ON THE AMOUNT OF DUST IN THE ASTEROID BELT

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Calculations of upper limits to the quantity of small particles in the asteroid belt are based on (1) the brightness of the counterglow coupled with observations and theory for the zodiacal cloud near Earth's orbit and (2) the destruction and erosion of asteroidal particles as they spiral toward the Sun because of solar radiation via the Poynting-Robertson effect. These calculations place the likely upper limit on asteroidal space particle density at the order of 5 to 10 times and the hazard to space vehicles at 2 to 4 times those near Earth's orbit. No such evidence indicates, however, that the hazard from small particles is actually much greater in the asteroid belt.

Observations near Earth, coupled with theory, can provide some upper limits to the quantity of small particles in the asteroid belt, which may possibly be hazardous to space vehicles venturing into that region. Measures of the counterglow and the zodiacal cloud of particles in the neighborhood of Earth's orbit provide a basis for one such limit. The destruction or erosion of particles by impact as they spiral from the asteroid belt inward toward the Sun under the influence of solar radiation by the Poynting-Robertson effect provide another limiting calculation. These limits are discussed in the sections that follow.

THE COUNTERGLOW

The brightness of the counterglow limits the quantity of dust that may be present in the asteroid belt. Roosen (1969, 1971)[1] shows that the counterglow cannot arise from any source within a million or so kilometers of the Earth because of the Earth's shadow in sunlight on backscattering particles. His observations indicate that the counterglow reaches a peak intensity exactly at the antisolar point in the plane of the ecliptic (Earth's orbit) and not in the fundamental plane of the solar system where the asteroids tend to move. This fact weakens his conclusion that the light of the counterglow is reflected from the asteroid belt and not from the zodiacal cloud, which provides the fine material we observe as meteoritic dust near Earth and meteors in Earth's atmosphere.

[1] Also see p. 363.

Roosen does not discuss the backscattering properties of dust but it is well known that rough materials tend to have peak reflection at exactly 180° backscatter. It follows from simple diffraction optics that the counterglow peak cannot be filled by particles of diameter much less than 100 μm (some 200 wavelengths of visual light) for a peak of diameter ¼° to ½°.

From the distribution of particle sizes in the zodiacal cloud (Whipple, 1967) derived from space probes and meteors, we can calculate the effective surface area for backscatter. The derived space density near Earth's orbit is some 2×10^{-22} g-cm^{-3} and the flux on the surface of a nongravitating sphere is 1.6×10^{-16} g-cm^{-2}-s^{-1}. Integrating the apparent area of the particles πs^2, where s is the radius, for $s > 50\ \mu$m, I find the apparent area per unit volume for zodiacal particles near Earth,

$$A_0 = 1.3 \times 10^{-20} \text{ cm}^{-1}$$

The effective fractional area for backscattering of sunlight, referred to total reflection near Earth, becomes

$$\text{effective area} = \int_{R=0}^{\infty} A_0 \left(\frac{R_0}{R_0 + R} \right)^{2+n} dR \qquad (1)$$

where $R_0 = 1$ AU, R = distance from Earth, and n represents the inverse power law of zodiacal cloud density with solar distance r, or r^{-n}.

The total effective fractional area for reflection in the antisolar direction then becomes $A_0 R_0 (1 + n)^{-1}$ for $n \geqslant 0$. Let us then assume that the density of the zodiacal cloud falls off as r^{-1}, inversely as the solar distance. The total effective fractional area of the zodiacal cloud becomes $A_0 R_0/2$ or 0.97×10^{-7}, compared to a perfect backscattering surface near Earth.

Let us further assume that the zodiacal particles backscatter like the average surface of the Moon. The apparent visual magnitude of the Moon at opposition is -12.70 mag (Allen, 1963), covering an area of 0.212 deg^2, or -14.38 mag-deg^{-2}. Our calculated effective fractional area at 1 AU of 0.97×10^{-7} corresponds to a magnitude loss of 17.5 mag, bringing the apparent surface brightness calculated for the counterglow to

$$17^{\mathrm{m}}.5 - 14^{\mathrm{m}}.4 = +3^{\mathrm{m}}.1 \text{ deg}^{-2}$$

or 580 tenth magnitude stars per square degree, 1.1 mag brighter than the commonly adopted value of 200 10 mag stars deg^{-2}.

First note that the meteoritic flux rate of 1.6×10^{-16} g-cm^{-2} is confirmed by Keays et al. (1970) and Ganapathy et al. (1970) by analysis of trace elements on the Moon, their values being, respectively, 1.2×10^{-16} and 1.3×10^{-16} g-cm^{-2}. The use of their mean value coupled with our distribution function would reduce the discrepancy by only 0.3 mag. The adopted mean velocity of 15 km-s^{-1} is a reasonable velocity with which to correct to space density, even though the value is not precisely measured.

That zodiacal particles backscatter like the Moon is, of course, an ad hoc hypothesis. As cometary debris they should be porous and perhaps even darker than surface lunar material. Thus our fair success in predicting the brightness of the counterglow suggests strongly, at least, that few additional reflective sources are needed; perhaps none are needed.

