DUST-PLASMA-GAS INTERACTIONS IN THE HELIOSPHERE

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ABSTRACT. Several different forms of how neutral gases and dusty media can interact with a plasma have been discussed in the literature. Common to all of these interactions is that they in principle lead to changes in both the composition and dynamical state of all interacting media. The most important scenarios in the heliosphere involving these kinds of interactions are described in this paper. Special emphasis is placed on the solar wind interaction with the zodiacal dust. In regard to the dust, this leads to severe complications with respect to its dynamics due to the plasma Poynting- Robertson effect and due to Lorentz scatterings. As for the plasma, this causes the appearance of dust-generated neutrals and secondary ions. An influence on the plasma dynamics, at least in the present solar system, can be neglected. The surface chemistry of the plasma-dust reactions is described in some detail here, and the densities and fluxes of exotic, dust-generated ions not originally belonging to the coronal solar wind are calculated. Observabilities of these neutrals and ions are investigated and it is discussed how physical, chemical, and dynamical parameters of the zodiacal dust cloud could be derived from these observations.

1. GENERAL INTERACTION SCENARIOS IN THE HELIOSPHERE

It is well known that neutral gases and magnetized plasmas cannot freely penetrate each other. The reason why a relatively strong plasma-gas coupling occurs is a rapid pick-up of newly created secondary ions by means of the magnetic fields which are frozen into the plasma and thus reflect the plasma dynamical state. Secondary ions are generated from neutrals either via photoionization, charge exchange, electron impact ionization, or critical velocity ionization (see, e.g., Holzer, 1977; Petelski et al., 1980; Formisano, Galeev and Sagdeev, 1982). Hence they belong, immediately after their creation, to the dynamical state of the neutral gas. Their incorporation into the plasma via electromagnetic re-acceleration to the plasma bulk speed results in a corresponding change of the momentum density of the plasma, leading to a deceleration and a nonthermal heating of the plasma (discussed by Holzer and Axford, 1971;

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Fahr, 1971; Axford, 1972; Fahr, 1973; Holzer and Leer, 1973). For the plasma, this can be described as a local effect inducing a systematic change of the plasma properties. In contrast, the local neutral gas properties are not affected by secondary neutrals because of their large mean free paths. This will in general lead to the existence of two independent populations of neutrals in velocity space.

A large series of interaction phenomena in the heliosphere are characterized by processes based on momentum and energy exchanges between gases and plasmas. For instance, in the context of planetary exospheres, plasma-gas interactions take place in two different forms:
(a) The interaction of neutral atmospheres and ionospheres of planets causes an enhanced escape of neutral gases from the planetary gravitational field. This topic has just recently been reviewed by Fahr and Shizgal (1983). While its importance for the terrestrial case has again been stressed recently in a paper by Nass and Fahr (1984), the extraordinary role of this interaction for the non-terrestrial exospheres has been emphasized in papers by Wallis (1978), Hodges and Tinsley (1981), Cloutier et al. (1978), Eviatar et al. (1979), Ip and Axford (1980), Goertz (1980), Brown and Schneider (1981), Goertz and Ip (1982), and Ip (1982).
(b) The interaction of the neutral atmosphere of a comet or an unmagnetized planet, as for instance the planet Venus, with the approaching solar wind plasma leads to a solar wind mass loading, a plasma flow deceleration and possibly a shock-free transition to a subsonic solar wind flow (Biermann et al., 1967; Wallis, 1974). This, on the other hand, leads to an additional escape of atmospheric constituents (Bertaux et al., 1978; Richter et al., 1979).

More diffuse forms of a plasma-gas interaction, spread out in space over several 100 AU, are represented by the interaction of the local neutral interstellar medium with (a) the perturbed plasma regions ahead of the heliosphere and (b) with the supersonic solar wind in the heliosphere. Such interaction phenomena have been quantitatively treated for case (a) by Wallis (1974), Ripken and Fahr (1983), Wallis (1984), Fahr and Ripken (1984); and for case (b) by Axford (1972), Holzer (1977), Fahr et al. (1981a), Petelski et al. (1980), and Fahr et al. (1981b). It has been shown by the latter authors that a rigorous treatment of these interaction problems requires the simultaneous solution of a set of coupled differential equations describing the continuities of mass, momentum, and energy fluxes of both neutral and ionized media. The plasma and gas dynamics are formulated in a hybrid form of magnetohydrodynamic equations containing terms derived in a kinetic form that takes account of the exchanges of mass, momentum and energy between the two media. The terms that couple the two sets of differential equations describe the corresponding exchange rates per unit time and volume connected with the newly created ions and neutrals. A plot of typical solar wind and neutral gas properties resulting from this mutual interaction is given in Figure 1. Due to the large mean free paths of neutrals with respect to collisions with their own species, primary and secondary neutrals behave as independent populations. Thus, in this case, no momentum change of the primaries occurs. Thus for the neutrals we have given in Fig. 1 values only for the corresponding densities.

