Reports

Zodiacal Dust and Deep-Sea Sediments

Abstract. *The recent detection of radioactive Al^{26} in marine sediments has led to the conclusion that it is brought into the earth's atmosphere by micrometeorites which have been exposed, in interplanetary space, to solar high-energy protons. The Al^{26} method is not precise enough to yield directly a reliable value for the mass accretion rate to the earth to better than about 3 orders of magnitude, but it is sufficiently accurate to allow a crucial decision between two widely differing models of interplanetary dust which have been proposed to explain observations of the zodiacal light. The two models lead to Al^{26} concentrations which would differ by about 5 orders of magnitude. Thus, the presence of Al^{26} is consistent only with the zodiacal dust model with particles of some tens of microns rather than with submicron particles. From this model a mass accretion to the earth can then be calculated which is set at 1250 (upper limit, 2500; lower limit, 250) tons per day, or 2.8×10^{-15} g/cm² sec, or 4.5×10^{11} g over the earth per year. This value does not depend on the flux of the solar high-energy particles, which may be uncertain by an order of magnitude or more. The presence of Al^{26} supports the idea that an important fraction of the dust is stony in composition and material density, and thus eliminates some more exotic dust models, such as one consisting entirely of carbon grains. We may also conclude that the accreted dust particles have been in the solar system and exposed to protons from solar high-energy particles for a time interval which is greater than a significant fraction of the Al^{26} half-life (0.74×10^6 years).*

Zodiacal light is commonly interpreted as sunlight scattered from tiny dust particles which are in gravitational orbits in the inner part of the solar system. The detailed properties of the particles, that is, their size distribution and spatial concentration, as well as their shape, composition, and light-reflecting power (albedo), are in doubt and cannot be deduced solely from the astronomical observations of zodiacal light. Two widely differing models for zodiacal dust have been proposed. The earlier model, proposed by van de Hulst (*1*), Allen (*2*), and improved by Öpik (*3*), arrives at a distribution of particle radii $n(a)da = Ca^{-p}da$ having a size range of from 1 to 350 μ with a relatively flat population index of $p = 2.6$ to 3.0. A similar interpretation has been given by Elsässer (*4*), and Siedentopf (*5*). The observed polarization of zodiacal light was usually explained by these authors in terms of scattering from interplanetary electrons.

More recent measurements by Blackwell (*6*) established that the electron concentration must be quite small, while direct measurements of the interplanetary plasma (solar wind) give values of the order of a few electrons per cubic centimeter (*7*). These findings have influenced newer interpretations of zodiacal light (*8–10*) in terms of a steep distribution of particle radii, with $p \sim 4.0$, and extending down to particles of 0.1 μ (Table 1). A comparison of particle size distributions is given in Fig. 1.

The interpretation derived from the optical observations of zodiacal light must be consistent with other more direct observations involving the same types of particles. Here one makes use of the fact that the particles, when under the influence of the earth's gravitational field, come into the vicinity of the earth, and in many cases are accreted to the earth where they can be examined at close range. It is possible to obtain additional and perhaps crucial information concerning the properties of the dust particles: (i) by observations from a spacecraft in the vicinity of the earth, involving impacts on microphones and penetrations of thin films; (ii) by collection of dust particles in the upper atmosphere after they have had a chance to slow down and their concentration has increased; (iii) by optical observations with laser light backscattering from dust particles near 80 km; (iv) by collection from high-altitude balloons and aircraft; and (v) by analysis of ice and snow cores and of deep sea cores. Unfortunately, these methods have given quite contradictory results. The satellite impact data (*11*) have been thrown into doubt recently (*12*). High altitude collection results vary widely (*13*), presumably because of contamination. Laser experiments have shown a positive (*14*) as well as a negative result (*15*). Finally, surface and deep sea analyses have given a spread of values for the dust influx to the earth from less than 10 tons per day to 7×10^6 tons per day (*16*)!

