2.1.8 ## Sources of Interplanetary Dust: Asteroids

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Abstract

The asteroid belt is examined as a potential source of interplanetary dust. Using results from the Pioneer-10 experiments the relative contribution of asteroidal and cometary particles to the Zodiacal cloud is estimated using methods developed in earlier studies of meteoroidal collisions (collisional model). It is found that the contribution of asteroidal particles to dust in the asteroidal belt is small compared with the number density of cometary type particles. Similar conclusions apply to the Zodiacal cloud between the sun and the asteroid belt. When definitive criteria for differentiating between comets and asteroids become available, a reexamination of some of our conclusions may become necessary.

The distribution of asteroidal rotations is analyzed; it is found that the gross features of the distribution can be reproduced using the collisional model.

I. Introduction

The zodiacal light is thought to originate from material given off by comets (Whipple, 1951, 1955, 1967 and Dohnanyi, 1970, 1972). Because of insufficient observational material, the relative contribution of asteroidal material to the zodiacal cloud has always been difficult to estimate (Whipple, 1971, Dohnanyi, 1972 and Wetherill, 1974). It is therefore of interest to examine the significance of the asteroid belt as a potential source of zodiacal particles in the light of the new observational data obtained from Pioneer 10 and 11 satellites; this present paper summarises such a study.

II. Asteroidal Belt Particle Densities

NASA model: Our current knowledge on the distribution of dust in the asteroid belt will be briefly reviewed, in this section.

The density of large objects in the asteroidal belt has been estimated (Dohnanyi, 1971, 1972) using the collisional model of asteroids in the asteroidal belt (Anders, 1965, Bandermann, 1972, Dohnanyi, 1969, Hartmann and Hartmann, 1968, Wetherill, 1967). In this model destructive collisions between asteroids and their resulting fragmentation

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https://doi.org/10.1017/S0252921100051708 Published online by Cambridge University Press

are found to be the dominating process in the dynamic evolution of the asteroidal population. In an attempt to estimate the density of dust in the asteroid belt one can start with extrapolating down to microparticle sizes the asteroidal number density obtained from the collisional model (Dohnanyi, 1969). The observational material (Kuiper et al., 1958, Van Houten et al., 1970) which is well explained by the collisional model consists of large objects with such a large number density that collisions with the comparatively few comets are thought to have a negligible influence on the dynamic evolution of the asteroidal population. The density of cometary microparticles may, however, be so large that destructive collisions with these cometary particles will significantly influence the dynamic evolution of the population of asteroidal microparticles (Dohnanyi, 1969). The result of such an extrapolation of the earlier results of the collisional model to microparticle size ranges therefore becomes uncertain.

Keeping in mind the possible limitations of our extrapolation, we take the steady state solution of the collisional model (Dohnanyi, 1969).

$$f(m)dm = Am^{-11/6}\,dm \quad (1)$$

where $f(m)dm$ is the number density of asteroidal objects in the mass range m to $m + dm$ and where A is a constant in the region of space occupied by the asteroidal belt and is zero elsewhere.

A more detailed representation of A as a function of distance from the sun has been given by Kessler (1970). He calculated the mean number density of asteroids as a function of distance from the sun. He has carried out this calculation by computing the fraction of time spent by each catalogued asteroid at each point in its orbit and from this result he obtained a statistical estimate of the number density of asteroids as a function of distance from the sun. The mass distribution was assumed independent from the spatial distribution and of a form similar to the steady state solution of the collisional model, Eq. 1.

Figure 1, given by Roosen (1971), is a plot of the spatial variation of the particle number density for constant mass compared with the number density near earth. The curve, labelled asteroidal distribution, is a plot of the spatial dependence of the asteroidal particles obtained by Kessler (1970). The other curves represent particle distributions varying as $R^{-2.5}$, R^{-1} and a constant particle distribu-