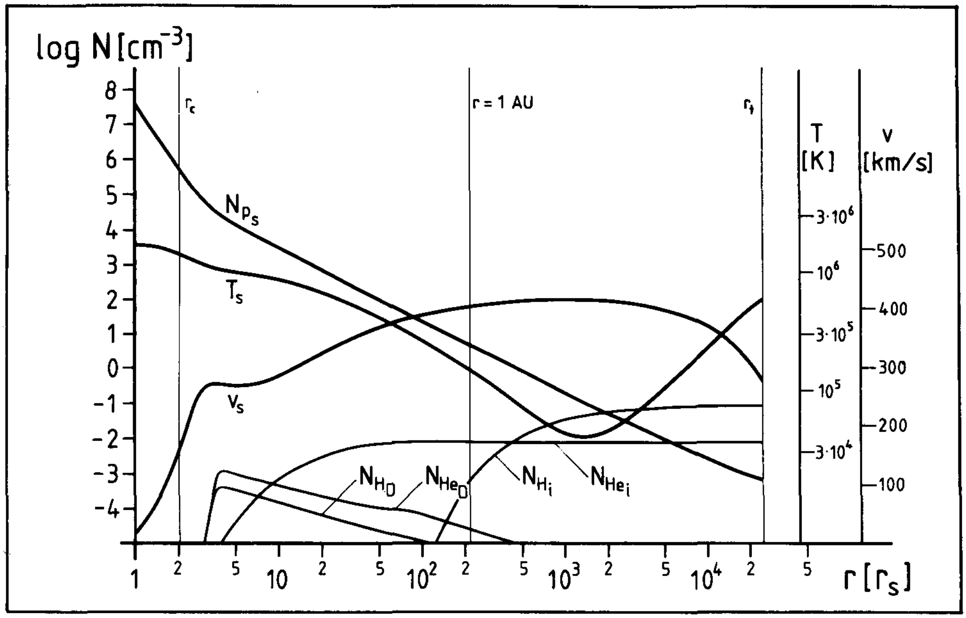

Figure 1. Solution for a solar wind-interplanetary neutral gas interaction model. Solar wind parameters shown are the velocity v_s, temperature T_s, and proton density N_{p_s}. Four density curves of the neutral gas are given: interstellar hydrogen N_{H_i} and helium N_{He_i}, dust-generated hydrogen N_{H_D} and helium N_{He_D} (Fahr et al., 1981b).

We now address the role of dust particles in the gas-plasma interaction scenario. It has become evident by measurements of the zodiacal light (Giese, 1977; Leinert et al., 1977; Schwehm and Rohde, 1977) and the F-corona of the sun (Koutchmy and Magnant, 1973; Beard, 1979), and by infrared measurements of dust emissions and by direct particle detection of dust particles, that the sun, even in its closest environment, is surrounded by dust particles of different physical, chemical, morphological, and dynamical properties. These dust particles are known to have amorphous, fluffy structures rather than a highly organized cristalline consistency, and mostly they are of a silicate or carbonate type. Within the solar wind regime, these particles give rise to a plasma-solid body interaction. The most evident form of such an interaction is an ion and electron interception by the dust surfaces due to the impinging solar plasma. Seen from this aspect, dust particles should simply serve as sinks in the plasma flow, leading to an extraction of some plasma species from the flow. The ion and electron bombardment of the dust surfaces, in competition with the photoelectron emission and thermionic emission (see e.g. Millet et al., 1980; Lafon et al., 1981), will soon lead to an equilibrium electric charge of the dust particle and to a balanced rate by which, in response to the impinging ions, some neutral products will desorb from the surface. The details of this process are considered in section 3 of this paper. It can be already mentioned here that whenever saturation of the outer cristalline lattice of the dust particles with trapped neutralized solar wind ions is reached, these surface layers act as a prompt converter of ionic species into neutral species. Dust particles therefore act as sources of neutrals in the solar wind regime.

If the dust particles would act only as a sink of ions, no influence on the solar wind bulk velocity could be expected since the kinetic energy per mass would not be changed by this process. However, due to the fact that dust particles act as sources of neutrals, most probably as sources of hydrogen and helium atoms (as is discussed later), a momentum exchange of these neutrals with the solar wind plasma flow occurs that will influence the solar wind dynamics in just the same way as the interstellar neutrals do.

However, one can easily estimate that under the present conditions of the tenuous zodiacal dust cloud no significant change of the unperturbed solar wind momentum flow is possible. Assuming an average dust cross sectional area per unit volume of G = 1.0E-18 cm-1 (see, for instance, Banks, 1971; Holzer, 1977) at the Earth's orbit and adopting a radial dust density dependence according to $n = n_E(r_E/r)^{1.3}$, one arrives at the following probability of converting an original solar wind ion on its way from the corona through the zodiacal dust cloud into one with vanishing radial velocity

$$W = 1 - \exp \left| - \int_{2r_\odot}^{\infty} (r_{E/r})^{1.3} dr \right| = 2\cdot 10^{-2} \qquad (1)$$

Thus only about two percent of the outflowing coronal solar wind ions will be converted due to reactions at zodiacal dust surfaces.

For the T-Tauri phase of the sun conditions may have been very different because in the phase immediately following the collapse of the protosolar cloud, primordial dust which preferentially settled down into the ecliptic plane (see, e.g., Morfill, 1983) may have caused much higher values of G there. Thus it may be very likely that the T-Tauri-phase solar wind was choked off totally near the ecliptic plane and only could expand to larger distances only at higher ecliptic latitudes. In addition, as was shown by Fahr (1980) and Ripken and Fahr (1980), the solar wind may not have had developed at all during the early phases of the solar system when the protosolar core still was surrounded by high density gases and dust. Later on, however, after the development of a supersonic solar wind phenomenon, the passage of the heliosphere even through a very dense interstellar dust or gas cloud cannot lead to a choke-off.

