7 January 1966, Volume 151, Number 3706 SCIENCE

Dynamics of Interplanetary Dust

The solar wind and its magnetic field complicate the study of dust in the solar system.

Michael J. S. Belton

Cosmic dust plays an important role in theoretical and observational astrophysics. It is apparently an important factor in the process of star formation. The polarization of starlight which is induced by aligned particles of interstellar dust gives information about the magnetic field in galactic systems, including our own. Through its wavelength-dependent extinction properties, it introduces uncertainties in the measurement of stellar distances and colors. In the solar system the presence of dust in a planetary atmosphere may lead to misinterpretations of photometric and polarimetric data that would otherwise give important information about the total mass of the atmosphere (*1*). And finally, dust is responsible for such interplanetary phenomena as the F corona, zodiacal light, gegenschein, and type-II comet tails.

With the advent of manned and unmanned space probes, there has been new interest in the properties of cosmic and, in particular, interplanetary dust particles in the vicinity of the asteroid belt. In order to design a system which will have a reasonable chance of completing a mission, the space engineer must have as complete a knowledge of the space environment as possible. In this respect the abrasiveness of high-energy dust particles has placed them high on the list of important environmental factors, and consequently their dynamics and their spatial distribution are of great current interest (*2*).

In this article I attempt to outline broadly our understanding of the properties of interplanetary dust. The dynamics of these particles is perhaps the most interesting aspect of the subject, particularly since we have come to realize (*3–5*) the important role of Lorentz forces and electrodynamic drags. In the classical discussion of the motion of zodiacal (interplanetary) particles, only their interaction with the solar radiation and gravitational fields was considered. I also discuss type-II comet tails. These tails, which are composed of dust particles, are intimately connected with the origin of the zodiacal cloud. They are also of interest in terms of a much wider problem: the origin of the solar system. Any clue regarding the origin and fabrication of the comets has traditionally been considered a clue to the origin of the solar system. In the past it was thought that the dynamics of type-II comet tails were well understood. Now this is far less certain.

I define dust particles as solid objects with linear dimensions smaller than 100 microns. The general physical and chemical structure of the interplanetary dust is still a matter of debate. Estimates of the characteristic mass densities range over two powers of 10, indicating a range from highly compact particles to "fluffy" dustball structures. Chemically the particles are of two known types: metallic and stony. Which type is predominant in interplanetary space remains an open question. It is possible that there is a third type, particles composed of what is loosely termed "ice"—that is, mixtures which are predominantly solid CO_2, NH_3, H_2O, and so on. Such particles may be injected into interplanetary space by the disintegration of comets or by direct accretion from interstellar space. While there is little doubt that such particles can exist for considerable periods in the far reaches of the solar system, within 5 astronomical units of the sun their lifetimes must be very short. To give an extreme example, a water-ice particle of 100-micron radius would evaporate in less than a year at a heliocentric distance of 5 astronomical units. It is therefore difficult to justify the view that ice particles are a major constituent of the dust in interplanetary space. Many attempts have been made to secure, in a way that rules out ambiguity, specimens of interplanetary dust; possible samples have been obtained from the ice caps, from the ocean bottom (by deep-sea dredges), from caves, and from the upper atmosphere (by high-flying airplanes and high-altitude rockets). Perhaps the most successful of these rocket studies was the "Venus flytrap" experiment (*6*), conducted some time ago by C. L. Hemenway and R. K. Soberman. Figure 1 (left) is a photograph of a particle, collected by these workers, which is thought to be a grain of interplanetary dust. The shape of this particle is especially interesting in view of the fact that, in the theoretical discussion, the particles are always assumed to be spherical.

The author is a junior astronomer in the space division of the Kitt Peak National Observatory, Tucson, Arizona.

Charge on Interplanetary Dust

Much of the discussion which follows is predicated on the view that the dust carries an electric charge. Thus, the problem of evaluating the magnitude and sign of this charge is a basic one. The electrodynamic drag force is proportional to the square of the charge, while the Lorentz force depends on both the magnitude and the sign.

The problem, of course, is not new to astronomy (*3, 4, 7*). But, despite the relatively large amount of attention it has received, the results of the various calculations (see Table 1) are, because the estimates vary widely and oscillate between plus and minus values, somewhat disturbing (*8*). Nevertheless, the variations in the results given in Table 1 are perhaps understandable when one considers the multitude of effects that must be taken into account. The difficulties which the investigator meets are not difficulties of principle but simply of detail. In calculating the equilibrium potential V, it is necessary to take into account at least the following processes occurring at the surface of the dust particle: photoelectric emission, electron and ion accretion, secondary electron emission, cold (high-field) emission, and possibly, at small heliocentric distances, thermionic emission. In a definitive calculation one must consider the influence of the chemical composition, motion, and shape of the particle. The investigator must have information about electron and ion densities and about temperatures in interplanetary space; knowledge of the reflection coefficients of the various impacting particles and data showing the dependence of these coefficients on impact energy; and information about the energy distribution of secondary particles and photoelectrons. Figure 2 illustrates the basic processes involved and indicates their dependence on local conditions.

The uncertainties in the calculations by which the estimates of Table 1 were obtained mainly derive from neglect of one or more of the effects shown in Fig. 2. Because of this I have attempted a calculation of this type (*9*). Despite the fact that the results are still somewhat unsatisfactory, it nevertheless seems worthwhile to discuss them here and to point out where the chief problems lie. I took into account, as far as was possible, all the effects shown in Fig. 2. Many simplifying assumptions were made. The interplanetary gas was considered to be a fully ionized electron-proton gas whose distribution in velocity space was representable by a flow velocity (solar wind) independent of heliocentric distance and a superposed Maxwellian velocity distribution. The particles were considered to be spherical, the calculations being made for two materials, iron and glass. It appeared that, due to the close similarity of their curves for photoelectric yield (that is, the number of electrons ejected per incident photon as a function of photon energy) in the vacuum ultraviolet, the resulting equilibrium potential was quite insensitive to the general nature of the material. This conclusion, however, must remain tentative until better data on the energy distribution of photoelectrons from various materials are available. Figures 3 and 4 show the results obtained for grains at 1 astronomical unit from the center of the sun for the indicated range of electron densities, temperatures, and relative solar-wind velocities. The dependence of the potential on heliocentric distance was found to be very weak, but we may expect to find a slight decrease in potential with decrease in heliocentric distance. As was perhaps to have been expected,

Table 1. Estimates of the equilibrium potential on dust particles in interstellar and interplanetary space. The potentials listed in the column headed "Cosmic dust" apply only in interstellar space away from the vicinity of hot stars.

