DYNAMICS AND SPATIAL DISTRIBUTION OF INTERPLANETARY DUST

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ABSTRACT. Three attempts to explain the radial power law distribution $n(r) \sim r^{-1.3}$ of interplanetary dust are reviewed, which include the influence of Poynting-Robertson effect, collisions and interplanetary magnetic fields. Electromagnetic forces are unlikely to affect appreciably the spatial distribution. The replenishment of the cloud of interplanetary dust by the disruption of larger meteoritic particles in catastrophic collisions appears to give the most natural explanation for the observed spatial distribution.

1. INTRODUCTION

The spatial distribution of interplanetary dust is determined by its sources and the forces acting on the individual particles. Vice versa, measuring the spatial distribution should help to learn about origin and dynamics of the dust. Zodiacal light space experiments (Leinert et al. 1981, Hanner et al. 1976) yielded a power law spatial distribution somewhat steeper than the dependence 1/r, which would result under the action of Poynting-Robertson effect alone (Wyatt and Whipple 1950). Different mechanisms have been proposed to explain this steepening: a focusing of particle orbits by inelastic collisions, leading to multiplied in-ecliptic density closer to the sun (Trulsen and Wikan 1980); addition of dust from a source region extending into the inner solar system (Leinert et al. 1983); subtraction of particles at larger heliocentric distance, where Lorentz scattering off the ecliptic would be most effective (Mukai and Giese 1984). In the following, after a comment on the observed spatial distribution, I give a critical review of these three papers.

2. OBSERVED SPATIAL DISTRIBUTION

The Helios zodiacal light experiment (Leinert et al. 1981) found the scattering cross section per unit volume to vary with heliocentric distance as power law $r^{-1.3}$ from 0.1 AU to, roughly, 1.5 AU or 2 AU.

R. H. Giese and P. Lamy (eds.), Properties and Interactions of Interplanetary Dust, 369–375.

This is compatible with Pioneer 10 observations (Schuerman 1980). For this paper and until more is known about interplanetary dust I adopt the simplest interpretation: that the radial spatial distribution is given by the above power law. Future discussions and measurements may or may not show that part of the variation is due to changing particle properties, like albedo; however, I consider the case to be strong in favour of a variation of particle number density steeper than 1/r, and this steepening has to be explained.

If one takes the strong variation of scattering cross section found by Helios and a "normal" scattering function (i.e. one with enhanced forward scattering) it is difficult to match exactly the observed brightness distribution of zodiacal light at 1 AU (Levasseur-Regourd and Dumont 1978). This is a difficulty between two different sets of measurements and not to be overcome simply by assuming another spatial distribution. But Figure 1 shows that the discrepancies are small except closer than 5° to the sun and suggests that this may be at least in part a mathematical problem resulting from finite accuracy and calibration differences of the observations.

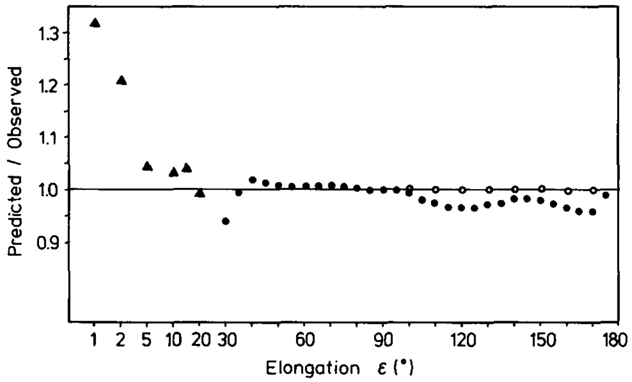

Figure 1. Zodiacal light brightness, predicted from $n(r) \sim r^{-1.3}$ and an empirical scattering function with enhanced forward scattering, in comparison to the observations summarized by Leinert (1975, o), Levasseur-Regourd and Dumont (1980, ●), and Fechtig et al. (1981,▲).

3. FOCUSSING OF PARTICLES BY INELASTIC COLLISIONS

This is the basic idea of Trulsen and Wikan's (1980) paper and visualized in Figure 2. They assume a source far out. As particles are drifting inwards due to the Poynting-Robertson effect, their eccentricities are decreasing. Because collisions tend to equalize average inclination and average eccentricity, the inclinations also are decreasing, unless the initial inclinations were quite small, leading to an enhancement of density in the ecliptic by about a factor $i_o/\langle i(r)\rangle$.

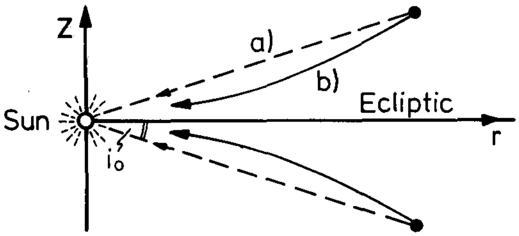

Figure 2. Drift path, under Poynting-Robertson effect, for particles with initial inclination i_o. a: unperturbed b: affected by non-destructive collisions.

