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THE CLOUD OF INTERPLANETARY BOULDERS

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Abstract

An attempt is made to evaluate the density of boulders (roughly 10m sized objects) in interplanetary space. Such bodies cannot be directly observed and the most direct evidence comes from impacts on the earth. We show that the most plausible density, consistent with various types of data, is $\sim 4 \times 10^{-28}$ cm^{-3}. This is about three orders of magnitude higher than the density usually quoted. The difference arises because we postulate that the boulders have orbits of low eccentricity and their approach rate toward the earth is slow because the (weak) Poynting-Robertson effect is the only means by which the boulders are impelled into orbits of smaller diameter. The low orbital eccentricity is consistent with an asteroidal origin of the boulders. We show that the unusually high concentration of boulders postulated here, can indirectly produce interplanetary dust at a rate high enough to compensate the Poynting-Robertson losses. The high concentration of boulders can also explain the observed rate of splitting among parabolic comets, and is consistent with the observation that these comets split near the ecliptic plane.

1. Introduction

We know a great deal about two types of interplanetary objects, the very small and the very large. We observe the small meteors and meteorites which impact on the earth and make themselves known through atmospheric trails and impact craters. Their diameters normally are below a meter. The much larger asteroids, at the other extreme of the size range, are observed through telescopes. Their diameters range from one kilometer to more than a hundred. In the size range between these limits -- the range from ten to several hundred meters -- we have little first hand knowledge of interplanetary objects. Our only clue comes from a handful of craters on the earth and a much larger number visible on the moon.

For simplicity we will call the 10m to 0.5km sized projectiles 'boulders', and we will examine the available evidence to show that boulders may be far more abundant than previously thought. Current estimates on boulder densities in space are based on two types of data a) on the number and size distribution of lunar craters and b) on a simple interpolation between estimated number densities of observable asteroids and meteorites. These two sets of data cannot be directly intercompared because the lunar data is cumulative over a long period of time and gives little information about current boulder densities, while the asteroidal and meteorite studies are related to current number densities in interplanetary space. Even here, there is an important difficulty. The orbits of meteorites before impact are not yet well known, although the data being gathered by the Prairie Network will give the information we need. Meteorite trajectories -- just as the orbits of meteors -- may well turn out to be quite different from asteroidal orbits. And the orbits of boulders may be quite different from both asteroidal and meteoritic orbits.

We will argue here that the orbits of boulders may have low values of eccentricity and inclination, so that a dense cloud of boulders may survive in interplanetary space for many aeons without appreciable self destruction. Further we will postulate that those boulders which initially had trajectories intersecting the earth's orbit about the sun, soon were eliminated by collisions with the earth or moon. The boulders impacting on the earth or moon at the present epoch are the few objects which, at any given time, are slowly drawn in toward the sun by virtue of the Poynting-Robertson effect. Because the boulders are massive and the P-R effect is weak, relatively few boulders approach the earth in this way.

Those that do come close, are predominantly scattered into orbits of greater eccentricity and inclination (Arnold 1963, 1965a) where they can be rapidly destroyed through collisions with other boulders in the cloud. Only those few boulders that escape this fate, can eventually impact on the earth to give rise to craters. We will show that an interplanetary cloud of boulders with overall number density $\sim 4 \times 10^{-28}$ cm^{-3}, mass density $\sim 2 \times 10^{-18}$ g cm^{-3}, total mass $\sim 5 \times 10^{23}$ g is consistent with information obtained from

a) impact rates on the earth and moon,

b) zodiacal light observations,

c) apparently required dust supply rates for replenishing dust lost from the zodiacal cloud through the Poynting-Robertson or other loss mechanisms,

d) celestial mechanical effects, and

e) possibly observable impact rates on asteroids and comets.

