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THE PROCEEDINGS OF A SYMPOSIUM

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METEOR ORBITS AND DUST

THE PROCEEDINGS OF A SYMPOSIUM

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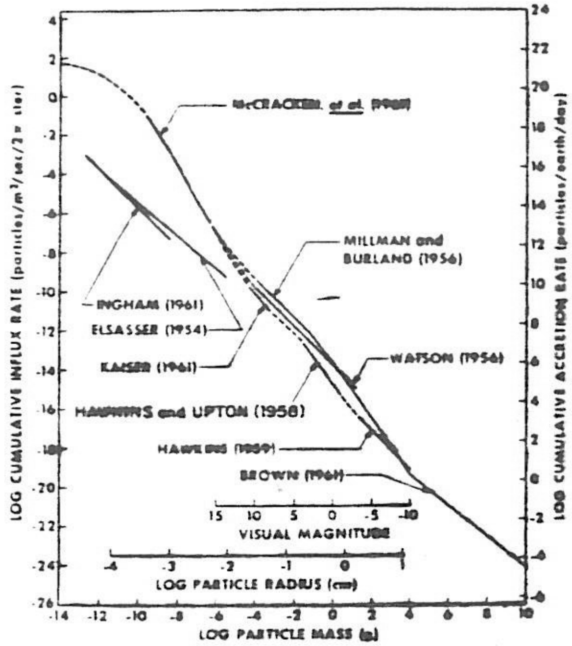

FIGURE 1.—Cumulative flux distribution compiled from the data in table 1 to show the enhancement of the flux of small dust particles in the vicinity of the earth.

frequency of meteorite falls are used to represent the flux of dust particles and meteoroids at the earth's distance from the sun but in regions removed from the earth. The direct measurements made in the vicinity of the earth are used to represent the flux near the earth. The flux of meteoroids is essentially the same for both regions of space, since the known distributions of orbits and the high speeds of encounter (20 to 40 km/sec, on the average, as determined by radar and photographic studies of meteors) preclude any appreciable geocentric enhancement of the flux of meteoroids. The flux of 10^{-8} particles/m²/sec/2π ster for meteoroids with masses $m \sim 1.3 \times 10^{-6}$ g, observed by Elford, Hawkins, and Southworth (1964) by means of radar, indicates that no measurable geocentric enhancement of the flux occurs for the faint radar meteors.

Comparison of the flux in interplanetary space with the higher flux measured in the vicinity of the earth leads to the conclusion that a geocentric enhancement of the flux of small dust particles exists. The degree of this enhancement and the particle mass at which the flux begins to increase both depend on which of the various size distributions derived from studies of the zodiacal light and solar F corona is used to represent the flux of small dust particles in interplanetary space. The size distribution derived by Ingham (1961) and shown in figure 1 represents the best fit to the distribution of surface brightness of the zodiacal light that was observed by Ingham and Blackwell. This size distribution, if extended to smaller sizes of dust particles, is in good agreement with the size distribution of small dielectric spheres (water ice) used by Giese (1962) in calculating models for the zodiacal light. The photoelectric observations of the surface brightness and polarization of the zodiacal light reported by Weinberg (1964) are fitted more closely by the size distribution given by Giese than by any of the other size distributions that have been suggested. The size distribution given by Elsässer (1954) has subsequently been altered and was included in figure 1 only to indicate the desirability of a smooth transition between the cumulative flux distribution for the zodiacal dust particles and the one for the radar meteors.

The geocentric enhancement of the flux of small dust particles, as shown in figure 1, begins to appear at a particle mass between 10^{-6} and 10^{-7} g and reaches a maximum ($\sim 10^4$ enhancement) for dust particles with masses in the neighborhood of $m \sim 10^{-11}$ g. This suggests that some nongravitational force, such as that of solar-radiation pressure, may play an important role in this phenomenon. If so, similar enhancements of flux can be expected to exist in the vicinity of other planets. Investigation of this possibility again requires that radiation pressure be included in the conditions of encounter between small interplanetary dust particles and the planets.

The following sections are devoted to an approximate treatment of the conditions of encounter between the planets and small interplanetary dust particles. Solar-radiation pressure is included in the treatment, but other

An enhancement of the flux by a factor $\sim 10^4$ therefore requires $v_\infty \sim 0.1$ km/sec. The concept of the sphere of influence inherent in the simplified treatment using Liouville's theorem causes trouble, for 0.1 km/sec is not small compared to the speed of escape at the distance of the boundary of the sphere of influence for the earth. A realistic treatment of the problem therefore requires numerical integration of the three-body equations of motion with radiation pressure included.

