Dust Near The Sun

Ingrid Mann* and Hiroshi Kimura
Institut für Planetologie, WWU, Münster, Germany

Douglas Biesecker
NOAA/SEC, Boulder, CO, USA

Bruce T. Tsurutani
NASA/JPL, Pasadena, CA, USA

Eberhard Grün†
Max-Planck-Institut f¨r Kernphysik, Heidelberg, Germany

Bruce McKibben
Department of Physics and Space Science Center, University of New Hampshire, Durham, NH, USA

Philippe Lamy
Laboratoire d'Astrophysique Marseille, France (to be confirmed)

Jer-Chyi Liou
Lockheed Martin Space Operations, Houston, TX, USA (to be confirmed)

Robert M. MacQueen
Rhodes College, Memphis, TN, USA

Tadashi Mukai
Department of Earth and Planetary Sciences, Kobe University, Kobe, Japan

Lika Guhathakurta
NASA Headquarters, Washington D.C., USA (to be confirmed)

Abstract. We review the current knowledge and understanding of dust in the inner solar system. The major sources of the dust population in the inner solar system are comets and asteroids, but the relative contributions of these sources are not quantified. The production processes are: Poynting-Robertson deceleration of particles outside of 1 AU, fragmentation of dust due to particle-particle collisions, and direct dust production from comets. The loss processes are: dust collisional fragmentation, sublimation, radiation pressure acceleration, and rotational bursting. These loss processes as well as dust surface processes release dust compounds in the ambient interplanetary medium. Between 1 and 0.1 AU the dust number densities and fluxes can be described by inward extrapolation of 1 AU measurements, assuming radial dependences that describe particles in close to circular orbits. Observations have confirmed the general accuracy of these assumptions for regions within 30° latitude of the ecliptic plane. The dust densities are considerably lower above the solar poles but Lorentz forces can lift particles of sizes $a < 5$ μm to high latitudes and produce a random distribution of small grains that varies with the solar magnetic field. Also long-period comets are a source of out-of-ecliptic particles. We show that under present conditions no prominent dust ring exists near the sun. We discuss the recent observations of sungrazing comets. Future in-situ experiments should measure the complex dynamics of small dust particles, identify the contribution of cometary dust to the inner solar system dust cloud and study dust interactions in the ambient interplanetary medium. The combination of dust in-situ measurements with particle and field measurements is recommended.

Keywords: sample, LaTeX

1. Introduction

The near-solar dust cloud is the central region of the meteoritic complex that evolves from the small bodies or our planetary system. With its complexity of acting forces, physical processes, and interactions, it provides the unique opportunity for directly studying a cosmic dust-plasma cloud and therein processes that also appear in other cosmic environments. Dust particles in the inner solar system produce the solar F-corona and the zodiacal light. Yet, these astronomical phenomena reveal only a part of the dust cloud in the inner solar system and especially do not yield sufficient information about the vicinity of the sun, which is obscured by dust particles in the vicinity of the Earth. Further information is obtained from studies of the near-Earth environment. and from dust in-situ measurements, that in one case ranged to distances as close as 0.3 AU from the sun.

The current discussion of space missions to the inner solar system within ESA and NASA raises the question as to what experiments are most suitable for improving our understanding of the inner solar system dust cloud. Here we give an overview of different studies of the inner solar system dust cloud and discuss their results in the context of understanding the evolution of small bodies in the solar system as well as in the context of the physics of the interplanetary medium. We summarize the current knowledge of the dust parameters near the sun. This provides a data compilation for estimates of the dust environment that spacecraft encounter in the inner solar system.

Since the knowledge of near-solar dust is limited at this time we give estimates derived from coronal observations, from model calculations of the dynamical and collisional evolution, and from extrapolating the measured 1 AU values toward smaller distances. We attempt an extrapolation from zodiacal light data that is consistent with in-situ measurements and merge the extrapolation with observations of the solar corona.

In this paper we first describe the best observational studies and in-situ measurements of dust in the inner solar system from 1 AU

---

[*] ESA Space Science Department ESTEC, Noordwijk, The Netherlands
[†] HIGP, University of Hawaii, Honolulu, HI, USA

inward (Section 2). The most reliable data exists for dust near 1 AU. Observational results in combination with knowledge about the dust sources (described in Section 3) justify and constrain the extrapolation of the dust distribution from 1 AU inward. This is valid for dust near the ecliptic plane. We subsequently discuss the knowledge of dust at high latitudes outward from the ecliptic plane in Section 4. The destruction of dust as a result of mutual catastrophic collisions, sublimation, and rotational bursting is discussed in Section 5. Comets are expected to be a major source of dust inward from 1 AU and sungrazing comets are the major local source of dust in the vicinity of the sun. This is discussed in Section 6. The variation of dust orbits under radiation pressure and magnetic forces that takes place in the close vicinity of the sun is discussed in Section 7. A summary of the present best estimates of the near-solar dust environment is given in Section 8. In Section 9 we discuss interactions with the interplanetary medium where refined measurements point to the connections between dust and solar wind pick-up ions. We end with a summary of this work which shortly discusses the issues of dust physics that can be addressed with future near-solar dust studies.

2. Observational Evidence of Dust

2.1. Zodiacal Light

Scattering of sunlight and thermal emission of dust particles produce the observed brightness, called zodiacal light for night-time observations pointing away from the sun and called solar F-corona in the vicinity of the sun (Figure 1).[1] A compilation of F-corona and zodiacal light observations is given in Leinert et al. (1998). Observations provide an integrated brightness along the line-of-sight (LOS) leading, however, to some ambiguity in the inversion. It is well established that zodiacal light observations describe predominantly particles in the 1 to 100 μm size interval, which covers the approximate mass interval from 10^{-11} to 10^{-5} g.

Based on observational results we can conclude that the majority of dust outward from 0.3 AU is distributed in a flat, rotationally symmetric cloud that is concentrated near the ecliptic plane (Mann, 1998).

---

[1] For corona observations, the elongation of the line-of-sight (LOS) is often given in distances, r from the sun: $r = \sin(\epsilon) \cdot 1$ AU for observations from Earth. Strictly speaking 'r' denotes the minimum distance from the sun that the LOS crosses. This is not identical to the elongation of the LOS given in solar radii ($R_\odot$) but the difference is small for small angles.Note; 1 $R_\odot = 6.96 \times 10^8$ m $\approx 1/215$ AU, $\epsilon = 1°$ (4 $R_\odot$).

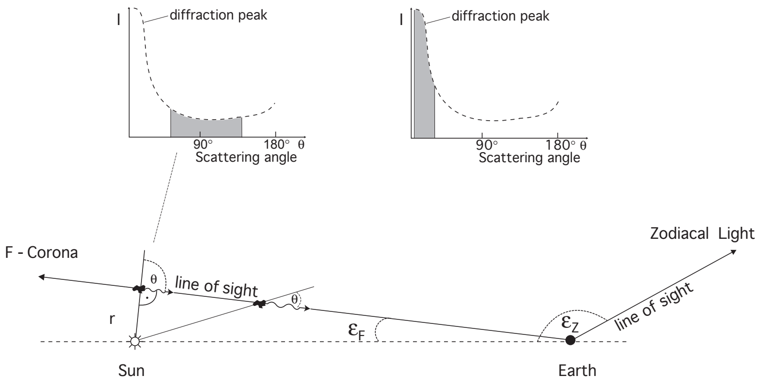

Figure 1. Geometry of zodiacal light and F-corona observations: Both phenomena are caused by the same physical effect: scattering of light and thermal emission from dust distributed along the line-of-sight (LOS), but are observed at different elongations, ϵ, of the LOS, in this figure r denotes the minimum distance from the sun that is seen along the LOS with elongation ϵ. A sketch of the scattering pattern is given in the upper part of the figure: dust particles close to the Earth contribute to the LOS brightness with enhanced scattering at small angles θ. Dust particles near Earth efficiently scatter the sunlight under small scattering angles toward the observer and therefore have a large contribution to the integrated LOS brightness.

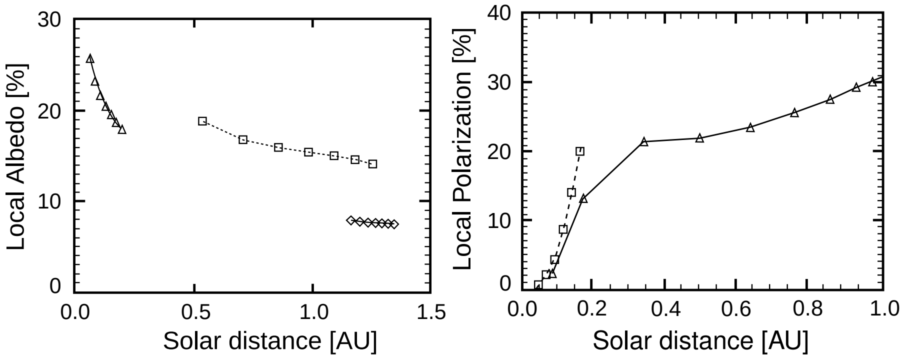

Figure 2. Average local optical properties derived from F-corona and zodiacal light observations assuming a homogeneous dust cloud: the variation at small distances from the sun is so drastic, that it points to a change of the dust cloud composition.

The number density increases with decreasing distance from the sun, roughly proportional to r^{-1}, where r is the distance from the sun. The average polarization and geometric albedo, as well as the spectral variation of the albedo change with distance from the sun and with latitude (Kneissel and Mann, 1991a; Mann, 1998) as shown in Fig. 2. Variations of these derived average properties may stem from several effects: changes of single particle properties, changes of the overall dust cloud composition, and changes of the size distribution. The increase of albedo inward from 0.3 AU is very steep and most likely not explained with a gradual change of the particle properties, but rather with a change in the dust cloud composition. [2]

2.2. F-Corona

The lack of observational data as well as problems of the LOS inversion prevent us from deriving firm number densities and optical properties for dust near the sun. The solar corona results from a smooth continuation of the zodiacal light brightness to small elongations of the LOS. But the signal from the K-corona produced by Thomson scattering of electrons near the sun has to be subtracted in order to derive the F-corona brightness. Moreover, the observations are hampered by the presence of coronal and atmospheric straylight and therefore F-corona observations are preferably made in the near infrared and during solar eclipses or with coronagraphs from space (see Fig. 3). As a result of the LOS geometry, the brightness that stems from dust near the Earth is scattered at small angles to reach the observer, while dust near the sun is scattered at angles around 90° (see Fig. 1). For particles in the 1–100 μm size range the scattering is very efficient for small angles ('forward scattering') while it is less efficiently scattered at larger angles. That has the effect that dust components near the observer yield a larger contribution to the F-corona than to zodiacal light observations. This influence of dust near the observer makes observations in the near infrared more favorable because thermal emission from near-solar dust may contribute to the brightness. But still the ambiguities of the LOS inversion remain, and severely limit the results that can be derived about near-solar dust from the remote observations.

---

[2] While in-situ measurements typically provide data for the mass of particles, brightness observations provide information on their size. Throughout the paper we give the parameter that is used in the particular case and give the estimate for the other parameter based on the assumption that the particles are compact spherical grains with bulk density, $\rho = 2.5$ g/cm^3 (with mass, $m = 4/3\pi\rho a^3$ where a is the radius of the particle). This is a good estimate for the average properties, but neglects the fact that the bulk density might vary with the size of the grains, which may for instance be the case for porous particles.

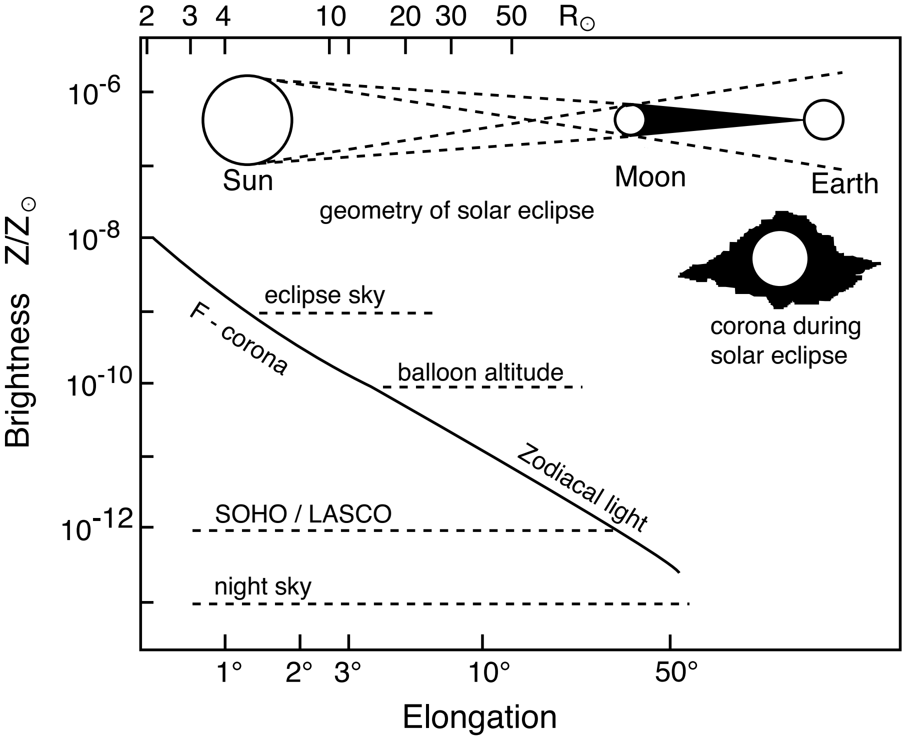

Figure 3. Straylight levels of the nightsky and eclipse sky in comparison to the corona and zodiacal light brightness. The geometry of the solar eclipse is sketched in the upper part of the figure.

