SPATIAL DISTRIBUTION OF INTERPLANETARY DUST

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Interplanetary dust can be defined as solid particles outside Earth's atmosphere in the size range larger than a molecule and smaller than an asteroid. It is studied by a number of quite different techniques. For Earth-based observers, these techniques include measurement of the brightness and polarization of the interplanetary light,[1] optical radar studies of particles entering the upper atmosphere, photographic and radar meteor observations, study of meteorites, and various methods of collecting dust particles in the atmosphere, in ice cores, and in deep sea sediments. Observations made from spacecraft include some interplanetary light observations and measurements of individual particles by means of microphones, penetration sensors, and collection experiments. These observational techniques are described by Millman (1969) and Bandermann (1969).

EARTH-ASSOCIATED DUST?

At the beginning of the last decade it was generally considered probable—if not certain—that interplanetary dust was concentrated at a number of preferred locations in the near-Earth environment. In particular, Whipple (1961) reported evidence for a high concentration of dust near Earth with a maximum concentration with respect to the average interplanetary medium perhaps as high as 10^5 (the so-called geocentric dust cloud (GDC)). Kordylewski (1961) reported that he had observed concentrations of dust (the so-called libration clouds) associated with the quasi-stable triangular Earth-Moon libration points L_4 and L_5 (fig. 1). He further stated, "The surface intensity of the libration clouds is a little less in their opposition than that of the Gegenschein[2] [counterglow]." Also, there was a widespread belief that the

[1]"Interplanetary light" has been suggested by Roosen (1971*a*) as a general term to describe all light scattered (or emitted) by interplanetary material. It includes the zodiacal light, which by definition is concentrated toward the plane of the ecliptic, the counterglow, which is a weak brightening in the antisolar direction, and also the light known to come from high ecliptic latitudes, up to and including the ecliptic poles.

[2]*Editorial note:* The responsibility for replacing "Gegenschein" with "counterglow" is entirely mine; I thank Dr. Roosen for accepting this change, which he did reluctantly and only because it had already been made when he received galley proofs.—T. Gehrels.

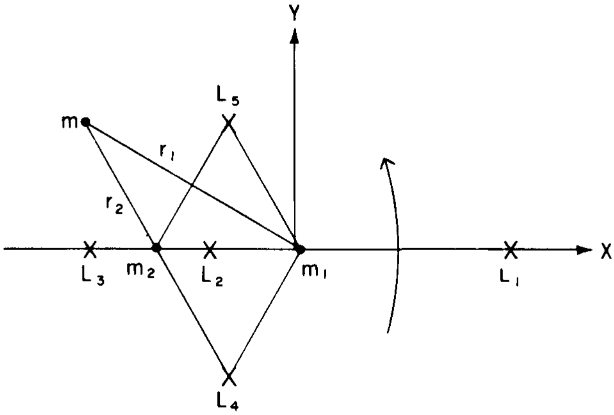

Figure 1.–Geometry for the restricted three-body problem showing schematically the positions of the libration (or equilibrium) points. The arrow indicates the direction of rotation of the system. In the Gyldén-Moulton counterglow hypothesis, m_1 is the Sun, m_2 is Earth, and the dust cloud is at the libration point L_3. For the Earth-Moon libration clouds, m_1 is Earth, m_2 is the Moon, and the dust clouds are near L_4 and L_5. See van de Kamp (1964) or Szebehely (1967) for further discussion.

counterglow was due to a collection of dust around the L_3 libration point in the Sun-Earth system (fig. 1). This suggestion was first made by Searle (1882), but it is generally attributed to Gyldén (1884) and Moulton (1900). It also was thought that the counterglow might be due to an Earth's dust tail populated by lunar ejecta (Brandt and Hodge, 1961).

All of these suggestions were quite controversial, and in the last 10 yr a prodigious amount of work has been done to test their validity. It now seems safe to say that they are all wrong.