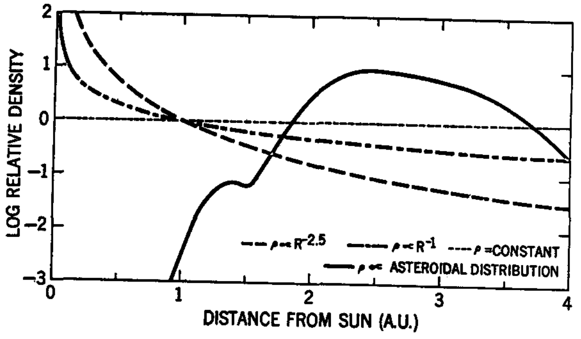

Fig. 1

Spatial distribution of particle number density relative to the number density near earth (from Roosen, 1971). R is the distance from the sun in AU and ρ is the number density at constant mass in arbitrary units.

tion, respectively. R is the distance from the sun in AU. It can be seen, from Fig. 1, that an extrapolation of the distribution of large asteroids, using the results of the collisional model, predicts a dust concentration in the asteroid belt about an order of magnitude higher than the dust density near earth.

Evidence from the Gegenschein: An upper limit to the particle number density in the asteroidal belt can be obtained from the brightness of the Gegenschein (cf. Roosen, 1971a and b). If one assumes that the Gegenschein is caused by the backscatter of light by particles along the line of sight in the anti sun direction, then reasonable assumptions for the particle albedo will enable one to estimate the upper limit to the particle density for given forms of the particle distributions in mass and space.

On this basis Whipple (1971) placed a likely upper limit on the dust density in the asteroidal belt of about 5 to 10 times the dust density near earth orbit (also cf. Kessler, 1968 and Roosen, 1971c).

Spacecraft Measurements: During the Pioneer 10 and 11 missions to Jupiter, direct measurements of the frequency of dust particles have been performed. These have been penetration measurements (Humes et al., 1974) detecting particles with sufficient kinetic energy to penetrate the walls of pressurized meteoroid detector cans ("beer cans") and optical experiments (Sisyphus) detecting particles in the field of view of an assembly of four telescopes (Soberman et al., 1974a and b). A further measurement consisted in the use of the Sisyphus telescopes for measuring the surface brightness of the zodiacal cloud (Hanner et al., 1974).

Results of the penetration experiment are given in Fig. 2 where densities of meteoroids at constant mass have been computed, using

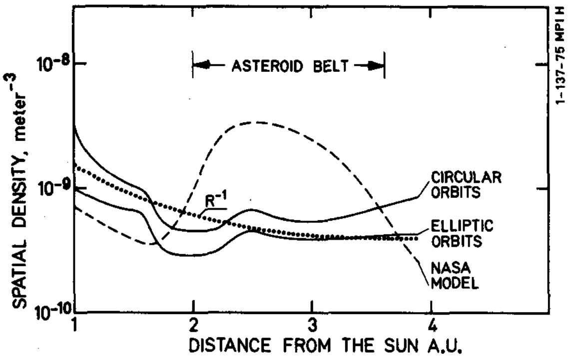

Fig. 2

Spatial distribution of the particle number density deduced from the Pioneer 10 penetration measurements. Solid lines are densities implied by the data for particles in circular and elliptic orbits, as indicated. Dotted curve indicates a density which varies inversely with the distance, R, from the sun and dashed line curve is the NASA model, discussed in the text.

two different orbital distributions for these particles (D.H. Humes, 1975, Kinard et al., 1974). The dashed line is the earlier NASA model for the distribution of cometary and asteroidal particles (Cour-Palais, 1969 and Kessler, 1970). Another curve, labelled as 1/R represents a dust density that varies inversely with the distance R from the sun.

(2) $n(R) \sim 1/R$

This inverse relationship between the number density and heliocentric distance is in good agreement with the results of zodiacal light observations from Pioneer 10 (Hanner et al., 1976). It can be seen, Fig. 2, that the number density of interplanetary dust inferred from the penetration data is a slowly decreasing function with heliocentric distance and, to within the limits of uncertainty inherent in the estimate, a constant distribution (Humes, 1974) or a distribution that varies as R^{-1} (Eq. 2) appears to fit the results quite well, to a first approximation.

