The correctness of this hypothesis on the origin of the dust cloud around the earth could be checked when rockets are sent to Venus. Moving, like the earth, within a zodiacal cloud of particles, Venus should possess a similar concentration, possibly even a denser one, since the density of the zodiacal cloud increases toward the sun. A lunar source of the cloud, as suggested by Whipple, does not exist in the case of Venus.

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Earth's Dust Envelope

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As reported by F. L. Whipple,[1–3] an analysis of micrometeorite research using rockets and satellites shows that the earth is surrounded by a concentration of interplanetary dust which decreases with the increase of height from 100 to 100,000 km in accordance with an $h^{-1.4}$ law. Thus we now must add this dust envelope to the earth's hydrogen envelope—the geocorona—and belts of energized particles. Following are some notes on this surprising phenomenon.

1. Let us first review the observational data. To the material in Ref. 1 we must add new material obtained from measurements made on Soviet satellites, space probes, and geophysical rockets,[4–6] and the results of a detailed analysis of the measurements made on Explorer I.[7] In all analyzed experiments, both Soviet and American, micrometeorite impacts are recorded by piezoelectric counters of one kind or another. When an impact occurs the counter emits an electric pulse, which is recorded. The result of the measurement is in the form of the number of pulses per unit of time on a unit of surface and an estimate of the minimum recorded mass (or range of masses) of the particles.

Such an estimate of minimum mass is rather uncertain, since the recorded signal u is some function of mass and velocity which has not been clearly defined. Some writers[7,8] believe that $u = f(m, v) \sim mv^2$, others[9,10] that $u \sim mv$. Furthermore, it is not entirely clear what average velocity should be taken for the micrometeorites. As a rule the minimum recorded mass lies between 10^{-10} and 10^{-8} g, and the velocity is assumed to be 30–40 km/sec. This is probably too fast even if we ignore the dust concentration, which in itself makes such velocities practically impossible. We can in fact assume that most of the micrometeorites recorded belong to the zodiacal cloud and move around the sun in direct orbits with slight eccentricities.[11,12] The geocentric velocity in the vicinity of the earth is determined by the inclination i and eccentricity e. To determine the velocities of the meteoric particles, we can take i and e as equal to the average values of these parameters for asteroids ($\sin i = 0.149$, $e = 0.144$), since the form of the zodiacal cloud shows a similar value for the average inclination.[13] The average geocentric velocity of particles at infinity will then be $v_\infty \approx 5.6$ km/sec. In the earth's gravitational field at distance a from the earth's center $v = \sqrt{\bar{v}^2{}_\infty{}^2 + (2\gamma M/a)}$; at the surface of the earth it will be $v \approx 12.5$ km/sec. For the average values of i and e for seven asteroids intersecting the earth's orbit we obtain a higher value for the velocity, 18 km/sec.[1] Allowing for the vehicle velocity, we estimate that the velocity of encounter with a particle should be somewhat greater than the velocity of the particle itself. In estimating in the present paper the mass of recorded particles, we will assume on a conditional basis that the velocity of encounter is constant at 15 km/sec, in agreement with Ref. 1. As other values hitherto have been used as a rule in reducing observations, we will reduce the minimum masses to account for this chosen value of 15 km/sec. We will use the form of the dependence $f(m,v)$ assumed in each case by the individual experimenter.

To compare impact frequencies recorded by instruments of various sensitivities we must know the integral distribution of particles by mass $n(> m) = km^{-\beta}$. If the differential distribution of particles by radius has the form $n_1(r)dr = c_r{}^{-p}dr$, then $\beta = (p - 1)/3$ (on the assumption that the particle density does not depend on the radius, which, for particles with $r = 10^{-4}$–10^{-2} cm, is very reasonable).[12] Analysis of observations of the F corona[14] and counterglow or gegenschein,[15] ignoring the dependence of n_1 on $R_\odot$, where $R_\odot$ is the distance from the sun, gave $p = 2.6$ and 2.8. However, a review by Beard[16] taking account of this dependence argued convincingly that the value p for interplanetary dust is close to $p = 4$ (that is, $\beta = 1$), as suggested earlier by V. G. Fesenkov.[11] Idlis[17] showed that the value $p = 4$ is obtained naturally if it is assumed that the particles are formed in the asteroid belt as a result of fragmentation and then approach the sun and are decelerated by the Poynting-Robertson effect. Finally, a collation of direct measurements of micrometeorite impacts on Explorer I and Vanguard III[9] indicates that $\beta = 1$. The results obtained with Explorer VI[1] also agree with this spectrum. Therefore, $\beta = 1$ can be considered the best substantiated value. Thus, to determine the expected frequency of impacts of micrometeorites with mass greater than m_2 when the impact frequency $N(> m_1)$ with mass