Numerous theoretical investigations were carried out to find a justification for the existence of a GDC. The most complete was a series of papers by Lautman, Shapiro, and Colombo (1966) who considered a number of physical processes including gravitational focusing, Jacobi capture, meteor-Moon collisions, and sunlight-pressure air-drag capture. They found that, under any set of reasonable assumptions, none of these mechanisms lead to a significant concentration of material. Peale (1967, 1968) has made an excellent analysis of many dynamical and observational investigations and has set an upper limit of 1 percent on any geocentric contribution to the interplanetary light.

Evidence for concentrations of material associated with the Earth-Moon libration points has been sought photographically and photoelectrically by Morris, Ring, and Stephens (1964); Wolff, Dunkelman, and Haughney (1967); Roosen (1966, 1968); Bruman (1969); and Weinberg, Beeson, and Hutchison (1969). None of these workers found any evidence for lunar libration clouds. The last mentioned study concluded that any brightness enhancement due to lunar libration clouds must be less than 0.5 percent of the background brightness. This is 200 times fainter than the brightness reported by Kordylewski (1961).

Roosen (1969, 1970) has investigated the Earth-associated theories for the counterglow using the fact that they require such a concentration of material near Earth that Earth's shadow would be visible in the center of the counterglow. Because the shadow was not visible to within an accuracy of 1 percent, dust accumulated at the L_3 libration point in the Sun-Earth system can account for no more than 1.2 percent of the counterglow's light. Because the hypothetical dust and gas tails are assumed to have a 3° westward displacement from the antisolar point, the base of the tail in either case would be quite close to Earth (inside the umbra). The lack of a shadow indicates that less than 1 percent of the counterglow light is produced by a dust or gas tail.

We can conclude, therefore, that to within an observational limit of 1 percent, there is no evidence for accumulations of material in the near-Earth environment. Thus, for the purposes of this discussion, we can assume that essentially all of the interplanetary dust is in heliocentric orbits.

RADIAL DISTRIBUTION

A large number of models of interplanetary dust distribution have been built based on observed interplanetary light isophotes and the assumption that the radial distribution of material could be described by a simple power law R^{-p} where R is heliocentric distance. Examples of these can be found in Sandig (1941), Allen (1946), van de Hulst (1947), Fesenkov (1958), Beard (1959), Giese (1962), Ingham (1962-63), Gindilis (1963), Gillett (1966), Aller et al. (1967), Singer and Bandermann (1967), Divari (1967, 1968), Giese and Dziembowski (1967), Powell et al. (1967), Southworth (1967), and Bandermann (1968). Values of p ranging from 0.1 to 3.5 were derived or assumed for the various models.

Southworth (1964) and Bandermann (1968) have shown that if the interplanetary dust is due to cometary debris, then Poynting-Robertson drag causes the dust concentration to vary as R^{-1} for $R < q$ and as $R^{-2.5}$ for $R > q$, where q is the comet's perihelion distance. Essentially all of the comets that have been suggested as sources of interplanetary dust are short-period comets with perihelia less than 1 AU. In particular, Whipple (1967) has stated that "over the past several thousand years" comet Encke with $q = 0.338$ has been "quite probably the major support for maintaining the quasi-equilibrium of the zodiacal cloud." Thus, dust from these comets would be expected to follow an $R^{-2.5}$ law outside Earth's orbit. Dust from a cloud of particles injected with perihelia greater than 1 AU would follow an R^{-1} law as long as the injection is a steady-state mechanism (i.e., a large cloud was not injected fairly recently).

Thus the assumption that the radial density follows an inverse power law is based on very reasonable physical arguments. However, Roosen (1969, 1970) has shown that these assumed distributions require such a concentration of material near Earth that Earth's shadow should be visible in the center of the counterglow. Such a shadow is not observed (fig. 2), and hence the spatial density of reflecting material must *increase* at some distance outside Earth's orbit. The source suggested by Roosen is the asteroid belt, and figure 3 shows the relative density of reflecting material that results. The curves for R^{-p} contributions are upper limits based on the lack of an observed shadow to an accuracy of 1 percent. Note that this result does not say anything about the source or distribution of interplanetary dust inside Earth's orbit. However, models based on an R^{-p} distribution of material outside Earth's orbit are incorrect.