The results of the Sisyphus experiment indicate a distribution from 2 AU to 3.5 AU from the sun for small particles (smaller than .15 cm in radius) that is constant with heliocentric distance to within a factor of 2 (Soberman et al., 1974). Difficulties with the calibration of this experiment (Auer, 1975) may, however, lead to a revision (Roosen, 1975) of their interpretation and we defer discussion of the Sisyphus results until this matter has been resolved.

III. Interaction between Cometary and Asteroidal Particles

It is clear, from Fig. 2, and from the results of the zodiacal light experiment (Hanner et al., 1976) that there is no abrupt change in the particle number density as we enter the asteroidal belt. To be more specific, there is no evidence for the existence of an asteroid

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belt concentration of micrometeoroids comparable to the concentration of large asteroids, as indicated in Fig. 1. The concentration of cometary particles therefore is likely to be about the same in the asteroid belt as it is outside of it without a sharp brake in their distribution as one enters the asteroid belt. By cometary particles we shall mean, rather loosely, those particles whose orbital distribution differs from that of the known asteroids in the asteroid belt and are therefore presumably of cometary origin (see Fechtig, 1976, for a recent review on the distribution of interplanetary microparticles).

If the number density of cometary particles is significant compared with the number density of the asteroidal particles in the asteroid belt, then, because of the relatively high relative velocity of the cometary particles, they will have a strong influence on the survival time of the asteroidal particles. Before discussing the influence of collisions, however, we turn our attention to Fig. 3.

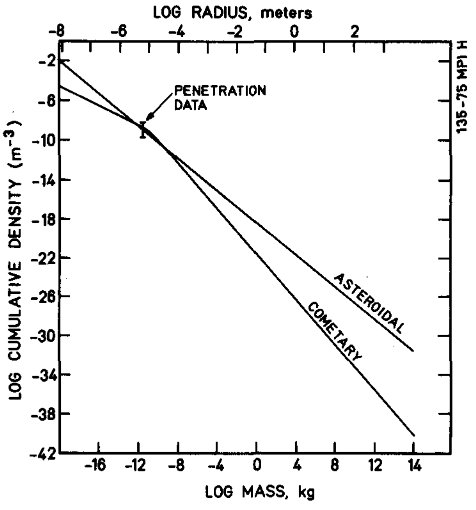

Fig. 3

Cumulative number density of cometary particles at 1 AU from the sun and the asteroidal number density obtained from the collisional model and extrapolated here into the size ranges of micrometeoroids.

Plotted in Fig. 3 is the cumulative number density of presumably cometary particles at earth's orbit and an extrapolation of the cumulative density of the asteroidal particles obtained from the collisional model. We have also indicated the results from the penetration experiment from Pioneer 10 (Humes et al., 1974).

The values used for the densities are, for the asteroidal density,

(3) $f(m)dm = 2.48 \times 10^{-19} \, m^{-11/6} dm,$
for $2 \text{ AU} \leq R \leq 3.5 \text{ AU}$

$f(m)dm = 0,$ otherwise

and, for cometary particles,

(4) $f(m)dm = 2.94 \times 10^{-22} \, m^{-13/6} dm,$
$m \geq 10^{-10}$ kg,

$f(m)dm = 1.36 \times 10^{-15} \, m^{-1.5} \, dm,$
$m \leq 10^{-10}$ kg

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for all relevant values of R. f(m)dm is the number density of particles, per cubic meter in the mass range m to m+dm kg. The value of f(m)dm in Eq. 4 is obtained from Dohnanyi (1973) and Eq. 3 is taken from Dohnanyi (1969). Eq. 3 is the quasi steady state solution to the collisional model representing the case when, in any given small time period, the number of asteroids in a given mass range destroyed by disruptive collisions is replenished by fragments, in the same mass range, produced by the disruption of larger objects during the same period of time. Cumulative densities are then obtained by simple integration.

It can be seen, from Fig. 3, that if the number density of cometary particles in the asteroid belt is comparable to its value at 1 AU, and this is suggested by the Pioneer 10 penetration measurements, then the number density of cometary particles is comparable to the extrapolated asteroidal number density in the asteroid belt.

We shall presently consider the influence of collisions on the population of the asteroidal particles and show that they cannot coexist in a steady state with the cometary particles in significant numbers because of the destructive influence of catastrophic collisions with cometary particles.