Investigator	Date	Cosmic dust (volt)	Interplanetary dust (volt)
Jung	1938	+ 10	
Spitzer	1941, 1950	Between + 10.2 and − 0.16	
van de Hulst	1949	− 0.5	
Öpik	1956		+ 200
Kurt and Moroz	1962		Between + 4 and − 2.5
Wyatt	1963		"Strongly negative"
Parker	1964		+ 10
Chopra	1965		"Small and positive"

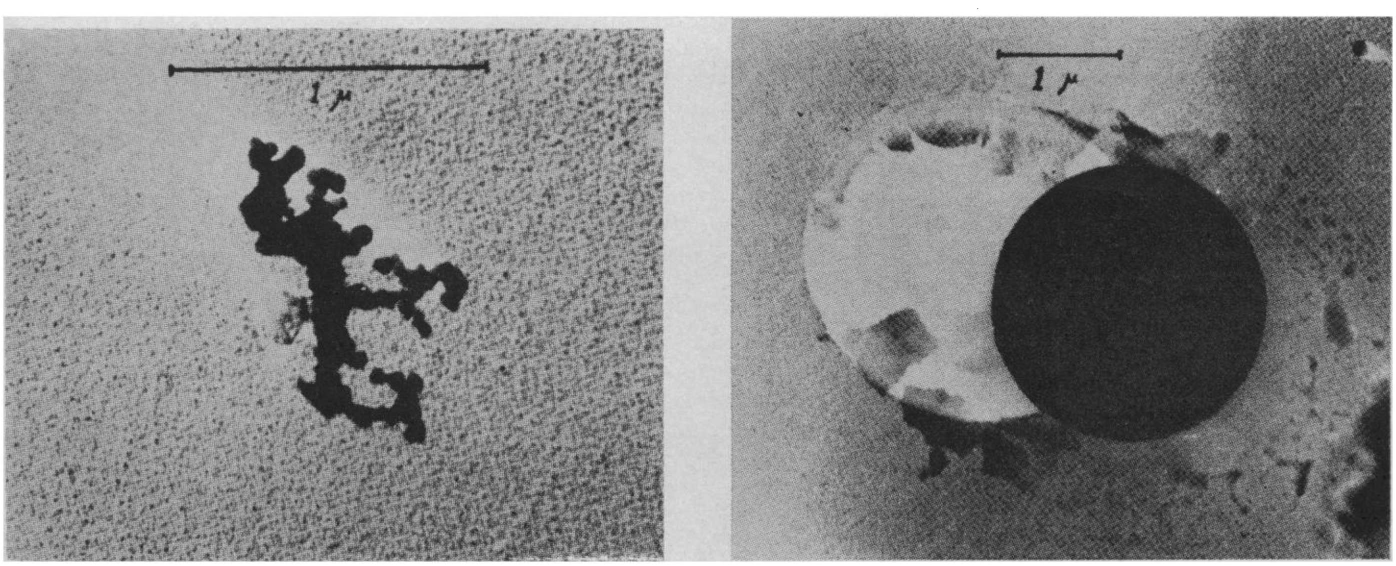


Fig. 1. Photographs of two particles thought to be grains of interplanetary dust. [From Hemenway and Soberman (*6*), reproduced with permission]

the potentials were found to be positive, owing to the strong flux of ultraviolet radiation and the high photoelectric efficiences in this region (*10*). In the case of the dielectric particles this would have been the result even in the absence of ultraviolet radiation. When the impact energies of electrons on dielectric particles are in excess of about 30 electron volts, the yield of secondary electrons generally exceeds unity; thus, if the temperature of interplanetary gas is greater than 3×10^5 degrees Kelvin, [which indeed may be the case (*11*)], then the grain may, depending on its initial conditions, acquire a positive potential. Of course if the grain has a sufficiently high negative potential to start with, this shift to a positive potential will not occur; thus, in regions of high electron density (for example, in comet-tails of ionized gas), the potential may have two equilibrium values.

I have already mentioned that the results of my calculation are somewhat unsatisfactory. This is chiefly a result of the lack of pertinent experimental data. It was, for example, necessary to use a very coarse model of the energy distribution of the photoelectrons stimulated by ultraviolet photons. In view of the fact that the value for equilibrium potential depends sensitively on the model chosen (at least when the potential is positive) and that, in the calculation, the effect of photons with energy greater than 30 electron volts was neglected, the results given in Figs. 3 and 4 should be treated as lower limits. A rough estimate which includes the effects of the neglected photons suggests that the "actual" equilibrium potentials to be expected at a heliocentric distance of 1 astronomical unit are about 30 volts. In instances where the particles are negatively charged, serious difficulty is encountered in making an estimate of the cold emission, which strongly limits the magnitude of the equilibrium potential. The trouble arises from the probable presence of sharp corners or spikes on real dust particles. It is extremely difficult to allow for such shapes in calculating equilibrium potential. Similarly, the lack of knowledge about the state of the surface makes it impossible to assess realistically the role played by the surface photoelectric effect, which may be important in the case of negatively charged grains.

Nonstationary Effects

Of course, the mere calculation of an equilibrium charge under a specified set of conditions is far from being the end of the problem. Interplanetary space is known to be inhomogeneous and variable with time. "Blast waves" (*12*) occur, and the distribution of the gas is very "lumpy" (*13*). The temperature of the gas is also variable (*14*). Clearly it would be of interest to know how the charge on dust particles is affected by the changing conditions they experience, and to consider the dynamical effects which might be associated with these changes.

My method of calculating V was an iterative one, and by following the step-by-step results of the calculation it was a simple matter to estimate the time required for an initially uncharged grain to collect, say, 90 percent of its equilibrium charge. Taking electron density = 1, temperature = 3.10^5 degrees Kelvin, and solar-wind velocity = 200 km/sec, I calculated this time, for a particle at a heliocentric distance of 1 astronomical unit, to be roughly 5 minutes. Since it takes a particle roughly an hour to pass through a relatively high density "filament" in interplanetary space (*15*), we may expect that the charge (and drag) on a dust grain will be continuously modulated in passing through such inhomogeneities. The amplitude of the modulation is, of course, most uncertain.

At the time of passage of a blast wave, the bulk velocity of the plasma may reach 1000 kilometers per second. The density of the plasma increases also. The chief effect here is a strong increase in the flux of ions (protons) onto the dust particle. Thus there is a tendency for the particle to acquire more positive potentials. A most interesting result which is connected with this effect is also associated with the dependence of the charge on the temperature of the ambient plasma. At the low electron densities (less than 10 electrons per cubic centimeter) which are characteristic of the interplanetary gas, the equilibrium potential shows little sensitivity to temperature changes in the range 10^4 to 10^6 degrees Kelvin. The situation, however, becomes very different as the electron density rises toward 100 electrons per cubic centimeter, as it may do, for instance, in the vicinity of a comet. As may be seen in Fig. 5, the potential drops, over a considerable temperature range, to large negative values as the electron flux onto the grain [$\sim (T_e)^{\frac{1}{2}}$] dom-