A summary of F-corona observations is given in Kimura and Mann (1998). Moreover, the detection or non-detection of features in the F-corona and its speculated connection to dust rings and to the existence of a dust-free zone around the sun is discussed there. It is also shown that the differences in near infrared brightness that were observed over the past few decades may result from a time variation of the material properties of dust in the near-solar environment (Kimura et al. 1998). As shown in Figure 4, the appearance of an IR feature is expected for a coronal brightness that has significant amount of thermal emission, while the scattered light components tend to occult this features. Therefore the feature is observed during periods when a high amount of absorbing dust particles is present. Recent infrared observations of the 1998 eclipse (Mann et al., 1999; Ohgaito et al., 2002), where no feature was observed, are, for instance, best described with dust particles that are weakly absorbing. The F-corona polarization in the visible is close to zero indicating the predominance of forward scattered light and possibly, as mentioned above, also a change of the (average) polarization and geometric albedo with distance from the sun (Mann, 1996). The size range of observed particles may change in the F-corona compared to the zodiacal light, but still the majority of observed particles are expected to have sizes larger than 1 μm (i.e. about 10^{-11} g). The solar corona was recently observed at visible wavelengths with the Large Angle Spectrometric Coronagraph (LASCO) instruments C2 and C3 from the Solar Heliospheric Observatory (SOHO). They provide valuable information about dust from sungrazing comets as will be dicussed in section 6. But no clear information about the spatial distribution of dust has been derived from the data. The SOHO/LASCO observations show that the F-corona is extremely stable in time. This might indicate a major contribution from dust near 1 AU to the brightness rather than provide information about the stability of the near-solar dust cloud. Usually brightness data yield no information on the orbital distribution in the dust cloud. Fraunhofer lines were measured in the inner zodiacal light and through their Doppler shift provide information about the velocity of dust particles in LOS direction. But their Doppler shifts were not precise enough to derive orbital information on the dust (see Mukai and Mann, 1993, for a summary).

2.3. IN-SITU MEASUREMENTS

Aside from astronomical observations, further data are obtained from in-situ measurements in space and meteor observations of particles entering the Earth's atmosphere (see Fig. 5). In situ measurements typically detect particles of sizes below several μm while the majority of meteors are observed in the size range above 100 μm.

In-situ measurements near 1 AU including meteor data (cf. Ceplecha, 1977) are summarized in Grün et al. (1985). These observations are the basis of the size distribution near 1 AU that is also in agreement with zodiacal light observations. For dust inward from Earth orbit, Helios impact measurements between 0.3 and 1 AU indicate the presence of two distinct dust components (Fechtig, 1982). Dust from the major component is in low to medium eccentricity orbits near the ecliptic, and a second component of dust is in orbits with presumably higher eccentricities, as indicated by its higher impact velocities. The latter component consists of dust of low material strength (Grün et al., 1980). The flattest trajectory observable with Helios was 4° to 10° tilted to the ecliptic, but there is no direct information about the inclination of the dust orbits. Differences in the material strengths of particles inferred from the Helios in-situ measurements point to the existence of dust components with different properties. But we show in Section 5 that the data are insufficient to reveal a change in the size distribution for masses

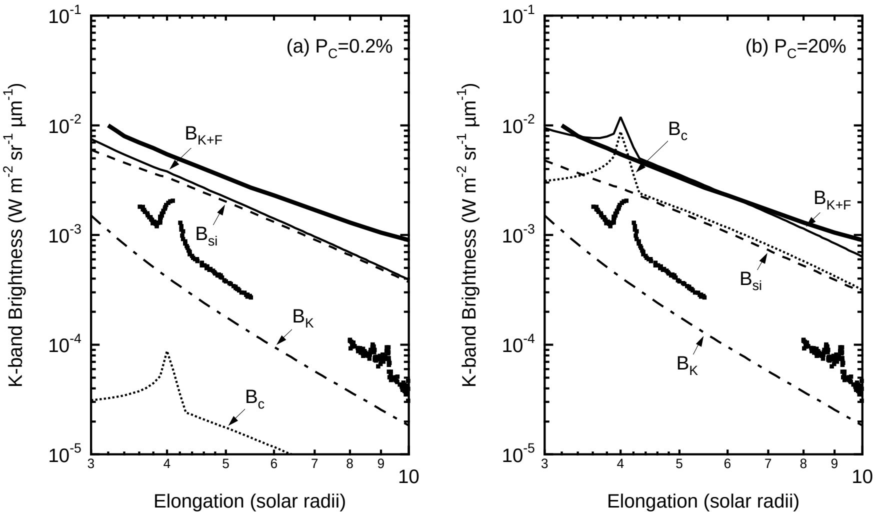

Figure 4. The calculated F-corona brightness in comparison to observations of the IR feature: the left hand side describes a model with predominantly silicate particles and 0.2% carbon, the right hand side describes calculations for 20% carbon particles.

between 10^{-14} to 10^{-10} g (which model calculations indicate to possibly result from collisional fragmentation of dust). The observation of photographic and radar meteors includes mostly sporadic meteors that are not associated with any particular stream. The majority of sporadic meteors (cf. Ceplecha, 1977) are concentrated to the ecliptic plane, but less so than the zodiacal dust cloud (Kneissel and Mann, 1991a). The orbital parameters of dust particles measured from spacecraft are estimated from the spacecraft orientation and detector geometry, but these measurements are limited by the wide opening angle of the detectors. Recently, impact measurements with the SPACE DUST (SPADUS) instrument aboard the Advanced Research and Global Observation Satellite (ARGOS) attempted to directly measure the impact velocity vector relative to the spacecraft, but the statistical significance of the acquired data was negligible (Tuzzolino et al., 2001a; 2001b). New observations of the head echoes that are produced upon the entry of meteoroids in the atmosphere (cf. Pellinen-Wannberg and Wannberg, 1994) allow a better estimate of initial velocities outside the Earth atmosphere, but also in this case the number of detected impacts is statistically small. These measurements of the dust velocity vectors provided no sufficient data yet but may do so in the future.

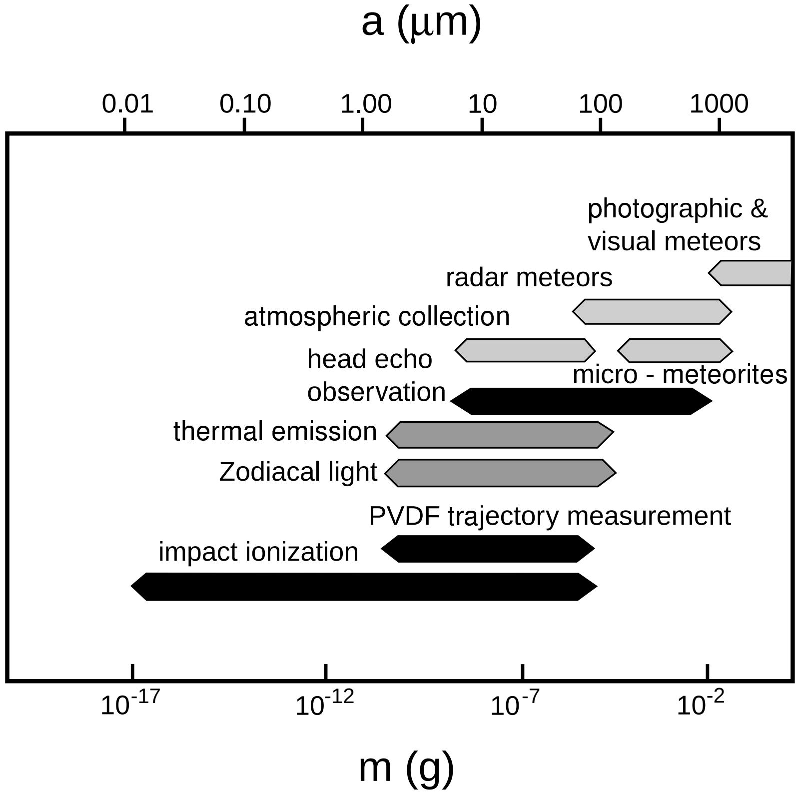

Figure 5. Different methods of dust detection near Earth: while different in-situ instruments can also be used from deep space probes, the knowledge of larger dust components is restricted to meteor observations taken from Earth.

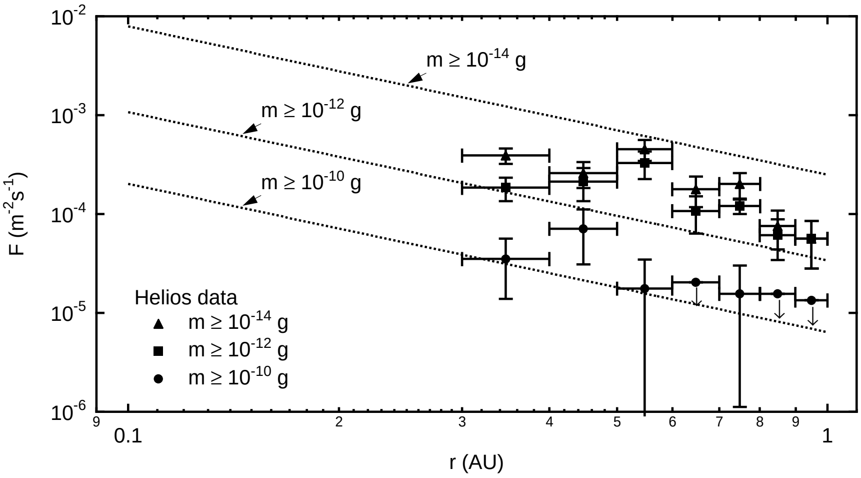

Figure 6. The flux rates measured with Helios in comparison to a flux $\propto r^{-1.5}$.

3. Dust Sources and Orbital Evolution

Interplanetary dust particles are a component of the small bodies in the solar system. The small bodies being closely related through mutual collisions and orbital dynamics, dust particles are the end product of what is ascribed as the 'evolution of the meteoritic complex'. Dust particles are released from comets and asteroids or are produced by fragmentation of larger cometary or asteroidal fragments (meteoroids). Other components are Kuiper belt dust (cf. Liou et al., 1996) and interstellar dust (cf. Grün et al., 1994). Their fluxes extrapolated to the inner solar system are small compared to those of the other components. The Kuiper belt dust will not be considered further. Also the contribution of interstellar dust in the inner solar system is small, but it was measured near 1 AU and can be identified through the variation of the flux along Earth orbit that is caused by gravitational focusing (Mann and Kimura, 2000).