2. The Cloud of Boulders

We think of a cloud of boulders whose members have typical diameters d, mass density ρ, mass m and spatial number density n. These boulders move in eccentric orbits about the sun. From time to time they collide and the rate of collision is determined by the relative velocity v, which in turn depends on the semi-major axis a, the eccentricities e and the inclinations i of the orbits involved. If the boulders were moving randomly, the time T_c moved by an individual before colliding with another boulder would be of order

$$T_c = (4nd^2v)^{-1} \quad . \tag{1}$$

This collision time is a minimum, in the sense that boulders moving in non-intersecting orbits cannot collide no matter what the value of v may be. If a dense cloud of boulders is to survive long in the solar system, the boulders must move on non-intersecting or seldom intersecting orbits. This is the situation when all the orbits are direct and when the eccentricities and inclinations of the orbits are low. Parenthetically, these are the same features that one usually holds responsible for the survival of planets and the stability of the solar system.

3. Impacts of Boulders on the Earth

We are in the habit of thinking of the earth and moon as impact counters for all kinds of interplanetary debris ranging from submicroscopic and microscopic grains all the way up to boulder sized objects, asteroids and comets. Hand in hand with this concept goes the assumption that impacts on the earth and moon represent some kind of random sampling of the cloud of interplanetary debris. This postulate is deeply ingrained in our thinking and seldom is stated explicitly. We assume that impact of interplanetary debris on the earth constitutes a random process and that the impact rates can be used to derive true interplanetary densities of debris near the earth's orbit.

For small grains, the random sampling postulate can be partially justified. We know that the Poynting-Robertson effect shrinks the orbital diameter of small grains at such a fast rate that a large fraction of these grains can cross the earth's orbit without ever coming close enough to the earth to be strongly perturbed. A grain that does impact on the earth, presumably will then do so the very first time that it enters the earth's sphere of gravitational influence. It therefore represents an essentially unperturbed orbit from the cloud of grains which, guided by solar gravitational attraction and light pressure, slowly drifts inward through the earth's orbit, and into the sun.

The orbits of boulders, on the other hand, need not lead to collisions with the earth similar to those expected on the basis of random collisions, provided that the eccentricity of boulder orbits is low. We will present the detailed argument for this in the following paragraphs.

If a boulder has orbital eccentricity $\epsilon \ll 1$ and its perihelion distance q is close to the earth's orbit, then the velocity at perihelion is

$$v_q \sim v_E(1 + \epsilon/2) \quad , \qquad (2)$$

where v_E is the mean orbital velocity of the earth.

We wish to calculate the impact parameter s for a boulder whose approach velocity to the earth is $v = \epsilon v_E/2$. If the earth's radius is r and the velocity for earth grazing particles is v, at closest approach, conservation of angular momentum gives

$$rV = sv \quad . \qquad (3)$$

Conservation of energy gives

$$\frac{v^2}{2} \sim \frac{V^2}{2} - \frac{M\gamma}{r} \quad . \qquad (4)$$

For the earth, $M\gamma/r \gg \epsilon^2 v_E^2/8$ as long as $\epsilon < 1/3$. For this reason $V \sim (2M\gamma/r)^{1/2}$ and from equation (3),

$$s \sim \frac{(8M\gamma r)^{1/2}}{\epsilon v_E} \sim 4.8 \times 10^8/\epsilon \text{ cm} \quad . \qquad (5)$$

This means that for low eccentricity orbits the capture cross section of the earth, πs^2, can be much larger than its geometrical cross section.

We can now compute the capture probability of a boulder per orbit about the sun. The earth's eccentric orbit, precesses about the sun, sweeping out a torus whose projected area on the ecliptic plane is

$$A = 2\pi a(2a\epsilon_E) = 5 \times 10^{25} \text{ cm}^2 \quad . \qquad (6)$$

If the boulder passes through the torus, once per revolution, it has probability

$$\frac{\pi s^2}{A} \sim \frac{1.4 \times 10^{-7}}{\epsilon^2} \qquad (7)$$

of colliding with the earth. For eccentricities as low as $\epsilon \sim 0.1$ the collision probability reaches unity in a time of the order of 7×10^4y. For more highly eccentric orbits, this time interval may increase by two orders of magnitude, but the mean life of a boulder, once it crosses the earth's orbit cannot well exceed 10^7y, in the absence of other effects.

This result appears to hold well enough for boulders which at some initial time were injected into trajectories that crossed the earth's orbit about the sun. Such boulders would soon be removed from the solar system through impact on the earth (or, to lesser extent, the moon).