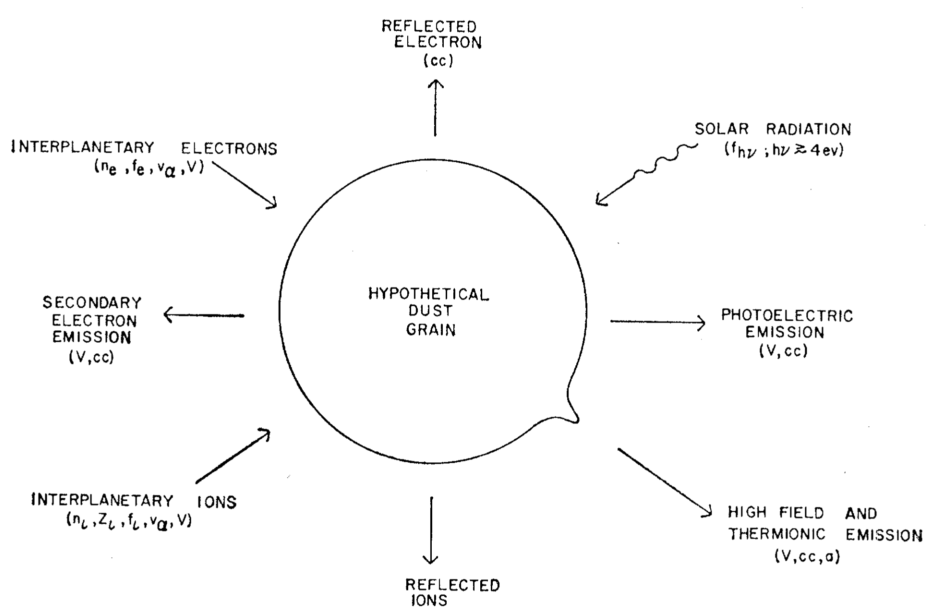


Fig. 2. Schematic representation of the processes which are important in determining the electric charge on an interplanetary dust particle. a, Dimension of the grain, including an indication of roughness of surface; *cc*, chemical composition and state of surface; f_e, electron velocity distribution; f_i, ion velocity distribution; $f_{h\nu}$, distribution of photon energy in the interplanetary radiation field; n_e, electron number density; n_i, ion number density; V surface potential of dust particle; v_α, "orbital" velocity of dust particle; Z_i, ionic charge.

inates the photoelectric current. This situation is dramatically changed at higher temperatures, since the more strongly temperature-dependent secondary emission soon controls the whole current balance and the grains again have positive potentials. This "temperature dip" phenomenon is, however, wiped out as the flow velocity increases, because of the larger part played in the current balance by the ion flux.

In concluding this brief summary of the charge problem, it is perhaps worth stressing the fact that present calculations are far from "definitive." Indeed, it may never be possible to make definitive calculations. We can only say that, before more reliable calculations can be made, we must have many more data on the various contributory effects—in particular, data on the energy distribution of photoelectrons.

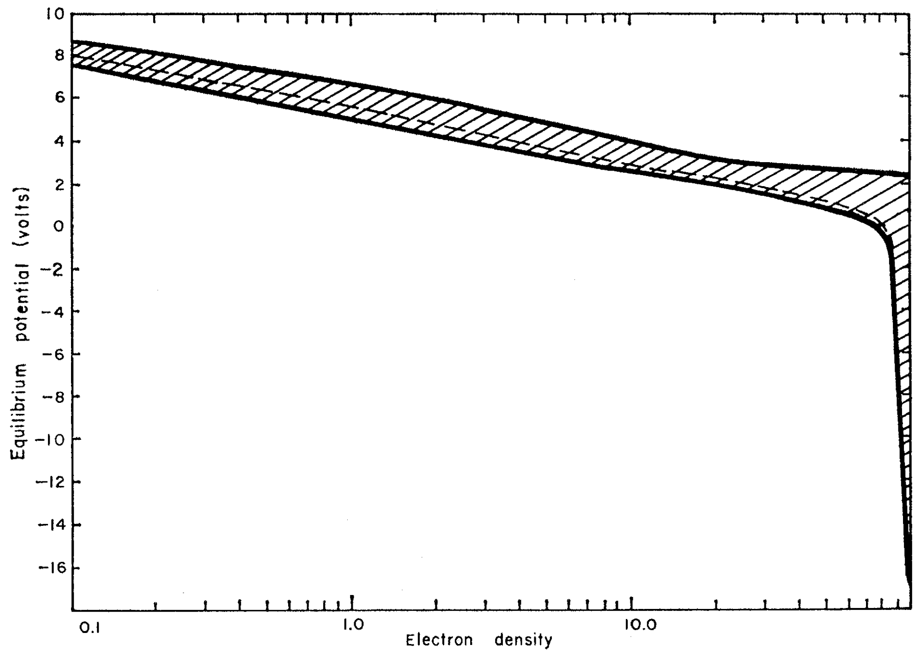


Fig. 3. Results of a calculation of the charge on metallic particles at a heliocentric distance of 1 astronomical unit. The hatching denotes the region in which the equilibrium potential V will fall if the temperature is between 10^4 and 10^6 degrees Kelvin, the solar-wind velocity is between 0 and 1500 kilometers per second, and the electron density is between 0.1 electron and 100 electrons per cubic centimeter. The dashed line is defined by a solar-wind velocity of 200 kilometers per second and a temperature of 3.10^5 degrees Kelvin.

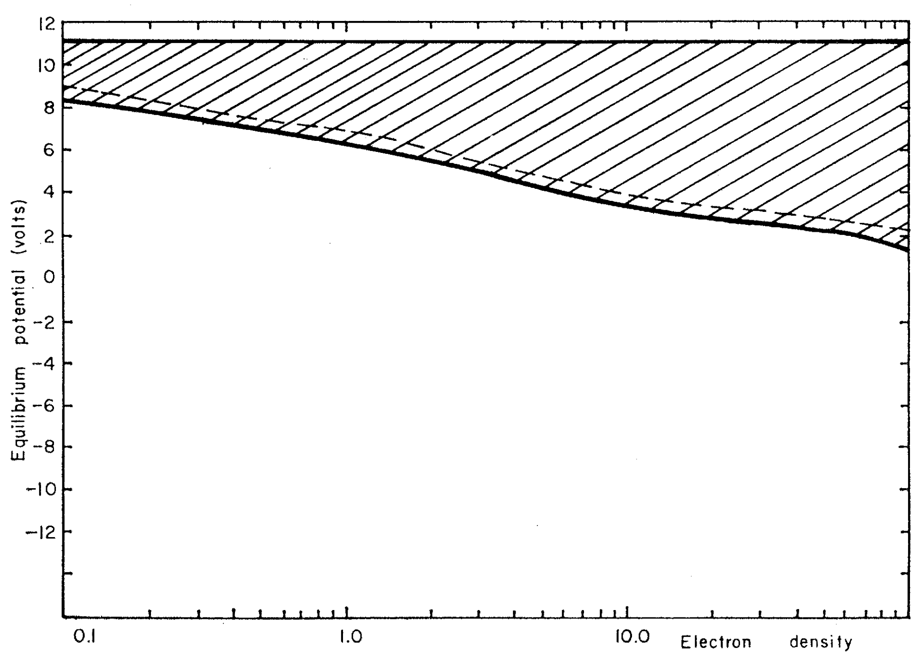


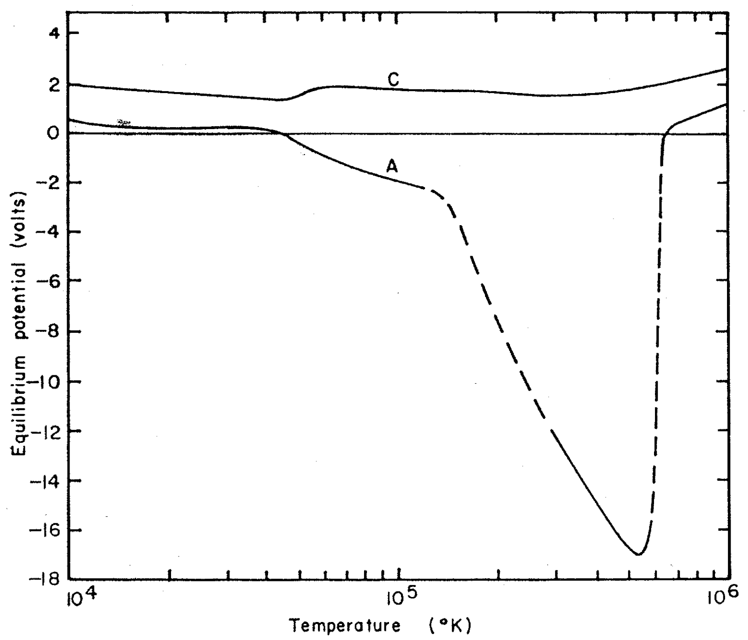
Fig. 4. Results of a calculation of the charge of dielectric particles at a heliocentric distance of 1 astronomical unit. The hatching denotes the region in which the equilibrium potential V will fall under the assumptions given for Fig. 3. The locus of V (dashed line) is defined as in Fig. 3.