The orbits for which very low speeds at encounter are possible for dust particles of various sizes were discussed earlier and are represented in figures 3, 4, and 5. The speed at encounter v measured in units of the speed of escape v_e at the altitudes of the near-earth satellites is given as the ordinate on the right in figures 3 and 4.

Singer (1961) assumed that relatively large dust particles ($s \sim 200\ \mu$) have almost circular heliocentric orbits of very low inclination ($e \doteq 0$, $i \doteq 0°$) in order to justify taking $v_\infty = 1$ km/sec, which leads to a flux enhancement $\sim 10^2$. A subclass of these orbits was investigated by Dole (1962), who numerically integrated the geocentric trajectories of dust particles with initial circular heliocentric orbits of zero inclination ($e=0$, $i=0°$). Southworth (1963) has criticized the two-dimensional model used by Dole and argued that the fraction of zodiacal dust particles with such heliocentric orbits must be quite small.

A dust particle of radius $s \sim 200\ \mu$ and mass density 1 g/cm^3 has a value of $\beta \sim 2.4 \times 10^{-3}$, which justifies the neglect of radiation pressure by Singer (1961). But the same dust particle has a mass $m \sim 3.3 \times 10^{-5}$ g, which removes it from the region of particle mass covered by the direct measurements and places it in the region of radar meteors. The available direct measurements apply for dust particles with masses $m \lesssim 10^{-7}$ g, with the maximum enhancement of the flux occurring for dust particles with masses in the neighborhood of $m \sim 10^{-11}$ g. A dust particle of mass $m = 10^{-11}$ g and mass density $\delta = 2.5$ g/cm^3 has a radius $s \doteq 1\ \mu$. The value of β is about 0.23, according to figure 2. The speed of encounter for such a dust particle with an earth-like orbit is about 3.6 km/sec. If we take this as an average speed we obtain a flux enhancement of only 8, which is very much less than the factor $\sim 10^4$ given by the direct measurements.

The shortcomings of the treatments by Singer (1961) and Dole (1962) are shared by numerous other proposed explanations for the geocentric enhancement of the flux of small dust particles in which radiation pressure was neglected. The work of Dole was mentioned here because such numerical integrations should be extended to a three-dimensional model and to the case in which radiation pressure is not neglected. The formulation of the problem of the gravitational enhancement of flux in terms of Liouville's theorem as given by Singer (1961) is useful, provided two important changes are made, namely, (1) radiation pressure should be included so that the discussion can be directed to the range of particle size for which the measured geocentric enhancement of the flux occurs, and (2) the assumption that the small dust particles that produce the zodiacal light have predominantly circular heliocentric orbits of very low inclination should be avoided. The assumption that small dust particles with orbits of fairly low inclination contribute most to the enhancement of the flux near a planet cannot be avoided, but the restriction on the range of the inclination can be relaxed slightly because of the presence of the term $(1-\beta)^{1/2}$ in the expression for U_s. The low-speed encounters occur only for noncircular orbits of fairly low inclination when dust particles of the sizes involved in the measured enhancement of the flux are considered.

The remaining unsolved problem consists of integrating over the unknown distribution of orbits and the rather poorly determined size distribution for the small interplanetary dust particles in an attempt to ascertain whether appreciable planetocentric enhancements of the flux can occur directly. The boundary conditions that must be met by any distributions of orbits and size distributions assumed for use in such an integration include the observed distribution of surface brightness and polarization of the zodiacal light over the celestial sphere.

Summary

The conditions of encounter between planets and small interplanetary dust particles have

cratering theory of Öpik. Despite the different assumptions, the results reported by the two groups are in fair agreement concerning the flux of dust particles of any given mass.

There are some experimental data that support the assumption that microphone systems respond to the momentum of a dust particle impacting at high speed. Calibrations performed at the Stanford Research Institute showed that systems using crystal microphones constructed by Professor J. L. Bohn of Temple University responded (within a factor of 2) to the particle momentum for steel spheres accelerated by shaped charges to speeds as high as 4 km/sec (Dubin, 1960b). The microphones used in the systems on Explorer 1, Pioneer 1, and the U.S. rockets were all constructed by Professor Bohn.