2. REACTION KINETICS AND THE MINOR IONS PROBLEM

Neutral gas in the solar system is being generated by plasma interaction with saturated solid body or dust grain surfaces, as was discussed in the previous section. Solar wind ions with energies in the keV range impinge onto the surfaces and penetrate about 10 to 100 nm into the mineral (Lord, 1968; Ducati et al., 1973). At the end of the particle trajectory, neutralization via electron capture occurs. The newly created neutrals are temporarily retained in the dust grain, undergoing diffusion processes and chemical reactions. Depending on the type of mineral, hydrogen atoms react to form OH, water, and hydrogen molecules (Zeller et al., 1966; Zeller and Ronca, 1968; Cadenhead and Buergel, 1973; Fastie et al., 1973), as well as various carbon and silicon hydrids. Helium, generated from deionized solar wind alpha particles, will stay in its atomic form. The grains cannot accumulate intercepted particles indefinitely; saturation occurs on very short time scales compared to the typical Poynting-Robertson residence times in the inner solar system (Fahr et al., 1981b). After saturation is reached, on the average one molecule or atom will be released from the dust grain surface for each impinging solar wind ion.

For particles released from the surface by an evaporative process, the initial orbital dynamics essentially are the same as those of the parent grains and can be calculated in an analogous manner (Banks, 1971; Burns et al., 1979; Hughes, 1980). These particles are immediately subject to strong interaction processes with the solar wind and with the solar radiation field. Photoionization, charge exchange reactions, electron impact ionization, and molecular dissociation take place. Ionized particles will be "picked up" by the magnetized solar wind plasma and form singly-charged secondary solar wind constituents (protons, helium ions, and ionized molecular hydrogen). In addition, singly-charged hydroxyl, carbon and silicon hydrids, and other molecular ions are formed in this process, depending on the type of the parent grain. Only very few dust-generated neutrals will reach the orbit of the Earth as low-energy neutral particles.

Besides these surface-evaporated particles, the processes of erosion, disruption, sputtering, vaporization, and sublimation of dust grains generate atoms, molecules, and clusters of molecules not containing solar wind material as prime constituents. With observed average erosion rates of about 0.001 nm/yr (at the orbit of the Earth) and an average sputtering yield of 0.03 atoms per incident ion, the dust surfaces are saturated and fully reduced (see, e.g., McDonnell and Ashworth, 1972; McDonnell et al., 1976; Flavill et al., 1980). The neutralized solar wind particles will predominantly desorb as molecular hydrogen from the grains. The non-solar wind material, in its singly-charged ionic forms, is subsequently incorporated into the solar wind and can be traced as very minor constituents. The most prevalent ones are ions of oxygen, silicon, iron, and carbon compounds.

The generation of solar wind minor ions by means of plasma-dust interaction processes takes place predominantly in regions very close to the sun (heliocentric distances of 4 to 20 solar radii) where erosion, sputtering, and desorption processes are strongest and where the dust particle density is highest. Figure 2 shows the mean densities of solar wind ions (protons and alpha particles), of interstellar neutral gas (hydrogen, helium, and oxygen), and of dust-generated singly-charged solar wind minor ions. Singly-charged helium is also being generated by ionization of interstellar neutral helium; this causes the double-hump signature of the N_{He^+} density curve. Analysis of ionized dust grain molecules (not shown in Fig. 2) can give substantial insight into the physical and chemical composition of the zodiacal dust cloud, whereas an analysis of the elemental abundances of converted solar wind material yields information on sputtering and erosion rates.

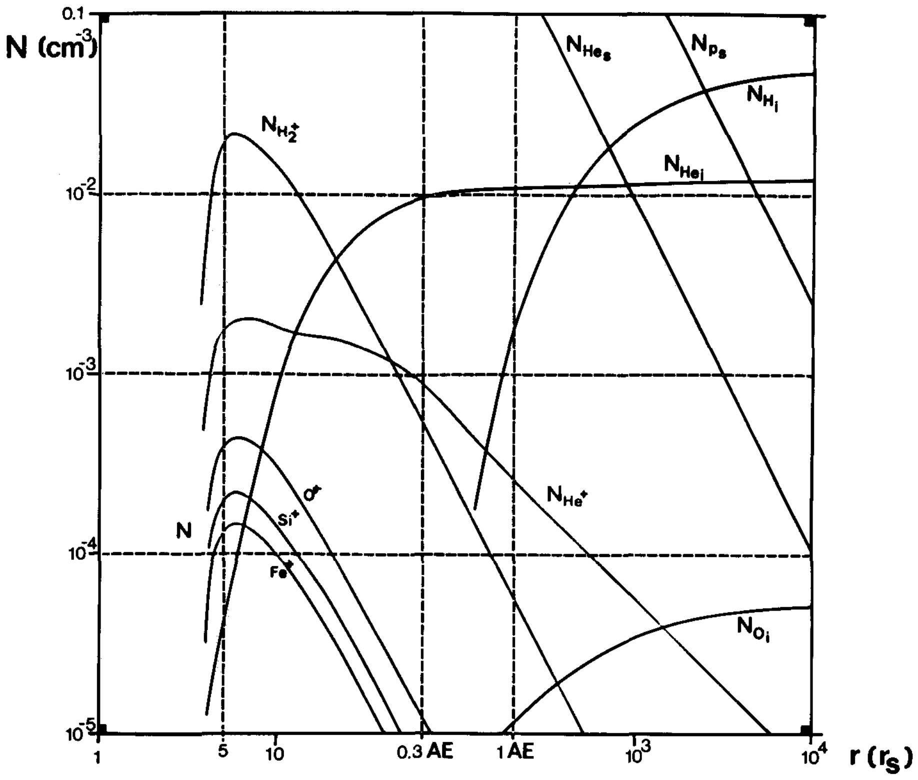

Figure 2. Shown versus solar distance in units of r_s (solar radii) are densities of various interplanetary neutral and ionic species. N_{O_i}, N_{H_i}, N_{He_i} are interstellar oxygen, hydrogen, and helium densities. N_{p_s} and N_{He_s} are solar wind proton and alpha particle densities. The remaining curves present densities of secondary ions in the solar wind regime that are due to dust-plasma-gas interactions as described in section 2: H_2^+, He^+, O^+, Si^+, Fe^+ ions.