Zodiacal Dynamics

The zodiacal light, which is best observed at low geographic latitudes and best of all in the early spring and fall just before sunrise or just after sunset, is a broad, faint, band of light which is symmetrical about the ecliptic and which decreases in intensity rapidly with increasing angular distance from the sun. It is caused by the scattering of solar light from dust particles in interplanetary space (the zodiacal cloud).

A considerable amount of effort has been spent on photometric and polarimetric studies of the phenomenon, and its nature has been much discussed. Modern views, based on knowledge of the scattering properties of the dust in the visible region of the spectrum, are aired in review articles by Ingham (*16*), Elsässer (*17*), Giese (*18*), and Weinberg (*19*). Nearly all the investigations are of one type: the photometric results are interpreted in terms of a simple and what would appear to be a physically plausible model with a considerable number of free parameters (usually six) describing the spatial and size distributions of the particles and their albedo, polarizability, and so on. In this way the investigator achieves some insight into the nature of the particles, although it must be noted that there are two rather divergent schools of thought concerning the size distribution, albedo, and space density of the dust (see *16* and *17*). The discussion by Giese (*18*) is particularly illuminating from the point of view of building such models from photometric and polarimetric data on the basis of Mie scattering.

More recently an interesting extension of the photometric problem from the visible to the infrared region of the spectrum has been discussed by Harwit and Peterson (*20*). They call attention to the thermal radiation from the dust, and it is possible that a study of this radiation may resolve the divergence in views noted above. Unfortunately both these workers use a black-



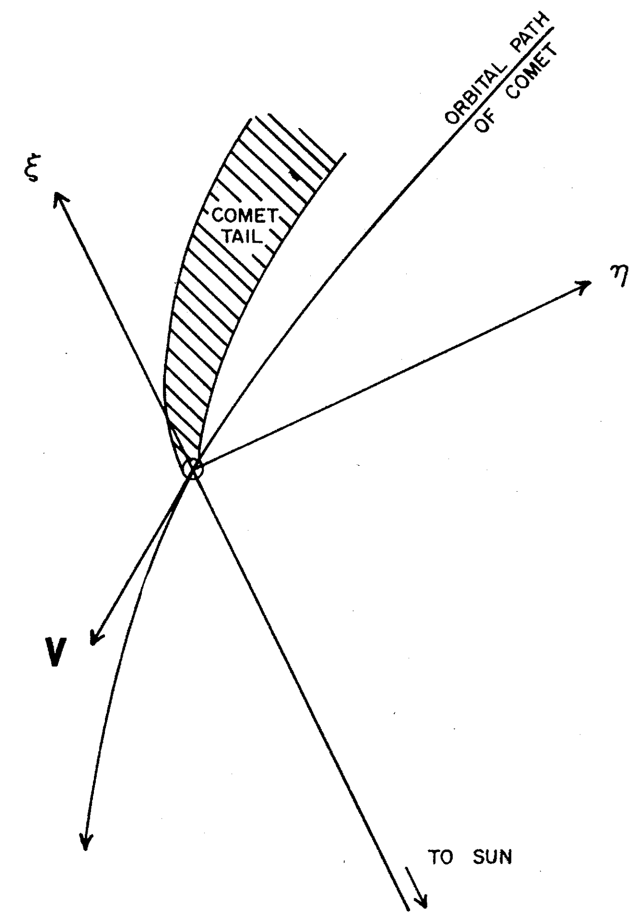


Fig. 5 (above). Schematic representation of the "temperature dip" phenomenon (see text) for a metallic particle at a heliocentric distance of 1 astronomical unit. For curve A, the electron density is 100 electrons per cubic centimeter and solar-wind velocity is zero; for curve C the electron density is 100 electrons per cubic centimeter and the solar-wind velocity is 150 kilometers per second. Fig. 6 (right). Schematic representation of the cometocentric coordinate system (see text).

body approximation for the temperature of the dust particles in space. That this leads to a vast overestimation of the thermal radiation (from siliceous grains at least) may be seen from the calculations by Over (*21*) of the temperature of SiO_2 grains as a function of heliocentric distance. For instance, the use of black-body approximations leads to an estimated temperature of 1290°K for grains at a heliocentric distance of 10 solar radii, whereas Over finds that 400°K is probably a more realistic figure.

Although one can very successfully duplicate nearly every facet of the available observations, using the procedures described above, one gains little insight into such perplexing problems as the origin, maintenance, mass, and velocity distribution of dust in the cloud. Thus, an alternative interpretation of the zodiacal isophotes, based on an assumed origin and the subsequent dynamics of the particles, has attracted much interest. The best-known investigations based on this approach are those of Fessenkov (see *22, 23*), who pioneered in this field, and of Briggs (*24*). Fessenkov takes the view that the general appearance of the zodiacal isophotes is almost independent of the scattering properties of the dust particles, and that the isophotes are more intimately connected with the origin and dynamics of the particles. Unfortunately it is now clear that this approach also leads to interpretational difficulties. For example, Fessenkov (see *23*), basing his interpretation of the dynamics of the dust particles solely on their interaction with the solar radiation and assuming, in turn, that the particles originate both in asteroids and in periodic comets, was able to get good agreement between isophotes obtained from observation and those obtained from computation. Briggs, in what may well be the last attempt to base a model of the dynamics of zodiacal dust on radiation pressure and drag alone, has given the problem a somewhat more sophisticated treatment. Utilizing an empirical injection function (a function which describes the spatial and velocity distribution of the sources of interplanetary dust) based on photographic observation of meteors, he has calculated the steady-state density distribution for interplanetary particles. His method is to write down the conservation equation governing the rate of change of the particle distribution function in orbital element space (a space defined by elements of a hypothetical solar orbit). A theorem describing the trajectory of an individual dust particle in (q, x) space, where q is the perihelion distance and x is the reciprocal aphelion distance, then allows him to find the steady-state solution for the particle density in orbital element space. A transformation to physical space and certain assumptions about the light-scattering properties of the particles finally allow calculation of isophotes; the results of the computations compare well with the observational results. However, since the injection function used by Briggs is based on photographic-meteor orbits, which have been shown by workers at the Smithsonian Observatory to be closely associated with both long- and short-period comets (*25*), we can only conclude that Fessenkov's hypothesis is overly optimistic. The isophotes, being duplicated in analyses based on three distinct origins for the particles (asteroids and long- and short-period comets), can hardly be considered sensitive indicators of the past history of the particles.