We now restrict our discussion to the evolution of the dust cloud that is produced from comets and asteroids. The major effects that determine the distribution of dust in interplanetary space are solar gravitation, the influence of magnetic fields, radiation pressure and solar wind pressure, including the Poynting-Robertson effect, pseudo Poynting-Robertson effect, mutual collisions, and the gravitational forces exerted by the planets. Like meteoroids, the produced dust particles are initially in orbits with inclinations similar to those of their parent bodies. Parent body asteroids are in orbits with inclinations, $i < 30^\circ$ and eccentricities, $e < 0.1$. Short period comets are in orbits with inclination, $i < 40^\circ$ and eccentricities, $e < 0.4$, long period comets have inclinations ranging from 0° to 180° with $N(i)di \sim \sin(i)di$ where $N(i)$ denotes the number of orbits between i and $i+di$ (spherical distribution in number density). The radiation pressure force deflects small particles directly outward and they may leave the solar system after they are ejected from a comet or formed by collision, the exact condition depending on the initial orbital parameters. Particles for which solar gravity amounts to more than twice the radiation pressure may stay in bound orbits. They form the main content of the interplanetary dust cloud. The radiation pressure influences the orbital evolution of this latter component mainly through the Poynting-Robertson effect: The momentum transfer caused by radiation falling onto a moving particle includes, when seen in the reference frame of the sun, a small component anti-parallel to the particle's velocity that stems from the Lorentz transformation of radiation pressure force in the frame of the particle. This is the case for particles that move in orbital motion about the sun and are exposed to the photon flux that is directed radially outward. The small deceleration that is induced by the anti-parallel component is denoted as the Poynting-Robertson effect. Thus a drift toward the sun is superimposed on the motion in Keplerian orbits and, just as collisions do, limits the lifetime of the dust particles. In addition to radiation pressure, bombardment with solar wind particles transfers momentum to the dust particles. The tangential component of this drag force gives rise to the so-called 'pseudo' or 'plasma' Poynting-Robertson effect. Mukai and Yamamoto (1982) have shown that for some particles (namely those with very low optical absorption) the drag force due to the solar wind can exceed the drag force due to radiation pressure. Moreover, the plasma Poynting-Robertson effect varies with the plasma parameters and therefore depends on the latitude and on the solar activity. Banaszkiewicz et al. (1994) suggest that this causes the radial migration rates for particles close to the ecliptic to be about 5 to 10% greater than those at higher inclinations. Although the Poynting-Robertson effect may vary strongly with the size, composition and structure of particles, the radial drift of the particles that it causes is small compared to the orbital velocities. Our following considerations do not directly depend on precise assumptions of the Poynting-Robertson lifetime, but it should be noted that the influence of radiation pressure and solar wind pressure on dust particles is not well measured. The deceleration of particles by the Poynting-Robertson effect reduces the eccentricities and semimajor axes of their orbits. This leads to an increase of dust number density with decreasing solar distance. The Lorentz force acting on charged dust particles moving in the solar magnetic field moderately deflects the particles from their orbits (Morfill and Grün, 1979). Depending on the local magnetic field direction the particles are subsequently pushed to either lower or higher latitudes, which broadens the range of inclinations of the orbits but still the orbital inclinations are similar to those that are induced by the parent bodies. Also the gravity of the planets can deflect dust particles that closely encounter a planet in unbound and/or high inclination orbits. But the influence of these processes on the overall spatial distribution of the dust cloud is small. While the inclinations of the majority of orbits are less affected, orbital perturbations by planets modify the arguments of the perihelia and the ascending nodes over time spans that are long compared to the orbital period. As a result, the particles essentially form a rotationally symmetric cloud. It should be noted that such a smooth spatial distribution of the dust forms only at a sufficient distance from local sources.

Assuming the dust particles are in bound circular orbits (eccentricity $e = 0$) around the sun, the density dependence is $n(r) = n_0(r/r_0)^{-\nu}$, where n_0 is the number density at $r_0 = 1$ AU and the exponent $\nu = 1.0$.

Orbits with eccentricity $e > 0$ lead to $\nu > 1$, namely a steeper increase of dust number density toward the sun. Assuming the deceleration of dust particles that have 'typical' asteroidal or cometary orbits at 1 AU, the resulting orbits at 10 $R_\odot$ have eccentricities of about 0.01 for particles whose sources are asteroids, and about 0.1 for particles whose sources are short-period comets (see Mann et al., 2000). (Note that dust from comets shows a steeper density increase at larger distances but reaches this flat slope inward from 10 $R_\odot$.) We conclude that a dust spatial distribution proportional to $r^{-1.0}$ is a reasonably good assumption and we describe the overall structure of the dust cloud starting from dust near Earth's orbit as given in the next paragraph. The approximation is valid for dust particles in low eccentricity orbits with inclinations $< 30°$ assuming they stem from asteroids and short period comets and are in majority produced outward of 1 AU. The cumulative flux of dust with masses $> m$ at $r_0 = 1$ AU derived from several in-situ and meteor measurements is given as (Grün et al., 1985):

$$F(m, r_0) = (c_4 m^{g_4} + c_5)^{g_5} + c_6 (m + c_7 m^{g_6} + c_8 m^{g_7})^{g_8} + c_9 (m + c_{10} m^{g_9})^{g_{10}}, \tag{1}$$

with $c_4 = 2.2 \times 10^3$, $c_5 = 15$, $c_6 = 1.3 \times 10^{-9}$, $c_7 = 10^{11}$, $c_8 = 10^{27}$, $c_9 = 1.3 \times 10^{-16}$, $c_{10} = 10$, $g_4 = 0.306$, $g_5 = -4.38$, $g_6 = 2$, $g_7 = 4$, $g_8 = -0.36$, $g_9 = 2$, and $g_{10} = -0.8$, where $F(m, r_0)$ is given in units of $\mathrm{m}^{-2}\ \mathrm{s}^{-1}$ and the mass, m is given in g. The relation between cumulative flux and cumulative spatial density $N(m, r)$ for the case of an isotropic flux is:

$$F(m, r) =< v(r) > 1/4 N(m, r), \tag{2}$$

where $< v(r) >$ is the average impact velocity and 1/4 is a geometry factor. The average impact or relative velocity is:

$$< v(r) >= v_0 (r/r_0)^{-0.5}, \tag{3}$$

where $v_0 = 20$ km/s is the average impact speed at $r_0 = 1$ AU. For extrapolation to distances inside of 1 AU, the flux variation in the case of nearly circular orbits is:

$$F(m, r) = F(m, r_0)(r/r_0)^{-1.5}. \tag{4}$$

The cumulative flux increases proportional to $r^{-1.5}$ inward to the sun for particles in nearly circular orbits under Poynting-Robertson drag. While the observations near 1 AU provide clear evidence for the contribution of asteroids and short period comets to the dust cloud, the contribution from long period comets is not well established. This makes it difficult to estimate the cloud at high latitudes.

4. Dust at High Latitudes

It is well established that outward from about 0.5 AU the dust cloud is concentrated primarily in the ecliptic. Dust particles from long-period comets will form a spherical distribution with orbital inclinations distributed isotropically. This spherical component, which is present near the ecliptic as well as at high latitude, has half of its dust in retrograde orbits. The observed distribution of sporadic meteors near Earth (cf. Ceplecha, 1977) includes a small but noticeable component at high latitude and in retrograde orbits that can be described with isotropically distributed orbital inclinations. Also some models interpreting the visible zodiacal light assume an isotropic background component of dust, i.e. a spherical distribution of dust with orbital inclinations distributed isotropically. Kneissel and Mann (1991a) have shown that models of the orbital distribution of dust derived from brightness data agree with a component of dust at high latitudes up to 10% of the number density of dust near 1 AU. The extrapolation of this component to smaller distances from the sun depends on its orbital eccentricities: If the particles are in orbits with high eccentricity then this component increases more steeply toward the sun than the ecliptic main component does. Zodiacal light data (describing dust outward from 0.3 AU) could still be explained, if the number density in this component increases as $n \sim r^{-1.5}$ (Kneissel and Mann, 1991a) and the increase could be clearly seen only inward of 0.3 AU. As mentioned before, F-corona observations do not reveal clear information on the dust distribution near the sun. None of the 3D models of the zodiacal dust cloud reproduce, for instance, the isophotes of the F-corona brightness derived from the SOHO/LASCO observations using the scattering function derived by Lamy and Perrin, 1986). It is reasonable to assume that the shape of the isophotes is dominated by forward scattering from dust near the observer, so that we cannot derive the spatial dust distribution from them. Ulysses performed the only in-situ measurements of dust at high latitudes. The results are not relevant in the present context because Ulysses detected mostly interstellar dust. If measured impact events are combined with measurements of the impact velocity, in-situ measurements even within the ecliptic can provide information as to whether the dust is in prograde or retrograde motion (Kneissel and Mann, 1991b). The new dust detectors and improved radar techniques may provide some information in the future. Already today, the distribution of sporadic meteors mentioned above shows the existence of dust in retrograde orbits. Recently, Baggaley (2002) reported the true flux percentage of retrograde meteor orbits to be about 5%. Beside these 'normal' retrograde orbits, there is evidence for meteor orbit that have high eccentricities and an aphelion at Earth, indicating their perihelia are close to the sun, e.g. 10 $R_\odot$. We conclude that zodiacal light models and meteor data agree with up to 10% of the particles at 1 AU belonging to an isotropic component, half of which are in retrograde orbits. The inward extrapolation of this component is uncertain: If the particles are in highly eccentric orbits, then the radial dependencies for the number density and flux are steeper than those given for the ecliptic component. An additional component outward from the ecliptic is produced by the deflection of dust in initially low inclination orbits to high latitudes. This will be discussed in context of the dust dynamics in the vicinity of the sun.

5. Mechanisms of Dust Destruction

5.1. Dust Destruction at Distances Between 0.1 and 1 AU from the Sun

In-situ measurements at 1 AU and beyond indicate collisional destruction of dust in the inner solar system: The dust experiment aboard Ulysses detected β-meteoroids, dust particles of sizes below 1 μm moving away from the sun in hyperbolic orbits that are presumably collision fragments of larger particles (Wehry and Mann, 1999). The analysis of radar head echoes produced by particles of sizes greater than 100 μm, on the other hand, shows an overabundance of ingoing particles compared to outgoing particles for orbits with small perihelia (Janches et al., 2001), which possibly indicates the collisional destruction of these particles in the inner solar system.

Also model calculations indicate that mutual collisions of dust inward from 1 AU could shift the size distribution towards smaller particles (Ishimoto and Mann, 1998; Ishimoto, 2000). Figure 7 shows different models of the number density of dust at 0.1 AU (Ishimoto, 2000). Collisional evolution causes a narrowing of the mass spectrum, i.e., the number of particles with masses $m > 10^{-6}$ g is strongly reduced. Small fragments may be removed by radiation pressure, which causes a reduction of particles in the 10^{-14} to 10^{-12} g interval shown in Figure 7. The location and the width of this gap depend on assumptions on the ratio of radiation pressure force to gravitational force. Figure 8 shows the cumulative flux of dust particles predicted with the same model calculations at 0.5 AU in comparison to results of in-situ measurements with the "ecliptic" sensor onboard Helios (Grün, 1981). Unfortunately, due to the limits of the Helios measurements and the similarity of the models, we cannot rule out any of them at this

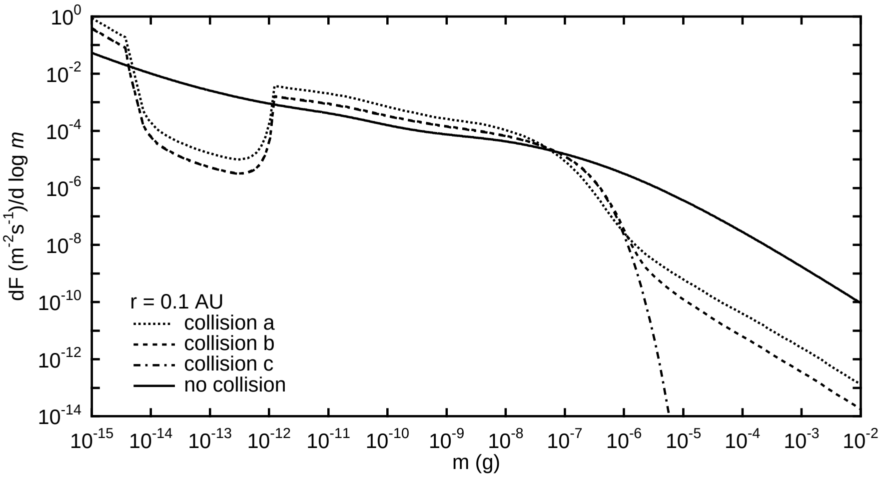

Figure 7. The differential flux of dust at 0.1 AU near the ecliptic: The solid line denotes the distribution derived by equations (1) and (4), compared to collision calculations that assume (a) an increasing mass supply from 1 to 0.5 AU and then a constant supply, (b) constant mass supply from 1 AU inward, and (c) a constant mass supply from 1 to 0.5 AU and no additional mass supply further inward (Ishimoto, 2000).

point. Brightness observations are not suitable for a verification of the models: Although the distribution of geometric cross sections for the discussed size distributions changes as shown in Figure 9, we expect the average optical properties to be more influenced by parameters such as structure and material composition than by this variation of the size distribution. It should be noted, however, that the small polarization that was derived for dust near the sun (Mann, 1992) could be explained with a high contribution of μm and sub-μm sized particles to the integrated brightness as opposed to the zodiacal light brightness that stems mainly from particles of several μm and larger. It should be noted that the relations that are used to describe the size distribution of collision fragments largely rely on scaling laboratory measurements to smaller particles and larger impact speeds. The parameters of high-velocity collisional fragmentation have never been measured directly and cannot be simulated in laboratory experiments.