There exists yet another source of information on the radial distribution of interplanetary dust; that is, impact measurements made by two Mariner and two Pioneer spacecraft. Alexander et al. (1965) found that over the heliocentric distance range 0.72 to 1.56 AU the interplanetary dust density was roughly constant. This result is based on two impacts measured by Mariner 2 (Alexander, 1962) and 215 impacts measured by Mariner 4. Berg (1971, personal communication) reports that Pioneers 8 and 9 have ranged in heliocentric distance from 0.75 to 1.1 AU and have measured a total of over 150 impacts. His preliminary analysis also indicates that the interplanetary dust particle density is constant in that range of distances. It is immediately apparent that the number of impacts measured is too small for an R^{-1} distribution to be detected. However, an $R^{-2.5}$ distribution should be detectable. Hence the $R^{-2.5}$ distribution can be questioned on yet another ground.

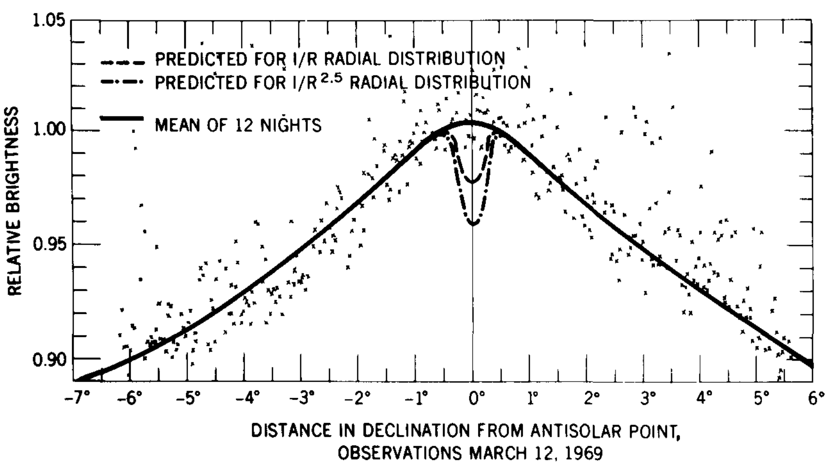

Figure 2.—Brightness curves predicted for two possible radial distributions of interplanetary dust. The points are from observations made on a single night. The points that lie well above the mean curve are due to faint stars passing through the field of view. Data are from Roosen (1969, 1970).

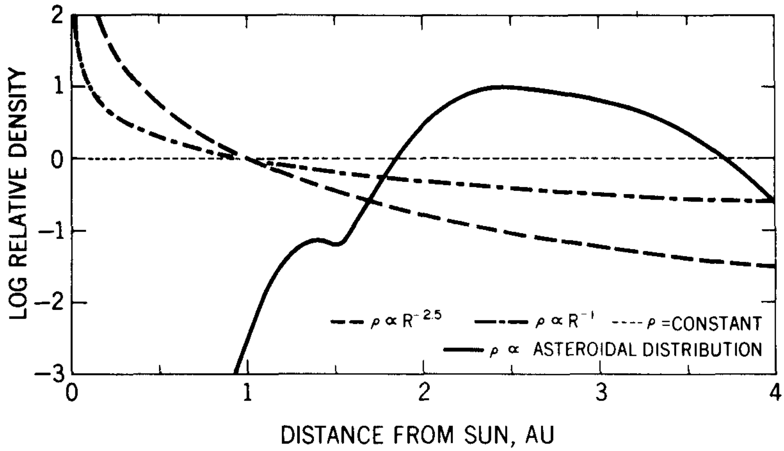

Figure 3.—Relative spatial densities for four possible radial distributions of material. The R^{-p} curves are upper limits with respect to the asteroidal distribution set by Roosen (1969, 1970).

