.

For estimates of the hydrogen and helium sputtering yields of candidate grain materials see also Barlow (1978) and Tielens et (1994), for reviews of experimental data on sputtering see Andersen and Bay (1981) and Betz and Wehner (1983), and for a theory of the sputtering process see Sigmund (1969; 1981).

4. Grain Transport

Interplanetary dust dynamics

In this paragraph we review the basic dynamic effects which act on meteoroids in interplanetary space. All dust particles in space feel the gravitational pull of the sun. Table II gives values for the solar gravitational force on particles of different masses and compares them with other forces acting on particles in interplanetary space. For particles with masses $> 10^{-8}g$ this is by far the dominating force. As a consequence meteoroids move on Keplerian orbits which are conic sections with the sun in the focus – other forces

Table II

Main forces on dust in interplanetary space at $5AU$, radius for spherical particles, absorbing particle, density $1000kg/m^3$, $5V$, $v_{rel} \approx 400km/s$, $B \approx 1nT$, $\alpha \approx 80°$.

mass (kg)	10^{-20}	10^{-17}	10^{-14}	10^{-11}	10^{-8}
radius (μm)	0.01	0.1	1	10	100
F_{grav} (N)	10^{-24}	10^{-21}	10^{-18}	10^{-15}	10^{-12}
F_{rad}/F_{grav}	0.5	2	0.5	0.05	$5 \cdot 10^{-3}$
charge-to-mass ratio (C/kg)	600	6	0.06	$6 \cdot 10^{-4}$	$6 \cdot 10^{-6}$
F_L/F_{grav}	2000	20	0.2	$2 \cdot 10^{-3}$	$2 \cdot 10^{-5}$

are only small disturbances. Certainly, all observations of big particles are compatible with such orbits.

The force F_{rad} exerted by the solar radiation on dust in interplanetary space decreases with the inverse square of the distance to the sun, i.e. this is the same dependence as the gravitational pull F_{grav}. Therefore, the ratio of both forces F_{rad}/F_{grav} is constant everywhere in interplanetary space and it is only dependent on material properties (Burns et al., 1979). This ratio is generally termed β:

$$\frac{F_{rad}}{F_{grav}} = \beta = 5.7 \cdot 10^4 \frac{\langle Q_{pr} \rangle}{\rho s}, \tag{5}$$

where $\langle Q_{pr} \rangle$ is the efficiency factor for radiation pressure on the meteoroid averaged over the solar spectrum, s is the radius of a spherical particle, and ρ is its density. E.g. for $s = 10^{-6} m$, and $\rho = 100 kg/m^3$ follows $\beta = 0.57$. For big particles $\langle Q_{pr} \rangle$ is of the order of 1, depending somewhat on the material properties, but it decreases for particles smaller than the effective wavelength of sun light. As a consequence β increases for smaller s values and reaches its maximum value between 0.1 and 1 microns. The maximum value is about 0.5 for non-absorbing dielectric materials and increases with increased absorptivity; it reaches values of 3 to 10 for metallic particles.

There are important consequences for the dynamics of small particles because of the radiation pressure. Small particles which are generated from big particles (e.g. ejection from comets or impact ejecta from meteoroids or asteroids) carry specific kinetic energy of their parents but find themselves in a reduced potential field of the sun. As a consequence they move on different orbits than their parents. E.g. a dust particle with radiation pressure constant b which is released from a big parent object on an eccentric orbit (eccentricity e_p) at perihelion will leave the solar system on a hyperbolic orbit if

$$\beta > \frac{1}{2}(1 - e_p) \tag{6}$$

It can be seen that even for a parent object on a circular orbit the ejected dust grain will move on an unbound hyperbolic orbit if its β value is only 0.5. In the data from Pioneers 8 and 9 spaceprobes (Berg and Grün, 1973) a flow of beta meteoroids leaving the solar system on hyperbolic orbits was first detected.