If we extrapolate the dust mass distribution to about 0.1 AU ($\sim 20\ R_{\odot}$) according to Equations (1) through (4) then the real fluxes and number densities of dust with masses $10^{-12} < m < 10^{-7}$ g can be a factor of 2 to 5 higher than the those derived from this extrapolation, because these particular particles are more frequently produced by the collision of larger particles. The real fluxes and densities for $m < 10^{-12}$ g can be lower than the extrapolated fluxes and densities

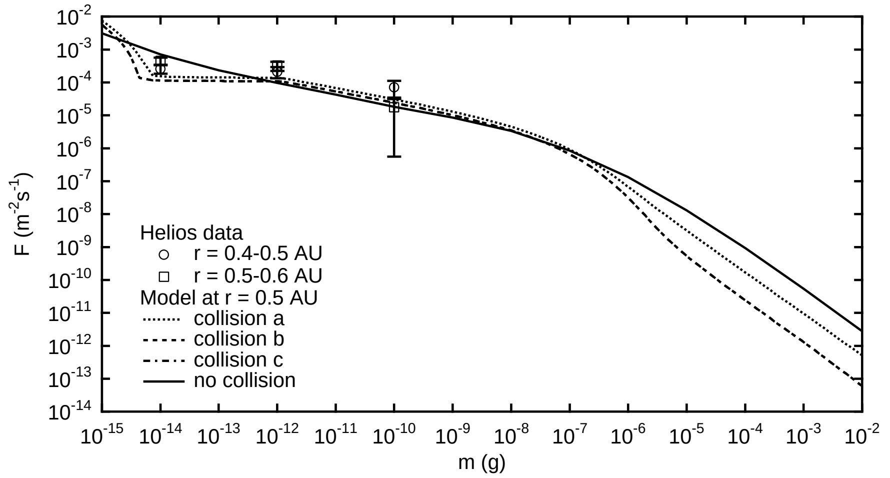

Figure 8. The calculated cumulative dust flux at 0.5 AU for the same models as in Figure 7 shown in comparison to Helios measurements with the 'ecliptic sensor' as discussed in the text.

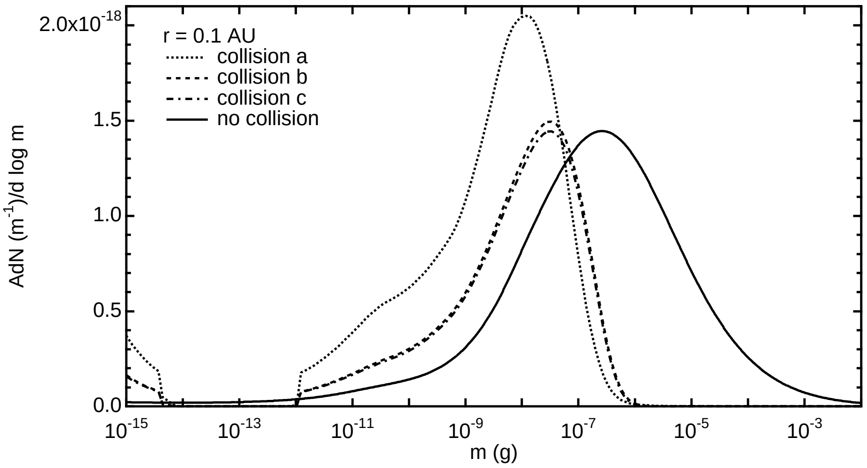

Figure 9. The area of the geometric cross section for the mass distributions of dust at 0.1 AU shown in Figure 4 (derived by assuming spherical compact dust grains with bulk density 2.5 g/cm^3).

because they are probably blown off by radiation pressure. Those for $m > 10^{-7}$ g can be significantly lower, since the particles are more frequently destroyed by collisions. The size distribution of dust discussed here is valid for latitudes $\leq 30°$. Due to a lack of information, the same size distribution may also be assumed for high latitudes.

5.2. Dust Destruction at Distances Within 0.1 AU Around the Sun

Russell (1929) was the first to estimate the drift of particles toward the sun as a result of the Poynting-Robertson effect and to predict the presence of a dust free zone caused by sublimation of the dust particles near the sun. Then Over (1958) estimated the sublimation of SiO_2 particles to predict a dust-free zone at 4 $R_\odot$. Aside from sublimation, erosion through sputtering by solar wind particles (Mukai and Schwehm, 1981), and rotational bursting of grains (Misconi, 1993) are expected to destroy dust particles inward of 20 $R_\odot$ (approximately 0.1 AU) around the sun. Peterson (1963) calculated that the near infrared brightness has a peak feature at the edge of the dust free-zone and tried to observe this. Mie calculations for spherical dust particles (Lamy, 1974b) have shown that particles with the absorption and scattering properties of FeO-poor obsidian, depending on their size, can exist very close to the sun (up to 2 $R_\odot$). Carbonaceous grains such as graphite and glassy carbon sublimate near 4 $R_\odot$. Model calculations for porous dust particles (Mann et al., 1994) have shown that depending on the amount of absorbing material versus silicate material (based on the optical properties of FeO-poor obsidian for the silicate) they can reach as close as 2–3 $R_\odot$ from the sun. Pyroxene and olivine are the dominant forms of silicate minerals in interplanetary dust particles collected in the stratosphere of the earth (Jessberger et al., 2001). Therefore numerical estimates of the dust sublimation in sungrazing comets were based on these materials. They show that pyroxene grains sublimate at 4–6 $R_\odot$ and olivine grains at 10–13 $R_\odot$ (Kimura et al., 2002). The dust particles are also heated by solar wind sputtering. This process was shown to increase compared to heating by solar radiation with decreasing size of grains, but even for small grains it is small compared to the influence of solar radiation (Mukai and Schwehm, 1981). Near infrared observations of the 1991 eclipse from Hawaii (Hodapp et al., 1992; MacQueen and and Greeley, 1995) can be explained if the slope of the dust number density is continued inward to about 10 $R_\odot$ and is constant further inward (Mann and MacQueen, 1993). It is possible and even likely that the disappearance of dust happens gradually with heliocentric distance, depending on the size and material composition of the dust particles (see Table I) and that the dust-free zone is possibly not observed since it is in a region of the corona where the K-corona signal exceeds the F-corona signal.

Misconi (1993) has discussed the rotational bursting of dust particles as another process for dust destruction. There are several different mechanisms that cause dust rotation. Irregular transfer of solar wind

Table I. The zone of sublimation calculated for different materials.

	sphere	fluffy	Ref.
graphite	$\leq 5\ R_\odot$	$\leq 2\ R_\odot$	2,3,6,8,9
glassy carbon	$4\ R_\odot$	3–4 $R_\odot$	10,11
magnetite	10–40 $R_\odot$	—	7
iron	11–24.3 $R_\odot$	—	4,5
water ice	1–2.8 AU	—	2,5,7
FeO-poor obsidian	1.9–7 $R_\odot$	2.5–3 $R_\odot$	4,6,7,8,9,10,11
FeO-rich obsidian	2.9–6 $R_\odot$	—	6,9
andesite	9–10.5 $R_\odot$	—	3,4,5
basalt	$6\ R_\odot$	—	9
quartz	1.5–4 $R_\odot$	—	1,2,5
astronomical silicate	$14\ R_\odot$	—	9
crystalline Mg-rich olivine	$10\ R_\odot$	9.5–11 $R_\odot$	12
amorphous Mg-rich olivine	13.5–15.5 $R_\odot$	12–15 $R_\odot$	12
crystalline Mg-rich pyroxene	$5\ R_\odot$	$5\ R_\odot$	12
amorphous Mg-rich pyroxene	5.5–6.5 $R_\odot$	5–6.5 $R_\odot$	12

References. — (1) Over (1958); (2) Mukai and Mukai (1973); (3) Mukai et al. (1974); (4) Lamy (1974a); (5) Lamy (1974b); (6) Mukai and Yamamoto (1979); (7) Mukai and Schwehm (1981); (8) Mann et al. (1994); (9) Shestakova and Tambovtseva (1995); (10) Kimura et al. (1997); (11) Krivov et al. (1998); (12) Kimura et al. (2002).

particle momentum due to surface irregularities ('windmill rotation') or irregular transfer of photon momentum due to albedo irregularities across the surface ('Radzievskii effect') increases during coronal mass ejections (CMEs). These processes are effective in the corona and highly time variable. Dust destruction by this process is expected to take place at distances $3 < r/R_\odot < 8$ and to vary with the solar activity. In conclusion, we expect that inward from 10 $R_\odot$, dust destruction varies with size and material composition and may even vary with time, while we expect the size distribution to be only gradually varying between 0.1 and 1 AU. It is not clear whether the production or the destruction of dust is the predominant mechanism between 0.1 and 1 AU. The extrapolation that we presented describes the case of no additional major source or sink of dust particles or meteoroids inward of 1 AU, meaning that the dust cloud evolves from the dust and meteoroids that are measured near the Earth orbit. The dust production from comets inward 1 AU is discussed in the next section.

6. Dust Production from Comets

6.1. Dust Production from Comets between 0.1 and 1 AU

There are no direct measurements to estimate the dust sources inward from 1 AU but remote sensing observations point to the possibility of dust production from comets. While the production of cm-sized and larger fragments was shown by infrared observations of cometary dust trails, new optical observations of a cometary dust trail, Ishiguro et al. (2002) suggest it consists of very dark (geometric albedo < 0.01) fragments of sizes of a few cm. Due to their low albedo and low number density these fragments are not easily detected at visible wavelengths, but brightness observations in the inner solar system were mainly made at visible wavelengths. At this point, it is not clear how large the contribution of these cometary fragments to the inner solar system dust cloud could be. The dust fluxes that were measured from Helios show that the dust production cannot be significantly larger than the collisional losses between 0.3 and 1 AU. Also brightness data indicate that the production most likely does not strongly exceed the dust destruction due to collisional fragmentation. But measuring precise size distributions at various distances from the sun would allow better estimates of the loss and supply of dust than those derived from present data. We conclude that, although the dust production from comets between 0.1 and 1 AU is unknown, the resulting total dust fluxes between 0.1 and 1 AU do not greatly exceed the extrapolations given in Section 3.

6.2. Dust Production from Comets Inside 0.1 AU

A spectacular proof of dust production near the sun is the appearance of sungrazing comets. During early observations with space coronagraphs Michels et al. (1982) reported a major change in the coronal brightness distribution that lasted for more than a day and followed the observation of a sungrazing comet. The occurrence of a CME around the same time, does not allow for a clear interpretation of the observed enhancement in the coronal brightness, which was discussed by Sheeley et al. (1982) to stem partly from the CME and partly from the comet. The dust supply from a comet can be comparable to the dust densities in the solar environment (Mann et al., 2000), but, due to the fact that the coronal brightness stems to a large amount from dust components near the Earth rather than near the sun, this does not necessarily cause an observable variation of the coronal brightness. The sungrazing comets that are frequently observed with SOHO/LASCO neither cause a variation of the corona brightness nor do they provide a significant dust source: An analysis and a summary of the SOHO/LASCO observation

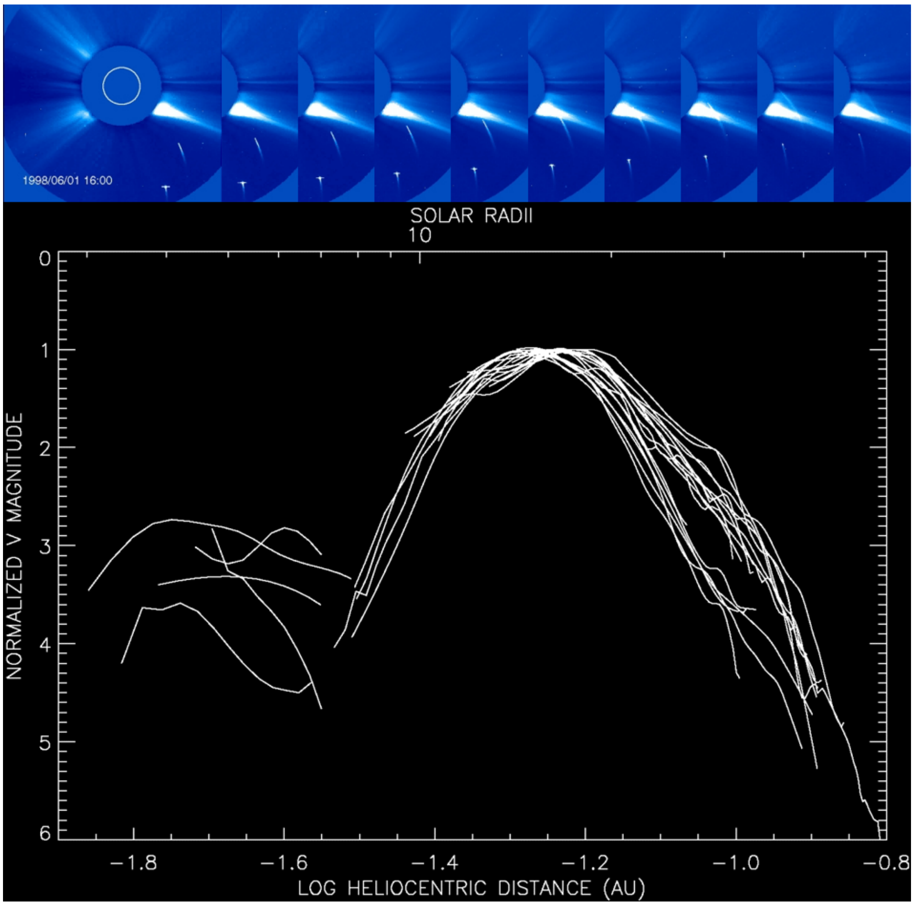

Figure 10. Observation of sungrazing comets with SOHO/LASCO: the upper panel shows a series of C2 images of the comets C/1998 K10 SOHO-54 and C1998 K11 SOHO-55. The lower panel shows the normalized light curves of YY sungrazing comets in the field of view of the SOHO/LASCO C2 and C3 instruments from Biesecker et al. (2002).