Thus the asteroid belt need contain only enough dust to produce, say, one-half the light in the counterglow, or perhaps a negligible amount. At a mean solar distance of some 2.5 AU the surface brightness for the same reflective area would be reduced by a factor of 6.2. If the asteroid belt is 1 AU thick at the same space reflectivity as zodiacal dust near Earth, the reduction factor for the reflective area would increase by a factor of about 2 as compared to our calculations above. The presumed higher density of asteroid dust, say 3.0 g-cm^{-3} as compared to perhaps 0.5 g-cm^{-3} for cometary dust, would increase the corresponding mass by a factor of 3.0/0.5 = 6. The albedo of asteroid dust would surely exceed that of cometary dust, but the factor is unknown. Let us call it 2.

If we combine the factors of the last paragraph to predict the density of meteoritic material in the asteroid belt, averaged over a 1 AU radial distance to produce ½ the light of the counterglow, we find the factors ½ (brightness), 6.2 (distance), ½ (for 1 AU), 6 (density), and ½ (albedo), assuming the same distribution function of particle size as for the zodiacal cloud. Thus we should not expect the asteroid belt to exceed near-Earth space in particle mass by a factor of more than about 5, leading to a space density $< 1.0 \times 10^{-21}$ g-cm^{-3}. The Poynting-Robertson effect of solar radiation momentum exchange with small particles in the asteroid belt should tend to bring in the dust from the major concentration of asteroids and to reduce this maximum calculated density.

SPACE EROSION AND THE POYNTING-ROBERTSON EFFECT

As the Poynting-Robertson effect (Robertson, 1937) causes asteroidal particles to spiral in toward the Sun, space erosion from particle impacts in space will tend to destroy and to reduce the radii of the asteroidal particles. For convenience let us express the space erosion in terms of reduction in radius of the particles

$$\frac{ds}{dt} = -\frac{\epsilon}{r^2} \qquad (2)$$

where ϵ is the erosion rate in centimeters per year at Earth's orbit and r is the solar distance measured in astronomical units. The r^2 term arises from an assumed falloff of particle density as r^{-1} and velocity of impact as $r^{-1/2}$.

The Poynting-Robertson effect differentiated gives for the time dt (years) to reduce a circular orbit of radius vector r AU by dr the equation

$$dt = -2C\rho sr\, dr \tag{3}$$

where $C = 0.7 \times 10^7$ to give t in years, ρ is particle density in grams per cubic centimeter, and the spherical radius s is given in centimeters.

Equations (2) and (3) combine to give

$$\frac{ds}{s} = 2C\epsilon\rho \frac{dr}{r} \tag{4}$$

The lunar landings give values for ϵ at the lunar surface from nuclear track studies by Crozaz et al. (1970),

$$1 \times 10^{-8} < \epsilon < 10 \times 10^{-8} \text{ cm-yr}^{-1}$$

and from micrometeoritic craters by Hörz, Hartung, and Gault (1970),

$$2 \times 10^{-8} < \epsilon < 4 \times 10^{-8} \text{ cm-yr}^{-1}$$

The suggested value of

$$\epsilon = 3 \times 10^{-8} \text{ cm-yr}^{-1}$$

is considerably smaller than that adopted by the author (Whipple, 1967) from the cosmogenic ages of stony meteorites. The actual value for a particle in space should, indeed, be greater than that for lunar rocks because the latter are partially protected by a thin layer of dust from the smallest particles of the zodiacal cloud.

Let us, however, adopt as a minimum erosion rate in space the values

$$\epsilon = 3 \times 10^{-8} \text{ cm-yr}^{-1}$$

$$C = 0.7 \times 10^7 \text{ yr}$$

$$\rho = 3 \text{ g-cm}^{-3}$$

to derive from equation (4) the numerical result

$$\frac{ds}{s} > 1.3 \frac{dr}{r} \tag{5}$$

Hence from equation (5) an asteroid particle released in circular orbit at $r = 2.5$ AU would be reduced to less than 1/6 in radius and less than 1/200 in mass by the time it had reached Earth's orbit. Its surface area would have been reduced to less than 1/30 of its original value. Thus we see that an assumed

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total particle space density in the asteroid belt of five times that in the near-Earth zodiacal cloud would be reduced to $5 \times (2.5)^3 \times 0.005$ or <0.4 the total space density of the zodiacal cloud by the time the particles reached Earth's orbit. Thus it seems quite possible that the hazard to a space vehicle from small meteoritic particles might exceed that near Earth's orbit by a factor of 5 or 10 for mean space density, reduced by a factor of 1/2.5 for velocity, or two to four times greater.

The minimal hazard from larger particles, capable of producing serious damage but not contributing significantly to the zodiacal cloud, might be somewhat greater in the asteroid belt than near Earth's orbit, but not by a large factor. Calculations for these larger particles should be based on Dohnanyi's (1967, 1969, and 1970)[2] thorough study of the theoretical distribution function for asteroidal bodies.

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[2] Also see p. 263.