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Table 1

Experiment	Minimum recorded pulse, 10^{-3} g/cm/sec	Particle velocity used, km/sec	Minimum mass, 10^{-9} g	Impact frequency N, m²/sec	Exposure St, 10^8 cm²/sec	Mass reduced to velocity, 15 km/sec, 10^9 g	Impact frequency N reduced to mass, 10^{-8} g, m²/sec	Height h, avg, 10^3 km
Soviet geophysical rockets[a]	15	15	10	0.3	0.15	10	0.3	0.2
U. S. geophysical rockets[1]	0.89	15	0.6	1.2	20	0.6	$7\cdot10^{-2}$	0.13
3rd Soviet satellite[6b]	...	40	8	$2\cdot10^{-3}$	...	60	$1.2\cdot10^{-2}$	0.9
Explorer I,[10] summary	2.5	...	...	$8.4\cdot10^{-3}$	1.8	1.7	$1.4\cdot10^{-3}$	1.4
Explorer I,[7] quiet component	2.5	...	...	$1.5\cdot10^{-3}$	1.8	1.7	$2.5\cdot10^{-4}$	1.4
Vanguard III[9]	10	...	...	$1\cdot10^{-3}$	300	7	$1.5\cdot10^{-3}$	2
Explorer VI[1]	17	...	...	$5\cdot10^{-6}$	36	11	$5.5\cdot10^{-6}$	22
	0.7	...	...	$7.2\cdot10^{-5}$	36	0.47	$3.4\cdot10^{-6}$	22
1st Soviet space probe[4]	...	40	2.5	$<2\cdot10^{-3}$	<7	14	$<3\cdot10^{-3}$	180
2nd Soviet space probe[4]	...	40	2.5	$9\cdot10^{-5}$	20	14	$1.5\cdot10^{-4}$	180
3rd Soviet space probe[4]	...	40	1	$2.8\cdot10^{-3}$	4.5	6	$1.8\cdot10^{-3}$	300
Pioneer I[10]	0.15	...	...	$4\cdot10^{-3}$	0.42	0.1	$4\cdot10^{-5}$	60

[a] Average of three experiments.[5]
[b] Average values for May 16–17.

greater than m_1 has been measured, we need only multiply $N(> m_1)$ by m_1/m_2. We will reduce all measurements to a sensitivity corresponding to 10^{-8} g. After verifying the observed data (Table 1) by using the two reductions mentioned, we entered them on the graph (Fig. 1) as a function of distance from the earth's surface. The relative weight of any particular experiment depends on "exposure" (the product of the area of the counter by the working time) and on the recorded number of impacts. The exposures are given in Table 1 and the total number of impacts for all points for which such data were published is shown on the graph.

Especially interesting are two experiments (Explorer I and Pioneer I) in which a distribution of the number of impacts as a function of distance was obtained. For Explorer I the distribution was obtained by Hibbs,[7] who isolated and discarded sporadic increases in the number of impacts. This procedure reduced the average impact frequency by one order of magnitude in comparison with that originally published.[9] For this paper we have determined the dependence of impact frequency on distance for Pioneer I in accordance with the data in Ref. 10. We have broken up the trajectory into sections $\Delta h = 2R_E$, where R_E is the radius of the earth, and have found the impact frequency for each section; each point on our graph represents one of these sections. For all remaining experiments we have used heights which were averages between apogee and perigee.