is given by Biesecker et al. (2002). They report the observation of 347 comets with SOHO/LASCO, most of them being Kreutz sungrazing comets. The brightness distributions of the Kreutz comets detected with SOHO/LASCO indicate an increasing number of comets with decreasing size and the size distribution of nuclei is probably described with a power law. The diameter of the sungrazing comet SOHO-6 is estimated to be 6.7 m (Raymond et al., 1998) and the radii of SMM[3] comets (SMM-10, SMM-7, or SMM-5) were estimated to be 16 m (MacQueen and and St. Cyr, 1991). The number of comets observed with

---

[3] SMM stands for Solar Maximum Mission, where these comets were discovered

a limit of 9th magnitude is about 60 comets/year and the extrapolated total is 180 comets/year. It seems that the number of observed fragments is currently decreasing. The observed cometary light curves, although different in the absolute magnitude, are very similar in their relative slopes (Biesecker et al., 2002) and can be divided into two groups with virtually identical light curves having their maxima about 1 $R_\odot$ apart (at 11.2 and 12.3 $R_\odot$) and having slightly different slopes. These maxima were attributed to the sublimation of dust particles consisting of crystalline or amorphous olivines, respectively (Kimura et al., 2002) that are assumed to make up a significant component of the coma brightness. For some comets that can be observed at $r < 12\ R_\odot$, sudden increases in the light curve inside 7 $R_\odot$ may indicate fragmentation of a nucleus but this can also be explained by the sublimation of pyroxene particles. The Kreutz group sungrazing comets have perihelion distances, q, $0.004 < q < 0.01$ AU, eccentricities, $e \approx 1$ and inclinations, $128 < i < 145°$ (Marsden, 1967; Biesecker et al., 2002). For an estimate of the dust supply, we assume a spherical comet of 20 m radius is fragmented into 10 μm spherical particles and distributed in a sphere of 10 $R_\odot$ radius. An estimated number density of 10^{-17} cm^{-3} is found, which is below typical densities of 10^{-14} cm^{-3} for particles of this size range. We assumed this large size of dust grains, since for size distributions that are similar to that in the interplanetary dust cloud, the majority of mass would be contained in fragments of this size. But analysis of the dust tails of sungrazing comets shows that the sungrazers emit small particles of sizes $a = 0.1\ \mu$m (Sekanina, 2001) and that the dust in the sungrazing comets has a narrow size distribution. When making this rough estimate for 0.1 μm spherical particles, the number density amounts to 10^{-12} cm^{-3}. Moreover, the dust that is produced by sungrazers will quickly leave the solar corona: The Kreutz comets are in highly elliptic or hyperbolic orbits, their speed is approximately 230 km/s at 7 $R_\odot$ and can be described as bodies with initial speeds of zero at infinity that fall into the sun. Dust grains released from the sungrazers are in similar orbits. Sungrazing comets of the Kreutz group form two sub groups based on different perihelion distances and ascending nodes (Marsden, 1967). From SOHO/LASCO observations, a further comet group with currently 33 members (Meyer group) and two groups with 14 members each (Marsden group, Kracht group) were identified in near-sun orbits (see Marsden, 2002 and IAU Circular 7832). The perihelion distances of the three groups are 0.036, 0.047, and 0.047 AU, respectively. The size of these comets is likely to be similar to the Kreutz family fragments SOHO sees, but because of the larger perihelion distances, the smallest members of the groups are probably not detected. The apparition rates of these comet groups and therefore the input to the near-solar dust cloud are clearly below those of the Kreutz group comets. We conclude that the dust supply from the frequently observed sungrazing comets is negligible. The dust supply from larger comets near the sun can produce dust density enhancements that are comparable to the dust densities in the solar environment (Mann et al., 2000). This rarely happens but can raise the dust density over time spans of weeks. While the expected total number densities within 0.1 AU around the sun may not vary considerably from the extrapolation given in Section 3, the description of size distributions and fluxes depends on the dust dynamics near the sun.

7. Dust Dynamics Near the Sun

Although the overall distribution of dust in the solar system seems stable on the time scales of our space missions, the dust dynamics becomes complex in the vicinity of the sun. Lorentz and radiation pressure forces increase since the solar magnetic fields and the solar radiation increase and since dust particle may attain a higher electric surface charge. Particles that are only moderately deflected at large distances experience a significant change in their orbital inclination, even if the increase of surface charge is not taken into account (Morfill and Grün, 1979). If the influence of the Lorentz force becomes even stronger, then particles can be deflected into randomly oriented orbits. The dust dynamics are also influenced by transient events, like the increasing solar wind drag during CMEs (Misconi and Pettera, 1995). There are no direct measurements of these processes and the number of unknown parameters prevents us from making precise estimates. In order to obtain a qualitative idea of the dust evolution in the vicinity of the sun, we here refer to model calculations that give a scenario of the dynamics of dust particles that reach the vicinity of the sun within the 'main' component of the interplanetary dust cloud in orbits with low inclination and low eccentricity. The calculations by Mann et al. (2000) describe the dynamics of charged dust particles under solar magnetic field parameters that are derived from observations, the dust surface charge was estimated based on the influence of the solar wind and the solar photon flux. The derived distributions in latitude for small dust particles near the Sun is shown in Figures 11a and 11b. Assuming an initial distribution with latitudes ±30°, dust particles of size 2–5 μm will be scattered to latitudes ±50° at 10 $R_\odot$. Particles in the size range 0.5–2 μm show the strongest variation with the solar magnetic field. They reach latitudes of $\leq \pm 70°$ for weak magnetic fields and as high as ±90° for strong magnetic fields. Smaller silicate particles are almost

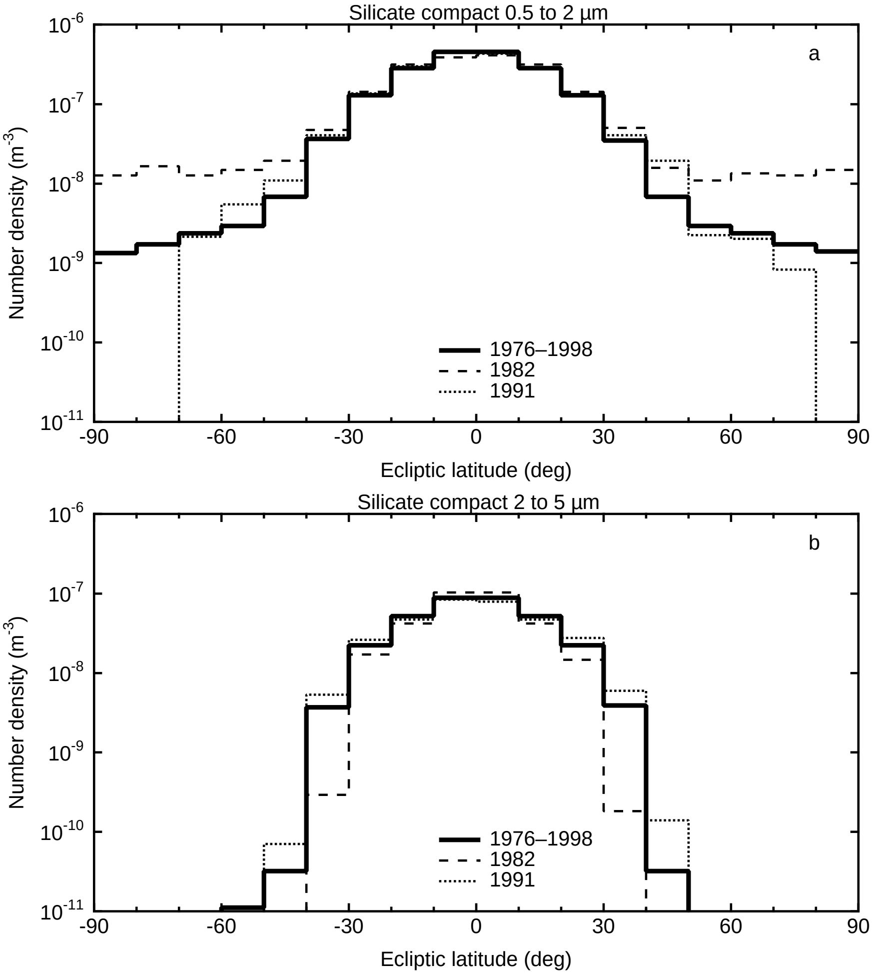

Figure 11. The variation of dust number density with latitude due to Lorentz force perturbations for compact silicate particles with an initial distribution ±30°. The solid line denotes an average profile for the entire solar cycle, the dashed line shows the profile for a strong magnetic field (1982) and the dotted line the profile for a weak magnetic field (1991). The upper figure shows particles with sizes 0.5–2 μm. The lower figure shows number densities for particles with sizes 2–5 μm.

randomly distributed at all phases of the solar cycle. Small carbon dust particles are ejected before their orbits can be randomized. We conclude that dust particles beyond 10 μm in size are only weakly influenced by the solar cycle magnetic field variations and that this can be neglected.

In addition to the Lorentz force, radiation pressure becomes more important close to the sun. The β-ratio, the ratio of radiation pressure force to solar gravitational force, increases when the sizes of particles are diminished either by sublimation or by collisional destruction. Radiation pressure can also lead to the formation of β-meteoroids that are ejected from the corona into hyperbolic orbits and leave the near-sun environment. The interplay of sublimation and increasing β-ratio for the diminished size of dust particles (see Figure 12) can lead to the formation of dust rings (see Mukai et al., 1974). Recent estimates for the dust number density in the dust rings indicate enhancement ≤ 2 over a distance of less than 1 $R_\odot$ for silicate particles (porous, fluffy) with initial eccentricities $e < 0.1$ when averaged over 0.2 $R_\odot$ distance range. For carbon particles, the predicted maximum enhancement in number density is a factor of 4. The strongest enhancement is seen for 10 μm fluffy carbon particles, but only if the initial orbits are almost circular (Mann et al., 2000). Carbon and silicate are used as examples for absorbing and less absorbing material.

8. Results

Our knowledge of the near-solar dust environment, at present, is limited to theoretical modeling and remote sensing. The complexity of interactions that are expected for the near-solar dust will constrain our estimates for particles with sizes smaller than a few μm, but still, we can summarize our knowledge for the near-solar dust parameters in a way that helps spacecraft designers.

a) The mass distribution of dust at 1 AU can be extrapolated toward the sun to about 0.1 AU ($\sim 20\ R_\odot$) with a dependence of $\sim r^{-1}$ (Figure 1 and Equation 1). Assuming a density of 2.5 g/cm^3 independent of the size of dust particles over the entire mass interval leads to a reasonable estimate of the size distribution. Due to collisional fragmentation and the influence of radiation pressure, number densities of dust with masses $m < 10^{-7}$ g may differ by one order of magnitude from this extrapolation and number densities for $m > 10^{-7}$ g can be significantly lower. The size distribution discussed here is valid for the dust at latitudes within 30° of the ecliptic plane. Due to a lack of information, we assume the same size distribution for high latitudes. Inward from 20 $R_\odot$ the size distribution changes as a result of sublimation in a presently unknown way, depending on the material properties of dust.

b) The dust number density at latitudes within 30° of the ecliptic plane is approximated with equations (1) and (2) and varies with distance from the sun as $n(r) \sim r^{-1}$. The dust density above the poles is model dependent and ranges from zero to densities that are of the same order of magnitude as the ecliptic component. The increase