In the past, several observations of exotic minor ions in the solar wind have been accomplished. Recently Bame (1983) reviewed the more important measurements. Singly-charged helium is an invaluable tracer of the solar wind-dust grain interaction process, and has been observed for example by M/Q mass spectrometers onboard IMP 7, VELA 5A, and HELIOS I. While normal or hot spectra show adequate fits of count rates by calculated ionization state envelopes, cold plasma can exhibit prominent peaks of surplus ions, i.e. singly-charged helium, and double- and triple-charged oxygen. Threshold limits of the present instruments prohibit the detection of the minor ion background of dust-generated origin; the background is expected to reach about 10% to 15% of the observed anomalous surplus component discussed above.

3. PLASMA-INDUCED DYNAMICS OF DUST PARTICLES

As was already noticed many years ago (e.g. Haug, 1958; Briggs, 1962; Divari, 1968), the interplanetary dust density distribution is closely connected with the interplanetary dust dynamics and the relevant dust particle sources inside and outside of the solar system. This connection results from the fact that the dust density is expressed as a 3-dimensional velocity space integral of the velocity distribution function $f_{\mathfrak{D}}(\underline{r},\underline{v})$ of interplanetary dust particles which in turn is determined by Boltzmann kinetic approaches employing the dynamical trajectories of dust particles. Except for the protosolar collapse phase, a kinetic approach to the problem is always justified in the later stages of the solar system evolution. This is correct even in view of stochastic scattering processes of electrically charged dust particles with the varying solar wind magnetic fields (first studied by Parker, 1964) and in view of systematic drag effects of the solar wind plasma sweeping over the dust grains (treated, e.g., by Lamy, 1974a).

Therefore the Boltzmann integro-differential equation will always yield a proper formulation of the function $f_{\mathfrak{D}}(\underline{r},\underline{v})$ dependent on the dynamical variables $\underline{r}$ and $\underline{v}$, i.e. the position and velocity vectors of the dust particles. Together with the boundary conditions for the dust, a solution of this function can then be generated provided that the dust dynamics is known. Many attempts to determine the dust dynamics under a variety of complicating conditions connected with the radiation and plasma environment of the dust have been undertaken in the past (the most important contributions were given by Briggs, 1962; Parker, 1964; Lamy, 1974a,b; Burns et al., 1979; Mukai, 1981; Mukai and Yamamoto, 1982; Morfill and Grün, 1979a,b; Barge et al., 1982b; Mukai and Giese, 1984). In a paragraph later in this section we will briefly review these attempts.

If the dynamical trajectories of individual dust particles can be given in a mathematically satisfactory form for each set of dynamical variables, it is advised to transform the Boltzmann equation into its characteristics form (see, e.g., Hays and Liu, 1965). Here the invariance of $f_{\mathfrak{D}}$ along the dynamical trajectory is formulated, assuming no dust particle sources and sinks. This then allows a solution for the function $f_{\mathcal{D}}$ if at some boundary surface the value for $f_{\mathcal{D},\infty}$ is known.

Rigorous formulations of this problem in terms of the Boltzmann kinetic approach in its original form have been given by Morfill et al. (1978), Völk et al. (1978), and Fahr et al. (1981b). Fokker-Planck type treatments of the problem have been used by Morfill and Grün (1979a,b), Consolmagno (1980), Barge et al. (1982a, b), and Mukai and Giese (1984) in order to include the additional difficulty of Lorentz-force-induced stochastic scattering of dust particles by the solar wind magnetic fields.

For a realistic solution of these types of equations both the appropriate boundary conditions of the dust problem and the dust dynamics have to be known. For the interstellar dust particles one would need information about the function $f_{\mathcal{D},\infty}$ at the border of the solar system, e.g. on a closed boundary surface surrounding the sun at a sufficiently large distance. For the zodiacal dust problem some complication arises from the fact that the origins of this dusty material are not securely known. As for the component connected with the primordial dust of the collapsing solar cloud still entering the inner solar system from beyond the asteroid belt, one needs to know the accretion rate and distribution of inclination angles of the orbital planes. The contribution to the zodiacal dust cloud from asteroid belt material requires information about density, mass, and size distributions of this material, while the initial orbital elements of its motion can be assumed to be known. In regard to the cometary dust release, one needs to know the source functions of dust particles (a) as functions of time and position in interplanetary space and (b) as functions of size and orbital elements of generated particles. In addition to these somewhat open boundary conditions, the solution of the dust problem requires a determination of the dust particle dynamics. This problem has a variety of aspects that can only briefly be touched here.

Dust particles are generally assumed to move at each instant of time along specific Keplerian orbits around the sun, either hyperbolic, elliptic (ballistic), or parabolic. These particles, however, are subject to non-conservative forces which cause secular temporal changes of the orbital elements such as total energy, angular momentum, eccentricity, and semimajor axis. Among these forces, the classical Poynting-Robertson effect (see Robertson, 1937) and its plasma analogon, the plasma Poynting-Robertson effect, have to be considered as the most important ones. The P-R effect for orbiting dust particles, simply expressed, results from the fact that solar material (photons and/or ions) with a specific velocity vector is adsorbed at the dust grain surface per unit time; this is equivalent to a temporal change of the dust particle momentum. This obvious principle of mass charging has not always been presented clearly in the literature. This has its roots in the somewhat confusing and in its quantitative form incorrect presentation of this effect by Robertson (1937). As pointed out by Burns et al. (1979), the radiative P-R effect is caused only by the momentum change due to an absorption of solar photons by the dust grains. It does not have a second contribution from a later photon reemission from the dust particle when the grain is in radiative equilibrium. It is evident that an isotropic emission from a moving particle cannot cause its deceleration and will not lead to a net drag force in the solar rest frame.