An examination of Fig. 1 verifies the existence of the strong dependence $N(h)$ noted by Whipple, but it is difficult to accept the form of the dependence $N(h) \sim h^{-1.4}$ which he suggests. An examination of the graph suggests that three zones may be identified with reasonable certainty in the dust cloud surrounding the earth: 1) a zone* from 100 to 400 km, where $N \approx 0.1$–1 m^{-2} sec^{-1}; 2) a zone from 400 km to a height of the order of $2R_E$, where $N \approx 10^{-4}$–10^{-2} m^{-2} sec^{-1}; 3) a zone $h \geqslant 2R_E$, where $N \approx 10^{-6}$–10^{-4} m^{-2} sec^{-1}.

For purposes of reference, Table 2 gives estimates of the mass flux density M and the concentration n and density ρ in the corresponding zones. In computing M and ρ it has been assumed that for each particle $m = 10^{-8}$ g. If $\beta = 1$ the inclusion of larger and smaller masses increases the estimated values by scarcely more than one order of magnitude. In any case the estimates of M and ρ in Table 2 are minimum values. In estimating n and ρ the velocity has been rounded to 10^6 cm/sec. It has also been assumed that $N = \frac{1}{4}nv$ and $M = \frac{1}{4}\rho v$. The data given in this table for the zodiacal cloud are outside estimates obtained by classical methods. (Here the relationships between n and ρ and between N and M are different; they have been obtained on the basis of the spectrum $n(m)$, which differed for the different estimates.) In the light of Beard's work[16] it appears probable that the density of the zodiacal cloud does not exceed 10^{-22} g/cm³, the expected impact frequency being 10^{-5}/m²/sec.

* At a height of about 95–100 km the dust is decelerated and falls in accordance with the Stokes-Milliken law until the fall velocity decreases to approximately the diffusive equilibrium velocity. Thus a distinctive zone of dust in suspension begins below 80–95 km. The concentration here may be much greater than in Zone 1. Although the velocity of the particles in this zone is low, it can be recorded in rocket experiments because of the velocity of the rocket itself. In this paper we are considering only phenomena occurring above 100 km.

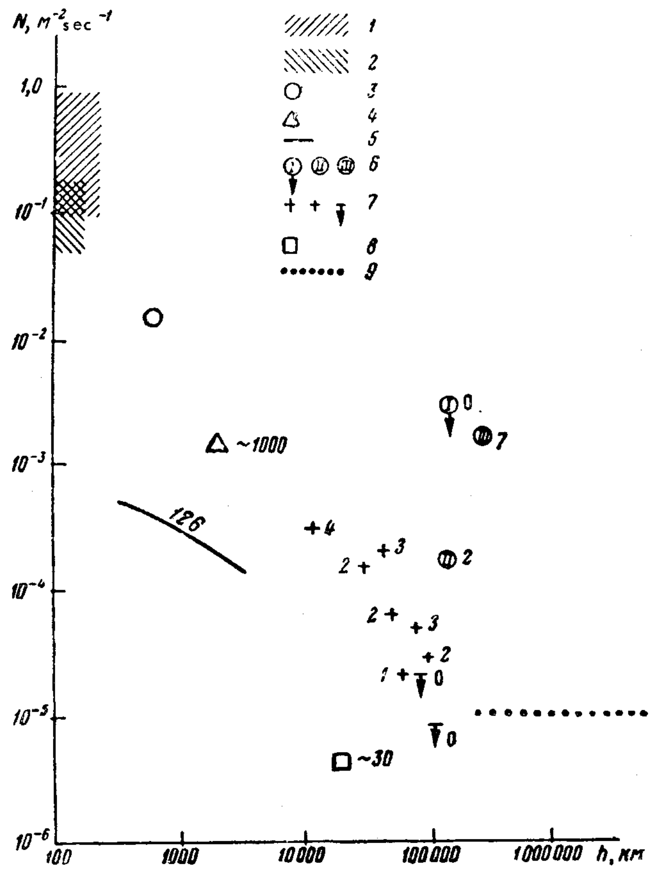

Fig. 1 Dependence on height h of impact frequency N, reduced to a single sensitivity: 1) Soviet geophysical rockets; 2) US geophysical rockets; 3) Third Soviet satellite (May 16–17, 1958); 4) Vanguard III; 5) Explorer I; 6) Soviet space probes (first, second, and third in order); 7) Pioneer I; 8) Explorer VI; 9) Zodiacal cloud. Figures beside designations show total number of impacts on the basis of which the given point was obtained.