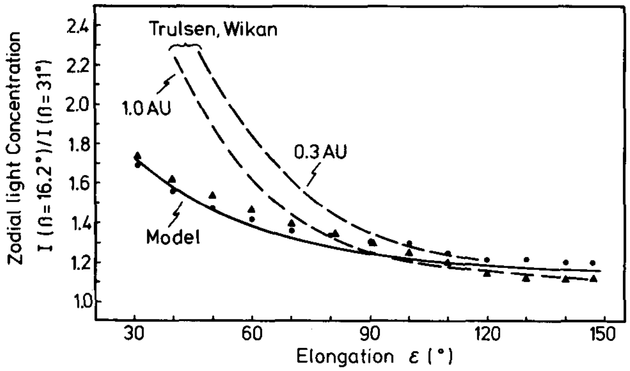

Figure 3. Zodiacal light concentration measured by Helios at 1 AU (●) and 0.3 AU (▲) compared to predictions according to Trulsen and Wikan (---, $n(z) \sim \exp\left[-5(z^2/r^2)r^{-0.3}\right]$) and model $n(z) \sim \exp(-2.1|z/r|)$.

The problem with this approach is that it assumes non-destructive collisions and therefore may not be applicable to interplanetary space where most collisions are catastrophic. Also it necessarily predicts a particular form for the z-dependence of dust distribution which does not at all fit the zodiacal light observations shown in Figure 3.

4. DENSITY INCREASE IN AN EXTENDED SOURCE REGION

Leinert et al. (1983) refer to the fact that, although a single source tends to produce a 1/r spatial distribution, a superposition of sources in an extended source region will result in a steeper distribution (Figure 4). They show that in absence of collisions and with an unbound input region an input distribution in semimajor axis of $f(a) \sim a^{-\nu}$ leads to a spatial distribution $n(r) \sim r^{-\nu}$, for $\nu \geqslant 1.0$. Collisional losses tend

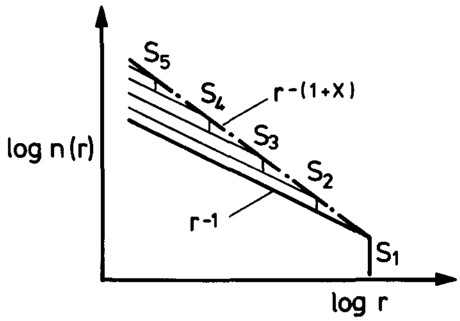

Figure 4. Steepening of the spatial distribution, resulting under Poynting-Robertson effect by a distribution of sources.

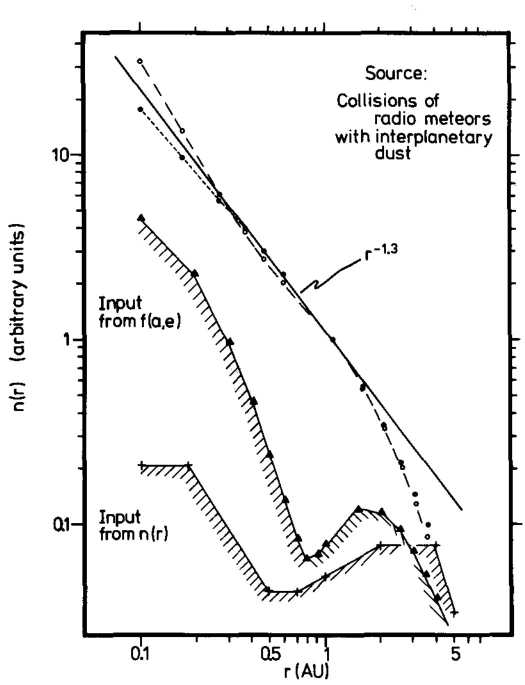

Figure 5. Relative spatial distribution expected if interplanetary dust is replenished by collisional debris from meteors (see Leinert et al., 1983).

to flatten, a limitation of the input region tends to steepen the distribution; for very strong collisional losses the simple relation holds again.

In the interplanetary complex of dust and meteors destructive collisions have the net effect that dust (i.e. particles with radii less than 100 μm) is produced at the expense of larger meteoritic particles. Taking the spatial distribution of radio meteors given by Southworth and Sekanina (1973) the calculated overall dust input is ≈ 1.2 t/sec, sufficient to maintain in equilibrium the dust density at

1 AU. There is some uncertainty regarding the spatial distribution of this dust input, because f(a,e) and n(r) for meteors given by Southworth and Sekanina are not consistent, but roughly half of the input occurs within 1 AU as needed to explain a dust distribution $n(r) \sim r^{-1.3}$ (Figure 5).

A weakness of the paper by Leinert et al. (1983) is that they do not take into account the effect of collisions on the size distribution of dust and that the calculations heavily depend on our knowledge on dust and meteor number densities.