Both the radiative and the plasma-induced P-R effect lead to non-conservative forces with a radial and an orbital force component connected with radiation and plasma pressure and with an angular momentum loss. Quantitative calculations on the basis of Mie scattering theory lead Mukai and Mukai (1973), Lamy (1974b, 1976), Schwehm (1976), and Burns et al. (1979) to the conclusion that the P-R pressure (except for iron and magnetite grains of sizes between 0.2 and 0.06 microns) does not compensate gravity. Iron particles smaller than 0.06 microns will again be subject to an attractive solar force field. Furthermore, it is found by Lamy (1974b), Burns et al. (1979), Mukai and Schwehm (1981), and Mukai and Yamamoto (1982) that the plasma-induced P-R effect is only a small addition to the radiative effect, the radial component being totally negligible and the orbital component attaining up to 20% of its radiative counterpart. These results remain unmodified whether or not the plasma ions impinging on the dust surfaces stick there, or are deflected, or cause in addition some sputtering or evaporation of dusty material.

For the temporal change of the orbital elements of particles moving in quasicircular orbits, one arrives at the following results:

$$\frac{de}{dt} = \frac{H}{gmM} \left| F_r \cdot \sin \phi + F_o(\cos \phi + \cos \Psi) \right| \tag{2}$$

$$\frac{da}{dt} = 2 \left(\frac{a^2}{mH}\right) \left| F_r \cdot e \cdot \sin \phi + F_o(1+e \cos \phi) \right| \tag{3}$$

where m = dust particle mass, M = solar mass, a = semimajor axis, e = eccentricity, H = angular momentum per mass, g = gravitational constant, ϕ = true anomaly, and Ψ = eccentric anomaly. F_r and F_o are the radial and orbital components of the total P-R force. Since no normal (latitudinal) component of this force exists, the inclination angle i of the dust particle orbit is not subject to a first order temporal change. A change of this quantity, however, results from stochastic Lorentz force scatterings that electrically charged particles at small and moderate ecliptic latitudes suffer while moving on their main trajectories in interplanetary magnetic fields of alternate polarities. This kind of plasma-induced diffusion of charged dust particles moving near the ecliptic plane has been carefully treated by Morfill and Grün (1979a,b), Consolmagno (1980), Barge et al. (1982a,b), and Mukai and Giese (1984). For an as realistic as possible determination of this diffusion effect, Morfill and Grün (1979b) calculate values of the needed Fokker-Planck diffusion coefficients in velocity space. However, in this effort they have used the incorrect assumption that the electrically charged particles, while moving in the interplanetary magnetic fields, do not suffer any kinetic energy changes. This is true only in a reference frame co-moving with the solar wind plasma in which the magnetic fields are frozen-in. In contrast, in the solar reference system also electrical forces will be noticed by the dust particles with charge Q and a velocity $\underline{v}_{rel}$ relative to the plasma flow. Thus the kinetic energy L will change in time by

$$\frac{dL}{dt} = \frac{Q}{c} \left[\underline{v} \cdot (\underline{v}_{rel} \times \underline{B})\right] \tag{4}$$

where $\underline{v}$ is the orbital velocity of the dust particle. Thus the changes of the parallel and perpendicular velocity components are not related anymore by

$$d\, v_{\parallel} = -\, d\, v_{\perp} \frac{v_{\perp}}{v_{\parallel}} \tag{5}$$

as used in Morfill and Grün (1979b), unless particles with orbits in the ecliptic plane are considered for which the scalar triple vector product vanishes. This fact had already been noticed in the work of Parker (1964), in which the Fokker-Planck type diffusive treatment was first applied to the problem of charged zodiacal dust grain motions influenced by Lorentzian forces due to interplanetary magnetic fields. As could be shown in this early approach, an appreciable increase of the inclination angles i of dust particle orbits can be expected for dust particles of diameters less than 1 micron that move in the ecliptic plane.

A much more thorough and comprehensive treatment of this problem, on the basis of the Fokker-Planck equation in the diffusive approximation derived by Chandrasekhar (1943), was published recently by Barge et al. (1982a, b). In their first paper, the authors give a very fundamental derivation of the Fokker-Planck equation describing diffusive motions in 3-dimensional parameter space for particles orbiting in first-order Keplerian orbits with eccentricity e, semimajor axis a, and inclination i. The diffusion formalism is developed on a very general physical basis and can in this form even be applied to very different stochastic diffusion processes, as for instance the cosmic ray propagation in the fluctuating interplanetary magnetic fields. The diffusion terms are obtained as functions of the time-integrated components of the Lorentzian perturbation forces. However, this theoretical approach is only viable if the orbital revolution periods of the dust grains in their first-order orbits can be considered to be long in comparison to the characteristic fluctuation periods of the perturbation forces. Thus, this approach does not seem to be applicable for close solar orbits with $a < 40\, r_s$ if magnetic sector passages are to be taken as indicative for the fluctuation periods.

In their second paper (Barge et al., 1982b), the authors make use of their very general formalism, applying it to the concrete problem of the stochastic Lorentz force scatterings of dust grains with diameters between 1 micron and 0.2 micron. As is pointed out here for the first time, the Lorentz scattering process is composed of three different contributions due to independent fluctuations of the three quantities Q, $\underline{v}_{rel}$, and $\underline{B}$ appearing in Eq. (4). As will be mentioned later in the text, the electric charge of the dust grain, Q, fluctuates in accordance with solar wind density and velocity changes with a small time delay of about one day (i.e. the charging time scale; Hill and Mendis, 1979). Thus, Q and $\underline{v}_{rel}$ fluctuate in the rhythm of successive high speed and low speed solar wind signatures. The stochastic diffusion thus is driven by magnetic sector structures corotating with the sun and by the temporal changes of the solar wind plasma properties.