We see that in Zone 3 both direct and classical methods give values of approximately the same order of magnitude, whereas in Zone 2—and in Zone 1 particularly—the cosmic dust is denser. From Zone 3 to Zone 2 the increase is relatively smooth; from Zone 2 to Zone 1 it is more abrupt.

It is interesting to note the presence of the instabilities observed in Zone 2. The sporadic increase of May 15 observed on the flight of the third satellite is especially large: a stream was recorded which registered approximately 10 m^2/sec.[6] Equipment on Explorer I repeatedly recorded sporadic increases, but they were smaller in amplitude. Both of these experiments show that in the dust envelope, at least in Zone 2, there are two components of impact frequency, a quiet and a sporadic one. It is possible that the sporadic component exceeds the quiet one not only at the "burst" impact frequency but also at the average frequency (cf. Refs. 7 and 10).

In analyzing the measurements made on Explorer I the latitude dependence was investigated[7] along with the height dependence. No statistically reliable latitude effect was obtained.

2. What is the reason for the presence of the dust envelope around the earth? It is not difficult to show that the condensation of particles and the increase in their velocities in the earth's gravitational field—their motion being in hyperbolic orbits—give, at distance a from the earth's center, an average particle stream of a given mass through an arbitrarily oriented area equal to

$$N_a = \alpha N_\infty[1 + (u_a^2/\bar{u}_\infty^2)] \qquad (2)$$

where u_a is the parabolic velocity at distance a, $\bar{u}_\infty$ is the average geocentric velocity far from the earth, N_∞ is the stream far from the earth, α is a coefficient characterizing the shielding of part of the stream by the earth (near the earth $\alpha = \frac{1}{2}$, far away $\alpha = 1$). With $\bar{u}_\infty = 5.6$ km/sec and $a = R_E$, we have $N_a/N_\infty \approx 3$. If $\bar{u}_\infty = 1$ km/sec^{-1}, which is too small, then $N_a/N_\infty \approx 50$.

A decrease in the rocket velocity at great distances produces a decrease in the encounter velocity, which corresponds to an increase in $m_{\min}$ and consequently to a decrease in the recorded impact frequency N. We can expect this factor to reduce N by 3–10 times.

Thus part of the increase from Zone 3 to Zone 2 may be explained simply as the result of insufficient rigor in reducing observations. (A constant velocity and one unchanging minimum mass for different distances from the earth should be adopted.) This explanation is adequate if $\bar{u}_\infty$ is small enough (a few km/sec). But in the present case the effect of gravitational concentration is involved as well, and should also increase N several times. These two effects in combination might be expected to account for the increase in impact frequency of $1\frac{1}{2}$ orders of magnitude observed in the transition from Zone 3 to Zone 2. But from Zone 2 to Zone 1 the impact frequency increases by another 2 or 3 orders of magnitude.

De Jager[18] considered that the dust particles of the zodiacal cloud could be captured into closed orbits around the earth. According to him, the semimajor axis of the orbit of a particle would gradually be shortened (first as a result of the radiative and corpuscular Poynting-Robertson effect and then by deceleration in the earth's atmosphere) and the captured particles would then fall to earth. But capture in a restricted three-body problem as referred to in Ref. 18 is of course impossible. The possibility of capture in a four-body problem (sun-earth-moon-particle) has not yet been seriously investigated and cannot be excluded.