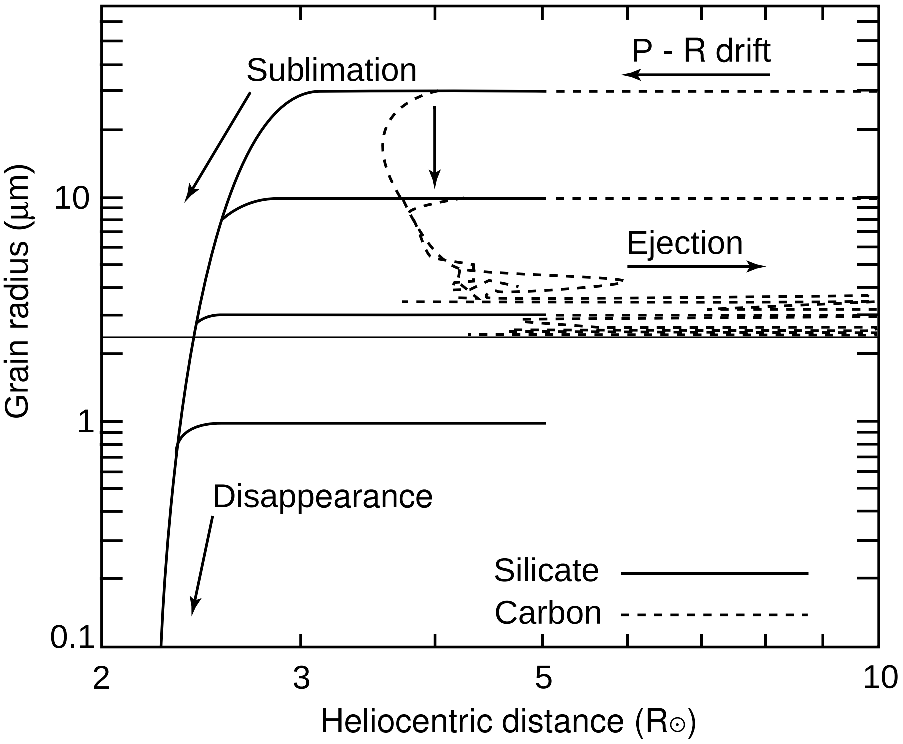

Figure 12. Dust ring formation depicted with the evolution of particle size vs. distance from the sun for carbon particles (dashed lines) and silicate particles (thick solid lines). The change in distance from the sun is caused by direct radiation pressure and Poynting-Robertson drift, respectively. While silicate particles disappear due to the sublimation, carbon particles are exposed to higher radiation pressure force compared to solar gravity once their size is reduced by sublimation. As a result they are pushed to larger distances and the sublimation rate decreases again until the Poynting-Robertson effect brings them inward to the sublimation zone again. The exact slope of this size-distance curve depends on the exact initial conditions but this interplay of radiation pressure and sublimation leads to an enhancement of dust number density at the sublimation zone. The thin horizontal line shows the size limit of carbon particles that are rejected by radiation pressure and cannot reach the vicinity of the sun.

of dust number density in a possible dust ring near the sun in the ecliptic plane extends over a region of width $\sim 1\ R_\odot$ in the radial direction. The enhancement amounts to a factor of 4 or less over a distance range of $0.2\ R_\odot$. This is only expected for particles of sizes $a < 10\ \mu$m.

c) The majority of dust near the sun is in Keplerian, near-circular, near-ecliptic orbits. Particles that drift toward the sun due to deceleration resulting from the Poynting-Robertson effect are in orbits

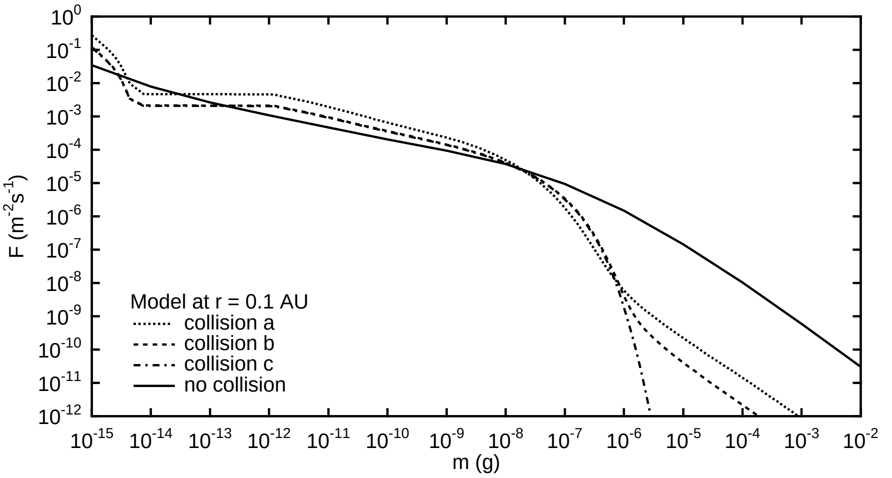

Figure 13. The mass distribution of dust shown as the cumulative flux at 0.1 AU (from Ishimoto, 2000) compared to the flux that is extrapolated from the distribution at 1 AU given on Equation (1) in Section 3. Equation (2) describes the conversion from fluxes to number densities.

Table II. Dust fluxes inward of 10 $R_\odot$ averaged over the solar cycle. The fluxes near the ecliptic are several times higher than the listed mean flux at latitude $\leq 30°$. The fluxes are estimated for a spacecraft moving in a circular orbit in the ecliptic plane and given in m^{-2} s^{-1} (Mann et al., 2000) and averaged of latitudes within 30° around the ecliptic and outward from 30° around the ecliptic.

distance from the sun	ecliptic latitude	dust flux in m^{-2} s^{-1}		
		0.5–2.0 μm	2–10 μm	> 10 μm
8–10 $R_\odot$	$< 30°$	$3 \cdot 10^{-3}$	$1 \cdot 10^{-3}$	$7 \cdot 10^{-4}$
	$> 30°$	$6 \cdot 10^{-5}$	$9 \cdot 10^{-6}$	—
6–8 $R_\odot$	$< 30°$	$5 \cdot 10^{-3}$	$1 \cdot 10^{-3}$	$1 \cdot 10^{-3}$
	$> 30°$	$2 \cdot 10^{-4}$	$3 \cdot 10^{-5}$	—
4–6 $R_\odot$	$< 30°$	$8 \cdot 10^{-3}$	$2 \cdot 10^{-3}$	$2 \cdot 10^{-3}$
	$> 30°$	$3 \cdot 10^{-4}$	$8 \cdot 10^{-5}$	—
2–4 $R_\odot$	$< 30°$	$1 \cdot 10^{-2}$	$4 \cdot 10^{-3}$	$1 \cdot 10^{-3}$
	$> 30°$	$1 \cdot 10^{-3}$	$1 \cdot 10^{-4}$	—

with eccentricities $e < 0.1$ and inclinations $i < \pm 40°$, at $r \leq 0.1$ AU. Even for collisional fragments, the orbits are similar. Exceptions are β-meteoroids moving in hyperbolic orbits. Inward of 10 $R_\odot$, particles may have orbits with higher eccentricities as well as higher inclinations. Based on our discussion, we conclude that the dust fluxes at 1 AU can be extrapolated toward the sun to about 0.1 AU

($\sim 20\ R_{\odot}$). The flux rate dependence is $\sim r^{-1.5}$. The fluxes of dust with masses $10^{-12} < m < 10^{-7}$ g can be a factor of 2 to 5 higher than this extrapolation. Fluxes for $m < 10^{-12}$ g can be lower than the extrapolated values, fluxes for $m > 10^{-7}$ g can be significantly overestimated.

d) The given flux estimate is valid for latitudes within 30° of the ecliptic. We expect that the orbits of dust particles with sizes $a < 10\ \mu$m varies with the solar magnetic field. An estimate for the average dust fluxes in the solar corona close to the ecliptic and outward from the ecliptic is given in Table II. However, no dust that reaches the vicinity of the sun already in high inclination orbits is included in this estimate. The given dust fluxes above the solar poles solely stem from particles that were deflected out of their near-ecliptic orbits.

e) We expect a direct production of dust from comets to take place inward from 1 AU, but existing data are not precise enough to quantify these sources. The dust production from the frequently observed Kreutz group comets is negligible. The dust production from larger comets near the sun that are rarely observed, however, can temporarily be comparable to the dust densities in the solar environment.

f) Coronal observations in the visible wavelength range during eclipse or remote observations in the visible or infrared from spacecraft do not greatly improve the knowledge about dust near the sun. Aside from observational problems and problems of the inversion of the LOS brightness, the brightness data are biased to the larger end of the dust size distribution. Only in-situ measurements reveal the distribution of the small grains that show the interaction with the solar plasma and magnetic field in the corona and that make the dust cloud in the solar environment so unique.

9. Interactions with the Interplanetary Medium

The majority of refractory solids that are thought to be present in cosmic dust sublimate within several 1/10 AU around the Sun with some particles reaching as close as a few solar radii to the sun (see Figure 14). Through sublimation molecules and ions are released into the ambient interplanetary medium and in majority photo-ionized by solar UV radiation. Aside from the direct production of ions in the interplanetary

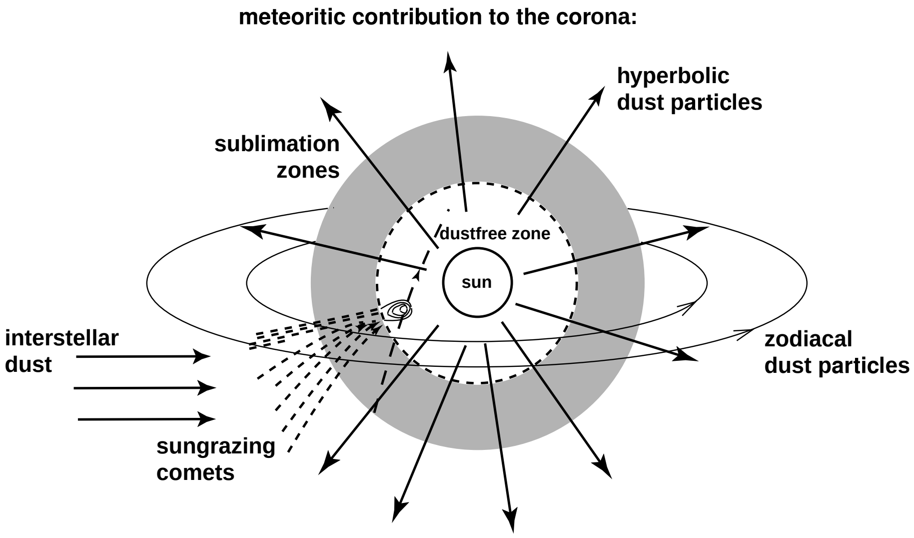

Figure 14. Meteoritic contributions to be expected in the solar corona are zodiacal dust particles in Keplerian, in majority prograde orbits around the sun, particles in hyperbolic orbits that are ejected by radiation pressure and/or Lorentz force, and small amounts of interstellar dust and dust from sungrazing comets

medium, dust particles are thought to provide a catalytic surface for solar wind processes. It is known from lunar samples that their outer layers are saturated with solar wind particles and this is also expected for the dust (Banks 1971). Moreover the recombination of solar wind particles on the surface of grains is expected to generate neutral atoms in the interplanetary medium (Fahr et al., 1981; Gruntman, 1996) and even the infall of heavy meteoritic ions into the solar corona is discussed to influence the solar wind composition (Lemaire, 1990). Fahr et al. (1981) suggest that the presence of dust particles in the solar wind plasma leads to the adsorption of solar wind particles on the surface and within the surface layer and to subsequent desorption of neutrals. They predict that inside 0.5 AU density of neutral hydrogen produced by this process exceeds that of the interstellar hydrogen density. For the case of helium the dust-generated component exceeds the interstellar component inward of about 0.05 AU. Gruntman (1996) estimated the different branches of the hydrogen evolution in the interplanetary medium. All these scenarios have this in common, that at the present time they are not directly proven by experiments.

The presently most widely discussed case of dust interactions in the interplanetary medium is that of the pick-up ions. Pick-up ions are produced through ionisation of neutrals in the interplanetary medium. After being released they are carried away with the solar wind. Gyration about the magnetic field lines transported with the solar wind plasma generates a velocity distribution of the pick-up ions that ranges from zero to twice the solar wind speed. This velocity distribution allows one to distinguish pick-up ions from the solar wind. Moreover, for heavier elements pick-up ions can be distinguished by their usually single charge state as opposed to the high charge states that are typical for the solar wind ions that stem from the corona. The major source of pick-ions are interstellar neutral atoms entering the solar system. Interstellar He^+ pick-up ions were first observed in 1985 (Möbius et al., 1985). Together with other observations they are now used to estimate the neutral gas content of the local interstellar medium that the solar system is embedded in (Gloeckler and Geiss, 1998, 2001). Measurements of the SWICS experiment aboard Ulysses discovered a second component of 'inner source' pick-up ions that are not associated with interstellar neutrals (Geiss et al., 1996), at present identified for the elements H, He, C, N, O, Mg, Si, and Ne. The production of inner source pick-up ions is assumed to be correlated to the presence of dust and possibly to stem from the adsorption and subsequent desorption of solar wind ions (Gloeckler and Geiss, 1998, 2001, Schwadron and Geiss, 2000). The connection between dust and solar wind pick-up ions may also be reflected in the composition of anomalous cosmic rays (cf. Cummings et al., 2002). Dust fluxes and mass distributions measured together with solar wind pick-up ions will allow to study the connection between dust and pick-up ions. More detailed studies are needed to trace the evolution from the inner source, through the formation and evolution of pick-up ions to the acceleration of anomalous cosmic rays.