In order to estimate the influence of collisions we shall use a method discussed by Dohnanyi (1969, 1970 and 1972). We shall only consider the influence of catastrophic collisions; it can be shown (Dohnanyi, 1969, 1970) that erosive collisions play only a minor role for populations of the type Eq. 3 and Eq. 4.

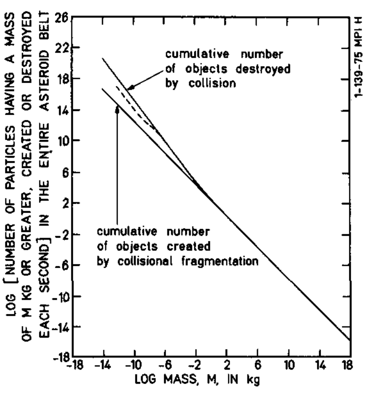

Fig. 4

Cumulative number of particles created or destroyed in the asteroid belt, as indicated, for an asteroid number density given by the collisional model and under bombardment by cometary particles, discussed in the text. Dashed line is the destruction rate implied when a refined model of cometary particle distribution is employed (see text).

The mean relative velocity between asteroidal particles in about 5 km/sec (Dohnanyi, 1969). The average relative velocity between asteroidal and cometary particles is unknown and it is therefore

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necessary to estimate it from first principles. If we take a "typical" short period cometary orbit with perihelion and aphelion distances of 1 AU and 4 AU, respectively, and an average inclination of the McCrosky and Posen (1961) meteors we obtain a velocity of 13.6 km/sec relative an asteroidal particle in circular orbit at 3 AU from the sun. If we use formula 7-9 given by Southworth and Sekanina (1973) for the relative velocity and an average eccentricity of .5 as obtained by these authors, then even for a zero inclination orbit we obtain a relative velocity of 16.4 km/sec for cometary particles at 3 AU from the sun. It is obvious that the relative velocity between an asteroid belt particle in near circular low inclination orbit and a cometary particle in highly eccentric and moderately inclined orbit will be much higher than the relative velocity among the asteroidal particles themselves.

For purposes of a rough, order of magnitude estimate, we shall adopt an average encounter speed of 14 km/sec between cometary and asteroidal particles and a material density of 3.5 gm/cm^3 for both cometary and asteroidal particles.

Following Dohnanyi (1973, 1969) we then estimate the amount of material crushed per unit volume and unit time in the asteroidal belt as well as the number of new fragments created by the crushing of larger objects.

Figure 4 summarizes our results: it is a double logarithmic plot of the number of objects having a mass of m kg or greater created or destroyed, as indicated, per second in the entire asteroid belt assuming an asteroidal population similar to the steady state distribution obtained from the collisional model (Dohnanyi, 1969).

It can be seen, from Fig. 4, that the creation rates are similar to the destruction rates for objects having a mass of many kg. The contribution to the collision rates by cometary objects causes the destruction rate to exceed the creation rate by an amount less than 8 % for objects larger than 100 kg and becomes negligible for even larger objects. For object with a mass of the order of 1 kg, however, the destruction rate exceeds the creation rate by about 33 % and this effect increases, rapidly, for smaller masses, where the destruction rate exceeds the creation rate by orders of magnitude.

The distribution rate, plotted in Fig. 4 as a solid line, is based on a cometary number density given by the first part of Eq. 4 and extrapolated into a mass range smaller than 10^{-10} kg without regard

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to the "flattening" in the distribution for those small masses. A more detailed calculation, including the change in the cometary meteoroid distribution for masses smaller than 10^{-10} kg as given by the second part of Eq. 4 and including the presence of ß-meteoroids (Dohnanyi, 1976) has been carried out. The results for the destruction rate are plotted as a broken line in Fig. 4.

The estimates for the destruction rate, plotted in Fig. 4, are probable lower limits because the particle removal rate by the Poynting-Robertson effect (Robertson, 1936) have not been included. It has been shown, (Dohnanyi, 1969) that this effect will contribute to the destruction rate by an amount equal to the creation rate plotted in Fig. 4 for particles with masses of about 10^{-13} kg; this effect increases rapidly for smaller particles.