In their calculations of the time-averaged changes of the first order orbital elements a, e, and i an integral scattering time Δt of 10 years has been used by the authors. This time interval Δt may sometimes become a critical quantity, since the Fokker-Planck treatment requires it to be both very long in comparison to the fluctuation periods and very short in comparison to the long period orbit evolution, i.e. the P-R residence times.

An interesting result of the study of Barge et al. (1982b) is the detection of the resonant character of the diffusion. the diffusion in parameter space is greatest for orbits with revolution periods that are multiples of the relevant fluctuation periods. Thus, it must be noted that diffusion ceases to operate inside the corotation orbit ($a < 37\ r_s$). Therefore the general result of the paper, that the main diffusion effect concerns the inclination angle i and occurs at solar distances between 20 to 60 r_s, has to be taken with some caution. It remains open whether or not the observed zodiacal dust distribution at high inclination angles (Leinert et al., 1976) can be ascribed to the operation of stochastic Lorentz scatterings on primary dust grains in the ecliptic plane slowly spiralling inwards. If stochastic Lorentz scatterings are indeed negligible, one is left with the alternate hypothesis that the original dust population already contains an appreciable fraction of high inclination orbits. At least for dust particles with radii larger than 0.5 micron this seems to be an unavoidable conclusion because they are nearly unaffected by the solar wind and interplanetary field environments.

The charge to mass ratio of the dust particles is strongly varying with the dust material and the environmental conditions of the dust particles. As a general fact it can be stated (Consolmagno, 1980) that the electric charges are very much size-dependent and may vary between electric voltages of +40 V and -10 V.

More careful studies of the specifics of the dust grain electric charging under different radiative and plasma environmental conditions have been carried out by Millet et al. (1980) and Lafon et al. (1981). Both papers use the concept of free orbital motions of electrons in the electric field of the charged dust grains. The field is assumed to be a radially symmetric Coulomb field; the space charge induced field perturbations in the Debye surroundings of the dust grains are not taken into account. The Coulomb potential barrier with respect to the plasma potential is then consistently determined, adopting no net electric current flowing onto the grain in the steady equilibrium state. This is based on the fact that charging time scales are on the order of 1 day (Hill and Mendis, 1979). Free electron trajectories in the Debye sphere between the dust grain surface and the unperturbed plasma region are divided into elliptic, ballistic and hyperbolic categories. Knowing the velocity distribution functions for the electrons at these two boundary sides, one can determine that specific grain potential which suppresses the net electric flow onto the grain surface.

For the solar wind ions and electrons simple Maxwellian and bi-Maxwellian velocity distribution functions have been adopted in the solar wind rest frame. The distribution functions for electrons leaving the dust grain surfaces are determined by the photoelectric emission (Lafon et al., 1981) and the thermionic emission from the surface (Millet et al.,1980). As is shown by the latter authors, the thermionic emission starts to play an appreciable role in the circumsolar regions inside 10 r_s where the grain temperatures according to Mukai and Yamamoto (1979) or Lamy (1974) increase to values beyond 1000 K. If the thermionic emission of the electrons out of the solid grain surface is treated in the Sommerfeld approximation, i.e. no electron coupling with the crystalline lattice, distibution functions can be generated relatively easy. With the use of this approximation Millet et al. (1980) can show that the electric charging effect by the dense solar wind plasma in the close solar environment, yielding according to earlier publications (Lefevre, 1975) negative potentials of -40 V to -120 V, is very much reduced in this region and even inverted to positive potentials inside solar distances of $r < 7\ r_s$. An electric disruption of the grains in this region thus does not appear very likely. The effect of intercepted solar wind ions is also studied by Lafon et al. (1981) who can show that, dependent on the grain temperature, a strong dependence of the grain potential on the solar wind bulk speed relative to the grain is apparent. For higher bulk velocities the intercepted ion current is strongly enhanced and the net negative potential of the grain is thus effectively decreased. These results also show that the grain potentials will vary strongly with the signature of the ambient solar wind, i.e. high speed or low speed wind, moving compression regions etc.

As was pointed out by Morfill and Grün (1979b), systematic effects resulting in a focusing or defocusing of dust particle orbits with respect to the ecliptic plane occur for particles moving at higher ecliptic latitudes under unipolar field conditions. For particles orbiting within the ecliptic plane, a stochastic scattering occurs due to repeated passages through magnetic sectors of opposite polarity. The overall effect of this kind of diffusive motion in configuration space and velocity space on a steady state zodiacal dust density distribution has recently been considered in some detail by Mukai and Giese (1984).

They find that the enforced diffusive motion perpendicular to the ecliptic plane results in a steady increase of the dispersion of the inclination angles i. Thus, the steady state radial density gradient obtained by $n = n_E (r_E / r)^{1.3}$ for the P-R effect alone steepens somewhat for particles with sizes between 30 to 50 microns. These particles contribute most to the zodiacal light intensity. This result depends on the inherent assumption that Lorentz scattering in the ecliptic plane unilaterally leads to a diffusive loss of particles out of the unperturbed orbits without compensation by diffusive gains from orbits at higher ecliptic latitudes.