The introduction of considerations of electric and magnetic forces into the

Table 2. Estimates of the magnitude of the forces acting on interplanetary dust particles. The forces are measured relative to the force due to radioactive pressure. In making these estimates I have assumed that the dust particle has a density of 5 grams per cubic centimeter and a surface potential of 30 volts. The interplanetary conditions at a heliocentric distance of 1 astronomical unit (AU) are assumed to be: electron density, 16 electrons per cubic centimeter; temperature, 10^5 degrees Kelvin; velocity of the solar wind, 350 kilometers per second. The conditions at a distance of 4 astronomical units are assumed to be: electron density, 1 electron per cubic centimeter; temperature and solar-wind velocity, the same as at a distance of 1 astronomical unit. The particle is assumed to be in a circular orbit, and the drags indicated refer, in each case, to the components directed back along the orbit. A magnetic field, always oriented for maximum effect, of 5.10^{-5} gauss is assumed.

Particle size (μ)	Radiation pressure	Gravity	Poynting-Robertson drag	Gas-kinetic drag	Coulomb drag	Lorentz force
			At 1 astronomical unit			
0.1	1	0.6	10^{-4}	10^{-4}	2.10^{-4}	0.6
1	1	6	10^{-4}	10^{-4}	2.10^{-4}	.06
10	1	60	10^{-4}	10^{-4}	2.10^{-4}	.006
			At 4 astronomical units			
0.1	1	0.6	5.10^{-5}	5.10^{-5}	10^{-4}	9
1	1	6	5.10^{-5}	5.10^{-5}	10^{-4}	0.9
10	1	60	5.10^{-5}	5.10^{-5}	10^{-4}	.09

dynamical problem appears to have opened up new opportunities for the differentiation of different dynamical models. Ingham (*16*) and Elsässer (*17*) agree that the size distribution of zodiacal particles, roughly approximated by a function of the form

$$f(a)da = a^{-p}da, \qquad (1)$$

leads to agreement with the photometric observations. Here a is the radius of the particle and p is a parameter which is chosen to fit the observations. Thus an "optically" important particle size for visible radiation

$$<a^2>^{1/2} = \left(\int_{a_1}^{\infty} a^{2-p}da \int_{a_1}^{\infty} a^{-p}da\right)^{1/2} = \left(\frac{p-1}{p-3}\right)^{1/2} a_1 \; (p > 3) \qquad (2)$$

can be defined. Here a_1 is the smallest particle size in the distribution and, in an approximate way, takes into account both the rapid falloff of the scattering efficiency as the particle size gets small relative to the wavelength of visible light and the radiation-pressure cutoff. Ingham (*16*) finds that p equals 4 and a_1 equals 0.4 μ give good agreement with the photometric observations; by way of Eq. 2 these values lead to an optically important particle size of 0.7 μ. Weinberg's (*19*) calculations lead to a somewhat smaller value for this quantity. Thus, a large part of what the observer "sees" in the zodiacal light is the space distribution of these very small particles. Elsässer's discussion, which is based on observations of the F corona, suggests a much lower value of p (= 2.0). In this case Eq. 2 must be replaced by the geometric mean of the largest and smallest particles in the assumed distribution. This procedure leads to a somewhat larger size ($\sim$ 10 μ) for the optically important particles.

Now let us consider the forces which might be expected to act on this dust. In Table 2 are given estimates of the magnitudes of the forces, expressed relative to the force exerted by radiation pressure, thought to be important to the motion of dust particles in the size range 0.1 to 10 μ. Such interactions as the Yarkovski drag, magnetic induction drag, electric induction drag, and wave drag (*26*) were found to be quite insignificant and so were not included in Table 2.

It is quite clear, as Singer (*4*) and more recently Parker (*5*) have pointed out, that the Lorentz forces are responsible for the major perturbation on the gravitational orbits of the dust particles. Also, gas-kinetic (collisional) and coulomb drags are not unimportant effects.

The property of the Lorentz force of greatest interest in this context is its ability to perturb the inclination of the orbits of the zodiacal particles. Also of interest, since we are concerned in interplanetary space with a convecting magnetic field, is the ability of this field to secularly accelerate the grains (*4, 27*). There is, therefore, reason to expect the spatial equilibrium distribution of interplanetary grains (of the size considered) to be strongly dependent on the configuration of the interplanetary magnetic field and on the particular source assumed for the particles. Thus, particles injected into interplanetary space in the region of the asteroidal belt will not only approach the sun, under the action of the various drags, but will also diffuse to high ecliptic latitudes under the action of the Lorentz force, the smallest particles experiencing the widest latitudinal dispersion. Associated with this process will be a characteristic oblateness of the isophotes as well as a characteristic distribution of color and polarization. On the other hand, particles originating in comets would be injected into interplanetary space much closer to the sun, in a region where the interplanetary magnetic field has rather different characteristics; such an origin would lead, one would hope, to a rather different equilibrium distribution of particles. Exactly what the general characteristics of these various distributions are is still a matter of conjecture since very little work has yet been done. It seems hardly necessary to add that the problem is a difficult one and, in view of the many parameters involved, "nondefinitive" in character.

Information about the velocity distribution of the zodiacal particles has recently become available; this should be of great importance to a discussion of their origin and dynamics. A brief report by Ring and his associates (*28*) of a blue shift in the position of H_β in the spectrum of the evening zodiacal light indicates that there may be a strong anisotropy in the velocity distribution of the particles. The few particle impacts counted in the Mariner II space probe experiment (*29*) can be given the same interpretation. Ring and his co-workers (*28*) interpret their observations as indicating that most of the dust must be moving in direct orbits (moving in the same sense as the earth) and at velocities which are more than twice the velocity of particles moving in circular orbits! They add, however, that the measures should not be given much weight until they have been confirmed by subsequent experiments. If future observations do indeed indicate that the motion of the interplanetary dust particles in their orbits is almost exclusively direct, then a predominantly cometary origin for the zodiacal cloud would seem to be excluded. This follows from the known fact that the orbital inclinations of the long-period comets are distributed randomly, and from the suspicion that the periodic (short-period) comets are probably incapable of providing the amount of material needed to maintain the cloud. It is hardly necessary

Table 3. Temperature and dynamical and evaporative lifetimes of interplanetary dust particles as a function of heliocentric distance. [Columns 2 and 3 are taken from J. Over (*21*)]

Heliocentric distance (solar radii)	T_g (°K)	T_b (°K)	τ_{dyn} (sec)	τ_{evp} (sec)
1.02	2500	4101	2×10^{6}	5×10^{-5}
1.12	2250	3820	3×10^{6}	5×10^{-4}
1.38	2000	3450	4×10^{6}	3×10^{-3}
1.65	1750	3150	6×10^{6}	1×10^{-0}
2.08	1500	2800	1×10^{7}	5×10^{-1}
4.10	1000	2000	4×10^{7}	4×10^{-7}
11.99	500	1170	3×10^{8}	1×10^{-20}

to add that observations of this type are very important for an understanding of the dynamics of the zodiacal cloud.

Direct information on the spatial distribution of interplanetary dust has recently become available from the dust-particle experiment of the Mariner IV space probe (*30*). The preliminary results indicate an increase in the number density of the particles with increasing distance from the sun in the region between 1 and 1.5 astronomical units. While such a relationship has not been suggested in the interpretation of photometric and polarimetric measures of the zodiacal light, such a trend is to be expected if the dust particles are of asteroidal origin, as was demonstrated in models constructed by Fessenkov (*22*) many years ago. These models, which entirely neglect any interaction between the dust and the interplanetary environment, were rejected on the basis of the very large injection velocities required. Because of the findings of Mariner IV it would seem that these models should be given further consideration.

