Dust Near The Sun

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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 inward from 1 AU are: Poynting-Robertson deceleration of particles outside of 1 AU, fragmentation into dust due to particle-particle collisions, and direct dust production from comets. The loss processes are: dust collisional fragmentation, sublimation, radiation pressure acceleration, sputtering, 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 < 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. 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 determine dust interactions in the ambient interplanetary medium. The combination of in-situ dust measurements with particle and field measurements is recommended.

1. Introduction

The near-solar dust cloud is the central region of the meteoritic complex that evolves from the small bodies of 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 (see Figure 1). 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. The latter observations are obscured by dust particles in the vicinity of the Earth. Further information is obtained from studies of the near-Earth environment and from in-situ dust 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 the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA) raises the question as to what experiments are most suitable for improving our understanding of the inner-solar-system dust. Here we give an overview of different studies of inner-solar-system dust 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 will 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 extrapolation of 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

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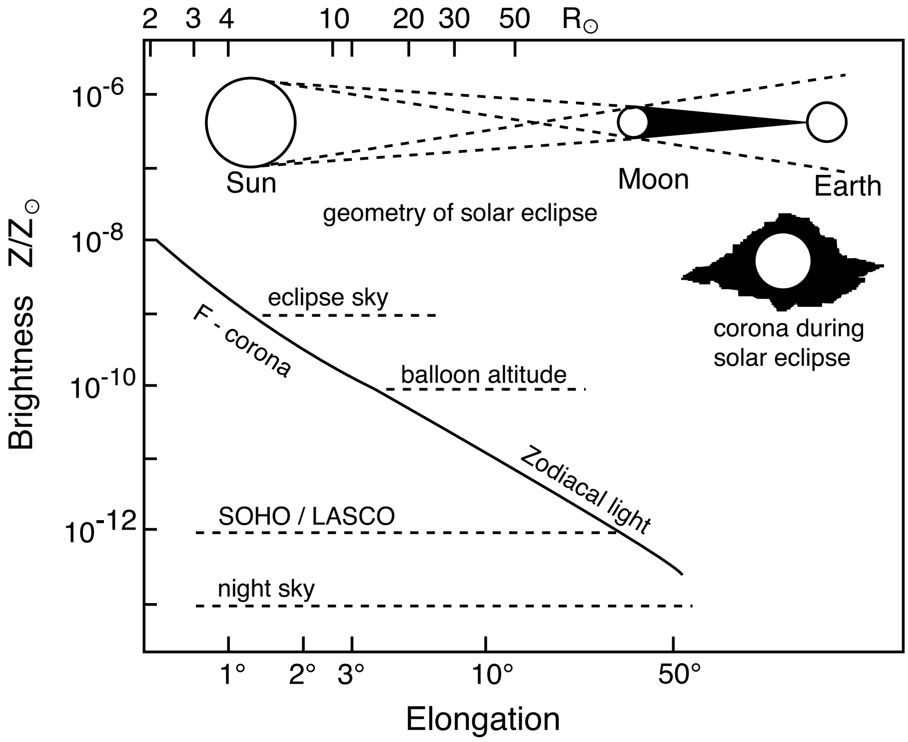

Figure 1. The visual brightness of the corona and zodiacal light near the ecliptic plane as function of the elongation of the line of sight (LOS) within the ecliptic plane. Corresponding minimum distances from the Sun that the LOS crosses are given in units of solar radii ($R_\odot$). Typical stray light levels of the night sky and eclipse sky are shown for comparison. The geometry of the solar eclipse is sketched in the upper part of the figure.

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, sputtering, 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 observational evidences of dust interactions with the surrounding interplanetary medium and we conclude in Section 10 with a final discussion of the physics that can be studied with future near-solar dust measurements.

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.[2]

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). 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). 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

[1] The elongation of the line of sight (LOS), as seen in Figure 1, is often given in distances, r, from the Sun: $r = \sin(\epsilon) \times 1$ AU for corona 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 $R_\odot$).

[2] While in-situ measurements typically provide data for the mass of particles, brightness observations provide information on their sizes. 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 be the case for porous particles.

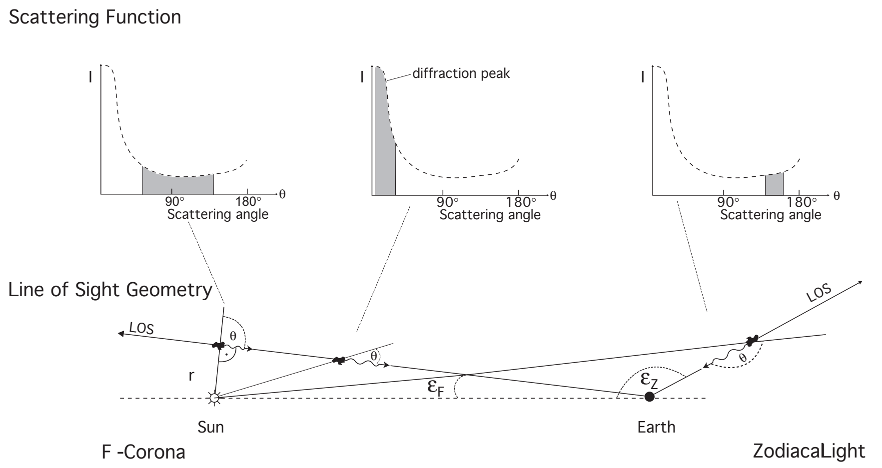

Figure 2. Geometry of zodiacal light and F-corona observations: Both phenomena are caused by the same physical effect: scattering of light and thermal emission from dust distributed along the line of sight (LOS), but are observed at different elongations, ϵ, of the LOS. In this figure r denotes the minimum distance from the Sun that is seen along the LOS with elongation ϵ. A sketch of the scattering pattern, i.e., intensity I of scattered light as function of scattering angle θ, 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. Note that in contrast to the depicted pattern for scattered light, thermal emission is isotropic, i.e., constant over θ.

0.3 AU is very steep and most likely cannot be explained by a gradual change of the particle properties, but rather by a change in the dust cloud composition.

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

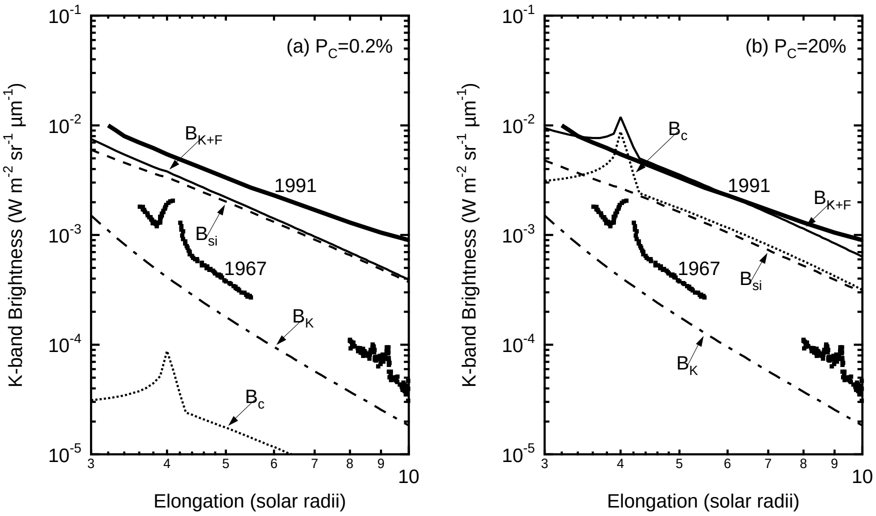

Figure 3. The calculated F-corona brightness in comparison to observations of the infrared feature in 1967 and 1991 (MacQueen, 1968; Hodapp, MacQueen, and Hall, 1992): the left-hand side describes a model with predominantly silicate particles and 0.2% carbon, the right-hand side describes calculations for 20% carbon particles (Kimura, Mann, and Mukai, 1998).

presence of coronal and atmospheric stray light and therefore F-corona observations are preferably made in the near infrared and during solar eclipses or with coronagraphs from space. 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 Figure 2). For particles in the 1–100 μm size range the scattering is very efficient at small angles ('forward scattering') while light 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.