There is an additional simple test to distinguish between the cometary and asteroidal hypotheses (Roosen, 1969, 1970). It requires that a photometer on a space probe traveling toward the outer solar system monitor the counterglow brightness. If the counterglow is due to asteroidal debris, its brightness will remain almost constant until the probe goes further than 2 AU from the Sun. If, on the other hand, cometary debris produces the counterglow, the observed brightness will steadily decrease, and the counterglow will only appear to be a tenth as bright at 2 AU as it is when seen from Earth's distance.

DISTRIBUTION OF INCLINATIONS

Bandermann (1968) and Singer and Bandermann (1967) fit a series of models to the interplanetary light observations reported by Smith, Roach, and Owen (1965) and found that the number of interplanetary dust particles with a given inclination i was best described by a function of the form

$$n(i) = K \sin i \exp(-3i)$$

This result was generally confirmed by Zook and Kessler (1968). Results of this type, however, are based on a faulty assumption.

The radial distribution assumed by Bandermann and Singer was proportional to $R^{-1.5}$. This means that most of the brightness contribution at elongations greater than 90° is assumed to come from material relatively close to Earth. Let us examine the situation at an elongation of 180°. From figure 4 we see that the closer to Earth the material is, the larger the geocentric latitude

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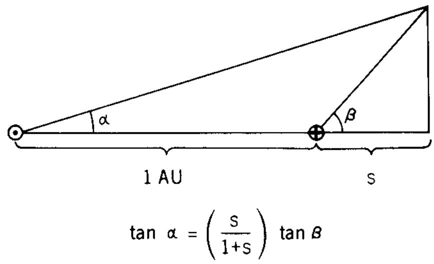

Figure 4.–The relation between the geocentric latitude β and the heliocentric latitude α at elongation 180°.

β at which one must look to see particles with a given heliocentric latitude α. In fact,

$$\tan\beta = \frac{1+s}{s}\tan\alpha$$

where s is the projection into the ecliptic plane of the distance of the material from Earth. As an example, let us look at two cases: (1) $s = 0.3$, the distance within which 50 percent of the counterglow brightness would arise for material distributed according to an $R^{-1.5}$ power law, and (2) $s = 1.5$, the mean distance for an asteroidal contribution. In case 1, in order to see a particle at a heliocentric latitude α of 5°, the observer must look at a geocentric latitude β of 21°. For case 2, β is 8° (fig. 5). In effect what this means is that if the $R^{-1.5}$

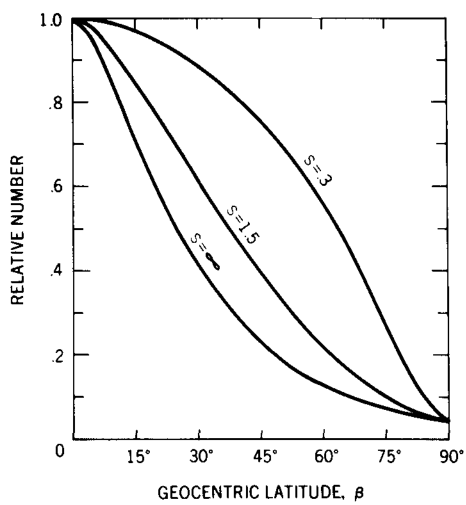

Figure 5.–Spatial density of material at 180° elongation as a function of geocentric ecliptic latitude for various values of s, the projected mean distance of the material from Earth, and Singer and Bandermann's distribution of inclinations.

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law is assumed, the distribution of particle density can decrease steeply with increasing α and still yield the relatively gently sloping observed brightness curve (fig. 5).

As we have already seen, however, the main contribution to the counterglow brightness cannot come from material close to Earth and may come, in fact, from material in the asteroid belt. Until the radial distribution of interplanetary dust is known more accurately, therefore, the orbital inclinations of the dust particles cannot be deduced in this manner.

However, the facts that the observed brightness at high ecliptic latitudes is relatively large (Smith et al., 1965) and that there is a slow decrease in particle concentration with increasing latitude observed in the counterglow seem to imply that the average dust particle inclination must be at least some tens of degrees. This is higher than the average inclinations of the numbered asteroids or short-period comets, but that is not surprising (Roosen, 1969).