Zodiacal Dust: Its Fate

I now call attention to one further unanswered question concerning the dynamics of the zodiacal cloud. What is the ultimate fate of a zodiacal dust particle? In the case of dielectric (nonabsorbing) particles it appears that particles in the size range between 10^{-6} and 10^{-5} centimeter will immediately leave the system on hyperbolic orbits, since the force of radiation pressure exceeds that of gravity (*31*). Similarly, all absorbing particles below a certain size (radii of $\sim 10^{-6}$ cm) will immediately leave the system. The remaining particles, under the action of momentum consuming drag forces, will gradually approach the sun. In the literature it is usually concluded that the particles will then fall into the sun in a short time (astronomically speaking) and be vaporized by the intense solar heat. Let us now consider what may actually be the case, taking a SiO_2 grain of 1-micron radius as an example, since Over (*21*) has already computed the equilibrium temperatures for such particles as a function of heliocentric distance, and since the vapor pressure of SiO_2 is known. In Table 3 the grain temperature, T_g, and the black-body temperature, T_b, are listed as functions of heliocentric distance r measured in solar radii. Also listed in Table 3 are the dynamical lifetime, τ_{dyn}, and the evaporative lifetime, τ_{evp}, of the particle. For simplicity, it is assumed that the grains are moving in circular orbits. From the data of Table 3 it is quite clear that the particle reaches the end of the road at a heliocentric distance of between 2 and 4 solar radii, where it is quickly volatilized. The question remains, however: Can the particle actually attain this heliocentric distance? Because evaporation is taking place at its surface the particle is continuously losing mass and, therefore, shrinking. The ratio of the magnitudes of the force due to radiation pressure and the force due to gravity varies inversely as the size of the particle, and so, as time goes on, we can expect radiation pressure to become more and more important until it actually equals the gravitational force. At that point the particle will leave the system on a straight-line orbit. All this will only happen, of course, if the particle is not vaporized first. In Table 4 I have compared, for this grain of 1-micron radius, the rate $(dr/dt)_{pr}$ at which the orbit is shrinking because of drag effects with the rate $(dr/dt)_{\mu}$ at which it is expanding because of the particle's loss of mass and consequent decrease in size.

It is clear from Table 4 that the orbit should stabilize at a heliocentric distance between 3 and 4 solar radii, where the evaporative lifetime is of the order of 10^{6} seconds or 10 days. This time is equivalent to about 100 orbital periods. Thus, the evaporization remains effectively a gradual process, and a particle, because of the increasing importance of radiation pressure, will move onto increasingly large and eccentric orbits until it finally leaves the system. To test this conclusion I have numerically integrated the differential equations governing the motion of an, initially, 1-micron SiO_2 particle. As expected, the particle at first spirals in toward the sun, until the orbit becomes stabilized at 3.2 solar radii. Vaporization is most rapid near perihelion, and this leads to a rapid increase in the eccentricity of the orbit. The orbit becomes hyperbolic after about 70 passes through perihelion and subsequently leaves the system. The radius of the particle is reduced to 0.3 micron.

Table 4. The rate $(dr/dt)_{pr}$ at which the circular orbit of a siliceous interplanetary dust particle is shrinking due to drag effects, compared with the rate $(dr/dt)_{\mu}$ at which it is expanding due to loss of mass by evaporation as a function of heliocentric distance.

Heliocentric distance (solar radii)	$(dr/dt)_{pr}$ (AU/yr)	$(dr/dt)_{\mu}$ (AU/yr)
1.02	-2.5×10^{-2}	2×10^{8}
1.12	-2.3×10^{-2}	2×10^{7}
1.38	-1.9×10^{-2}	5×10^{6}
1.65	-1.6×10^{-2}	2×10^{4}
2.08	-1.2×10^{-2}	4×10^{2}
4.10	-6.3×10^{-3}	2×10^{-4}
11.99	-2.1×10^{-3}	2×10^{-25}

We also note (Table 3) that the temperature of the particles in the region of closest approach is near the melting point for a grain of the type we are considering. Thus the particles have a good chance of melting and, under the influence of surface tension, forming into nearly ideally spherical particles. The view that this is the origin of some of the micron-sized spherical micrometeorites found by Hemenway and Soberman (see Fig. 1, right) is of course highly conjectural but is not altogether implausible.

This whole problem, which has been sadly neglected in recent years, requires intensive investigation, for a mechanism such as that proposed, apart from perhaps explaining the origin of nearly spherical micrometeorites, would also explain how stars could continuously seed the interstellar medium with large numbers of very small particles. Here, of course, I have discussed only a highly simplified version of the problem. The effects of interplanetary magnetic field, coronal drag, and, possibly, heating, sputtering, and so on which I have neglected may well be extremely important factors.

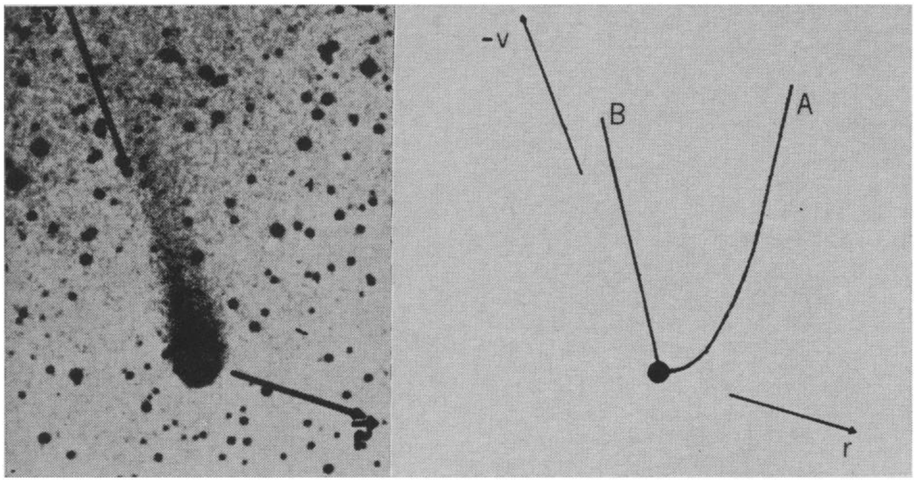


Fig. 7. (Left) An enlarged photograph of the comet Baade (1954h), taken 19 November 1955 by D. Osterbrock with the 48-inch Schmidt telescope on Mount Palomar, with arrows added to show the projected heliocentric velocity and radius vectors. (Right) The theoretical tail axes discussed in the text.

Fig. 8. Photograph of Comet Mrkos (1957d), clearly showing the synchronic bands, for which we have as yet no adequate dynamical explanation. [Photograph by John Farrell, published in *Sky and Telescope* **16**, 572 (1957) and reproduced with permission]

Type-II Comet Tails

Comet tails can be broadly classified into two types. Type-I tails are composed of ionized gases and generally occur only at heliocentric distances of less than 1.5 astronomical units (*32*). It is thought that these tails, which are strongly coupled to the expanding interplanetary gas (*33*), give important information about its velocity of expansion. However, the actual dynamics of the interaction involved in this coupling is not clearly understood at this time. Type-II or dust tails are, on the other hand, generally considered to be a well-explained phenomenon. Nevertheless, in spite of the apparently widespread belief that these tails can be explained fully in terms of what is known as the Bessel-Bredichin (or mechanical) theory (*33*), the observations by Osterbrock (*34*) of two comets at great heliocentric distances have posed what I call here "the problem of the distant comets." Also responsible for a reawakening of interest in the dynamics of the dust in these tails have been the comments by the Russian astronomer Vseksviatsky (*35*) on the spatial and temporal behavior of "synchronic" bands occasionally observed in the brighter type-II tails.