The detection and non-detection of features in the F-corona stimulated discussions about the possible connection to the existence of dust rings (see Kimura and Mann, 1998, for a summary). The superposition of scattered light and thermal emission components can lead to a feature in the coronal brightness at the point where the LOS crosses the dust-free zone (Peterson, 1963; Mann, 1992). Due to this

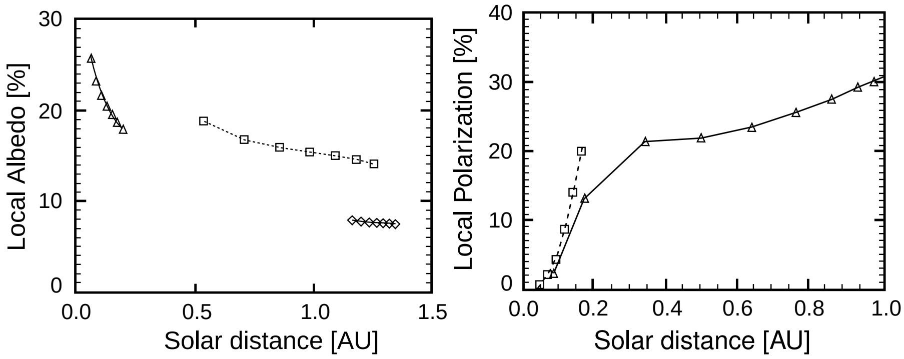

Figure 4. Average local optical properties derived from F-corona and zodiacal light observations assuming a homogeneous dust cloud: the variation at small distances from the Sun is so drastic that it points to a change of the dust cloud composition (compare Mann, 1998).

superposition, the appearance of the F-coronal brightness may depend on the material properties of dust (Kimura, Mann, and Mukai, 1998). As shown in Figure 3, the appearance of an infrared feature is expected for a coronal brightness that consists to a significant amount of thermal emission, while the scattered light components tend to occult this features. The feature is observed when a high amount of absorbing dust particles is present, while recent infrared observations of the 1998 eclipse (Mann *et al.*, 1999), where no feature was observed, are best described with dust particles that are weakly absorbing (Ohgaito *et al.*, 2002). Although being far from suggesting a model of the time variation of the near-infrared F-coronal brightness, the differences in the near-infrared brightness that were measured over the past decades possibly indicate a time variation in the material composition of dust near the Sun. As can be seen from Table I, interpretations of Isobe and Kumar (1993), C. (1995), and Ragot and Kahler (2003) to suggest a solar cycle variation of the infrared feature, however, are not supported by the observations. 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 as shown in Figure 4 (Mann, 1996). The size range of observed particles may change in the F-corona compared to the zodiacal light here with causing a change of the average optical properties, but still the majority of observed particles are expected to have sizes larger than 1 μm (i.e., about 10^{-11} g). Habbal *et al.* (2003) report on polarization measurements in the Fe XIII line at 1074.7 nm made during the total solar eclipse of 2001 June 21. Over most of the inner corona they detect radially polarized emission,

Table I. Near-infrared observations of the solar F-corona.[a]

Wavelength (μm)	Date	Feature(s)	Ref.
0.837	1970 Mar. 7	Yes	1
1.0	1973 Jun. 30	No	2
1.25	1983 Jun. 11	Yes	3,4
1.25	1998 Feb. 26	No	5,6
1.57	1970 Mar. 7	Yes	1
1.65	1983 Jun. 11	Yes	3,4
1.65	1991 Jul. 11	Yes[b]	7
1.6	1991 Jul. 11	No	8
2.23	1966 Nov. 12	Yes	9,10
2.2	1966 Nov. 12	Yes	11
2.2	1967 Jan. 9	Yes	11
2.23	1970 Mar. 7	Yes	1
2.2	1971 Oct. 24	Yes	12,13
2.2	1973 Oct.	Yes	13
2.2	1979 summer	No	14
2.35	1980 Feb. 16	No	15
2.25	1983 Jun. 11	No	3,4
2.12	1991 Jul. 11	No	16,17,18
2.23	1991 Jul. 11	No	19
2.28	1991 Jul. 11	No	20,21
2.2	1998 Feb. 26	No	6
2.8	1983 Jun. 11	No	3,4
3.61	1966 Sep. 3	Yes	9
3.53	1966 Nov. 12	Yes	9,10
3.5	1973 Oct.	Yes	13
3.5	1978 Jun.–Sep.	No	14,22
3.5	1979 summer	No	14
3.5	1979 Dec. 26	No	23
3.5	1980 Feb. 16	No	23
3.53	1991 Jul. 11	No	19

[a]Listed are wavelength and date of observation and whether a brightness feature was observed.
[b]Only after subtracting the continuum.
References. — (1) Peterson (1971); (2) Smartt *et al.* (1974); (3) Mizutani *et al.* (1984); (4) Maihara *et al.* (1985); (5) Mann *et al.* (1999); (6) Ohgaito *et al.* (2002); (7) Tollestrup *et al.* (1994); (8) Lamy *et al.* (1992); (9) Peterson (1967); (10) Peterson (1969); (11) MacQueen (1968); (12) Adney (1973); (13) Strong (1974); (14) Mampaso, Sánchez-Magro, and Buitrago (1982); (15) Rao *et al.* (1981); (16) Hodapp, MacQueen, and Hall (1992); (17) MacQueen *et al.* (1994); (18) MacQueen and Greeley (1995); (19) Skomorovsky, Druzhinin, and Salakhutdinov (1992); (20) Lamy *et al.* (1992); (21) Kuhn *et al.* (1994); (22) Mampaso *et al.* (1983); (23) Ney (1980, private communication to Mampaso *et al.*, 1983).

consistent with previous observations of Fe XIII emissions. However, they report tangentially polarized emission in the radial extension of low-temperature and low-density coronal holes, regions from which no Fe XIII emission would be expected. They suggest that this radiation is produced from solar ultraviolet (UV) excited fluorescence of silicon particles with sizes of a few nanometers at radii extending in to within 1 $R_{\odot}$ above the photosphere. This interpretation is open to discussion, but experimental tests are possible through future observations at other wavelengths where fluorescence from silicon nano-particles would be expected. The Large Angle Spectrometric Coronagraph (LASCO) instruments C2 and C3 from the Solar Heliospheric Observatory (SOHO) have recently observed the solar corona at visible wavelengths. They provide valuable information about dust from sungrazing comets as will be discussed in Section 6, but no clear information about the spatial distribution of dust. The SOHO/LASCO observations show that the visible 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; Mukai and Ishiguro, 2002, 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 Figure 5). In situ measurements typically detect particles of sizes below several micrometers 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