The situation is quite different for a boulder which first approaches the earth's orbit along a slow Poynting-Robertson spiral into the sun. Such a boulder's orbit initially must be altered primarily through scattering. In this process, the perihelion distance cannot be appreciably altered, but the aphelion distance is increased because the scattering process systematically leads to acceleration of the boulder. This comes about through a process first described by Arnold (1965a). Essentially it works on the same principle as Fermi's mechanism for the acceleration of cosmic ray particles in encounters with cosmic clouds.

A boulder interacting with the earth in this way, will not be able to impact on the earth, until the Poynting-Robertson effect has sufficiently decreased the boulder's perihelion distance. For a boulder in a low eccentricity orbit, the complete Poynting-Robertson trajectory into the sun would be traversed in a time

$$T = 3.5\ d\rho a^2 \text{ years} \quad , \tag{8}$$

where d is the boulder's diameter measured in cm, ρ is its density and a is the semi-major axis measured in astronomical units. The time required to alter the semi-major axis by an amount Δa is therefore

$$\Delta T = 7 \times 10^6\ \rho d a \Delta a \tag{9}$$

and the rate of perihelion decrease therefore is roughly

$$\Delta a/\Delta T \sim (7 \times 10^6\ \rho a d)^{-1} \tag{10}$$

for a boulder in a low eccentricity orbit.

If one sets Δa equal to ten capture radii of the earth (c.f. Arnold 1965a, b)

$$\Delta a \sim 5 \times 10^9/\epsilon \text{ cm} \sim \frac{3.3 \times 10^{-4}}{\epsilon} \text{ A.U.} \tag{11}$$

The time between initial onset of appreciable scattering by the earth, and eventual impact through crossing of the earth's trajectory, will be as long as

$$\Delta T \sim \frac{2.3 \times 10^3}{\epsilon}\ \rho d \quad . \tag{12}$$

If $\epsilon \sim 0.1$, $d \sim 10^3$cm and $\rho \sim 3$ to 8, one finds

$$\Delta T \sim 7 \times 10^7 \text{ to } 1.8 \times 10^8 y \quad .$$

This is an interval long compared to the previously computed impact time of 7×10^4y.

During this time interval, impact on the moon has a probability of order unity, and the probability of collision with other boulders may also be significant, provided the density of the cloud of boulders is high. Both these factors tend to decrease the probability of eventual impact on the earth.

The destruction rate through collision with other boulders becomes significant when the number density of boulders (see equation (1)) is such that

$$(4nd^2v) \sim 3 \times 10^{-16} \text{ sec}^{-1} \quad .$$

The least certain quantity here is v. We will assume that perturbations (scattering) by the earth increase the eccentricity of a boulder's orbit to 0.2 and produce an inclination angle of the order of 0.3 rad. Then $v \sim 10^6$ cm sec^{-1} and

$$n \sim 8 \times 10^{29} \text{ cm}^{-3} \quad .$$

If the destruction rate of boulders scattered by the earth is to be appreciable, n should be at least half an order of magnitude greater. One then has the somewhat surprising situation in which an increase in n decreases the absolute number of boulders that impact on the earth. This can be understood by considering that the approach rate of boulders to the earth is then proportional to n, while the removal of scattered boulders through inter-collision proceeds exponentially with n, for the 10^8 year interval before the Poynting-Robertson effect makes possible direct impacts on the earth.

In summary one sees that a count of direct impacts on the earth, as conducted, say, by Harrison Brown (1960) must always lead to a deceptively low computed number density of large interplanetary boulders, if one chooses to disregard the possibility of low eccentricity orbits and instead invokes a random impact hypothesis. Two factors contribute to this feature. First, the P-R approach rate of large boulders toward the earth will occur at a rate inversely proportional to the boulder diameter. This alone will lead to a factor as large as 10 when ten meter sized boulders are compared to meter sized meteorites. Second the slower approach rate toward the earth's orbit, once appreciable perturbations due to the earth's gravitational influence have commenced, makes impact on the moon or destruction through collision with other boulders a much stronger possibility. The effect of these alternate fates may be to reduce present day impact rates on the earth by another factor which might be as high as 10^2. Thus the total rate of impact of boulders on the earth, may be a factor as high as 10^3 less than one might compute on the expectation that impact on the earth was equally probable for interplanetary debris of all sizes. A number density of boulders in interplanetary space as high as $n \sim 4 \times 10^{-28}$ cm^{-3} should therefore be taken as a serious possibility.