The recent detection (*17*) of radioactive Al^{26} in cores taken in the Pacific Ocean, together with the concurrent measurement of atmospherically produced Be^{10} in the same samples, has led to the conclusion that Al^{26} is brought into the earth's atmosphere, and thence into the ocean sediments, by interplanetary dust particles which have been exposed in interplanetary space to solar high-energy protons. Assuming that the dust particles have the composition of chondritic meteorites, Wasson (*18*) had shown that three reactions are of principal importance: Mg^{26} (p,n), Al^{27} (p,pn), and Si^{28} $(p,2pn)$. Both Mg^{26} and Al^{27} have an abundance of ~ 1.5 percent, while Si^{28} has an abundance of 15 percent. With reasonable cross-sections and estimates of the average proton flux (and spectrum), Wasson obtains a steady-state concentration of 6.5×10^{12} atoms (of Al^{26}) per gram of dust. With Öpik's estimate of dust accretion, Wasson was able to make a quantitative prediction of the accretion of interplanetary Al^{26} of 6.5×10^5 atom/cm² year; he also calculated (*18*) the terrestrial contribution: (i) by way of spallation of atmospheric argon (6×10^3 atom/cm² yr), and (ii) by the interactions of cosmic-ray neutrons and muons with rocks (6.5×10^3 atom/cm² yr).

Aluminum-26 is a more certain indicator of incoming dust, as it does not have the ambiguities inherent in other methods which are based on morphology (spherules), magnetic properties, or chemical composition (nickel concentration). From the measured Al^{26} counting rate ($\sim 3 \times 10^{-3}$ count/min) and resulting concentration (~ 0.4 dpm/kg), a ratio of Al^{26} : Be^{10} activity is obtained as 0.12 ± 0.04

(*17*). Considering the different half-lives, 7.4×10^5 years for Al^{26} and 2.5×10^6 years for Be^{10}, Lal and Venkatavaradan deduce the rate of influx of Al^{26} as 5.0×10^4 atom/cm^2 yr. The required mass accretion rate is estimated by them as 10^4 tons per day over the earth; they arrive at this estimate by assuming an undersaturation of a factor 5, and an average low energy proton flux (> 10 Mev) of 100/cm^2 sec.

There is, however, great uncertainty in this estimate, which comes about from uncertainties in the solar low-energy proton flux (a factor of ~ 3 in the last solar cycle, and perhaps a greater factor over the last million years); the production cross-sections (a factor of ~ 2); the dust composition; the exposure time of the dust particles in space (in relation to the half-life of Al^{26}); and also from the uncertainty in the sedimentation rate (a factor of ~ 2); and in the measured activity of Al^{26} itself. Altogether, I estimated the overall uncertainty at two or even three orders of magnitude and deduce an influx rate of from 100 to 10^5 tons per day. However, as we shall see, it is only necessary to obtain an order of magnitude result in order to decide between the competing interpretations of zodiacal light and then derive a more precise figure for the accretion rate by another method.

While different dust models can be "stretched" to explain the same astronomical zodiacal light data, the accretion rates deduced from these models by simple theoretical considerations vary by several orders of magnitude (Table 1). Because of the Poynting-Robertson effect, the particles have nearly circular orbits; the spatial distribution of zodiacal light suggests that the particles have modest inclinations. Hence, the particle velocities relative to the earth would tend to be quite low, of the order of 2 to 5 km/sec (*19*). Assuming, to a first approximation, that the geocentric particle velocities u are isotropically distributed, one can use Liouville's theorem directly to calculate the influx of particles to the earth (*19*). In terms of the spatial mass concentration M, the accretion rate A is given as

$$A = M\,(\pi R^2)\,u\,(1 + v_e^2/u^2) \qquad (1)$$

where R is the radius of the earth (plus appreciable atmosphere) and v_e is the escape velocity (~ 11 km/sec). It can be seen that A varies as $1/u$ for very small u, and is proportional to u for very large values of u; A shows a minimum when $u = v_e$.