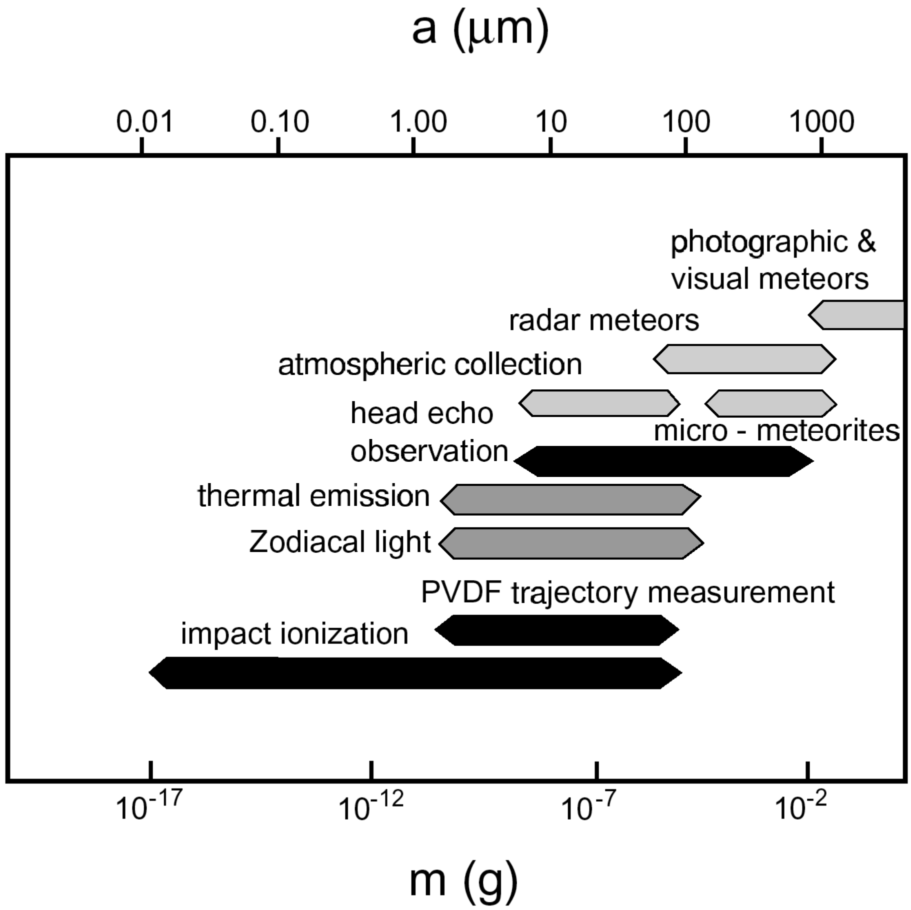

Figure 5. Methods of dust detection near Earth over the mass interval for which they are applicable: while in-situ instruments can also be used from deep space probes, the knowledge of larger dust components is restricted to meteor observations taken from Earth.

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 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 allow a better estimate of initial velocities outside the Earth atmosphere, but also in this case the number of detected impacts is statistically small (cf. Pellinen-Wannberg and Wannberg, 1994). These measurements of the dust velocity vectors provided no sufficient data yet but may do so in the future.

3. Dust Sources and Orbital Evolution

Interplanetary dust is 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, Zook, and Dermott, 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. The contribution of interstellar dust inside 1 AU is smaller than in the outer solar system. Yet it makes up a tenth part of the cumulative particle flux in the submicron-size range at 1 AU. 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. 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, $i < 30°$ and eccentricities, $e < 0.1$. Short-period comets are in orbits with inclinations, $i < 40°$ and eccentricities, $e < 0.4$, long-period comets have inclinations ranging from 0 to 180° with $N(i)di \propto \sin(i)di$ where $N(i)$ denotes the number of orbits between i and $i + di$ (i.e., spherical distribution in number density).

The major effects that determine the distribution of dust in interplanetary space are solar gravitation, the influence of magnetic fields, solar-radiation pressure and solar-wind pressure, including the Poynting-Robertson effect and pseudo Poynting-Robertson effect, mutual collisions, and the gravitational forces exerted by the planets. 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 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, Fahr, and Scherer (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 $e \approx 0.01$ for particles whose sources are asteroids, and $e \approx 0.1$ for particles whose sources are short-period comets (see Mann, Krivov, and Kimura, 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 $> m$ (in gram) at $r_0 = 1$ AU derived from several in-situ and meteor measurements is given as (Grün *et al.*, 1985):

$$F(m, r_0) = (c_1 m^{g_1} + c_2)^{g_2} + c_3(m + c_4 m^{g_3} + c_5 m^{g_4})^{g_5} + c_6(m + c_7 m^{g_6})^{g_7}, \tag{1}$$

with $c_1 = 2.2 \times 10^3$, $c_2 = 15$, $c_3 = 1.3 \times 10^{-9}$, $c_4 = 10^{11}$, $c_5 = 10^{27}$, $c_6 = 1.3 \times 10^{-16}$, $c_7 = 10^6$, $g_1 = 0.306$, $g_2 = -4.38$, $g_3 = 2$, $g_4 = 4$, $g_5 = -0.36$, $g_6 = 2$, and $g_7 = -0.85$, where $F(m, r_0)$ is given in units of $\mathrm{m}^{-2}\ \mathrm{s}^{-1}$. The relation between cumulative flux and cumulative spatial density $N(m, r)$ for the case of an isotropic flux is:

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

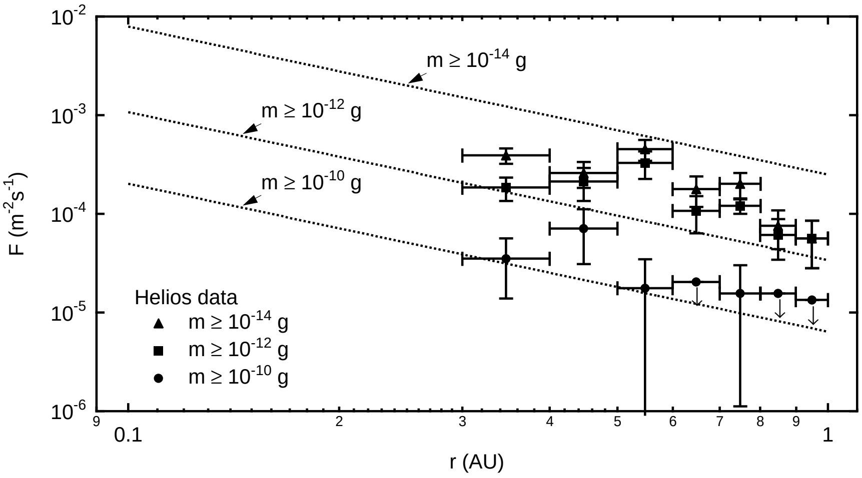

Figure 6. The flux rates measured with Helios in comparison to a flux $\propto r^{-1.5}$.