A converted 2-Mev van de Graff machine is now being used routinely in calibrating microphone systems with iron carbonyl particles having speeds that range up to 3 km/sec. These calibrations show that microphone systems somewhat more sensitive than those with which the data in figure 5 were obtained respond (within a factor of 2) to the momentum of a high-speed particle. Preliminary results for particles having speeds as high as 8 km/sec indicate that the effective coefficient of restitution is appreciably larger than unity.

We assume that the microphone systems represented in figure 5 responded to the momenta of impacting dust particles. The cumulative flux distribution shown is uncertain by the small factors previously discussed in connection with the revision known to be required for figure 5. The results could shift considerably in particle mass if the effective coefficient of restitution should prove to be markedly greater than unity. It is unlikely that any such shift would alter the slope of the distribution curve. A small change in slope could conceivably occur if the average speed is a function of the particle mass, but such an effect surely must be negligible for the range of particle mass encompassed by the direct measurements shown in figure 5. The presence of a size-dependent parameter in the hypervelocity cratering process might also cause a small change in the slope of the distribution. The suspected (or demonstrated) presence of such a size-dependent parameter would require further evaluation of the apparent discrepancy between the results obtained with the microphone type and the penetration type of dust-particle sensor.

It is evident from figure 5 that there are two basic ways in which to establish the mass distribution of small dust particles. The first involves the use of a microphone system having several levels of sensitivity that encompass a range of several powers of 10 in the particle mass. The second involves the use of a system with a single level of sensitivity or one with two or more levels of sensitivity that are limited in effectiveness by either close spacing or a limited data sample. The latter approach requires accumulated data from several flights of systems with different sensitivities; it is also necessary to assume that the flux remains fairly constant from one flight to the next. This assumption has been in question since the first flight of a microphone system on a satellite (Explorer 1), which gave evidence for large time variations in the flux.

The first approach is exemplified by the microphone system flown on Explorer 8, and the second by all the other microphone systems flown on rockets and near-earth satellites. The validity of both methods is well illustrated in figure 5, which shows the good agreement among the various data obtained in the vicinity of the earth. Due allowance should be made for the fact that Pioneer 1, Luniks 1 and 2, the Interplanetary Station, and SLV–1 operated at somewhat greater geocentric distances where the flux is undoubtedly intermediate between that near the earth and that in interplanetary space where Mariner 2 operated. The small number of impacts recorded at geocentric distances greater than about 2 earth radii currently limits a discussion of the mass distribution to the immediate vicinity of the earth.

The cumulative flux distribution shown in figure 5 is combined in figure 6 with other data on the flux of meteoroids and small dust particles. (The numerical data used in figure 6 are given in McCracken, see pp. 213-224.) The distribution curves refer to the average flux and do not show the effects of meteor showers and dust-particle showers. The flux of meteoroids is essentially the same near the earth as

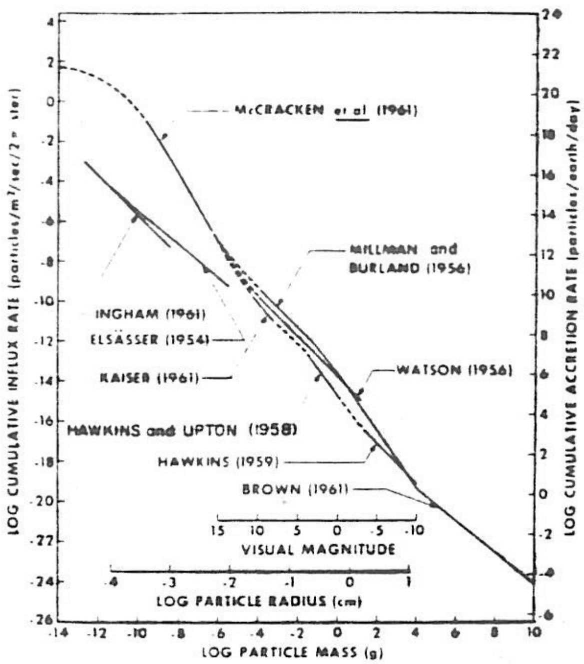

FIGURE 6.—Cumulative flux distribution based on data from various sources and showing the enhanced flux of small dust particles ($m < 10^{-6}$ g) in the vicinity of the earth.