A further point to be mentioned in the context of interactions is that of the influence that dust impacts have on spacecraft environments. The impact of dust particles on a solid target in space with the impact velocities that are expected in the inner solar system causes the complete destruction, sublimation, and ionisation of the dust particlse and also of some target material. The resulting impact ionisation clouds have been observed before: The Planetary Radio Astronomy instruments aboard the Voyager 1 and 2 spacecraft recorded a characteristic intense noise during crossing of the Saturn and Uranus rings. Also dust impacts on the Giotto spacecraft were observed to influence the time variation of the measured magnetic field; and simultaneous events were seen in the plasma analyser and an ion mass spectrometer. Other signals in plasma and magnetic field measurements that are possibly connected to dust impact were reported for Voyager 1 and 2 in the outer solar system, for ICE (International Cometary Explorer) during the encounter at comet Giacobini-Zinner and recently during the DS1 encounter at Comet Borrelly. The complexity of the impact ionization process and

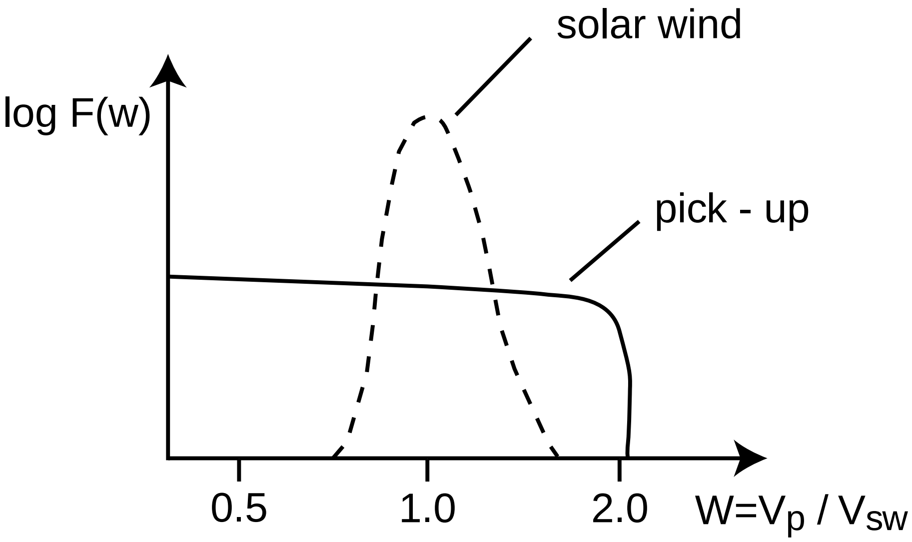

Figure 15. The velocity distribution of pick-up ions relative to the solar wind.

the non-linearity of the magnetic field response prevent us from deriving exact impact parameters from the experimental results. Dust fluxes are especially high in the inner solar system and fluxes of small particles are expected to be time-variable. Therefore, monitoring the dust fluxes is an important tool for determining the influence of dust impacts on plasma and field measurements aboard near-solar missions.

10. Summary

The major sources of the dust population in the inner solar system are long- and short-period comets, asteroids and interstellar dust. The production processes of dust inside Earth orbit are: Poynting-Robertson deceleration of particles outside of 1 AU, fragmentation of dust due to particle-particle collisions, and dust production from comets. Dust measurements aboard Helios between 0.3 and 1 AU already point to the existence of different components in the dust cloud, but the relative contribution of these different sources is unknown. The direct production of dust from cometary fragments inside Earth orbit is confirmed by the observation of sungrazing comets and their dust production, but the amount of the dust production from comets could so far not be derived from experimental data. The loss processes are: dust collisional fragmentation, sublimation, radiation pressure acceleration, and rotational bursting. These loss processes as well as dust surface processes release dust compounds into the ambient interplanetary medium. We hence expect the dust cloud in the inner solar system to be connected to the production of inner source pick-up ions, but the exact production mechanisms are not adequately quantified at present. Lorentz forces associated with particles of sizes $a < 5\ \mu$m can lift these particles to high latitudes, providing a sink for near-ecliptic dust and a source for dust at high latitudes. Between 1 and 0.1 AU the present best estimates come from inward extrapolation of 1 AU measurements, assuming radial dependences on the distance r from the sun as $r^{-1.0}$ and $r^{-1.5}$ for the number density and flux, respectively. Observations have confirmed the general accuracy of these assumptions. These estimates are accurate for regions within 30° latitude of the ecliptic plane. The dust fluences are considerably lower at higher (absolute) latitudes, but the accuracy of the given fluxes is less certain there. Calculations show that dust collisions change the size distribution inward of 1 AU and that sublimation reduces the size of particles inward from 0.1 AU. If the size of particles becomes sub-μm, they might be blown out of the near-sun environment by radiation pressure. Long-period comets produce dust particles at high inclination orbits in the out-of-ecliptic region. Meteor data indicate that the out-of-the-ecliptic plane particles crossing the lower latitude regions can produce as much as 10% of the in-plane fluxes near 1 AU. It is estimated that half of these particles are in a retrograde orbit. The inward extrapolation of this out-of-ecliptic component is uncertain and its increase with decreasing distance from the sun is possibly steeper than for the ecliptic component. We show that under present conditions no prominent dust ring exists near the sun. The dust production from comets between 0.1 and 1 AU from the sun cannot be accurately estimated at this time but it is concluded that the contribution from sungrazing comets is negligible in the context of the overall dust environment in the inner solar system.

Although the solar environment can be directly seen from Earth, observational results do not provide a full picture of neither the dust properties near the sun nor its interactions with the surrounding interplanetary medium. The outcome of the SOHO mission shows that even excellent remote observations cannot provide insights into the physical processes associated with dust particles in a plasma and magnetic field environment: As a result of the line-of-sight geometry the remote corona observations are strongly influenced by brightness components that stem from regions distant from the sun and from the Earth environment. Moreover, the brightness that stems from the near-solar region is biased to those large dust grains that provide the majority of the geometric and cross-sectional area. Hence, even brightness observations from spacecraft positioned in the inner solar system will not reveal the complex dynamics of small dust particles, nor would they allow one to derive the size distribution of dust. Several of the physical processes that were discussed through this manuscript are presently not directly measured, but rather derived from theory: The parameters of collisional fragmentation are derived from empirical scaling laws. The heating of dust particles is theoretically determined by calculating the balance of absorbed and emitted radiation and sublimation parameters are extrapolated from measurements under atmospheric conditions. The model of the recombination of solar wind ions on the surface of dust grains is solely based on theoretical considerations, as are the estimates of the electric surface charge that the grains attain in the interplanetary medium. The impact ionization process was measured of some materials for the impact parameters that can be realized with dust accelerator experiments. All these processes occur in the context of several other astrophysical phenomena. The inner solar system provides the unique opportunity to study these processes in-situ as can be illustrated for the case of the electric surface charge: Small dust particles are deflected in the interplanetary magnetic field. The degree of this deflection depends on the surface charge and on the exact magnetic field parameters. near-solar missions will allow to measure all relevant parameters: the solar radiation and solar wind parameters that cause the surface charge, the magnetic field that causes the deflection and the orbits of the deflected dust particles.

For this reason it is recommended that in-situ measurements be taken. Main goals for these measurements are to study the collision evolution of the inner dust cloud and the dynamics of small grains, to search for fresh cometary dust in the inner solar system and to observe interactions with the solar wind. To study physical interactions with the interplanetary medium in-situ studies would benefit from the combination with plasma and field measurements. Dust in-situ measurements have been extremely successful in the past not only aboard Helios but also with for instance Ulysses in the outer solar system. Missions to the solar vicinity are suggested and shown to be feasible with, for instance, Solar Probe (Tsurutani and Randolph, 1991; Möbius et al., 2000) and Solar Orbiter (Marsch et al., 2002). The basic questions to be addressed with dust measurements are:

- what are the mass distributions and the fluxes of dust particles as function of the distance from the sun and at varies helio-ecliptic latitudes;
- what is the amount of dust in bound orbits about the sun in comparison to the amount of dust in hyperbolic orbits, and how does this relation change with the mass of the grains and with distance from the sun;

- what is the size limit between particles in Keplerian orbits and particles that are predominantly influenced by the magnetic field;

- what is the correlation of dust fluxes with fluxes and velocity distributions of pick-up ions, what is the correlation with plasma wave measurements and is there any correlation to other measurements;

- what are the major elemental compositions and the bulk density of the dust particles and how do they vary with distances from the sun and are these parameters correlated with the size of particles.

Measurements of the dust elemental composition are desirable but extremely difficult (see Mann and Jessberger, 2003). Relatively simple dust experiments to measure mass and flux rates are state of the art, yet can provide valuable information. Their scientific return can improve through combination with laboratory studies and already help to constrain models of their chemical composition and structure. The combined analysis with particle and field measurements will enhance the scientific return of dust measurements and will allow a further step towards the understanding of the astrophysics of dust.

Acknowledgements

We thank Jack Baggaley, Hiroshi Ishimoto, Elmar Jessberger, Melanie Köhler and Tony Tuzzolino for helpful discussions and for providing us with information about their related work and Frank Bartschat for preparing the figures. A significant part of the science that contributed to this paper was supported by the Bunderministerium für Bildung, Wissenschaft, Forschung und Technologie (BMBF) under contracts 50 ON 9101 and RD-RX-50 OO 0101-ZA. While writing this paper I.M. was funded by the European Space Agency under ESTEC/Contract 14647/00/NL/NB .

References

Baggaley, J.: 2002, personal communication

Banaszkiewicz, M., Fahr, H.J., and Scherer, K.: 1994, ‘Evolution of Dust Particle Orbits Under the Influence of Solar Wind Outflow Asymmetries and the Formation of the Zodiacal Dust Cloud’, *Icarus* **107**, 358–374

Biesecker, D.A., Lamy, P., St. Cyr, O.C., Llebaria, A. and Howard, R.A.: 2002, ‘Sungrazing Comets Discovered with the SOHO/LASCO Coronagraphs 1996–1998’, *Icarus* **157**, 323–348

Ceplecha, Z.: 1977, 'Meteoroid Populations and Orbits', In ???, editors, *Comets, Asteroids, Meteorites: Interrelations, Evolution and Origins*, pages 143 – ???. University of Toledo, Proceedings of the Thirty-ninth International Colloquium, Toledo, Ohio

Cummings, A. C., Stone, E. C., and Steenberg, C. D.: 2002, 'Composition of Anomalous Cosmic Rays and Other Heliospheric Ions', *Astrophys. J.* **578**, 194–210.

Fahr, H. J., Ripken, H. W., Lay, G.: 1981, 'Plasma-Dust Interactions in the Solar Vicinity and their Observational Consequences', *Astron. Astrophys.* **102**, 359–370.

Fechtig, H.: 1982, 'Cometary Dust in the Solar System', In H. Wilkening, editor, *Comets*, pages 383 – ???. University of Arizona Press, Tuscon

Geiss, J., Gloeckler, G., and von Steiger, R.: 1996, 'Origin of C+ Ions in the Heliosphere', *Space Sci. Rev.* **78**, 43–52.

Gloeckler, G. and Geiss, J.: 1998, 'Interstellar and Inner Source Pickup Ions Observed with SWICS on ULYSSES', *Space Sci. Rev.* **86**, 127–159

Gloeckler, G. and Geiss, J.: 2001, 'Heliospheric and Interstellar Phenomena Deduced From Pickup ion Observations', *Space Sci. Rev.* **97**, 169–181.

Grün, E.: 1981, 'Physikalische und chemische Eigenschaften des Staubes - Messungen des Mikrometeoroitenexperimentes auf Helios', Max-Planck-Institut für Kernphysik, Heidelberg, BMFT-FB-W 81-034, Forschungsbericht, Bundersminister für Forschung und Technologie.

Grün, E., Pailer, N., Fechtig, H. and Kissel, J.: 1980, 'Orbital and Physical Characteristics of Micrometeoroids in the Inner Solar System as Observed by HELIOS 1'. *Planet. Space Sci.* **28**, 333–349

Grün, E., Zook, H.A., Fechtig, H. and Giese, R.H.: 1985, 'Collisional Balance of the Meteoritic Complex', *Icarus* **62**, 244–272

Grün, E., Gustafson, B., Mann, I., Baguhl, M., Morfill, G.E., Staubach, P., Taylor, A., and Zook, H.A.: 1994, 'Interstellar Dust in the Heliosphere', *Astron. Astrophys.* **286**, 915–924.