ORIGIN OF THE MATERIAL

Discussions of the origin of the interplanetary dust make the necessary assumption that the distribution of dust is in a steady-state condition; i.e., the sources and sinks for the dust are in equilibrium. This means that there must be a continuous injection of small particles into the interplanetary dust cloud because the Poynting-Robertson effect, destructive collisions, sputtering, planetary perturbations, and other dissipative processes make the mean lifetime of the small particles that most likely produce the interplanetary light much less than a million years. (See, e.g., Bandermann, 1968; Whipple, 1967.) Somewhere around 10^4 kg/s of small particles must be continually injected into the interplanetary dust cloud to maintain its quasi-equilibrium (Whipple, 1967). Possible origins for the interplanetary dust that have been suggested (Vedder, 1966) include cometary debris, asteroidal debris, and interstellar grains.

Harwit (1964), Bandermann (1969), and Bandermann and Wolstencroft (1970) have examined the mechanisms for capture of interstellar dust and have found that none of them is sufficiently effective to produce a sensible contribution to the interplanetary dust cloud. Harwit suggests that there may be a contribution from dust particles that remained in the outer solar system when comets were formed that is now "drizzling" into the inner solar system. Although the work on the radial distribution of the dust by Roosen (1969, 1970) would seem to disallow this hypothesis, the possibility that there is a large concentration of dust from this source outside the "Jupiter gravitational barrier" cannot at this time be ruled out completely.

At present, however, there seems to be general agreement that the dust is due to either cometary or asteroidal debris (or a combination of both; see the paper by Whipple in this volume[3]). A firm decision as to which of these

[3]See p. 389.

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sources produces most of the interplanetary dust seems to be extremely remote at this time. Indeed, much of IAU colloquium number 13, *The Evolutionary and Physical Problems of Meteoroids,* will be devoted to this question. However, it is proper here to discuss a few of the more general approaches that have been taken.

One way to approach this problem is to examine the rate of production of interplanetary dust by the various mechanisms. There have been a number of papers written on this subject. Whipple (1967), for instance, presented a model wherein the interplanetary dust cloud is produced and replenished entirely by debris from short-period comets, and asteroidal debris makes no contribution. Harwit (1963) found that, although the amount of dust produced by comets was insufficient to maintain the equilibrium concentration of the interplanetary dust cloud, asteroidal collisions could produce sufficient debris. (The injection rate, however, would be extremely variable because most of the debris must be produced in very rare collisions between the largest asteroids.) Bandermann (1968) and Gillett (1966) also found that comets could not produce enough material, but asteroidal debris was quite sufficient. See also the discussion by Dohnanyi (1969). It seems apparent that too many uncertainties are involved in the calculations to allow a definitive solution to be reached by this approach.

The radial distribution arguments discussed earlier seem to imply that most of the interplanetary dust outside Earth's orbit is asteroidal in origin. There are a number of apparently valid objections, however, to the suggestion that all interplanetary dust comes from the asteroid belt.

First, the correlation of photographic meteors with cometary orbits (e.g., Jacchia, 1963) shows that comets do produce dust particles with elliptical orbits. (Most of the dust from comets immediately escapes from the solar system (Harwit, 1963).) It is intriguing that these correlations disappear for very faint meteors (Elford, 1965), but this effect may well be indicative of the lifetimes of the particles or the perturbing forces acting on them rather than indicative of their origin (Dohnanyi, 1970).

Another strong argument against the existence of asteroidal debris intersecting Earth's orbit in large quantities is the apparent low density of observed meteors (Jacchia, 1963). However, the densities derived from the observations depend on a raft of assumptions (primarily the luminous efficiency), and the trend in recent years has been to revalue the densities much higher than originally thought (Baldwin and Sheaffer, 1971).

Another problem with an asteroidal origin for interplanetary dust inside Earth's orbit is to find a mechanism by which the dust can be brought in past Earth without a shadow being observable.