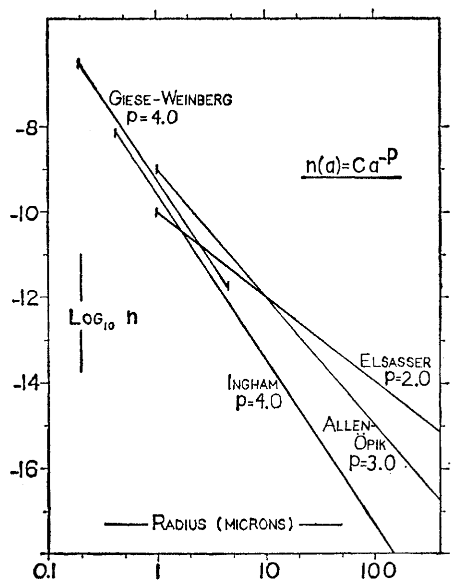

Fig. 1. Models of zodiacal dust distributions, given by $n(a) = Ca^{-p}$, expressed in number of particles per cubic centimeter per interval da (in centimeters).

The calculated accretion rates for different models are shown in Table 1. The accretion rates derived from the Al^{26} results, that is, 10^2 to 10^5 tons per day, favor the flat distribution which involves particles whose radius is typically some tens of microns.

It is necessary to consider carefully whether the particle-size distribution really follows a power law with a single exponent over the whole range. What is relevant here is whether the particles which contribute most to the mass accretion are the same particles which contribute to the zodiacal light. Since mass ~ a^3, light reflection ~ area = πa^2, and diffraction ~ circumference = $2\pi a$, different portions of the particle distribution can be effective, depending on which power of radius enters into the phenomenon under study (*20*).

In general, we can define some property b as an exponential function of a, that is, $b = Ba^\beta$. Then the distribution $n(a) = Ca^{-p}$ transforms into the distribution

$$f(b) = C_b b^{(1-\beta-p)\beta^{-1}} \qquad (2)$$

The integral distribution F_{12} between limits b_2 and b_1, or limits a_2 and a_1, can then be expressed as

$$F_{12} \sim \left[b_2^{(1+\beta-p)\beta^{-1}} - b_1^{(1+\beta-p)\beta^{-1}} \right]$$
$$\text{or} \left[a_2^{1+\beta-p} - a_1^{1+\beta-p} \right] \qquad (3)$$

We have calculated the limiting values of a so that 25 percent of the contribution lies between successive values of a, for the two dust distributions, and for $\beta = 1$, 2, and 3. The results are shown in Table 2, and are now used to further refine the discrimination between the two dust models.

A factor which greatly reduces the amount of Al^{26} carried in by the steep submicron particle distribution is the lack of saturation of Al^{26} brought about by the short exposure time. The lifetime of a particle, defined as the time (in years) required to spiral in from a distance R to the vicinity of the earth, is given by the Poynting-Robertson effect (*21*).

$$T = 7.0 \times 10^2\,a\,\delta\,(R^2 - 1) \qquad (4)$$

where a is in microns, δ in grams per cubic centimeter, and R in astronomical units. If it is assumed that the particles start out near the asteroid belt,

Table 1. Properties of zodiacal dust models. The model is characterized by a size distribution $n(a)da = Ca^{-p}da$, extending from a minimum radius $a_<$ to a maximum radius $a_>$ (in microns). The participle density is δ (in grams per cubic centimeter). The number concentration N and mass concentration M in space are in units of the reciprocal of cubic kilometers and 10^{-23} g/cm^3, respectively. The accretion rates A_u (in tons per day) are given for geocentric velocities u = 2 km/sec and 5 km/sec (1 g/cm^2 sec over the earth corresponds to 4.4×10^{17} tons per day).