Whipple[2] has stated that meteorite impacts on the moon could send an additional quantity of dust into the vicinity of the earth. When meteorites explode on the moon's surface a certain proportion of the material is sent into a hyperbolic velocity relative to the moon and should be captured into orbits around the earth. The deceleration effects mentioned earlier will contract the orbits, which in time will approach circularity. In the geocorona ($h < 25{,}000$ km) aerodynamic drag may be considered fundamental. For orbits that are approximately circular, it can be shown that, assuming a constant stream of particles approaching the earth in spiral orbits, the dependence of the concentration of these particles on a is determined according to the expression

$$n(a,r) = [CK(r)\delta r]/[Sa^{5/2}\rho(a)] \qquad (3)$$

where $K(r)$ is the injection velocity of the particles, that is, the average number of particles of radius r ejected from the moon in one unit of time and captured into circumterrestrial orbits; a is the radius of the orbit; $\rho(a)$ the atmospheric density at distance a; δ the density of the particles; S the ratio between their aerodynamic and their geometrical cross-section; and C a constant. Inside the hydrogen geocorona $\rho(a)$ changes slowly and $n(a,r)$ increases by $1\frac{1}{2}$ orders of magnitude as the radius of the orbit contracts from 4 R_E to 1.1 R_E in rough agreement with observation. However, below 1000 km $\rho(a)$ increases very rapidly while a undergoes only slight change (S also changes little). Consequently the concentration of particles $n(a, r)$ should quickly fall below 1000 km as a result of the rapid growth of $\rho(a)$, which is in absolute disagreement with observations. There thus seem to be serious objections to Whipple's hypothesis. There are similar difficulties in the case of any hypothesis involving the capture of particles into approximately closed orbits in the earth's gravitational field, especially that of Ruskol,[19] which explains the increase in concentration as being the result of meteorite collisions in the vicinity of the earth and the capture of the products of collision into approximately closed orbits.

The distribution of particles by mass in Zone 2 corresponds closely to what might be expected for the zodiacal cloud, especially in the light of Beard's work.[16] Since the particle density in this zone is not much increased, it may be due in large part to the gravitational concentration of particles of the zodiacal cloud. As we have indicated, for this to happen the geocentric velocities of the particles would have to be sufficiently small.

The basic problem appears to be the origin of Zone 1. The only reasonable source of the particles in this zone would appear to be the fragmentation of larger bodies by some mechanism which has not yet been identified. The idea that such a process might be possible is advanced in Ref. 20, with the comment that at the heights in question we may well expect to find fragmentation of ice bodies of cometary origin as a result of the interaction of free radicals with the atmosphere. It would be very useful to learn the distribution of particles

Table 2

	Zone	N, m^2/sec	M, 10^{-12} g/cm^{-2}/sec^{-1}	n, 10^{-13} cm^3	ρ, 10^{-21} g/cm^3
1	$100 \lesssim h \lesssim 400$	$0.1 - 1$	$0.1 - 1$	$4\cdot10^2 - 4\cdot10^3$	$4\cdot10^2 - 4\cdot10^3$
2	$400 \lesssim h \lesssim 2R_E$	$10^{-4} - 10^{-2}$	$10^{-4} - 10^{-2}$	$0.4 - 40$	$0.4 - 40$
3	$h \gtrsim 2R_E$	$5\cdot10^{-6} - 10^{-4}$	$5\cdot10^{-6} - 10^{-4}$	$0.02 - 0.4$	$0.02 - 0.4$
	Zodiacal cloud	$2\cdot10^{-6} - 12\cdot10^{-4}$	$10^{-5} - 10^{-3}$	$0.01 - 1$	$0.03 - 3$

by mass in Zone 1, which may possibly differ from that observed at greater heights.

V. I. Krasovskii has called attention to the following important point. The fragmentation and explosion of meteoric bodies entering the atmosphere at heights of 100–300 km should create shock waves. These shock waves can be recorded by piezoelectric counters at distances of up to several kilometers. The question requires further study, but preliminary estimates indicate that the effect of the direct action of the products of fragmentation can scarcely be less than the effect of the shock waves.

The mass of the dust envelope is very small—of the order of a few tens or hundreds of tons. But the rate at which it is replenished is high: all of the material in Zone 1 should fall into the dense layers below 100 km in a few tens of seconds.† Even at a height of 200 km a substantial part of the velocity of a particle with radius $r \approx 10^{-3}$ cm is lost in about 10^3 sec.