It is therefore clear that a population of small objects, obtained by extrapolating the steady state distribution of large asteroids is not stable under the influence of bombardments by cometary particles. Destructive collisions with cometary objects will rapidly deplete the small particle of an asteroidal population given by Eq. 3 (i.e. the steady state solution of the collisional model for large asteroids).

We shall now estimate, very roughly, the likely population of small asteroidal particles. We assume steady state conditions and approximate the asteroidal distribution by a function of the form

(5) $$h(m)dm = H\, m^{-\sigma}\, (B + m^{\beta})^{-1}\, dm \quad .$$

where h(m)dm is the number density of objects in the mass range m to m+dm and H, σ, B, ß are constants. h(m)dm has the property that for small objects, i.e. when

(6) $$m^{\beta} \ll B,$$

we have

(7) $$h(m)dm \sim HB\, m^{-\sigma}\, dm,$$

and for large objects

(8) $$m^{\beta} \gg B$$

we have

(9) $$h(m)dm \sim H\, m^{-\beta-\sigma}\, dm$$

We also require that for large asteroids h(m)dm approach the true number density of these objects, Eq. 3. This determines the values of $\sigma + \beta$:

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(10) $H = 2.48 \times 10^{-19}\ m^{-11/6}\ dm, \quad \sigma + \beta = 11/6$

In order to determine σ, we note that for masses much larger than $B^{1/\beta}$ we have a population given by the formula Eq. 7. This population is subject to collisions with the population of cometary objects given, as a first approximation, by

(11) $f(m)dm = 2.94 \times 10^{-22}\ m^{-13/6}\ dm$

i.e. the first part of Eq. 4.

Using a method discussed by Dohnanyi (1970, cf. Eq. 47 in that paper) the steady state solution to the dynamic problem of these two interacting populations is estimated by

(12) $\sigma = 1.5$

If we take, somewhat arbitrarily (cf. Eq. 6)

(13) $B \sim 1$ kg

which is the mass at which the destruction rate in Fig. 4 exceeds the creation rate by only about 25 % we have a very rough estimate of the resulting asteroidal distribution which we now can write as

(14) $h(m)dm \sim 2.5 \times 10^{-19}\ m^{-11/6}\ dm, \quad m \gg 1$ kg
$\sim 2.5 \times 10^{-19}\ m^{-1.5}\ dm, \quad m \ll 1$ kg

In estimating h(m)dm we have assumed that the density of cometary objects, Eq. 11, can be extrapolated down to masses smaller than 10^{-10} kg, as a zeroth approximation; this is not strictly correct, as can be seen from Eq. 4. The fact that the density of cometary microparticles ($m < 10^{-10}$ kg) is smaller than an extrapolation of Eq. 11 (cf. however, Dohnanyi, 1976) means that the asteroidal microparticle density is somewhat greater for very small particles than our estimate, Eq. 14, implies. It is, however clear, that the steady state density of asteroidal micrometeoroids is much smaller than that of the cometary particles. On the basis of our present results we estimate that, for masses very much smaller than 1 kg, the density of asteroidal particles is orders of magnitude smaller than is that of the cometary particles, in the asteroidal belt.

We summarize the situation in Fig. 5 which is similar to Fig. 3 but where we have sketched the estimate of the asteroidal number density, Eq. 14. The density of asteroidal dust is then somewhat underestimated as has been discussed above. The density of cometary micrometeoroids in the mass range smaller than about 10^{-14} kg is, however, also underestimated because we did not include the flux of ß-meteoroids

(Dohnanyi, 1976) in our zeroth approximation treatment. Accordingly, in Fig. 5, the cometary particle density curve should start bending upwards for masses decreasing to smaller values than about 10^{-14} kg.