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

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

where $v_0 = 20$ km s^{-1} 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 as shown in Figure 6 in comparison to Helios measurements. 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 $n \propto r^{-1.5}$ and the increase could be clearly seen only inward of 0.3 AU (Kneißel and Mann, 1991a). As mentioned before, F-corona observations do not reveal clear information on the dust distribution near the Sun. None of the 3-D models of the zodiacal dust cloud reproduce 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 distribution of near-solar dust from them. Ulysses performed the only in-situ measurements of dust at high latitudes. The results are not relevant in the present context because, due to the detection efficiency and geometry, Ulysses detected predominantly interstellar dust and small particles in hyperbolic orbits at large distances from the Sun. 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 reported the true flux percentage of retrograde meteor orbits to be about 5% (Baggaley, J.: 2002, private communication). Beside these 'normal' retrograde orbits, there is evidence for meteor orbits that have high eccentricities and an aphelion at Earth, indicating their perihelia are close to the Sun, e.g., 10 $R_\odot$. Such meteors possibly originate from near-Sun comets, which will be shortly discussed in Section 6.2, in a similar way as the recently suggested association between two groups of near-Sun comets and the Arietids meteor stream (see Ohtsuka, Nakano, and Yoshikawa, 2003).

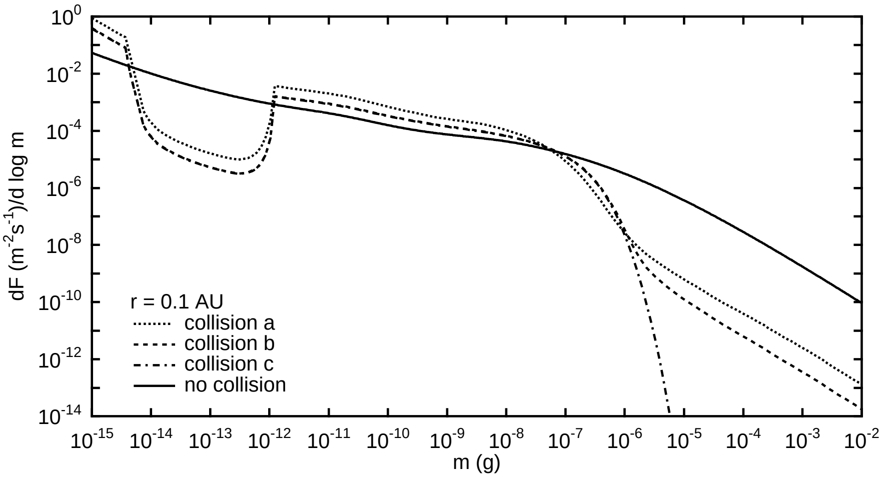

Figure 7. The differential flux of dust at 0.1 AU near the ecliptic: The solid line denotes the distribution derived by Equations (1) and (4), compared to collision calculations that assume (a) an increasing mass supply from 1 to 0.5 AU and then a constant supply, (b) constant mass supply from 1 AU inward,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

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: This is supported by the dust experiment aboard Ulysses that 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

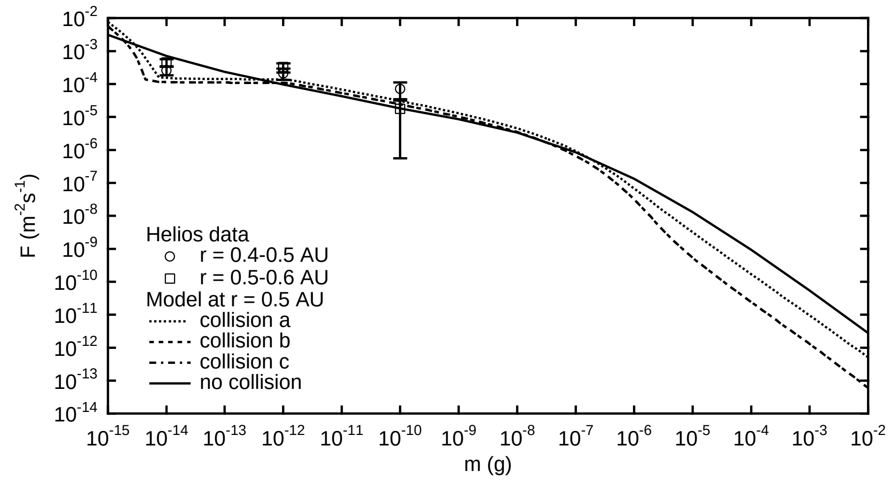

Figure 8. The calculated cumulative dust flux at 0.5 AU for the same models as described in Figure 7 shown in comparison to Helios measurements with the 'ecliptic sensor' as discussed in the text.

of ingoing particles compared to outgoing particles for orbits with small perihelia (Janches, Meisel, and Mathews, 2001). This possibly indicates the collisional destruction of these particles in the inner solar system.

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. 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 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 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.

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-

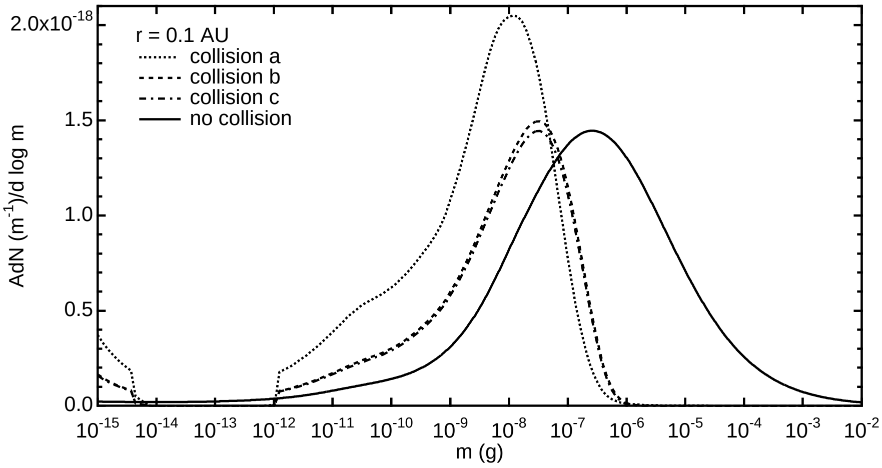

Figure 9. The area of the geometric cross section for the mass distributions of dust at 0.1 AU shown in Figure 7 (derived by assuming spherical compact dust grains with bulk density 2.5 g cm^{-3}).

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 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 micron and submicron sized particles to the integrated brightness as opposed to the zodiacal-light brightness that stems mainly from particles of several micrometers and larger.

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. Nevertheless, the collision models agree with observational data and allow for estimation of the dust mass distribution. 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 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 $R_\odot$) (Lamy, 1974b). Carbonaceous grains such as graphite and glassy carbon sublimate near 4 $R_\odot$ (Mukai *et al.*, 1974; Kimura, Ishimoto, and Mukai, 1997). Model calculations for porous dust particles 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 (Mann *et al.*, 1994). 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: Kimura *et al.* (2002) show that pyroxene grains sublimate at 4–6 $R_\odot$ and olivine grains at 10–13 $R_\odot$. The dust particles are also heated by solar-wind bombardment. 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, MacQueen, and Hall, 1992; MacQueen 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 II) 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.