A stream of 10^{-13}–10^{-12} g/cm²/sec produces the enormous accretion rate of 10^5–10^6 tons/day. Whipple[1] found that the accretion rate was 10^4 tons/day, taking a stream equal to 10^{-14} g/cm²/sec, that is, disregarding Zone 1 for no reason at all.

As such an accretion rate is scarcely admissible, and the question arises of where the material in Zone 1 goes. The problem can be solved if we assume that Zone 1, as we have said, is formed as a result of the fragmentation of fusible ice bodies, the residues of which evaporate in the lower layers of the atmosphere. The observed low accretion rate thus provides a good argument in favor of the suggested explanation of Zone 1.

3. Observations of the twilight glow provide good independent confirmation of the high concentration of micrometeorites in Zone 1. Above 120 km in a column of 1 cm² cross section the cumulative geometrical cross section of dust particles with radius 10^{-4} cm will be about 2×10^{-8} cm². At the same time the cumulative cross section of molecular scattering above the 120 km level is about 10^{-8} cm². Thus with solar depression below 11°, when layers above 120 km are illuminated, the dust in Zone 1 should provide a considerable part of the twilight scattered light. The spectrum of the twilight glow, its polarization characteristics, and the dependence of brightness on zenith distance and solar depression should change when solar depression exceeds 11°.

Observations of the twilight glow made at the Alma-Ata observatory[23] show that to a depression angle $\phi \approx 10°$ the intensity ratio I (4000Å)/I (6000Å) increases; around $\phi \approx 10°$ it reaches a maximum and then quickly falls. Furthermore, if $\phi < 10°$ the degree of polarization is $p(6000\text{Å}) > p(4700\text{Å})$; if $\phi > 10°$ then $p(6000\text{Å}) \ll p(4700\text{Å})$. The fact that there is a relative increase in the proportion of nonpolarized (or slightly polarized) red radiation above 100 km indicates that at these heights the dependence of scattering on wavelength is not governed by Rayleigh's law. (This can be explained only by the presence of meteoritic dust.) The dependence of the brightness of the scattered light on wavelength λ shows that when $\phi > 10°$ scattering occurs in dust particles with radii of 10^{-4} cm. If the stream of micrometeorites were smaller by 2 orders of magnitude, the area of significant Rayleigh scattering would extend to 150–160 km. N. M. Staude,[24] as early as 1936, suggested that twilight glow at heights of 90–160 km might be due to the presence of dust. It must be kept clearly in mind that at heights of more than 120 km the dust cannot be in suspension; it can exist only in the form of micrometeorites moving at almost escape velocities.

In the geocorona at a height of 2000–3000 km the density ratio of dust to gas is about 1:1. In analyzing the elementary processes in the geocorona, account must be taken of such a high dust concentration.

When soft electrons (with energy of less than 150 kev) collide with dust particles they will lose all of their energy. The cumulative cross section σ of the dust particles occurring in 1 cm³ depends on their minimum dimensions. With a stream N ($> 10^{-3}$ cm) $= 10^{-3}$ m²/sec and $r_{\min} = 10^{-4}$ cm we get $\sigma \approx 10^{-17}$ cm²; if $r_{\min} = 10^{-5}$ cm, then $\sigma \approx 10^{-16}$ cm². Let us take $\sigma = 10^{-16}$ cm². Then the lifetime of an electron with energy 20 kev will be of the order of 10^6 sec. Hard protons of the inner belt (a few tens of Mev) will penetrate through up to 1000 particles before losing much of their energy. Their lifetime is 10^8–10^9 sec. It is possible that the real value for σ differs considerably from the one used—it depends on distribution by radius. We wish only to emphasize that the dust envelope may be an important factor affecting the geocorona and soft electrons in the radiation belts.

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† In this connection it is clear that no effects of capture as a result of deceleration can explain the properties of Zone 1. It is conceivable that the "electrical fragmentation" proposed in Ref. 1 is also ineffective, not only in Zone 1 but also in the area of the radiation belts. Measurements with ion traps[21] suggest that even in the area of the radiation belts bodies do not have potentials in excess of 10 v.[22]

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