Besides the direct effect of radiation pressure on the trajectories of small dust grains there is also the more subtle Poynting-Robertson effect. It is caused by radiation pressure which is not perfectly radial on a moving dust particle but has a small component acting opposite to the particle motion. This drag force leads to a loss of angular momentum and orbital energy of the orbiting particle. The time, τ_{PR}, for a particle on a circular orbit to spiral to the sun is

$$\tau_{PR} = 2.2 \cdot 10^{13} \frac{s\rho}{Q_{pr}} \left(\frac{r}{r_0}\right)^2, \qquad (7)$$

with $r_0 = 1AU$. E.g for $s = 10^{-2}m$, $\rho = 1000kg/m^3$, $\tau_{PR} = 2.2 \cdot 10^{14}s$ or $7 \cdot 10^6$ years.

All meteoroids in interplanetary space are electrically charged. Several competing charging processes determine the actual charge of a meteoroid: collection of plasma ions and electrons and emission of secondary and photoelectrons. Because of the predominance of the photoelectric effect in interplanetary space meteoroids are mostly charged positive at a potential of a few Volts. The outward (away from the sun) streaming solar wind carries a magnetic field from the sun. The polarity of the magnetic field can be positive or negative depending on the polarity at the base of the field line in the solar corona which varies spatially and temporary. The Lorentz force on a charged dust particle near the ecliptic plane is mostly either up- or downward depending on the polarity of the magnetic field. Submicron-sized grains are carried by the magnetic field out of the solar system. Since the polarity changes due to the sector structure near the ecliptic at a frequency much faster than the orbital period of bigger interplanetary dust particles the net effect of the Lorentz force is small. Only secular effects on the bigger zodiacal particles are expected to occur (Morfill et al., 1979, 1986) which could have an effect on the symmetry plane of the zodiacal cloud close to the sun. Zodiacal light observations (Leinert et al., 1980) show such an effect on the symmetry plane but there are other explanations as well.

The overall polarity of the solar magnetic field changes with the solar cycle of 11 years. For one solar cycle positive magnetic polarity prevails in the northern and negative polarity in the southern solar hemisphere. Submicron-sized interstellar particles which enter the solar system are either deflected towards the ecliptic plane or away from it depending on the overall polarity of the magnetic field. Therefore, interstellar particles are either prevented (during one solar cycle) from reaching the inner solar system or are concentrated (in the other solar cycle) in the ecliptic plane.

Dust dynamics in the diffuse interstellar medium

In the local interstellar medium we find temperatures from $7000K$ to 10^6K and gas number densities 0.1 to 1 (Holzer et al., 1989; Lallement et al., 1994). Threshold energies for secondary electron emission under ion impacts are $\approx 100eV$, so that we can neglect this process. Potentials will be basically determined only by interactions with electrons and UV radiation. We will confine further our discussion to grains of radii $\geq 0.01\mu m$. In the case of the mentioned temperatures and grain radii, the ranges of electrons and ions are smaller than the grain dimensions, so that it is not necessary to consider a possibility of penetration of electrons or ions through grains with subsequent electron emission from the exit side (Svestka and Grün, 1991; Chow et al., 1994).

At a given potential non-spherical grains can carry more electric charges than spherical grains of the same mass; they can have higher charge-to- mass ratio compared to spherical grains. For example, if we keep in the case of conducting prolate and oblate spheroids the potential and mass constant, the total charge increases with the increasing ratio of the major to the minor axis. Calculations of charges on non-spherical grains of more complicated shapes have just started (Svestka et al., 1996).

In a Maxwellian plasma with electron and ion energy distributions at the same temperature, the velocity and, therefore, the charging current of electrons is higher - grains are charged negatively. As a result, ions are attracted and electrons repelled until both charging currents become equal in the magnitude and equilibrium negative charge is reached.