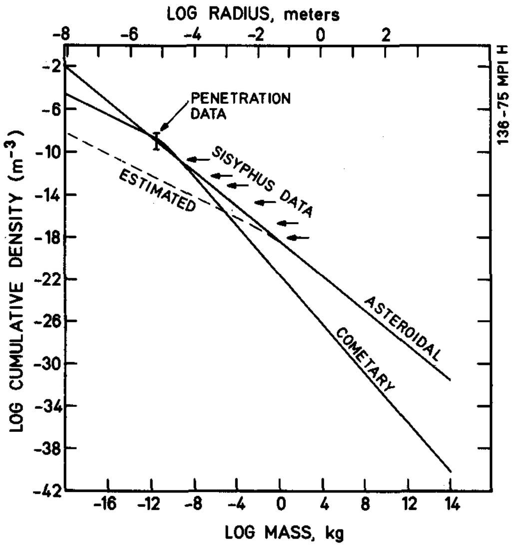

Fig. 5

Comparison of particle number densities implied by the Pioneer 10 and 11 data combined with the results of the present paper. Dashed line is a theoretical estimate of the asteroidal small particle distribution implied by the indicated cometary number density. Solid line, labelled "asteroidal" is the number density obtained from the collisional model and estimated to be valid for objects having a mass of many kg. The expected location of the Sisyphus optical data we indicated by arrows; their final calibration is in progress.

The published results of the Sisyphus (Soberman et al., 1974a and b) experiments are also plotted for comparison. These results are represented by arrows showing the direction in which the data points will probably move after final calibration of the results has been achieved.

IV. Leakage of Material out of the Asteroid Belt

Sofar we have considered the distribution of asteroidal dust only in the asteroidal belt and found that cometary particles appear to dominate the distribution of micrometeoroids in the asteroid belt. Since the distribution of cometary objects appears to be a slowly varying function with distance from the sun over the solar system within the orbit of Jupiter (Hanner et al., 1976) and since asteroidal objects are concentrated in the asteroid belt, it appears that the contribution of asteroidal particles to the micrometeoroid population outside the asteroid belt is much smaller than in the belt. One would therefore conclude that asteroid particles do not dominate the distribution of interplanetary dust in the solar system within the orbit of Jupiter.

In the foregoing discussion we have distinguished between objects of asteroidal and cometary origin on the basis of their orbits only.

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Objects in the asteroid belt having approximately circular orbits were labelled asteroidal and all other objects in more eccentric orbits and/or outside the asteroid belt were labelled cometary. Such a distinction is somewhat arbitrary and we shall presently discuss it in greater detail.

The possible origin of earth crossing objects has extensively been discussed in the literature (cf. Anders, 1971, Marsden, 1971, Opik, 1963 and 1966, Wetherill, 1974, Whipple, 1967). Whereas some authors favor a cometary origin for most of these objects and others regard them as asteroids, the only objects that are uniformly accepted as cometary are the ones that do or have exhibited a cometary tail.

Zimmerman and Wetherill (1973) have recently suggested a mechanism by means of which a great deal of asteroidal material may escape the asteroid belt and develop eccentric earth crossing orbits. This may be accomplished as follows: belt asteroids with orbital elements near the 2:1 resonance gap with Jupiter may eject substantial quantities of collisional fragments into the gap. Those fragments may then develop somewhat eccentric orbits librating with Jupiter in such a manner that they always avoide a close encounter (at the asteroid's aphelion passage) with the major planet. Subsequent collisions may then destroy this libration relationship with Jupiter resulting in strong Jovian perturbations leading to eccentric earth crossing orbits. Through this process, Zimmerman and Wetherill estimated that enough material may leave the asteroid belt that the population of earth crossing objects (McCrosky and Ceplecha, 1970) may, to a large extent, consist of these "runaway" asteroidal objects.

It therefore appears difficult to precisely determine the relative proportion of asteroidal object in the population of earth crossing objects having a size of the order of 1 kg or larger. The dynamics of the population of small objects has been discussed by Whipple (1967) and more recently by Dohnanyi (1970). It was found that our present knowledge of the distribution of meteoroids in the mass range of less than a kg down to micrometeoroidal sizes is consistent with a cometary origin and unless it can be shown that some dynamical process (e.g. the one proposed by Zimmerman and Wetherill) can populate the Zodiacal cloud with asteroidal small particles (smaller than about a kg) more efficiently than comets are believed to do (Whipple, 1967, Dohnanyi, 1970), we conclude that the population of small meteoroids in the solar system is dominated by particles given off by short period comets (Whipple, 1967, also cf. Lovell, 1954).