4. Self Destruction and the Origin of the Cloud of Boulders

The previous argument shows that there are two acceptable models of an interplanetary cloud of boulders. One model of such a cloud is very dense, $n \sim 4 \times 10^{-28}$ cm^{-3} with corresponding mass density of $\sim 2 \times 10^{-18} g\ cm^{-3}$ and a total mass of the order of $M \sim 3 \times 10^{23}$, a mass small compared to the mass in the asteroidal belt. It is clear that such a small mass would in no way significantly perturb the orbits of planets nor would it lead to other observable celestial mechanical effects.

The self destruction rate, however, is quite rapid for such a cloud. Even if the inclination and eccentricity of boulder orbits were as low as those of planetary orbits, appreciable self destruction of the cloud would be expected in a time of the order of 10^8y. Such a cloud would then have to be continually replenished, presumably through occasional collisions of boulders with asteroids.

The alternate model of the cloud of boulders takes a boulder density which is one and a half orders of magnitude lower, roughly $n \sim 10^{-29}$. The impact rate on the earth is then the same as for the denser cloud because we still have the same low approach rate dictated by the P-R effect, and in addition a loss factor of the order of 2 to 3 is possible through collision with the moon. A further reduction in impact rates by a factor of 30 is due to the reduction of the number density of boulders.

For each of these models the impact rate of boulders, roughly 10m in diameter is

$$\frac{dn}{dt} \sim \left(2\pi a^2 n \, 2(\sin i)\frac{\Delta a}{\Delta t}\right)x \sim 0.08 \qquad (13)$$

per year for the whole earth. About one boulder per century would fall on land. The expression in brackets in equation (13) gives the approach rate of boulders toward the earth's orbit and x is the probability that an approaching boulder will eventually impact on the earth. i represents a typical inclination of a boulder orbit, chosen as ~ 0.15 rad. and we take $\epsilon \sim 0.1$. We have taken $x \sim 1/30$ for $n \sim 10^{-29}$, and $x \sim 10^{-3}$ for $n \sim 4 \times 10^{-28}$.

The self destruction rate for the more tenuous cloud of boulders is consistent with a primordial origin. Such a cloud could have formed at the inception of the solar system. If it had been much denser at that time, its density would have rapidly decreased through the intercollision of boulders until it reached its present density for which the destruction time constant is just equal to the cloud's age. This equality is a characteristic of most self destructive systems.

5. Abrasion of Boulders

The abrasion rate of boulders in interplanetary space must be considered in order to determine whether or not boulders of a given size and composition can survive for several aeons. Whipple and Fireman (1959) first pointed out that the cosmic ray ages of meteorites could be used to place an upper limit on the abrasion rates of interplanetary bodies. Current estimates made on the basis of this technique, give abrasion rates well below 10^{-8} cm/y both for iron and stony meteorites.

In order to survive for the full 4×10^{9}y since the birth of the solar system a boulder would only have to be a meter in diameter. Ten meter sized boulders would be virtually unaffected by the abrasion process. This mechanism therefore appears to have little importance in determining the evolution of the cloud of interplanetary boulders. There will be a small drag on the boulders due to continual collisions with fine dust, but this drag is small compared to the Poynting-Robertson process.

6. The Zodiacal Light

The cloud of boulders can make both a direct and an indirect contribution to the zodiacal glow. The direct contribution comes from light directly scattered off boulders. The indirect contribution is due to intercollision of boulders that can produce debris which in turn scatters radiation.

a. Direct contribution

If the spatial density of boulders is n out to a distance $h \ll r$ from the ecliptic plane, the total scattered light received from a direction perpendicular to the ecliptic plane is of the order of

$$\int_0^h \frac{L_\odot}{4\pi r^2} \sigma n \frac{d\Omega}{4\pi} dh \sim 7 \times 10^{19} n \text{ erg/cm}^2 \text{sq}^\circ \text{sec}$$

where r is the earth's distance from the sun, σ is the scattering cross section of a boulder, n is the number density in cm^{-3} and the cloud of boulders is taken to extend out to 0.15 AU from the ecliptic, at the earth's distance from the sun.