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

Material	Sphere	Fluffy	Ref.
Quartz	1.5–4 $R_\odot$	—	1,2,3
FeO-poor obsidian	1.9–7 $R_\odot$	2.5–3 $R_\odot$	4,5,6,7,8,9,10
FeO-rich obsidian	2.9–6 $R_\odot$	—	5,8
Glassy carbon	4 $R_\odot$	4 $R_\odot$	9,10
Graphite	≤ 5 $R_\odot$	≤ 2 $R_\odot$	2,5,7,8,11
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
Basalt	6 $R_\odot$	—	8
Andesite	9–10.5 $R_\odot$	—	3,4,11
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
Astronomical silicate	14 $R_\odot$	—	8
Iron	11–24.3 $R_\odot$	—	3,4
Magnetite	10–40 $R_\odot$	—	6
Water ice	1–2.8 AU	—	2,3,6

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

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-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 $3 < r < 8$ $R_\odot$ 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 centimeter-sized and larger fragments was shown by infrared observations of cometary dust trails, from new optical observations of a cometary dust trail, Ishiguro *et al.* (2002) suggest that it consists of very dark (geometric albedo < 0.01) fragments of sizes of a few centimeters. 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. 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, did not allow for a clear interpretation of the observed enhancement in the coronal brightness, which was discussed by Sheeley *et al.* (1982) to originate 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, Krivov, and Kimura, 2000), but, due to the fact that the coronal brightness stems to a large

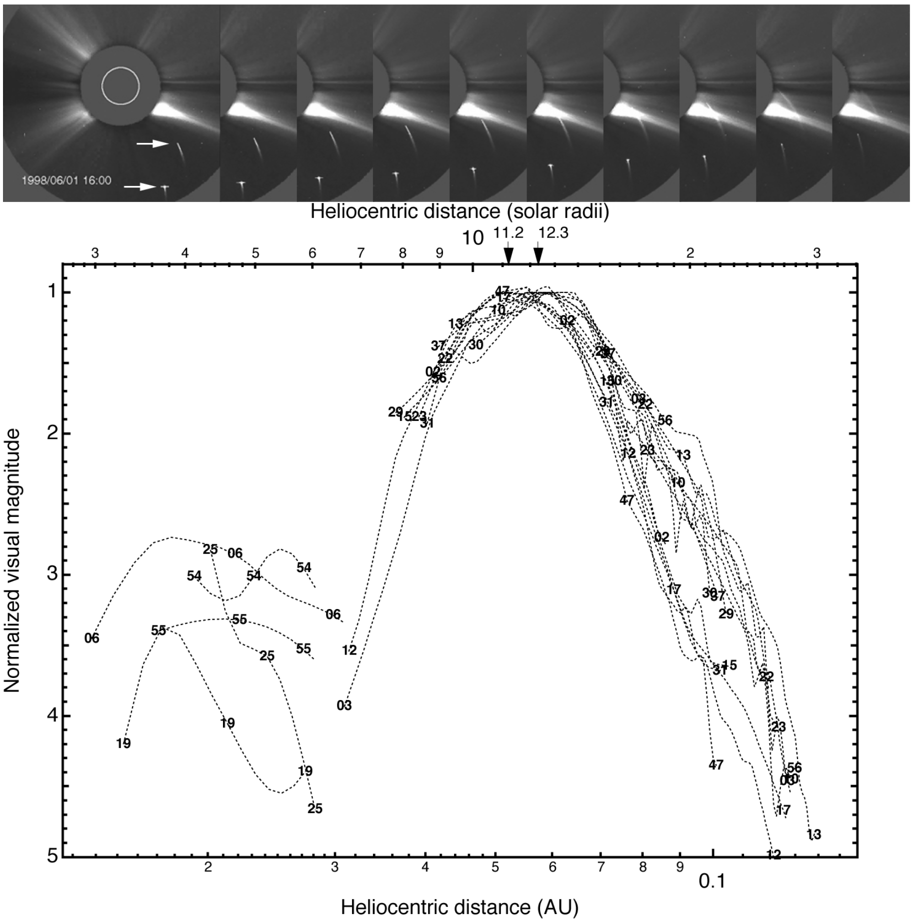

Figure 10. Observation of sungrazing comets with SOHO/LASCO: the upper panel shows a series of C2 images of the comets C/1998 K10 (SOHO-54) and C1998 K11 (SOHO-55). Note that the large extended brightness enhancement stems from coronal electrons, while the comets are seen in the lower right-hand part of the figure as indicated by arrows. The lower panel shows the normalized light curves of 20 sungrazing comets in the field of view of the SOHO/LASCO C2 and C3 instruments from Biesecker *et al.* (2002). The SOHO comet number is given along the each light curve.

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 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 St. Cyr, 1991). Sekanina (2003) estimates from his model that the initial diameters of SOHO sungrazers range from 17 to 200 m. The number of comets observed with a limit of 9th magnitude is about 60 comets per year and the extrapolated total is 180 comets per 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 (see Figure 10). These maxima were attributed to the sublimation of dust particles consisting of crystalline or amorphous olivines, respectively that are assumed to make up a significant component of the coma brightness (Kimura *et al.*, 2002). 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. In contrast, Sekanina (2003) attributes the light curves to sodium emission, which he estimates to exceed the signal from light scattering at dust. 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. Analysis of the dust tails of sungrazing comets shows that the sungrazers emit small particles of sizes $a = 0.1\ \mu$m and that the dust in the sungrazing comets has a narrow size distribution (Sekanina, 2001). When making this rough estimate for 0.1 μm spherical particles, the number density amounts to 10^{-12} cm^{-3}, which is comparable to typical dust densities in this size range. 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

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

230 km s^{-1} 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 subgroups based on different perihelion distances and ascending nodes (Marsden, 1967). From SOHO/LASCO observations, a further comet group with 37 members (Meyer group) and two groups with 15 members (Marsden group) and 14 members (Kracht group) were identified in near-Sun orbits by end of 2002 (Marsden and Meyer, 2002; Kracht *et al.*, 2002; Meyer, 2003). The perihelion distances and inclinations of the three groups are 0.036 AU and 72.4°, 0.049 AU and 27.4°, and 0.048 AU and 13.6°, respectively, where each value is the mean weighted by the total observational time (Meyer, 2003). The size of these comets is likely to be similar to the Kreutz family fragments SOHO detects, 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, Krivov, and Kimura, 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