In view of its rather unfamiliar terminology, it is perhaps advisable to give a brief explanation of the Bessel-Bredichin theory at this point. In its simplest form the theory is based on the assumption that the equation of motion for the individual tail particles can be written as follows:

$$\ddot{\mathbf{r}} = -\frac{\mu k}{r^3}\mathbf{r} \tag{3}$$

Here k is the product of the gravitational constant and the sun's mass and μ is a constant such that $(1-\mu)$ is equal to the ratio of the forces acting on the tail particle that are due to radiation and gravity, respectively; $\mathbf{r}$ is the position vector of the particle. By judicious use of Eq. 3 together with the equation of motion of the cometary nucleus (unaffected by radiation pressure) one obtains the following parametric representation of the tail axis at time t:

$$\begin{aligned} \xi &= \xi\,(1\text{-}\mu,\tau;\,t) \\ \eta &= \eta\,(1\text{-}\mu,\tau;\,t) \end{aligned} \tag{4}$$

where ξ and η are cometocentric coordinates in terms of which the position of a point in the tail (see Fig. 6) is measured and τ is the interval of time since the tail particle at that point in the tail left the comet nucleus. Because of the occurrence of two independent parameters in Eqs. 4, we can distinguish between two broad families of tails: (i) *synchronic*, in which τ is a constant (that is, in which all tail particles were ejected at the same time) and $(1 - \mu)$ has a wide range of values, and (ii) *syndynamic*, in which $(1 - \mu)$ is treated as a constant and τ is variable. As far as orientation is concerned, the axis of a syndynamic tail should be roughly tangential to the prolonged radius vector to the nucleus, while the axis of a synchronic tail is at increasingly large angles relative to that direction.

The problem of the distant comets, simply stated, is that their tails point in an unexpected direction. There seems to be little doubt that dust particles are continuously accelerated away from the comet nucleus and that the tails are syndynames. Thus one would expect the axis of the tail, as it emerges from the head of the comet, to be roughly tangential to the prolonged radius vector. According to observation, however, this is not the case. Instead, the tails become oriented roughly midway between the prolonged radius vector and the direction back along the comet's orbit. This observation suggested to Osterbrock that a new interaction must be involved in the dynamics of the tails. Being aware of the presence of the interplanetary gas, he therefore considered the tail dynamics in terms of the usual radiation pressure plus the effect of a viscous drag. The problem is illustrated in Fig. 7. Figure 7 (left) is an enlargement of a photograph of comet Baade obtained by Osterbrock with the 48-inch (122-cm) Schmidt telescope on Mt. Palomar. Arrows indicating the projected directions of the prolonged radius vector, **r**, and the direction back along the orbit, $-\mathbf{v}$, are superposed on the photograph. Figure 7 (right) refers exactly to the photograph in both scale and orientation. Tail axis A was calculated by means of the usual mechanical theory, with reasonable values assumed for the physical parameters involved. Tail axis B shows the effect of including in the calculation both the radiation pressure and a resisting force operating in the direction $-\mathbf{v}$ and having a magnitude equal to that of the radiation pressure. It is clear that B is a better representation of the observations than A is. Osterbrock's results, nevertheless, were not very encouraging, since calculated values for the expected drag were lower, by almost four orders of magnitude, than the values required for the above explanation (see Table 2).

Brandt (*36*) was responsible for the next development. Bypassing the dynamical problems involved, he noted that, if the tails were indeed interacting with the interplanetary gas, then they could be used to map out the interplanetary velocity field at heliocentric distances far exceeding the distance of 1.5 astronomical units within which type-I tails have been observed. Using Osterbrock's data, he put what was effectively an upper limit on the solar-wind velocity at 4 astronomical units and proposed the occurrence, between 2 and 4 astronomical units, of a shock transition in the expanding gas to subsonic velocities. Scrutiny of the behavior and orientations of several type-II comet tails at heliocentric distances of much less than 2 astronomical units has, however, led me to a different view of the dynamics involved. I have found (*37*) that pure type-II tails have the same orientation characteristics as the tails of distant comets, irrespective of their heliocentric distance. This result, interpreted in terms of a theory that expanding interplanetary gas produces a collisional drag, requires that the velocity of the solar wind, regardless of heliocentric distance, shall always be less than $42/(r_{AU})^{\frac{1}{2}}$ km/sec. This is clearly incorrect and leads immediately to the conclusion that, whatever the interaction with the interplanetary medium is, it certainly is not a direct result of collisions and is far more subtle than we have supposed. Vseksviatsky (*35*) discussed a second observation which appears to indicate that a dynamical effect not traditionally considered plays a part in the motion of dust particles in a type-II tail. He pointed out the difficulties in trying to explain the phenomenon of "synchronic" bands in terms of the mechanical theory. This phenomenon, which has now been observed in the tails of five comets, is illustrated in Fig. 8. The bands are the striations seen toward the end of the tail. The spatial regularity and "doublet" structure of the bands is hard to explain in terms of random explosions at the nucleus. Moreover, the observed orientation and duration of the bands are not those predicted by the Bessel-Bredichin theory. Vseksviatsky concluded that an explanation must lie in the operation of some electrodynamic force.

While a new attack on these problems has hardly been begun, it seems clear that a dynamical explanation of dust tails requires the assumption of some type of magnetoelectrodynamic interaction of the tail material with the interplanetary plasma (*38*). A dust tail, rather than being a collection of independent particles (as in the Bessel-Bredichin theory), appears to be, because of the electric charge carried by the particles, yet another example of a plasma in nature. The dynamics of these tails is thus removed from the pristine realm of celestial mechanics and becomes a rather difficult problem in plasma dynamics.

I have attempted to point out some of the major problems of interest to the astronomer in studies of the dynamics of interplanetary dust. There are, of course, many aspects of the subject which I have had to neglect for lack of space. For example, important questions remain to be answered concerning the observed concentration of dust in the vicinity of the earth, and concerning the gegenschein. Geophysical phenomena such as the noctilucent clouds are perhaps connected with the accretion of interplanetary dust by the earth, and it does not seem altogether impossible that their apparently preferential occurrence at high geographic latitudes may be a result of the dynamical trajectory of the particles.

The list of problems can be extended indefinitely. It is unfortunate that we have, as yet, so few answers.