Even for the denser cloud of boulders discussed in section 4, the number density is only $n \sim 4 \times 10^{-28} \text{cm}^{-3}$, so that the flux received is $3 \times 10^{-8} \text{erg/cm}^2 \text{ sec sq}^\circ$, an order of magnitude less than the brightness of the zodiacal light at high declination. We have assumed here that all the light incident on a boulder is isotropically scattered. This is a conservative assumption and the actually scattered light from boulders would probably be considerably less than the value calculated.

b. Indirect contribution

In section 4 we computed that the destruction of the dense model of the interplanetary cloud of boulders would take place with a time constant of about 10^8y, while that of the less dense cloud would take place in about 4×10^9y. These destruction rates are considerably higher than the abrasion rates computed in section 5. If small scale interplanetary debris is produced in the destruction of boulders, the relative contribution from the two models would be 300 tons/sec and 0.1 ton/sec respectively. This compares to a minimum supply rate of the order of 1 ton/sec required to keep the zodiacal cloud intact against elimination by the Poynting-Robertson effect. The dense cloud can, therefore, easily account for the required supply rate, even if only a small fraction of the intercollision debris produced is retained in the solar system as fine dust. The more tenuous cloud cannot maintain the required dust supply rate.

7. Collisions of Boulders with Comets

While boulders with low orbital eccentricity and inclination are not likely to collide with the earth or other planets they do have a high probability of impacting on parabolic comets.

Consider a new (parabolic) comet approaching the solar system for the first time. Such a comet may have spent several aeons in a circumsolar cloud at some 10^5 A.U. from the sun. The comet's diameter is $\sim$ 50km. During its transit across the inner solar system, it sweeps out a volume of order 3×10^{26} cm^3. If the density of boulders is $n \sim 4 \times 10^{-28}$ cm^{-3}, as suggested in section II, every tenth comet will suffer a collision with a boulder.

The relative velocity of the two objects just prior to collision is of the order of 10^7 cm/sec, so that the total kinetic energy made available on impact by the boulder is of the order of 10^{23} erg. It is not clear how this large amount of energy is used up. Since comets are believed to be rather loosely packed aggregates of ices and grains, it is possible that a boulder could penetrate to a depth of several hundred meters. (On the earth it would penetrate well over 100m -- particularly if atmospheric effects are neglected.) An explosion in the interior of the comet nucleus could then occur and it is possible that the comet would split into two or more fragments. Figure 1 taken from another publication (Harwit, 1967) shows that comets which split through non-tidal effects, undergo fission close to the ecliptic plane. The paper argues that the most plausible explanation for the concentration toward the ecliptic lies in the hypothesis that boulders impacting on comets can trigger a large enough energy release to cause fracture.

8. Discussion

The purpose of this paper has been to show that one can place useful bounds on the concentration of roughly 10m diameter boulders in interplanetary space. Two types of clouds are consistent with impact rates for boulders colliding with the earth. Very roughly the boulder concentration in these clouds is $n_1 \sim 4 \times 10^{-28}$ and $n_2 \sim 10^{-29}$ cm^{-3}. These values are respectively 10^3 and 25 times higher than one would estimate on the basis of meteorite impact craters, if boulders moved in random orbits through interplanetary space. The high densities suggested by the present paper arise from the consideration that boulders in earth crossing orbits are eliminated rapidly (in a time of the order of 10^7y) from the solar system and only those boulders having low eccentricity can survive. These spiral slowly toward the sun, and therefore enter earth crossing orbits infrequently.

Boulder densities between the two limits n_1 and n_2 are unlikely, because the impact rates on the earth would be too high. When the concentration exceeds n_1 the self destruction rate through boulder intercollisions becomes so high that impacts on the earth become unlikely, leading to the curious result that at higher boulder densities, impact rates on the earth actually decrease.