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V. Asteroidal Rotations

The rotation of asteroids has been discussed by McAdoo and Burns (1972) and more recently ny Napier and Dodd (1974). These authors concluded that collisional processes are definitely involved in spinning up some of the asteroids but found it difficult to explain the known distribution of asteroidal rotations in terms of a collisional origin. We shall show here that the known distribution of asteroidal rotations as given by Mc Adoo and Burns (1972) and by Gehrels (1970) can indeed be explained as having a collisional origin, thereby strengthening our confidence in the strong influence of collisions on the population dynamics of meteoroids developed in our earlier discussion. More specilically, we shall show that the gross features of the known distribution of asteroidal rotations can be reproduced from a simple random walk model.

We first consider the magnitude of the angular velocity that an asteroid may aquire over a period of time.

We assume that the number density of asteroids f(m)dm is given by Eq. 1; the flux and per (m^2sec 2π sterad) is (cf. Dohnanyi, 1972)

(15) $\quad \text{flux} = (1/4)\ v\ f(m)dm$

where v is the mean encounter speed.

The influx of particles per second into a sphere of radius r is then $(4\pi\ r^2)$x(flux) and into a sphere of radius (r+dr) is $4\pi(r+dr)^2$x(flux). Hence the influx, per second, of particles with an impact parameter r to r+dr around a point is $(8\pi\ rdr)$x(flux) which is the difference between the two previous expressions. The influx, per second, of the corresponding angular momentum f(m,v,r)dr around this point using Eq. 15 is,

(16) $\quad f(m,v,r)dr\ dm = (8\pi\ rdr)(rmv)\,\xi\, f(m)(1/4)vdm$

where ξ is the corresponding "momentum multiplication factor" and is generally some number greater than 1. The inclusion of ξ is necessary because the transfer of angular momentum to an asteroid by an impacting particle with momentum mv and impact parameter r is not only mvr but the momentum of the debris ejected from the impact crater will also contribute an additional angular momentum impacted to the target object. We shall attempt to include this effect with the use of the "momentum multiplication factor", ξ .

Integrating Eq. 16 over the size of the target object and over the mass of all projectile objects smaller than the critical particle size that would catastrophically disrupt the target object, using Eq. 1

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and Eq. 16, we have

$$(17) \quad \int_0^R dr \int_{\mu}^{m/\gamma} dm' \; f(m',v,r) \simeq 2\pi \; \xi (R^3/3) v^2 A6 \; (m/\gamma)^{1/6}$$

where the contribution of the lower mass limit at some minimum micro-meteoritic mass μ has been disregarded and where m/γ is the mass of the smallest projectile object capable to catastrophically disrupt a target object whose mass is m. γ is taken here as $\gamma = 250\ v^2$ (Dohnanyi, 1972) where the impact speed v is to be expressed in km/sec. Using Eq. 1 and an average meteoroid material density of 3.5 gram/cm^3 we now assume that the angular momentum imparted to the target adds up linearly. We can then calculate the expected value of the maximum angular momentum, H, imparted per second to our test object

$$(18) \quad H = 3 \times 10^{-20}\ \xi\ v^2\ m^{7/6}, \text{ MKS units.}$$

Assuming spherical asteroids with a moment of inertia $(2/5)mR^2$ and where ω is the angular velocity, we obtain for the period T,

$$(19) \quad T = 10^{-10} \sqrt{M}\ \xi^{-1} \quad \text{hr (per } 10^9 \text{ yr)}$$

which is the period (hr) aquired during 10^9 years of bombardment by an asteroid with an average albedo of .04 (Chapman, 1975a). T is the expected value of the smallest period of rotation (hr) that may be aquired by an asteroid having a mass M (kg) during 10^9 years of exposure to an environment similar to the present asteroid belt. Since, however, the number density of asteroids was very likely greater in the past, Eq. 19 should be regarded as conservative, i.e. when past values of asteroidal number densities are considered, a smaller value for T than the one given by Eq. 19 would be obtained. In addition to the influence of collisions on asteroidal rotations, radiation forces may also contribute to the rotational state of asteroids (Paddack, 1969, Icke, 1973) causing the expected value T to be even shorter.