References and Notes

1. J. W. Chamberlain and D. M. Hunten, *Advan. Geophys.* **3**, 299 (1965).
2. It is not now thought likely that interplanetary dust constitutes a real hazard to space probes in the inner region of the solar system. The number density of such dust particles is extremely small.
3. E. J. Öpik, *Irish Astron. J.* **4**, 84 (1956).
4. S. F. Singer, in *Scientific Uses of Earth Satellites*, J. A. Van Allen, Ed. (Univ. of Michigan Press, Ann Arbor, 1956), chap. 33.
5. E. N. Parker, *Astrophys. J.* **139**, 951 (1964).
6. C. L. Hemenway and R. K. Soberman, *Astron. J.* **67**, 256 (1962).
7. B. Jung, *Veröffentl. Sternw. Breslau No. 9* (1938), p. 425; L. Spitzer, *Astrophys. J.* **93**, 369 (1941); ———, *ibid.* **111**, 593 (1950); H. C. van de Hulst, *Res. Astrophys. Obs. Utrecht* **11**, pt. 2 (1949); P. G. Kurt and V. I. Moroz, *Planetary Space Sci.* **9**, 259 (1962); S. P. Wyatt, *Astron. J.* **68**, 300 (1963); K. P. Chopra, *Astronaut. Acta*, in press, and private communication; the foregoing references do not include calculations of charge on space vehicles where the size of the body is assumed to be comparable to, or greater than, the Debye length of the ambient plasma. Nor do I include calculations pertaining to particles in the earth's upper atmosphere.
8. In Table 1 are given values for the "equilibrium potential" of the grain which can, in

this context, be considered independent of the dimensions of the grains. The actual charge may be calculated if one has a measure of the capacitance of the grain. Only if the charge is strongly negative does the size of the dust grain enter significantly into the calculation of the equilibrium potential.
9. M. J. S. Belton, thesis, Univ. of California, Berkeley (1964).
10. H. Hinteregger, Ann. Rept. *Mass. Inst. Technol. Conf. Phys. Electron. 14th* (1954), pp. 41–49; *J. Geophys. Res.* **66**, 2367 (1961).
11. C. W. Snyder and M. Neugebauer, in *Space Res. Proc. Intern. Space Sci. Symp. 4th* (1964), p. 89.
12. E. N. Parker, *Interplanetary Dynamical Process* (Interscience, New York, 1963).
13. A. Hewish and J. D. Wyndham, *Monthly Notices Roy. Astron. Soc.* **126**, 469 (1963).
14. W. Bernstein, in *Space Physics*, D. F. Le Galley and A. Rosen, Eds. (Wiley, New York, 1964).
15. Radio observations of sources through the interplanetary gas by A. Hewish and J. D. Wyndham (see *13*) can be interpreted in terms of filamentary structures with a characteristic thickness of 10^3 to 10^4 km, extending out from the sun to at least 60 solar radii. E. N. Parker (see *12*) has suggested that these structures may exist as far from the sun as the earth's orbit. For particles moving with a characteristic velocity of 10 km/sec, the characteristic time for passage through such a filament is $\sim 10^3$ seconds.
16. M. F. Ingham, *Space Sci. Rev.* **1**, 576 (1963).
17. H. Elsässer, *Planetary Space Sci.* **11**, 1015 (1963).
18. R. H. Giese, *Space Sci. Rev.* **1**, 589 (1963).
19. J. L. Weinberg, *Ann. Astrophys.* **27**, 718 (1964).
20. M. Harwit, *Mem. Soc. Roy. Sci. Liege* **9**, 506 (1960); A. W. Peterson, *Astrophys. J.* **138**, 1218 (1963).
21. J. Over, *Koninkl. Ned. Akad. Wetenschap. Proc.* **51B**, 74 (1958).
22. O. Struve, *Astrophys. J.* **98**, 129 (1943).
23. F. G. Fessenkov, *Ann. Astrophys.* **22**, 820 (1959).
24. R. E. Briggs, *Astron. J.* **67**, 710 (1962).
25. L. G. Jacchia and F. L. Whipple, *Smithsonian Contrib. Astrophys.* **4**, No. 4 (1960).
26. K. P. Chopra, *Rev. Mod. Phys.* **33**, 153 (1961).
27. Secular acceleration is acceleration that is directly proportional to some power (not necessarily constant) of the time. The term is used further to imply that the acceleration is not a periodic function of time.
28. J. Ring, D. Clarke, J. F. James, M. Daihler, J. E. Mack, *Nature* **202**, 167 (1964).
29. W. M. Alexander, *Science* **138**, 1098 (1962).
30. ———, C. W. McCracken, J. L. Bohn, *ibid.* **149**, 1240 (1965).
31. It is not clear at the moment how important the "sweepout" effect (see *4*) of the convecting interplanetary magnetic field is. I neglect magnetic effects in this part of the discussion.
32. There are a few exceptions. The most notable of these is Comet Humason (1961c), which displayed a tail as far from the sun as 5 astronomical units. The tail, which was almost certainly composed of ionized gas, did not have the usual appearance of type-I tails.
33. A good exposition of current thought about the dynamics of type-I comet tails is given by L. Bierman and R. Lüst in *The Moon, Meteorites and Comets*, B. M. Middlehurst and G. P. Kuiper, Eds. (Univ. of Chicago Press, Chicago, 1963), chap. 18.
34. D. Osterbrock, *Astrophys. J.* **128**, 95 (1958).
35. S. K. Vseksviatsky, *Russ. Astron. J. (English Transl.)* **36**, 503 (1959).
36. J. C. Brandt, *Icarus* **1**, 1 (1962).
37. M. J. S. Belton, *Astron. J.*, in press.
38. ———, paper presented at the 13th Astrophysical Symposium, Liége, 1965.
39. This article is contribution No. 120 of the Kitt Peak National Observatory. The observatory is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation. Part of the work reported here was performed at the University of California and was supported by project NR 046-796 under grant Nonr (G)-00051-62.

Birth Order and Its Sequelae

Ordinal position among siblings is related to potential eminence and educational attainment.

William D. Altus

The relation of order of birth to achievement has been investigated for nearly a hundred years. The first known data appear in Sir Francis Galton's *English Men of Science*, published in 1874. Galton selected his scientists according to objective criteria, such as being a Fellow of the Royal Society, and then asked them for biographical data, including their order of birth. He found more only sons and first-born sons among them than his calculations showed chance should have allowed. This finding he thought easy to interpret: Through the law of primogeniture, the eldest son was likely to become possessed of independent means and to be able to follow his own tastes and inclinations. Further, Galton argued, parents treated an only child and a first-born child (who is also an only child for a period of time) as a companion and accorded him more responsibility than other children were given. Thus first arrivals on the family scene were favored from the start.

A generation later Havelock Ellis (*1*) published *A Study of British Genius*, based on 975 eminent men and 55 eminent women selected from the 66 volumes of the *Dictionary of National Biography*. In the main, he chose those to whom three or more pages were devoted in this dictionary, but excluded those who were of the nobility and also those whom he judged to be notorious rather than famous. Among those eminent people, Ellis found some striking linkages to order of birth: The probability of appearance was much greater for a first-born than for an intermediate child, and the youngest likewise was favored over the intermediate child, though not to the same degree. Ellis does not interpret his finding; he merely reports that it is congruent with an American study (*2*) published a decade earlier:

> This predominance of eldest and youngest children among persons of genius accords with the results reached by Yoder in studying an international group of 50 eminent men; he found that youngest sons occurred oftener than intermediate sons and eldest sons than youngest.

About the time Ellis published his survey of eminent Britishers, the American psychologist Cattell (*3*) published data based on 855 American scientists, which showed the same relation between birth order and eminence, the eldest and then the youngest being favored.

In 1915, Corrado Gini (*4*) showed a linkage between order of birth and being a university professor. From 445 replies to a questionnaire he sent to his fellow professors in Italian universities, he found that twice as many were first-born as would have been expected from chance, and that all the other birth orders were below expectancy or no higher than expectancy. Gini's published data do not allow comparisons between the youngest and the in-between. I report these data with considerable diffidence, since most of us have had personal experience with university professors who would not qualify as eminent people, no matter how lax a criterion one employed. Still, it is of some interest to know that the first-born also takes precedence in the academic milieu, if data

The author is a professor of psychology at the University of California, Santa Barbara.