If the concentration is as high as n_1 two interesting results are obtained. Firstly, there is then little difficulty in explaining the origin of interplanetary debris of the kind that gives rise to zodiacal scattered light. In the past, there has been great difficulty in accounting for a source which could supply enough dust to compensate the Poynting-Robertson loss which compels interplanetary debris to spiral into the sun (Harwit 1963). Secondly, collisions with boulders could account for the observed splitting of parabolic comets as they traverse the ecliptic plane (the comets in question are those that cannot have split through the tidal action of the sun).

The self destruction rate of a cloud of this density is high, and typical boulders cannot survive for more than $\sim 10^8$y. This means that a periodic replenishment of boulders would be required. This replenishment could come about through collisions of boulders with larger objects, mainly asteroids. In each such collision, a large amount of new material is liberated and injected into orbits of relatively low inclination and eccentricity, as required by the models described throughout this paper.

Neither the proper zodiacal dust supply rate, nor the correct probability of comet splitting can apparently be obtained from the more tenuous model having spatial density n_2. If all these considerations are appropriate the most likely density of interplanetary boulders, consistent with most of the observed data seems, therefore to be of the order of 4×10^{-28} cm^{-3}.

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Figure Caption

Distances from the ecliptic plane at which comets are observed to split (taken from Harwit 1967).

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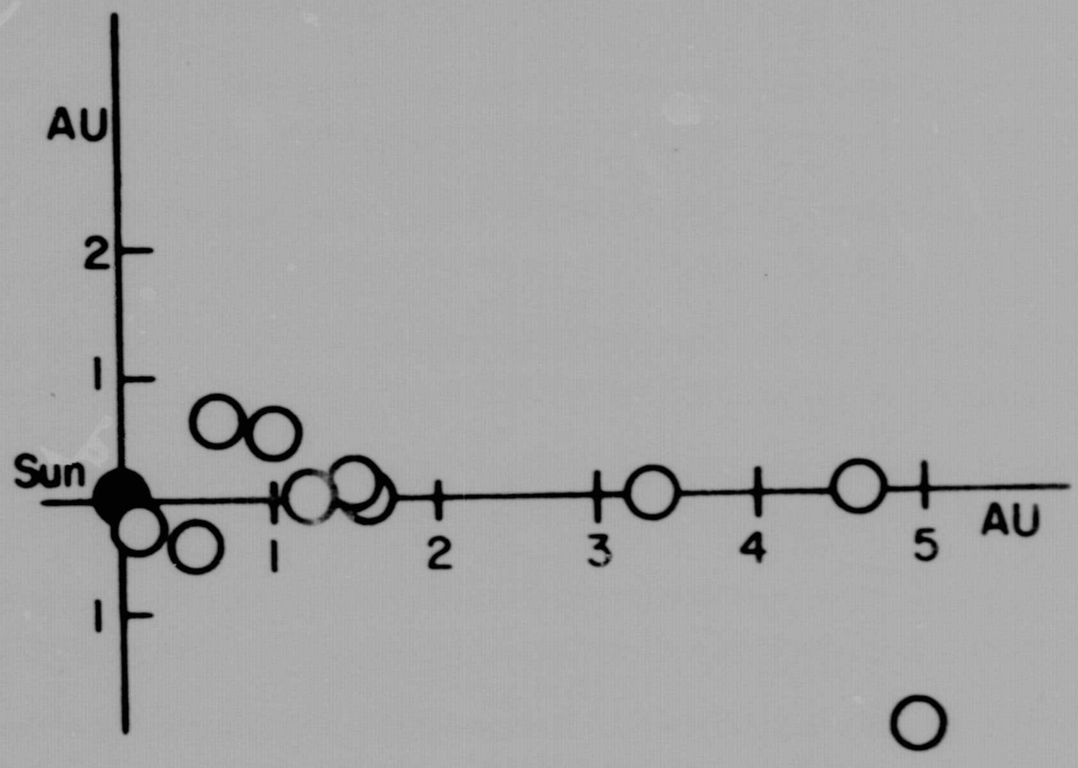

Figure 1