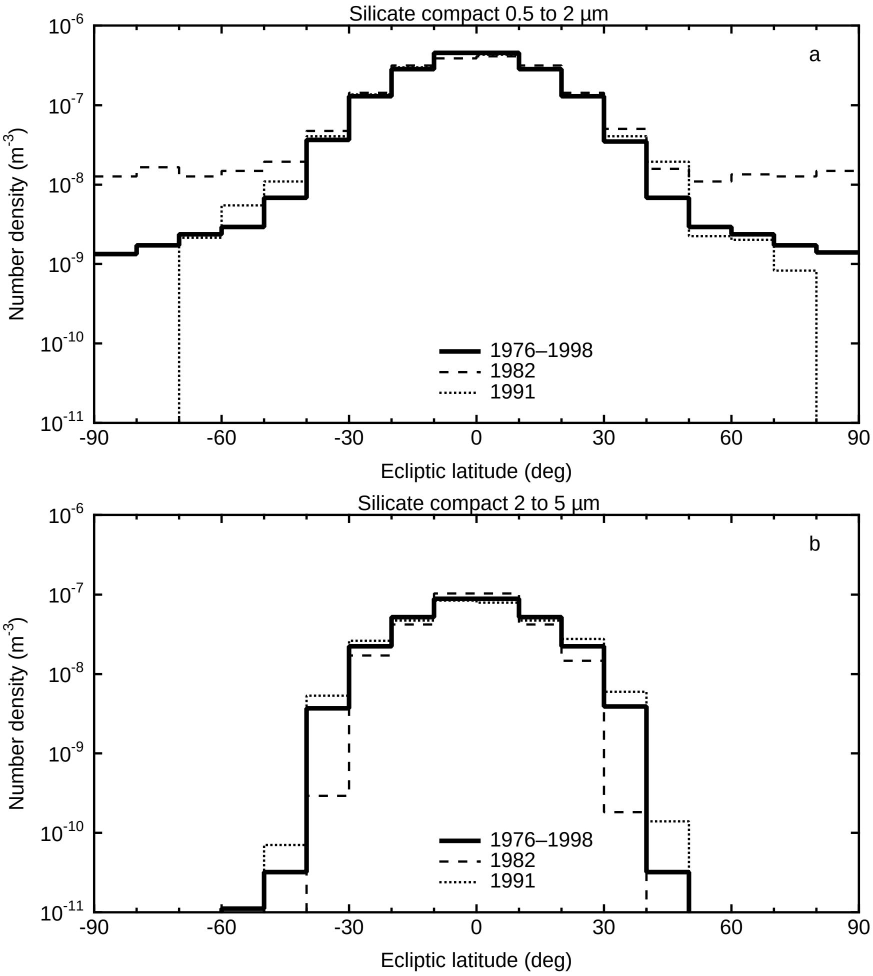

Figure 11. The variation of dust number density with latitude due to Lorentz force perturbations for compact silicate particles with an initial distribution $\pm 30°$. The solid line denotes an average profile for the entire solar cycle, the dashed line shows the profile for a strong magnetic field in 1982 and the dotted line the profile for a weak magnetic field in 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 (Mann, Krivov, and Kimura, 2000).

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, Krivov, and Kimura (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 $\pm 30°$, dust particles of size 2–5 μm will be scattered to latitudes $\pm 50°$ 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 $\pm 90°$ for strong magnetic fields. Smaller silicate particles are almost 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 greater than 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 for porous, fluffy silicate particles 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, Krivov, and Kimura, 2000). Carbon and silicate are used as examples for absorbing and less-absorbing material.

8. Present Best Estimates of the Near-Sun Dust Environments

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 micrometers, but still, we can summarize our knowledge for the near-solar-dust parameters in a way that helps spacecraft designers.

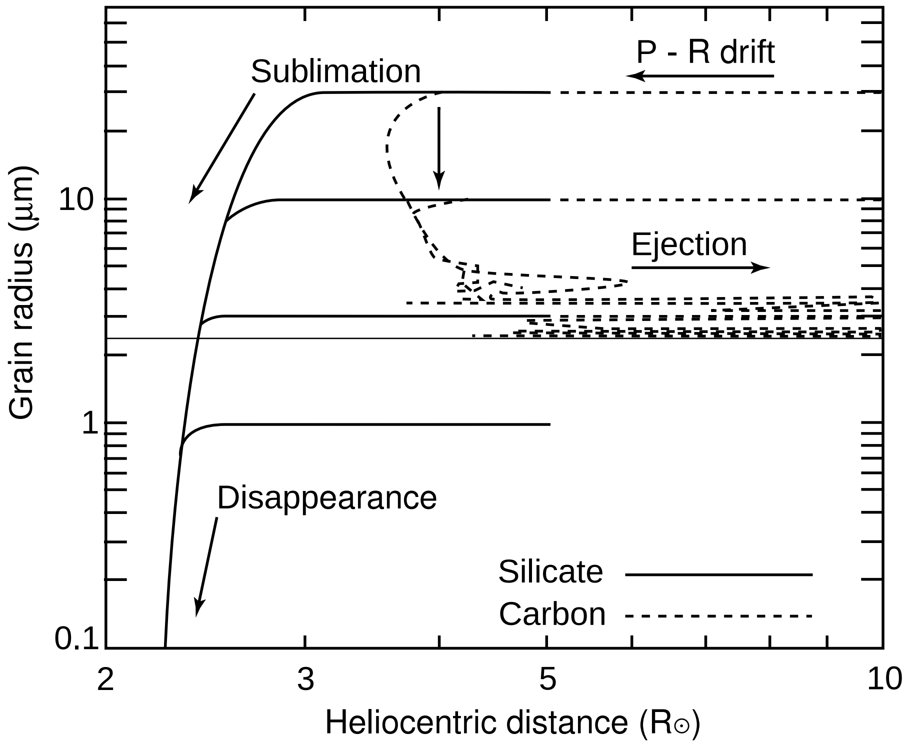

Figure 12. Dust ring formation depicted with the evolution of particle size vs. distance from the Sun for carbon particles (dashed lines) and silicate particles (thick solid lines). The change in distance from the Sun is caused by direct radiation pressure and Poynting-Robertson drift, respectively. 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 into high-eccentricity orbits and the sublimation rate decreases again until they approach their perihelia again. The exact slope of this size-distance curve depends on the initial conditions but this interplay of radiation pressure and sublimation leads to an enhancement of dust number density at the edge of 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 (Krivov, Kimura, and Mann, 1998).

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 $\propto r^{-1}$ (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 (see Figure 13). The size distribution discussed

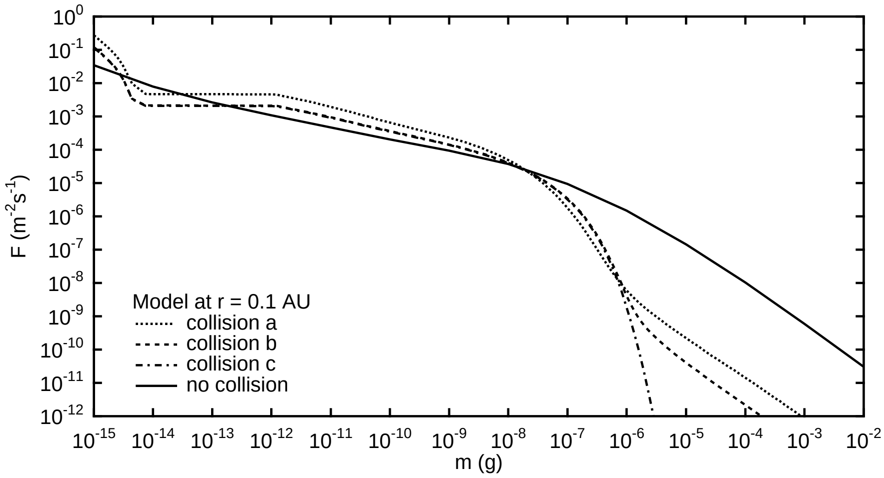

Figure 13. The mass distribution of dust shown as the cumulative flux at 0.1 AU (from Ishimoto, 2000) compared to the flux that is extrapolated from the distribution at 1 AU given on Equation (1) in Section 3. Equation (2) describes the conversion from fluxes to number densities.