Author	C	p	$a_<$	$a_>$	δ	N	M	A_2	A_5
v.d. Hulst (*1*)	3.5×10^{-20}	2.6	1	350	3.5	55	34	2400	1100
Elsässer (*4*)	1.0×10^{-18}	2.0	1	350	3.5	10	90	6400	3000
Allen-Öpik (*3*)	1.0×10^{-21}	3.0	1	350	3.5	50	5	360	170
Siedentopf (*5*)	1.6×10^{-21}	2.85	3.2	320	3.5	2.6	4	280	130
Öpik (*3*)	8.4×10^{-21}	2.85	1	350	3.5	110	20	1400	660
Ingham (*8*)	2.5×10^{-26}	4.0	0.4	840	2	130	0.016	1.2	0.53
Giese (*9*)	1.0×10^{-20}	2.5	1.6	6.4	3.5*	3	0.014	1.0	0.46
	7.4×10^{-26}	4.0	0.16	4.1	3.5*	5800	0.035	2.5	1.2
	2.2×10^{-26}	4.0	0.16	4.1	7.8	1700	0.023	1.6	0.76
Weinberg (*10*)	7.4×10^{-26}	4.0	0.17	4.4	3.5*	5000	0.035	2.5	1.2

* Both Giese and Weinberg use components having refractive index m = 1.33, that is, corresponding to that of H_2O. However, they do not suggest that the dust actually is ice. For that reason I have chosen a density of 3.5 g/cm^3.

Table 2. Quartiles of radii for interplanetary dust having a frequency distribution of radii given by a^{-p} and weighted with a function a^{β}, where β is 1, 2, or 3. Shown are values of a so that 25 percent of the integral distribution lies between successive values of a. For example, for the flat distribution (with $p = 2.8$, as an average between 2.6 and 3.0), 25 percent of the mass accretion (where $\beta = 3$) comes from particles between 1 and 110 μ, or from particles between 275 and 350 μ. Half of the mass accretion comes from particles with radii $\gtrsim$ 196 μ. On the other hand, half of the zodiacal light at larger elongations (produced by scattering; that is, $\beta = 2$) comes from particles $\gtrsim$ 42 μ. Half of the zodiacal light at elongation angles of 30° or less (*20*) (where $\beta = 1$) comes from particles >2.38 μ.

β	$p = 2.8$			$p = 4.0$		
	$a_< .1.0$ μ		$a_> = 350$ μ	$a_< = 0.17$ μ		$a_> = 4.4$ μ
1	1.43	2.38	5.66	0.196	0.240	0.340
2	9.2	42	135	.244	.327	.606
3	110	196	275	.384	.867	1.99

with $R = 3$ A.U., and if the median values of a are used in accordance with Table 2, that is, 196 μ and 0.87 μ, then the lifetimes become 3.8×10^6 years and 1.7×10^4 years. These are to be compared with 7.4×10^5 years, the half-life of Al^{26}. There is negligible undersaturation for the flat distribution, while for the steep distribution the undersaturation is a factor of about 40 (*22*).

An added discriminating factor is the escape of Al^{26} from submicron particles because of the recoil energy which it acquires as it is produced. For example, the reaction Mg^{26} (p,n) Al^{26} has a Q-value of -4.797 Mev. The energy level density in the Al^{26} nucleus is high enough so that a statistical model of reactions can be used (*23*). For an incoming proton energy of 20 Mev, the energy released is about 15 Mev. In this region, the angular distribution is more or less isotropic, so that one can compute a kinetic energy of the Al^{26} nucleus of about 0.85 Mev. The range of the heavy nucleus can, in moderately heavy material, quite adequately be represented by the relationship (*24*)

$$\text{energy}\left(\text{in } \frac{0.1 \text{ Mev}}{\text{amu}}\right) \approx \text{range (in mg per cm}^2\text{)}. \qquad (5)$$

This leads to a range of 1.2 μ if chondritic densities are assumed, and decreases the number of Al^{26} atoms retained within the submicron particle distribution by about a factor of 3 since about one-third of the mass of the particles is contained within 1.2 and 4.4 μ (Table 2).