From the conservation of energy and momentum of electrons and ions, and under the assumption that the radius of a grain is much smaller than the Debye length in the surrounding plasma, the collisional cross- section σ can be calculated for an electron or ion with charge q and kinetic energy E (in infinity) to collide with a grain of radius, s, and charge, Q, $\sigma = \pi s^2(1 - qU/E)$, where $U = Q/(4\pi\epsilon_0 s)$ is the surface electrostatic potential of a spherical grain and permittivity $\epsilon_0 = 8.859 \cdot 10^{-12} C/Vm$. If we integrate this cross-section over a Maxwellian velocity distribution of electrons or ions with temperatures T, masses m, and number densities n, we obtain for a charging currents $J = J_0 \exp(-qU/kT)$, for $qU > 0$, and $J = J_0(1 - qU/kT)$, for $qU < 0$, where J_0 is the current on a grain with zero charge (k is Boltzmann constant). In a fully ionized hydrogen plasma with Maxwellian distributions of electrons and ions at equal temperatures T, the equilibrium potential U is independent of the radius of a grain and it is given by $U = -2.51kT$ (Spitzer, 1941).

Interactions of electrons of sufficiently high energies with a grain leads to secondary electron emission. The shape of the secondary electron emission yield $\delta(E)$ (number of electrons released by impact of a single electron of energy E) normalized to the maximum yield, δ_{max}, at the corresponding energy E_{max} is approximated by

$$\delta(E) = 7.4\ \delta_{max} \frac{E}{E_{max}} \exp(-2 \left(\frac{E}{E_{max}}\right)^{\frac{1}{2}})$$

(Sternglass, 1954). δ_{max} is of the order of one for metals and semiconductors, for insulators it is higher (2 to 30, Bruining, 1954). According to Suszcynsky et al. (1992), δ_{max} of various ices equals 2 to 7. E_{max} is equal to 300–2000eV (higher δ_{max} implies higher E_{max}). Threshold energy of primary electrons to produce secondary ones is about 4 to $7eV$. It is expected that the energy distribution of secondary electrons is Maxwellian with mean energy of 1 to $5eV$. The yield, $\delta(E)$, increases with decreasing grain size (Chow et al., 1993). At energies above a few hundred eV, the yield $\delta(E)$ becomes > 1 and, therefore, the process of secondary electron emission is very important for charging of grains in a plasma of temperature $T \geq 10^6 K$.

UV photons, which are relatively abundant in interstellar space, release photoelectrons from a grain: Photon absorption leads to excitation of an electron to an energy level with enough energy to escape from the grain. Photoemission is very important charging mechanism for grains surrounded by a gas of temperature $T < 3 \cdot 10^5 K$. The photoelectric yield $Y(h\nu)$ is defined as the number of photoelectrons released by absorption of a single UV photon with energy $h\nu$. In the case of very small grains the yield can be strongly enhanced (Schleicher et al., 1994). From several theoretical estimates and observations, Drain (1978) fitted the "average" galactic UV radiation for photons of energies $h\nu = 5 - 13.6eV$ by $F(h\nu) = (1.658 \cdot 10^6 (h\nu/eV) - 2.152 \cdot 10^5 (h\nu/eV)^2 + 6.919 \cdot 10^3 (h\nu/eV)^3)$ photons $cm^{-2} s^{-1} sr^{-1} eV^{-1}$. As a result, he obtained for a flux of photoelectrons $J_{phe} = 2.4 \cdot 10^6 Q_{abs} cm^{-2} s^{-1}$, for $U < 0$, $J_{phe} = 2.4 \cdot 10^6 Q_{abs} (1 - U/5.6V)^3 cm^{-2} s^{-1}$, for $0 < U < 5.6V$, and $J_{phe} = 0$, for $U > 5.6V$, where the average UV absorption efficiency Qabs is an approximate fit for silicates and graphite.

In the local cloud we assume an ionization degree of 0.1 and average ultraviolet background. From calculations of Draine (1978) follows the equilibrium surface electrostatic potentials of graphite or silicate dust grains of radii 0.01 to $0.1\mu m$ will be very low and positive, equal to $+0.5$ to $+1V$. In the local bubble with a temperature of about $10^6 K$ and a hydrogen number density of about $0.1 cm^{-3}$ the equilibrium surface electrostatic potentials of dust grains of radii 0.01 to $0.1\mu m$ are again positive, higher compared to the local cloud. They depend on the material of a grain. The potentials of graphite grains are equal to about $+5V$, potentials of silicate grains $+12$ to $+13V$, potentials of iron grains about $+6V$.