In any case, it would appear to be safe at this time to state that both asteroids and comets contribute to the interplanetary dust cloud, but the exact contributions have yet to be determined.

REVIEWS

Reviews discussing in situ measurements, meteor observations, and interplanetary light observations have been published by Whipple (1959), Kaiser (1962), Hawkins (1964), Vedder (1966), Singer and Bandermann (1967), and Bandermann (1969). Reviews of in situ measurements have been published by Alexander et al. (1963), McCracken and Alexander (1968), and Kerridge (1970). A review of optical meteor observations is given by Jacchia (1963). Zodiacal light observations and models are discussed by Ingham (1962-63) and Divari (1964). Langton (1969) has discussed the meteoroid hazard question. Also, as part of NASA's meteoroid hazard study, estimates of interplanetary dust parameters have been compiled by Cour-Palais (1969) and Kessler (1970). The classical identification of components of the light of the night sky has been described by Mitra (1952) and Roach (1964).

Roosen and Wolff (1969) have discussed the status of lunar libration clouds. An extensive review on the counterglow was presented by Roosen (1969, 1971*a*). Weinberg (1967*a*) has summarized observations of the interplanetary light and collected an unannotated bibliography on that subject. An unannotated bibliography on meteoroids has also been prepared by Dohnanyi (1971). An annotated bibliography on interplanetary dust was collected by Hodge et al. (1961), and one on the counterglow was produced by Roosen (1971*b*). The proceedings of two recent conferences on interplanetary dust have been edited by Weinberg (1967*b*) and Hawkins (1967). Kresák and Millman (1968) edited the proceedings of a symposium on the physics and dynamics of meteors, and Millman (1969) edited the proceedings of a symposium on meteorite research.

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DISCUSSION

DUBIN: The shadow of Earth in the counterglow (and near-Earth dust) is not expected to be observed at all altitudes. You imply that because the shadow could not be observed, the dust of the counterglow is in the vicinity of the asteroid region and that the satellite results of dust measurements near Earth could not be correct. What is the lowest altitude for which the shadow measurements may be applied?

ROOSEN: The shadow technique that I used (Roosen, 1970) is useful only above about 6000 km. In the direction in which I was looking, material below that altitude would have been in Earth's umbra and hence could not contribute to the counterglow brightness.

DUBIN: The atmosphere extends to several hundred kilometers. It is doubtful that this measurement would work close in where the airglow would interfere. A source of the near-Earth measurements has been identified from the disintegration of the Prairie Network meteoroids, for example.

ROOSEN: As I have already mentioned, Peale (1968) has summarized a number of very convincing arguments against a near-Earth geocentric dust cloud.

DUBIN: Another point in regard to interstellar particles is the discovery of the penetration of the interstellar wind that has been made by Bertaux and Blamont (1971), and by Thomas and Krassa (1971). The results indicate that a hydrogen wind detected by resonant excitation in Lyman alpha penetrates into the solar system to a distance between 3 and 7 AU. Such an interstellar wind should be accompanied by interstellar grains that, accordingly, should also be able to penetrate into the asteroid region and may contribute to the counterglow without showing an Earth shadow. You indicated that there would be no contribution from interstellar dust based on a recent publication of Bandermann?

ROOSEN: I think that Dr. Bandermann should answer that.

BANDERMANN: The publication by Bandermann and Wolstencroft (1970) is concerned with the gravitational capture of interstellar dust into the solar system by a single encounter with a planet, rather than with the penetration of dust contained in a gas cloud colliding with the solar system, which involves gas-dust coupling and solar-wind interaction. These authors found a total capture rate of $\leqslant 10$ kg/s for interstellar dust densities of 3×10^{-26} g/cm^3 and compared this rate with the estimated rate of loss from the zodiacal cloud, $\sim 1 \times 10^3$ kg/s. They did not calculate the contribution by captured dust to the zodiacal light or counterglow surface brightness.

DISCUSSION REFERENCES

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