Conclusions. The Al^{26} data, by themselves, are not accurate enough to fix the dust accretion to the earth to better than about 2 to 3 orders of magnitude. However, they are accurate enough to distinguish between two competing models for the interpretation of zodiacal light. They are in good accord with the van de Hulst, Allen, Öpik model which has a flat distribution of particles which are in the range of a few microns to a few hundred microns in size. The presence of Al^{26} as found in deep sea deposits disagrees by about a factor of 10^5 with a particle distribution having a steep spectrum and consisting purely of submicron particles; of this discrepancy, about 3 orders of magnitude can be ascribed to the lower mass concentration given by the steep model, about 1½ orders of magnitude are due to undersaturation caused by the short lifetime in interplanetary space, and about ½ order of magnitude is due to the escape of Al^{26} from a small particle due to its recoil energy.

Mass accretion rate to the Earth. Once the "flat" size distribution has been selected, the accretion rate can be calculated from Eq. 1. The spatial mass concentration M is obtained from the data of Table 1, which are based on zodiacal light photometry, as an average between the van de Hulst and Siedentopf-Öpik (*3*) values. As judged from the spatial distribution of zodiacal light, the bulk of the dust particles have geocentric speeds between 2 and 5 km/sec. Thus the mean value of accretion rate is 1250 tons per day (from Table 1). This figure happens to fall near the center of the cited range of influx values (*16*), about 1000 times more than the lowest value and about 1000 times less than the highest value. Our uncertainty spans a factor of about 10, rather than 10^6.

The uncertainty in the influx arises partially from an uncertainty in the value of M, which is about a factor of 5 (*3*), but also from the effects of particles having higher and lower geocentric velocities u. An estimate for the minimum value of u can be obtained by assuming the heliocentric orbits of the dust particles to be completely circular and inclined to the ecliptic at an angle of about 2°, a mean value for the nearer planets. The Earth's orbital velocity is 29.8 km/sec, giving a geocentric velocity of the dust particles of more than 1 km/sec. Again, since the eccentricity of the Earth's orbit is 0.01675, the perihelion-to-aphelion velocity ratio turns out to be $1 + \epsilon/(1-\epsilon)$, or about 3 percent of the orbital velocity. We can therefore take $\mu = 1$ km/sec as a lower limit for the geocentric velocity of interplanetary dust.

A much more stringent lower limit to u can be derived from the penetration experiments in Explorer XVI and Pegasus satellites. It can be shown (*25*) that the penetration rate P varies as

$$\left(1 + \frac{R}{r}\,\frac{v_e^2}{u^2}\right)^{\frac{p+2}{3}} \qquad (6)$$

while the accretion rate from Eq. 1 varies as u^{-1} for small values of u. Near the Earth, with $r = R$, for small values of u and with $p = 2.8$, $P \propto (v_e/u)^{3.2}$; therefore, an appreciable dust component with $u < 1$ km/sec should produce a greatly enhanced penetration rate. There is no experimental evidence for such an enhanced rate (*26*); on the contrary, the data (within their own experimental uncertainties) support the existence of large dust particles (> 30 μ) with moderate geocentric velocities.

A reasonable upper limit is given by a dust particle moving at an inclination of 45° to the ecliptic and, therefore, having a geocentric velocity of $u = (29.8)\ (2 \sin 22.5°) = 23$ km/sec. The ratio of extreme accretion rates turns out to be $A_{1.0}/A_{23} = 4.3$, and it is not very sensitive to the upper limit of velocities; that is, $A_{1.0}/A_{11} = 5.5$; $A_{1.0}/A_{40} = 2.8$.