Table III

Gyroradius r_{gy} of charged particles in interplanetary and interstellar space. Surface potentials of 5 and $0.5V$, speeds of 400 and $5km/s$, and magnetic fields of 1 and $0.5nT$ have been assumed for interplanetary and interstellar conditions, respectively. $1AU = 1.5 \cdot 10^{11} m$, $1pc = 2 \cdot 10^5 AU$.

Size (μm)	mass (kg)	charge (C)	r_{gy} (AU)
interplanetary condition			
0.1	10^{-17}	$6 \cdot 10^{-17}$	500
1	10^{-14}	$6 \cdot 10^{-16}$	$5 \cdot 10^4$
10	10^{-11}	$6 \cdot 10^{-15}$	$5 \cdot 10^6$
interstellar condition			
0.1	10^{-17}	$6 \cdot 10^{-18}$	120
1	10^{-14}	$6 \cdot 10^{-17}$	$1.2 \cdot 10^4$
10	10^{-11}	$6 \cdot 10^{-16}$	$1.2 \cdot 10^6$

Charged dust couples to the ambient magnetic field. We will compare this effect in two different environments, in the local interstellar medium and in the heliosphere. In interplanetary space dust is charged to approximately $+5V$, and the typical magnetic field at $5AU$ distance is primarily azimuthal with a strength of about $1nT$. In interstellar space we assume a potential of $+0.5V$. The interstellar magnetic field is largely unknown but has been estimated to be $0.5 \pm 0.3nT$ (Holzer, 1989). The speed of the dust particle relative to the magnetic filed is assumed to be about $5km/s$. The gyroradius r_{gy} in a magnetic field B of a particle with charge Q traveling with speed v is $r_{gy} = mv/QB$.

In Table III we have compared the gyroradii for dust particles in interplanetary and interstellar space, respectively. It can be seen that in interplanetary space the resulting gyroradii are huge compared to the extend of the heliosphere ($\approx 100AU$), even for $0.1\mu m$-sized particles. To the contrary, in interstellar space smaller than micron-sized dust particles couple to the magnetic field on a distance scale which is short compared to the extend of the local cloud (a few pc).

Besides coupling to the magnetic field interstellar grains couple to the ambient gas via collisions. The dust–gas–coupling length can be estimated from the distance l a dust particle travels through the gas until it has traversed a column density of gas with a similar mass as that of the particle $l \approx 4\pi\rho_d/3m_g n_g$ (Egger et al., 1995). Using $\rho_d = 1000kg/m^3$ a frictional coupling length of $l \approx 300 \cdot s_\mu pc$ is obtained, where s_μ is the dust size in microns. This length scale is larger than the extend of the local interstellar cloud even for $0.1\mu m$-sized particles. This implies that the gas and dust are not in frictional equilibrium. We conclude that in the diffuse interstellar medium electromagnetic coupling is much more important than frictional coupling. Interstellar dust is rather coupled to the large-scale galactic magnetic field than to the gas clouds in the diffuse interstellar medium. However, the ionized component of the interstellar medium provides the medium for coupling the neutral component to the galactic fields as well. Only in the cores of molecular clouds the gas density is high enough in order to couple directly interstellar dust to the gas.

New observations and updated theoretical considerations will eventually allow us to address important questions concerning the local interstellar medium:

1. Interstellar dust grains in the heliosphere are probes of the local interstellar medium: e.g. their speed dispersion is a function of the coupling to interstellar gas and interstellar magnetic field. Determinations of the speed dispersion may allow us to determine this coupling strength.
2. What is the size distribution of interstellar dust, which particles carry the most mass and what is the role of mutual collisions for the generation of submicron-sized grains?
3. Interstellar dust is considered to contain a major fraction of the condensable interstellar elementar inventory. It is generally believed that the large scale elementar average composition has to have cosmic abundance. How large can be local deviations from the average value?

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