Drawing a conclusion from all this, it can be stated that for those dust particles that predominantly contribute to the light scattering from zodiacal dust, i.e. particles of sizes between 30 to 50 microns (Hughes, 1980) a relatively simple motion in quasicircular Keplerian orbits can be assumed in first order for most of their lifetimes in the inner solar system. This conclusion is possible since the secular changes of the orbital elements have very long time periods compared to the orbital

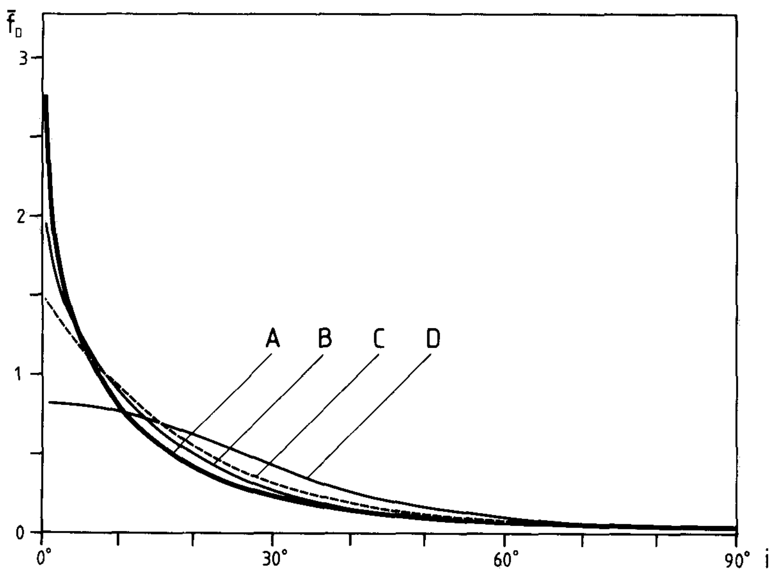

Figure 3. Distribution function $f_D(i)$ of dust particle orbital inclinations i at an arbitrary point in the ecliptic. The solid lines give three solutions for $f_D(i)$ based on different dust density distributions. Parameters are for curve A: $C = 2.1$, $H = 1$ (Leinert et al., 1978;) for curve B: $C = 2.6$, $H = 1.3$ (Leinert et al., 1976); for curve D: $C = 2.1$, $H = 2.0$. The dashed curve C shows $f_D(i) \sim \exp(-3i)$ (Bandermann, 1967).

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revolution periods, for particles not too close to the sun. In the close solar environment where rapid changes of mass and size of the particles due to enhanced melting, sublimation, and sputtering rates occur, the dynamics may be much more complicated (Lamy, 1974b; Mukai, 1981).

On the basis of a zodiacal dust density distribution as derived by Leinert et al. (1978) from Helios zodiacal light measurements, one can derive a solution for the dust distribution function f_D in the form of specific integral equations. One will obtain integral equations of the Abel type or of the Volterra type (Fahr et al., 1981b; Buitrago et al., 1983) if a motion of the relevant dust particles in quasicircular orbits, with a specific separable distribution function for the orbital inclination angles i, is assumed. Under these assumptions one can show that the distribution function $f_D(\underline{r},\underline{v})$ can be separated into a product of functions in the form

$$f_D(\underline{r},\underline{v}) = f_{De}(e) \cdot f_{Da}(a) \cdot f_{Di}(i) \tag{6}$$

as was done by Haug (1958) and Divari (1968). If in addition only circular orbits are admitted, this representation of f_D can be still more simplified (see Leinert et al., 1976; Fahr et al., 1981b):

$$f_D(\underline{r},\underline{v}) = n_{0E} \left(\frac{r}{r_E}\right)^{-1.3} \cdot \bar{f}_D(\cos\tau \cdot \cos\varphi) \tag{7}$$

where φ is the ecliptic latitude angle and τ is the azimuthal angle of $\underline{v}$, measured in the local tangential plane of the circumsolar sphere with radius r.

Assuming a loss-free motion on these circular orbits as first order approximation, one is led to an Abel type integral equation that can be solved numerically and yields an explicit solution of the function $f_D(i)$ (Fahr et al., 1981b):

$$f_{Di}(i) = \frac{e^{-c}}{\pi} \left(\frac{1-J \cdot \cos^2 i}{1-\cos^2 i}\right) \quad \text{with} \tag{8a}$$

$$J = e^c \int_0^{\cos i} \frac{\left[1-h \cdot c(\alpha^2+\sin^2 i)^{\frac{h}{2}}\right] \exp\left(-c(\alpha^2+\sin^2 i)^{\frac{h}{2}}\right)}{\cos i} \, d\alpha \tag{8b}$$

In Figure 3 we have shown different alternative representations for this function f_D obtained under various assumptions.

One new interesting access to the dust distribution function $f_D(\underline{r},\underline{v})$ is offered by the observation of resonance radiation emitted from neutral gases, like hydrogen and helium, that desorb from the dust surfaces (see section 2). Assuming that these atoms desorb with velocities small in comparison to the orbital velocities of the dust grains, one can calculate the spectral profiles of the resonance luminence of dust-desorbed H and He atoms. One can then set the velocity distribution function of the dust particles to be equal to that of the resonantly scattering desorbed gases. If one thus uses the distribution function for f_D given in Equ. (8) as the velocity distribution function for dust-generated helium and hydrogen atoms, one can calculate exact spectral profiles of the He I 58.4 nm emission and the H I 121.6 nm emission. In Figures 4 and 5 such theoretical spectra are shown. The observation of these spectra can serve as a tracer to the dust dynamics in the close solar environment and is the aim of the EUV rocket experiment INTER-ZODIAK scheduled for launch in March 1985.