Material density and composition of dust. The existence of Al^{26}, attributed to interplanetary dust (*27*), can be used quite effectively to eliminate the possibility of low material densities, of the order of 0.1 g/cm³ (similar to cometary densities) (*28*). Assuming unchanged optical properties of the particles, their mass concentration and their exposure time in space would both be reduced by a factor 30, and the range of the recoiling Al^{26} nucleus would increase by a factor 30, to about 36 μ. Thus the "steep" particle size distribution would bring in negligible amounts of Al^{26}, while the "flat" distribution would experience a reduction of $30 \times 6 \times 2 = 360$ (the factor of 6 is for undersaturation and the factor of 2 for recoil loss).

Similarly, the existence of Al^{26} supports the existence of a substantial stony component in interplanetary dust, as opposed to a mixture of pure Fe and H_2O [assumed by Giese (*9*) for computational purposes], or only carbon grains. This result may appear trivial, but we have no other evidence for the chemical composition of zodiacal dust.

Before drawing a final conclusion, however, some caution must be exercised because the portion of the distribution which contributes to the mass inflow overlaps only partially with the portion which produces the bulk of zodiacal light. It is conceivable, but unlikely, that two quite dissimilar distributions coexist. It will be important to obtain confirmation with the other methods currently used to study interplanetary dust.

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Geomagnetic Polarity Change and Faunal Extinction in the Southern Ocean

Abstract. *Paleomagnetic polarity changes have been detected in nine deep-sea sedimentary cores (from the Pacific-Antarctic Basin) in which an extinction horizon of a radiolarian assemblage was previously independently determined. The depths of the polarity change 0.7 million years ago and the faunal boundary are closely correlated, confirming that the faunal extinction was locally virtually synchronous. Although the reason for the faunal extinction is unknown, the possibility of causal relationships between faunal extinction and factors directly involved with sedimentation rate, sedimentation rate variation, and sediment type appears to be excluded.*

Uffen (*1*) suggested that during a geomagnetic polarity reversal the loss of magnetic shielding during the possible zero dipole field condition (*2*) and consequent excessive cosmic radiation at the earth's surface could lead to increased rates of genetic mutation. Although Simpson (*3*) believes that macropaleontological data, when combined with paleomagnetic polarity observations, support this possibility for the past 600 million years, the evidence is not convincing in view of lack of coverage and depth of appropriate data. At present the most promising sources for investigation of the hypothesis are microfossils and paleomagnetic data in deep-sea sedimentary cores.

Harrison and Funnell (*4*) noted that extinction of the radiolarian species *Pterocanium prismatium* and evidence for a geomagnetic polarity reversal occurred together in an equatorial Pacific core. Hays (*5, 6*) studied the distribution of radiolaria in the submarine sediments of the Southern Ocean and found four widespread well-defined successive assemblage zones, which he named, in order of increasing age, Ω, Ψ, χ, and Φ. On the basis of isotope data for the upper parts of a single core and on extrapolation, he inferred that boundaries between these four zones occurred at 0.4, 0.9, and 1.6 million years, respectively. Opdyke *et al.* (*7*) observed that the upper part of Hays's χ radiolarian zone, which is marked by the local extinction of several species (especially *Pterocanium tribolum*, *Saturnalus planetes*, and *Sethocorys* sp.) and the appearance of *Stylatractus* sp., *Lacopyle* sp., and *Prunopyle buspinigernum*, occurred in close association with a change in the magnetic polarity in four cores. Because of relatively low sedimentation rates in the cores concerned, it is not clear whether the observed faunal extinction horizon is associated with the polarity change at the Brunhes-Matuyama epoch boundary (*8*) 0.7 million years ago, or with the change marking the end of the Jaramillo event (*9*) about 0.85 million years ago (Figs. 1 and 3). The faunal horizon is apparently geologically synchronous. Opdyke *et al.* (*7*) did not dismiss the possibility that, in harmony with Uffen's hypothesis (*1*), there may exist a causal relationship between these extinctions and magnetic reversals. Much additional information is needed concerning this possibility (*7, 10*).

We have measured paleomagnetic polarity changes in the "Eltanin" core