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 $n(r) \propto r^{-1}$. 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 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 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

Table III. 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} and averaged of latitudes within 30° around the ecliptic and outward from 30° around the ecliptic (Mann, Krivov, and Kimura, 2000).

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 $R_\odot$	$< 30°$	3×10^{-3}	1×10^{-3}	7×10^{-4}
	$> 30°$	6×10^{-5}	9×10^{-6}	0
6–8 $R_\odot$	$< 30°$	5×10^{-3}	1×10^{-3}	1×10^{-3}
	$> 30°$	2×10^{-4}	3×10^{-5}	0
4–6 $R_\odot$	$< 30°$	8×10^{-3}	2×10^{-3}	2×10^{-3}
	$> 30°$	3×10^{-4}	8×10^{-5}	0
2–4 $R_\odot$	$< 30°$	1×10^{-2}	4×10^{-3}	1×10^{-3}
	$> 30°$	1×10^{-3}	1×10^{-4}	0

fluxes at 1 AU can be extrapolated toward the Sun to about 0.1 AU (~ 20 $R_\odot$). The flux rate dependence is $\propto r^{-1.5}$. 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 $a < 10$ μm 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 III. 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 near vicinity of the Sun is also the region where interactions of dust particles with the ambient interplanetary medium become particularly important. The principal effect of dust particles on the interplanetary medium and solar wind is to add neutral and ionized atoms to the environment. The neutral atoms are usually quickly ionized by solar UV, at which point they are picked up by the interplanetary magnetic field and carried outward with the solar wind as a distinct component of the solar wind called pick-up ions. While most of the pick-up ions are produced by ionization of neutral interstellar gas that penetrates the solar system, dust particle interactions with the solar wind provide a second source that contributes a different mix of elements to the pick-up ion population. As discussed below, pick-up ions are clearly identifiable as a result of their distinctive charge state and velocity distribution. Dust particles may contribute to the formation of pick-up ions through a number of processes, both direct and indirect. Unfortunately, all the scenarios so far discussed, while theoretically plausible, have yet to be directly proven by experiments.

The most direct mechanism by which dust particles can contribute to the pick-up ion population is by sublimation. The majority of refractory solids that are thought to be present in cosmic dust sublimate within several 1/10 AU from the Sun, and some particles can survive to reach as close to the Sun as a few solar radii (see Table II, Figure 14). Through sublimation neutral molecules and ions are released into the ambient interplanetary medium where most are quickly photo-ionized by the solar UV radiation and become pick-up ions.

Dust particles may also recycle solar wind particles into pick-up ions by adsorption and desorption. It is well known that the outer layers of lunar samples are saturated with solar wind particles; Banks (1971) studied this effect for dust particles. Rajan *et al.* (1977) detected significant ^{4}He concentrations in interplanetary dust particles collected in the atmosphere and concluded that this helium was implanted by the

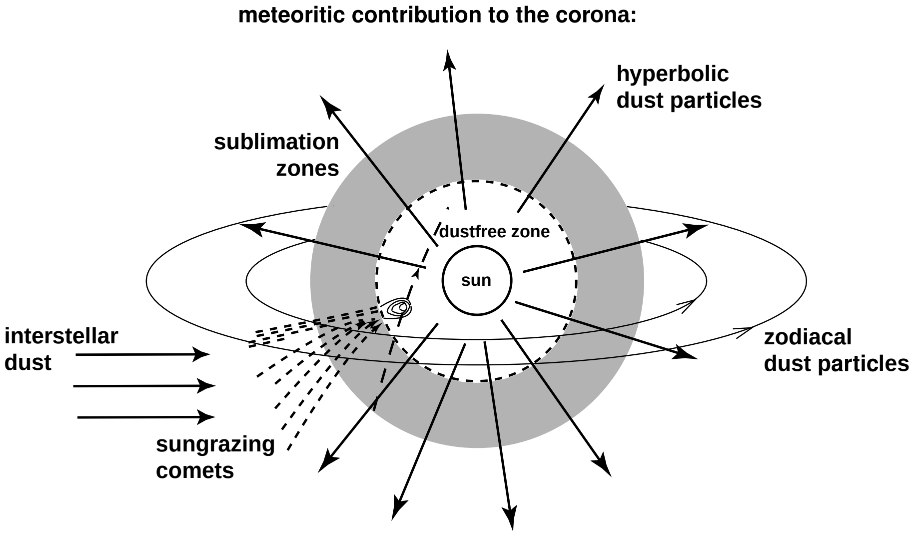

Figure 14. Meteoritic contributions to be expected in the solar corona are zodiacal dust particles in Keplerian, in majority prograde orbits around the Sun, particles in hyperbolic orbits that are ejected by radiation pressure, particles deflected in high-inclination orbits by Lorentz force, small amounts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

same mechanism. Heating experiments of interplanetary dust particles showed that the ^{4}He degassing pattern of the dust is comparable to that of the lunar samples (Nier, 1994). While implantation of heavier ions would also be expected, the relative concentrations of implanted heavier elements have not been measured.

Based on observations of solar wind implantation, Fahr, Ripken, and Lay (1981) suggested that adsorption of solar wind particles on the surface and within the surface layer of dust particles can lead to subsequent desorption of neutrals. They predicted that inside 0.5 AU the density of neutral hydrogen produced by this process exceeds that of the interstellar hydrogen found at these distances from the Sun. For the case of helium, they estimate that the dust-generated component exceeds the interstellar component inward of about 0.05 AU.

Fahr, Ripken, and Lay (1981) further suggested that solar-wind hydrogen atoms adsorbed on the surface of dust grains may frequently combine to form molecular hydrogen before being desorbed back into the interplanetary medium. Gruntman (1996) calculated the amount of neutral molecular hydrogen injected in this manner, and then considered the efficiency of various processes for conversion of the H_2 molecules to H_2^+ ions and for subsequent destruction of the H_2^+ ions.

He concluded that a significant fraction of H_2^+ ions should survive to form a unique molecular pick-up ion component.

For dust particles so small that the solar wind ions can pass through them, Wimmer-Schweingruber and Bochsler (2003) suggested that the passage through dust particles should change the charge state of the penetrating ions and generate predominantly singly charged and neutral particles. For this to be an important source of pick-up ions, however, they require a preponderance of small dust particles in the inner solar system which is not in agreement with observational results. Moreover, they do not discuss the energy distribution of emerging particles. The pick-up process, however, requires a significant velocity difference between the picked-up particle and the solar wind.

Even the in-fall of heavy meteoritic ions into the solar corona has been discussed as a possible influence on the solar wind and pick-up ion composition (Lemaire, 1990).