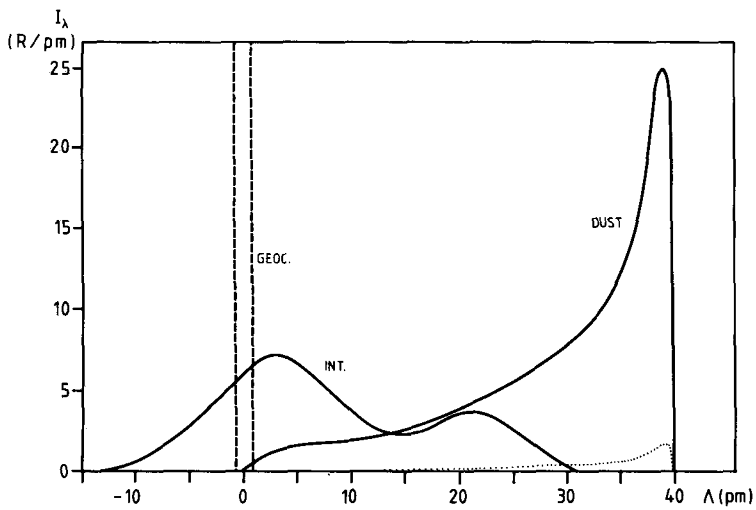

FIGURE 4: Spectral intensity distribution I_λ of resonantly scattered Ly-α radiation in Rayleigh per pm, versus distance from line center, Λ, in pm. The vertical dahsed lines mark the position of the geocoronal Ly-α intensity peak. The dust curves are given for ε = 0.9 (solid line) and for ε = 0.05 (dotted line) (see Fahr et al., 1981b)

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The experimental demands, to resolve with satisfactory resolution power the spectra shown in Figs. 5 and 6 and to suppress the geocoronal radiation contaminations encountered during a rocket flight, can only be fulfilled by application of resonance absorption spectrophotometric techniques. These techniques consist of the use of resonant atomic absorbers distributed along a specific part of the radiation ray path to the detecting photometer. For the spectral analysis of the Lyman alpha resonant emission profile one uses atomic hydrogen in the ground state, for the analysis of the helium emissions at 53.7 nm and 58.4 nm one uses helium atoms as resonant absorbers. The absorber gas is contained in a hermetically sealed cell. The cell is traversed by the relevant photons that enter and leave the cell through two oppositely mounted broad band filter windows, in a hydrogen cell made out of MgF_2 material, in a helium cell made out of a tin foil. These resonance cell techniques meanwhile are sufficiently well known and were described recently by Bertaux and Lallement (1984) for the hydrogen case and by Delaboudiniere and Carabetian (1975), Freeman et al. (1977), Fahr et al. (1977), Lay et al. (1978), and Crifo et al. (1979) for the helium case.

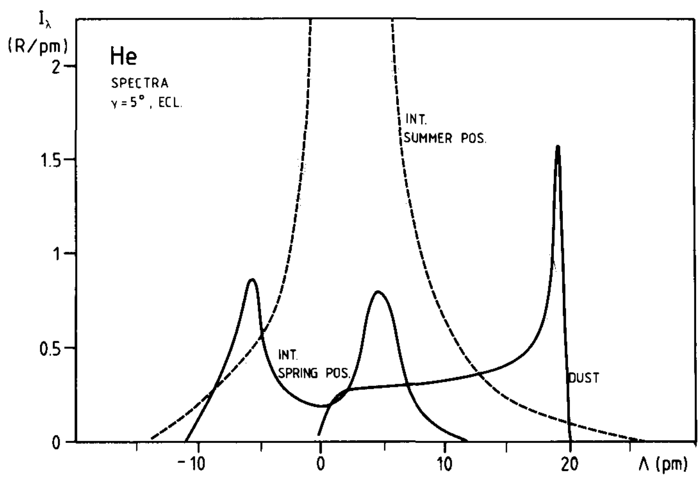

FIGURE 5: Spectral intensity distribution I_λ of resonantly scattered He I 58.4 nm radiation, in Rayleigh per pm, versus distance from line center, Λ, in pm. The interstellar radiation intensities are calculated for a geocentric observer on March 21 ("Spring Pos.") and on June 21 ("Summer Pos."). The dust-generated signal is independent of observation time.

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The emissions from dust-generated hydrogen and helium atoms are strongest in the close solar environment. Thus an experiment aiming at the identification of these emissions has to observe under as close as possible solar offset angles, only large enough to keep the solar coronal emissions at a contamination level that is tolerable. An experiment adhering to these restricting conditions has been conceived and optimized by Fahr et al. (1980) and is technically described in detail by Neumann et al. (1983). The experiment INTER-ZODIAK is aimed at the spectral analysis and total intensity measurement of resonance emissions from dust-generated hydrogen and helium atoms in the "ecliptic" and "out-of-ecliptic" 6-degree-solar-offset region around the sun, employing the resonance spectral absorption techniques.

Since the physico-chemical reactions between dust grains and the solar wind plasma relevant to the rate of helium atom production is known with the accuracy of the solar wind parameters, one will first evaluate the He I 58.4 nm spectra in order to derive basic characteristics of the circumsolar zodiacal dust cloud within 30 r_s. The absolute intensities of the resonance emission from dust-generated helium will yield a very good measure of the mean dust cross sectional area per unit volume and thus will help to find the absolute value for zodiacal dust density model fits, as for instance for that of Leinert et al. (1978). The intensity asymmetry apparent on a circular scan around the sun with a 6° solar offset will immediately reveal the particle size average of the inclination angle distribution $f_D(i)$. Furthermore, the spectral location of the intensity peak of the He I 58.4 nm emissions of dust-generated helium atoms will give a clear indication of the relevant dynamics of the dust in a 30 r_s circumsolar sphere. The ratio of the integrated intensities of H I 121.6 nm and He I 58.4 nm emissions will finally contain direct information about the chemical and physico-chemical conditions at the gas-desorbing dust grain surfaces.

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