in interplanetary space near the orbit of the earth, but the flux of small dust particles having masses $m < 10^{-6}$ g shows a geocentric enhancement of the flux. This enhancement appears as the difference between the flux measured in the vicinity of the earth and the flux inferred from studies of the zodiacal light for interplanetary space. The degree of enhancement of the flux depends on the particle mass and appears to reach a maximum of about 10^4 for a particle mass $m \sim 10^{-11}$ g. The interpolation between the flux distribution measured with microphone systems and that for radar meteors has recently been verified by the results of Elford, Hawkins, and Southworth (1964), who used radar to obtain a flux of 10^{-8} particles/m²/sec/2π ster for meteoroids having masses $m \sim 1.3 \times 10^{-6}$ g.

Several points regarding the validity of the direct measurements obtained with the microphone type of sensor deserve special comment. The open literature contains statements that these data are highly uncertain and that the flux measured with satellites decreases during the first day or so following launch. The known uncertainties in the calibration of the systems were discussed in the preceding paragraphs. The alleged uncertainty possibly refers to the large decrease in the flux measured with Sputnik 3 on the day of launch. This decrease represents a large variation in the flux rather than an uncertainty, if the data are to be accepted. Such large variations in the flux are not representative of the data obtained with the remaining microphone systems. Large time variations in the flux were recorded by the microphone systems on Explorer 1 and Vanguard 3, but these showers of dust particles occurred after these satellites had completed a considerable number of orbits. The system on Explorer 1 indicated eight impacts while the satellite was being injected into orbit, but there is nothing peculiar about the numbers of impacts recorded after injection was completed. These 8 impacts were questionable and were subtracted from the 153 nonredundant indicated impacts in order to obtain the 145 impacts reported for Explorer 1. The first available readout of the cumulative counter for the system on Vanguard 3 was obtained about 2 hours (almost 1 orbit) after launch. The detailed time history of the cumulative counter during the first day of operation shows no cause for alarm. The impact rate on the day after launch was lower than on the day of launch, but the impact rate on the second day after launch was higher than on either of the two preceding days (see fig. 4). Likewise, the time history of the cumulative counter for the microphone system on Explorer 8 shows no systematic trend in the impact rate following launch that would arouse suspicion concerning the validity of the data. The microphone system on Pioneer 1 did show an impact rate that decreased with time during the outbound portion of the trajectory. A probe that was meant to go to the moon should show such a decrease in the impact rate if the geocentric enhancement of the flux exists and the flux decreases with increasing geocentric distance. The data from Explorer 6 have not been published because instrumental difficulties occurred after the satellite was launched. The microphone system on Vanguard 3 was definitely subject to interference from interrogations of the magnetometer, but the effects of this interference have been largely removed from the latest data presented earlier in this paper. The data presented by us as valid are not characterized by a flux that decreases systematically following launch.

There is an acute need for data from composite dust-particle sensors for which a sequence of events absolutely unique to the impact of a dust particle is required before the system will register an impact. The data from the combination of microphone and photomultiplier flown on the short-lived Ranger 1 represent limited success in this direction. Further progress toward obtaining data that unquestionably apply for impacting dust particles has been realized with the development of the composite dust-particle sensor being flown on the Orbiting Geophysical Observatories. The data obtained with the microphone type of dust-particle sensor have been most essential in the development of the more complex sensors that are now being flown in order to obtain additional information about the speeds, directions of motion, momenta, and kinetic energies of small dust particles.

Summary

The microphone type of dust-particle sensors flown on rockets, satellites, and interplanetary probes has given information concerning the average flux and time variations in the flux for dust particles with masses between about 10^{-7} and 10^{-11} g. The flux is known as a function of particle mass for the vicinity of the earth, so the cumulative mass distribution for this region of space has been fairly well established. The cumulative flux distribution, if slightly extended toward larger dust particles, is in very good agreement with the flux of radar meteors.

The flux of small dust particles observed in the vicinity of the earth sometimes undergoes large systematic variations with time. On one occasion, the flux rose by a factor of 170 above the average value. The measured flux also shows variations by a factor of 10 within intervals of a few hours' duration. None of the intervals of enhanced flux can be positively associated with the known meteoroid streams.

Further investigation of the small-particle content of meteoroid streams and of the mechanism by which the flux of small particles is enhanced near the earth will have to await definitive data regarding the orbits of these particles.

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