The most convincing observational evidence for dust interactions with the interplanetary medium lies in measurements of a component of pick-up ions called the inner source pick-up ions (cf. Geiss, Gloeckler, and von Steiger, 1996; Gloeckler and Geiss, 1998, 2001).

The largest source of pick-up ions consists of interstellar neutral atoms that enter the solar system and are ionized in the inner solar system. He^+ pick-up ions were first observed in 1985 (Möbius *et al.*, 1985), and recent measurements from the SWICS (Solar Wind Ion Composition Spectrometer) experiment aboard Ulysses have allowed for a close study of both solar-wind ions and pick-up ions from H to Fe. Study of the pick-up ions has provided some of our best estimates of the neutral gas content of the local interstellar medium that the solar system is embedded in (Gloeckler and Geiss, 1998, 2001). In the course of these studies, SWICS discovered a second component, so-called 'inner source' pick-up ions that could not be explained by ionization of interstellar neutrals (Geiss, Gloeckler, and von Steiger, 1996). At present inner source pick-up ions have been identified for the elements H, He, C, N, O, Mg, Si, and Ne (Gloeckler and Geiss, 2001).

All pick-up ions, whether of interstellar or inner source origin, are identified by their distinct velocity distribution relative to the local solar wind speed as well as by their single charge state as opposed to highly charged solar wind ions. Upon pick-up, these ions have a shell-like velocity distribution in the plasma frame, with the radius of the shell equal to the solar wind speed. Thus gyration about the magnetic field lines transported with the solar wind plasma yields a velocity distribution of the pick-up ions that ranges from zero to twice the solar-wind speed in the spacecraft frame.

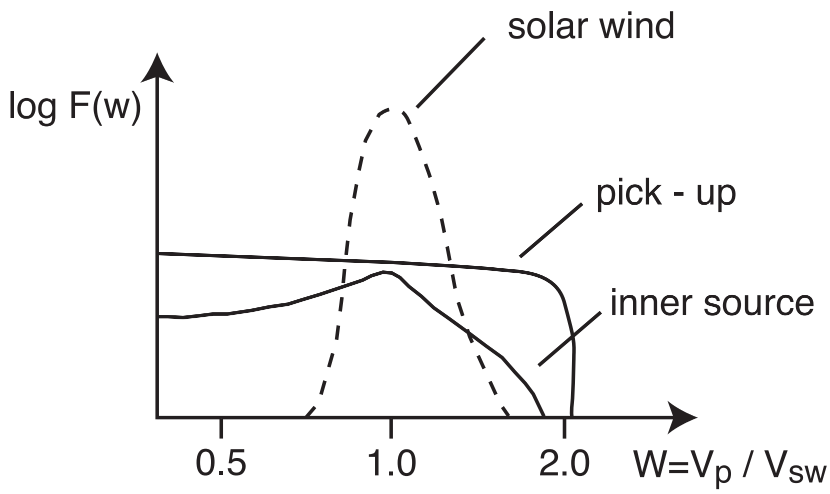

Figure 15. Phase-space velocity distributions (v_p: ion velocity, v_sw: solar-wind velocity) for different ion components of the solar wind as observed from Earth's or Ulysses orbit: bulk solar wind, pick-up ions originating from interstellar neutrals, and pick-up ions originating from the inner source.

Downstream from the pick-up point the radius of the distribution shrinks due to deceleration as a result of solar wind expansion. In effect, the ions which were picked up at some point further upstream occupy the inner part of the sphere in velocity space, while the freshly picked up ions fill the outer shell (as seen in Figure 15). In the case when the inner source dominates, the distribution downstream from the source would be relatively narrow, as indeed is observed by Ulysses.

The production of inner source pick-up ions is assumed to be correlated with the presence of dust since the production rate increases towards the Sun (Gloeckler and Geiss, 1998). Any of the mechanisms discussed above can then contribute to the inner source (Gloeckler and Geiss, 1998, 2001; Schwadron and Geiss, 2000) but so far no quantitative arguments have been developed to confidently identify the relative importance of the various processes. To trace the composition, origin, and evolution of dust in the inner solar system, simultaneous measurements of dust fluxes, dust mass distributions, magnetic field parameters, and pick-up ions are of great importance.

A further point to be mentioned in the context of dust interactions concerns the influence that dust impacts have on spacecraft environments. As a result of the velocities expected for dust in the inner solar system, dust impacts on a solid target in space cause complete vaporization and partial ionization of the dust particle and also of the target material in the region of impact. The signatures of the impact ionization plasma clouds have been observed before with plasma wave dipole antennas, plasma analyzers, and magnetometers sensing the electric space charge, the ions, and the diamagnetic effect, respectively. Events related to dust impacts were seen by the Voyager 1 and 2 spacecraft during crossing of the Saturn and Uranus ring planes (Gurnett *et al.*, 1983; Meyer-Vernet, Lecacheux, and Pedersen, 1986, 1996) as well as in interplanetary space in the outer solar system where the background noise is reduced (Gurnett *et al.*, 1997). Other signals in plasma and magnetic field measurements that are connected to dust impacts were detected by spacecraft encountering comet Giacobini-Zinner during the ICE (International Cometary Explorer) mission (Gurnett *et al.*, 1983), comet Halley during the Giotto mission (Neubauer *et al.*, 1990; Oberc and Parzydlo, 1992), and comet Borrelly during the DS1 mission (Tsurutani *et al.*, 2003a, 2003b). However, the complexity of the impact ionization process and the magnetic field response prevent derivation of exact parameters of the impacting particles 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. Discussion

The major sources of the dust population in the inner solar system are long- and short-period comets and asteroids, with interstellar dust contributing a minor portion. 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 production of dust from comets and cometary fragments inside Earth orbit is confirmed by the observation of sungrazing comets. The amount of the dust production from comets between 0.1 and 1 AU from the Sun cannot be accurately estimated at this time but it is likely that the contribution from sungrazing comets is negligible in the context of the overall dust environment in the inner solar system. The loss processes are: dust collisional fragmentation, sublimation, radiation pressure acceleration, sputtering, 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 of the spatial distribution of dust 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 submicrometers, 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.

Although the solar environment can be directly seen from Earth, observational results do not provide a full picture of either the dust properties near the Sun or its interactions with the surrounding interplanetary medium. The outcome of the SOHO mission shows that even excellent remote observations cannot provide complete insight into the physical processes associated with dust particles in a plasma and magnetic field environment. As a result of the LOS geometry, the remote corona observations are strongly influenced by brightness components that originate 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 cross-sectional area. 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 and model calculations. The parameters of collisional fragmentation are derived from empirical scaling laws. The heating of dust particles is numerically determined by the balance of absorbed and emitted radiation and sublimation parameters are sometimes 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 using only the materials and conditions that can be realized with dust accelerator experiments. Yet, all these processes occur within normally quite different cosmic environments. The inner solar system is a unique environment requiring in-situ studies. The case for understanding electric surface charge is illustrative. 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 us to measure all relevant parameters, like 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 these reasons we recommend that in-situ measurements be taken. The main goals for these measurements are to study the collisional 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 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 various 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 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 and are suggested, for instance, for Solar Orbiter Mission (Mann *et al.*, 2001; Palumbo *et al.*, 2001). Their scientific return can improve through combination with laboratory studies and help to constrain models of the dust 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.

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