Gruntman, M.: 1996, 'H2 + Pick-up Ions in the Solar Wind: Out-gassing of Dust', *J. Geophys. Res.* **101**, 15555–15568

Hodapp, K.W., MacQueen, R.M., and Hall, D.N.B.: 1992, 'A Search During the 1991 Solar Eclipse for the Infrared Signature of Circumsolar Dust', *Nature* **355**, 707–710

Ishiguro, M., Watanabe, J., Tanigawa, T., Kinoshita, D., Suzuki, J., Nakamura, R., Ueno, M. and Mukai, T.: 2002, 'First Detection of an Optical Dust Trail Along the Orbit of 22P/Kopff'. *Astrophys. J.* **572**, L117–L120

Ishimoto, H.: 2000, 'Modeling the Number Density Distribution of Interplanetary Dust on the Ecliptic Plane Within 5AU of the Sun', *Astron. Astrophys.* **362**, 1158–1173

Ishimoto, H. and Mann, I.: 1998, 'Modeling the Particle Mass Distribution Within 1 AU of the Sun', *Planet. Space Sci.* **47**, 225–232

Janches, D., Meisel, D.D. and Mathews, J.D.: 2001, 'Orbital Properties of the Arecibo Micrometeoroids at Earth Interception', *Icarus* **150**, 206–218

Jessberger , E.K., Stephan, T., Rost, D. Arndt, P., Maetz, M., Stadermann, F., Brownlee, D.E, Bradley, J.P. and Kurat, G.: 2001, 'Properties of Interplanetary Dust: Information from Collected Samples', In E. Grün, B.Å.S. Gustafson, S.F. Dermott and H. Fechtig, editors, *Interplanetary Dust*, pages 253–294. Springer-Verlag, Astron. Astrophys. Library, Heidelberg

Kimura, H. and Mann, I.: 1998, ‘Brightness of the Solar F-corona’, *Earth, Planets Space* **50**, 493—499

Kimura, H., Ishimoto, H. and Mukai, T.: 1997, ‘A Study on Solar Dust Ring Formation Based on Fractal Dust Models’, *Astron. Astrophys.* **326**, 263–270

Kimura, H., Mann, I. and Mukai, T.: 1998, ‘Influence of Dust Shape and Material Composition on the Solar F-Corona’, *Planet. Space Sci.* **46**, 911—919

Kimura, H., Mann, I., Biesecker, D.A. and Jessberger, E.K.: 2002, ‘Dust Grains in the Comae and Tails of Sungrazing Comets: Modeling of Their Mineralogical and Morphological Properties’, *Icarus* **159**, 529–541

Kneissel, B. and Mann, I.: 1991a, ‘Spatial Distribution and Orbital Properties of Zodiacal Dust’, In A.C. Levasseur-Regourd and H. Hasegawa, editors, *Origin and Evolution of Interplanetary Dust*, pages 131–138, Kluwer, Dordrecht

Kneissel, B. and Mann, I.: 1991b, ‘Out-of-Ecliptic Distribution of Interplanetary Dust Derived from Near-Earth Flux’, *Adv. Space Res.* **11(12)**, 123–126

Krivov, A., Kimura, H. and Mann, I.: 1998, ‘Dynamics of Dust Near the Sun’. *Icarus* **134**, 311–327

Lamy, P.L.: 1974a, ‘Dynamics of Circumsolar Dust Grains’, *Astron. Astrophys.* **33**, 191–???

Lamy, P.L.: 1974b, ‘Interaction of Interplanetary Dust Grains with the Solar Radiation Field’, *Astron. Astrophys.* **35**, 197–207

Lamy, P.L. and Perrin, J.-M.: 1986, ‘Volume Scattering Function and Space Distribution of the Interplanetary Dust Cloud’. *Astron. Astrophys.* **163**, 269–286

Leinert, Ch., Bowyer, S., Haikala, L.K., Hanner, M.S. , Hauser, M.G., Levasseur-Regourd, A.C., Mann, I., Mattila, K., Reach, W.T., Schlosser, W., Staude, H.J., Toller, G.N., Weiland, J.L., Weinberg, J.L. and Witt, A.N.: 1998, ‘The 1997 Reference of Diffuse Night Sky Brightness’, *Astron. Astrophys. Suppl.* **127**, 1–99

Lemaire, J.: 1990, ‘Meteoric Ions in the Corona and Solar Wind’. *Astrophys, J.* **360**, 288–295.

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.

MacQueen, R.M.: 1968, ‘Infrared Observations of the Outer Solar Corona’, *Astrophys. J.* **154**, 1059–1076.

MacQueen, R.M. and St. Cyr, O.C.: 1991, ‘Sungrazing Comets Observed by the Solar Maximum Mission Coronagraph’, *Icarus* **90**, 96–106

MacQueen, R.M. and Greeley, B.W.: 1995, ‘Solar Coronal Dust Scattering in the Infrared’, *Astrophys. J.* **440**, 361–369

Mann, I.: 1992, ‘The Solar F-Corona: Modellings of the Optical and Infrared Brightness of Near Solar Dust’. *Astron. Astrophys* **261**, 329–335

Mann, I.: 1996, ‘Dust Near the Sun’, In B.A.S. Gustafson and M.S. Hanner, editors, *Physics, Chemistry and Dynamics of Interplanetary Dust*, pages 315–???, Astronomical Society of the Pacific, San Francisco

Mann, I.: 1998, ‘Zodiacal Cloud Complexes’, *Earth, Planets Space* **50**, 465–471

Mann, I. and MacQueen, R.M.: 1993, ‘The Solar F-Corona at 2.12 Micrometer: Calculations of near solar dust in comparison to 1991 eclipse observations’, *Astron. Astrophys.* **275**, 293–297

Mann, I. and Kimura, H.: 2000, ‘Interstellar Dust Properties Derived from Mass Density, Mass distribution, and Flux Rates in the Heliosphere’, *J. Geophys. Res.* **105**, 10317–10328.

Mann, I. and Jessberger, E.K.: 2003, ‘The in-situ Study of Solid Particles in the Solar System’. In T. Henning, editor, *Astromineralogy*, pages 98–122, Springer, Berlin

Mann, I., Okamoto, H., Mukai, T., Kimura, H., and Kitada, Y.: 1994, 'Fractal Aggregate Analogues for Near Solar Dust Properties', *Astron. Astrophys.* **291**, 1011–1018

Mann, I., Kuhn, J. R., MacQueen, R. M., Lin, H., Edmunds, D., Kimura, H., Streete, J., Judge, P. L., Hillebrand, P., and Tansey, G.: 1999, 'Observations of the Solar Eclipse on February 26, 1998: Study of the Solar F-Corona', In J. Büchner, I. Axford, E. Marsch, and V. Vasyliunas, editors, *Plasma Astrophysics and Space Physics*, pages 667–672, Kluwer Academic Publishers, Dordrecht

Mann, I., Krivov, A. and Kimura, H.: 2000, 'Dust Cloud Near the Sun', *Icarus* **146**, 568–582

Mann, I., Kimura, H., Jessberger, E., Fehringer, M., Svedham, H.: 2001, 'Dust in the Inner Solar System', In B. Battrick and H. Sawaya-Lacoste, editors, *Solar encounter*, pages 445–446, ESA Publications Division, Proceedings of the First Solar Orbiter Workshop, ESA SP-493, Noordwijk

Marsden, B. G.: 1967, 'The Sungrazing Comet Group', *Astron. J.* **72**, 1170–1183

Marsden, B. G.: 2002, Presentation, Asteroids, Comets, Meteoroids Conference, Berlin.

Marsch, E., Antonucci, E., Bochsler, P., Bougeret, J.-L., Fleck, B., Harrison, R., Langevin, Y., Marsden, R., Pace, O., Schwenn, R., and Vial, J.-C.: 2002, 'Solar Orbiter, a High-Resolution Mission to the Sun and Inner Heliosphere', *Adv. Space Res.* **29(?)**, 2027–2040

Michels, D.J., Sheeley, N.R., Howard, R.A. and Koomen, M.J.: 1982, 'Observations of a Comet on Collision Course with the Sun', *Science* **215** 1097–1102

Misconi, N.Y.: 1993, 'The Spin of Cosmic Dust: Rotational Bursting of Circumsolar Dust in the F Corona', *J. Geophys. Res.* **98**, 18,951–18,961

Misconi, N.Y. and Pettera, L.E.: 1995, 'On the Possibility of Solar Dust Ring Formation due to Increased Dust-Ion Drag From Coronal Mass Ejections', *Planet. Space Sci.* **43**, 895–903

Möbius, E., Hovestadt, D., Klecker, B., Scholer, M., and Gloeckler, G.: 1985, 'Direct Observation of He(+) Pick-up Ions of Interstellar Origin in the Solar Wind', *Nature* **318**, 426–429.

Möbius, E., Gloeckler, G., Goldstein, B., Habbal, S., McNutt, R., Randolph, J., Title, A., and Tsurutani, B.: 2000, 'Here Comes Solar Probe!' *Adv. Space Res.* **25(9)**, 1961–1964

Morfill, G. E. and Grün, E.: 1979, 'The Motion of Charged Dust Particles in Interplanetary Space', *Planet. Space Sci.* **27**, 1269–1292

Mukai, T. and Mukai, S.: 1973, 'Temperature and Motion of the Grains in Interplanetary Space', *Publ. Astron. Soc. Japan* **25**, 481–488

Mukai, T. and Schwehm, G.: 1981, 'Interaction of Grains with the Solar Energetic Particles', *Astron. Astrophys.* **95**, 373–382

Mukai, T. and Yamamoto, T.: 1979, 'A Model of the Circumsolar Dust Cloud', *Publ. Astron. Soc. Japan* **31**, 585–595

Mukai, T. and Yamamoto, T.: 1982, 'Solar Wind Pressure on Interplanetary Dust', *Astron. Astrophys.* **107**, 97–100

Mukai, T. and Mann, I.: 1993, 'Analysis of Doppler Shifts in the Zodiacal Light', *Astron. Astrophys.* **271**, 530–534

Mukai, T., Yamamoto, T., Hasegawa, H., Fujiwara, A., and Koike, C.: 1974, 'On the Circumsolar Grain Materials' , *Publ. Astron. Soc. Japan* **26**, 445–458

Ohgaito, R., Mann, I., Kuhn, J.R., MacQueen, R.M. and Kimura, H.: 2002, 'The J- and K-Band Brightness of the Solar F-corona Observed During the Solar Eclipse on February 26, 1998' *Astrophys. J.* **578**, 610–620

Over, J.: 1958, 'On the Evaporation of Solid Particles Near the Sun' *Proceedings, Koninklijke Nederlandse Akademie van Wetenschappen* **61 B**, 74–84

Pellinen-Wannberg, A. and Wannberg, G.: 1994, 'Meteor Observations With the EISCAT UHF Incoherent Scatter Radar' *J. Geophys. Res.* **99**, 11397–11397

Peterson, A.W.: 1963, 'Thermal Radiation from Interplanetary Dust', *Astrophys. J.* **138**, 1218–1230

Peterson, A.W.: 1967, 'Experimental Detection of Thermal Radiation of Interplanetary Dust', *Astrophys. J.* **148**, L37–L39

Raymond, J.C., Fineschi, S., Smith, P.L., Gardner, L., O'Neal, R., Ciaravella, A., Kohl, J.L., Marsden, B., Williams, G.V., Benna, C., Giordano, S., Noci, G. and Jewitt, D.: 1998, 'Solar Wind at 6.8 Solar Radii from UVCS Observation of Comet C/1996Y1', *Astrophys. J.* **508**, 410–417

Russell, H.N.: 1929, 'On Meteoric Matter Near the Stars', *Astrophys. J.* **69**, 49–71

Schwadron, N.A. and Geiss, J.: 2000, 'On the Processing and Transport of Inner Source Hydrogen', *J. Geophys. Res.* **105**, 7473–7482

Sekanina, Z.: 2001, 'Solar and Heliospheric Observatory Sungrazing Comets With Prominent Tails: Evidence on Dust-Production Peculiarities', *Astrophys. J.* **545**, L69–L72

Sheeley, N.R., Jr., Howard, R.A., Koomen, M.J. and Michels, D.J.: 1982, 'Coronagraphic Observations of Two New Sungrazing Comets', *Nature* **300**, 239–242

Shestakova, L.I. and Tambovtseva, L.V.: 1995, 'Dynamics of Dust Grains Near the Sun', *Astron. Astrophys. Trans.* **8**, 59–81

Tsurutani, B.T. and Randolph, J.E.: 1991, 'The NASA Solar Probe Mission: in Situ Determination of Interplanetary Out-Of Ecliptic and Near-Solar Dust Environments', In A.C. Levasseur-Regourd, and H. Hasegawa, editors, *Origin and Evolution of Interplanetary Dust*, pages 29–32, Kluwer, Dordrecht

Tuzzolino, A.J., McKibben, R.B., Simpson, J.A., BenZvi, S., Voss, H.D., and Gursky, H.: 2001a, 'The Space Dust (SPADUS) Instrument Aboard the Earth-Orbiting ARGOS Spacecraft: I-Instrument Description', *Planet. Space Sci.* **49**, 689–703

Tuzzolino, A.J., McKibben, R.B., Simpson, J.A., BenZvi, S., Voss, H.D., and Gursky, H.: 2001b, 'The Space Dust (SPADUS) Instrument Aboard the Earth-Orbiting ARGOS Spacecraft: II-Results From the First 16 Months of Flight', *Planet. Space Sci.* **49**, 705–729

Wehry, A. and Mann, I.: 1999, 'Identification of β-Meteoroids From Measurements of the Dust Detector Onboard the Ulysses Spacecraft', *Astron. Astrophys.* **341**, 296–303

Address for Offprints:
Prof. Ingrid Mann
Institut für Planetologie
Westfälische Wilhelms-Universität
Wilhelm-Klemm-Straße 10
D-48149 Münster
Germany
e-mail: imann@uni-muenster.de
Fax: +49 251 83 36301