5. RELATIVE DENSITY INCREASE BY DEFOCUSING OF PARTICLES FAR OUT

Mukai and Giese (1984) calculate that because of the slow Poynting-Robertson drift at large heliocentric distances Lorentz scattering due to the sector structure of interplanetary magnetic field may lead to higher average inclination of particle orbits than closer to the sun. The effect is a stronger reduction of in ecliptic dust densities in the outer solar system and a steepening of the dust distribution (Figure 6), e.g. to $n(r) \sim r^{-1.3}$ in the range 0.4 - 1 AU.

However, they appear to have overestimated the electromagnetic effects.

First, they refer to Consolmagno's (1979) calculations of spread in orbital inclinations. He finds for a 1 µm particle at 0.4 AU, charged to 6 V, in orbit with eccentricity e=0.5, that the root mean square change in inclination in 10 years is 4.0°, for example. Morfill and Grün (1979) predict this quantity to be 0.25°, Barge et al. (1982) even only 0.07°. It would be useful to clarify the reason for these different results, all based on the same interplanetary measurements. The true effect could be an order of magnitude smaller than Mukai and Giese assumed.

Second, for elegance of presentation and to save computer time, they estimate the reduction of in-ecliptic densities by a life-time factor $\exp(-t/\tau_L)$, where τ_L is a typical time scale for inclination

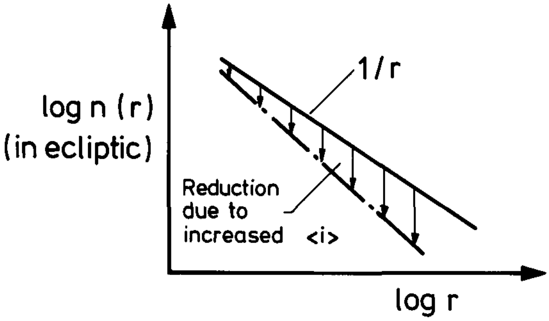

Figure 6. Steepening of spatial distribution by Lorentz scattering of interplanetary dust.

dispersion by Lorentz forces. Preferably one should calculate this reduction by considering the effect of a Gauss dispersion in inclination acting on the original inclination distribution. Figure 7 then shows that their estimate is an overestimate of the effect.

Third, their assumed average inclination of 1° is too small for interplanetary dust and overemphasizes the effect of inclination perturbations.

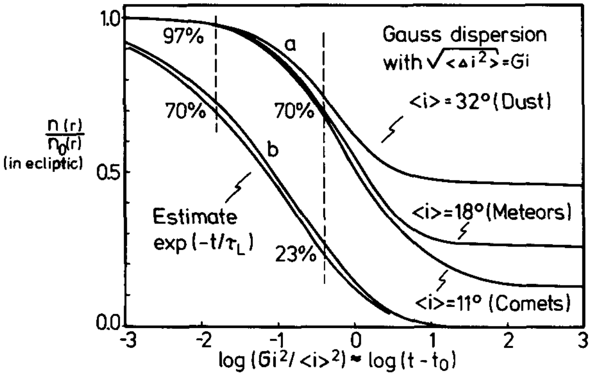

Figure 7. Reduction of spatial density in ecliptic by an added dispersion in inclination (a). The results are compared to the life time estimate of Mukai and Giese (b).

6. CONCLUSION

In view of the above, I find it unlikely that Lorentz forces appreciably affect the spatial distribution of interplanetary dust and have doubts whether the concept of non-destructive collisions may be applied to interplanetary space. On the other hand, collisions in the cloud of dust and meteors must occur all over the solar system. It appears that debris from disrupted meteors is able to balance the mass losses of the dust cloud due to Poynting-Robertson effect and collisions. The resulting extended source region is a natural explanation of the observed spatial distribution of interplanetary dust. The question how the reservoir of meteor particles is filled by comets or other sources remains open.

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DISCUSSION

Singer: EM force referred to as Lorentz force is actually the EM force due to moving plasma (which is an order of magnitude greater).

Answer: A question of terminology. The relative velocity counts. In the frame moving with the plasma this is a Lorentz force.

Singer: With half of zodiacal cloud input within 1 AU one would expect large secular variations in the zodiacal cloud, e.g. in the dust influx to the earth. Can you make some statement on this or find further evidence?

Answer: I do not see a necessary relation between temporal variations in the cloud and spatial distribution of input. We try to model steady state. The Helios observations show the zodiacal light to be remarkably stable.

Fechtig: Don Humes' results from the Pioneer 10/11 beer can experiments show that there are particles with excentricities e=0.99, semimajor axis 10 AU, random inclinations. Those particles are most likely cometary particles. My suggestion is that one includes these results in future calculations!

Mukai: In your treatment small sized collisional debris increases with decreasing solar distance. This variation of size distribution causes a change of colour of zodiacal light. Observed results, however, show neutral and/or reddening. How do you explain this evidence?

Answer: Our model does not explicitely deal with this effect and is not self-consistent with respect to the size distribution. At present a quantitative calculation would only reflect the assumptions made on the size distribution at smaller heliocentric distances. The question is worth being pursued.