Napier and Dodd (1974) estimated the critical rotational period, Tcr, for asteroids; asteroids with a shorter rotational period will burst because of excessive internal tension. Their result is

$$(20) \quad T_{cr} \sim 10^{-6}\ M^{1/3} \text{ hours}$$

where M is the asteroidal mass, in kg. A comparing of Eq. 19 with Eq. 20 shows that most asteroids "had a chance" to aquire enough angular velocity to cause rotational disruption.

We then consider the following statistical model: assume that we have

$$(21) \quad F(\omega)\ 4\pi\omega^2 d\omega$$

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asteroids with angular velocities in the range ω to $\omega+d\omega$ where

(22) $$\omega^2 = \vec{\omega}\cdot\vec{\omega}$$

We further assume that these angular velocities change randomly in time. If, furthermore, any asteroid aquires an angular velocity of ω_x or greater then it disappears (= it is disrupted) and another asteroid (the largest fragment) appears i.e. is created. These new asteroids may have any angular velocity smaller than ω_x with equal statistical probability.

Our function $F(\omega)$ in Eq. 21 then satisfies the diffusion Equation

(23) $$\frac{1}{\omega^2}\frac{\partial}{\partial\omega}\left(\omega^2\frac{\partial F(\omega)}{\partial\omega}\right) = S(\omega),\quad \omega\leq\omega_x,\ F(\omega_x) = 0$$

where the source function $S(\omega)$ is

(24) $$S(\omega) = \text{constant} \quad \omega<\omega_x$$
$$= 0 \quad \omega\geq\omega_x$$

The unique solution of Eq. 23 is

(25) $$F(\omega) = -\frac{1}{\omega}\left\{\int_0^{\omega}dy\int_0^{y}dx[xS(x)] - \frac{\omega}{\omega_x}\int_0^{\omega_x}dy\int_0^{y}dx[xS(x)]\right\}.$$

Using Eq. 24 we readily obtain

(26) $$F(\omega) = \text{constant}\ (\omega_x^2 - \omega^2)$$

and we have for the number density

(27) $$F(\omega)\ 4\pi\omega^2 d\omega = c(\omega_x^2 - \omega^2)\omega^2 d\omega$$

where

(28) $$c = (15/2)\ N\omega_x^{-5}$$

where N is the total number of asteroids represented by the density function Eq. 27.

Figure 6 is a plot of the density function Eq. 27 for two values of ω_x as indicated. A sample size of N = 35 was used in the numerical plot of Eq. 27 which approximates the number of asteroids having a critical frequency ω_x within about a factor of 2 from the value used in the plot.

It can be seen, from Fig. 6, that the gross features of the distribution of asteroidal rotations can be reproduced by our simplified steady state random walk model Eq. 27. It therefore appear that most asteroids have spin rates determined by the effects of random collisions with other asteroids. It will therefore be difficult to obtain statistical information regarding the initial state of asteroidal

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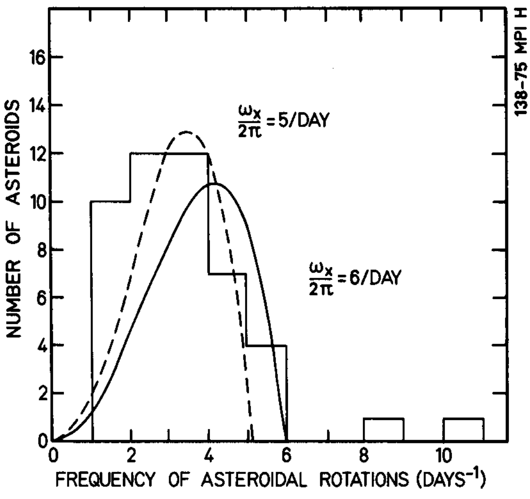

Fig. 6

Distribution of asteroidal rotations; histograms are empirical data and curves are theoretical results obtained in the text for two values of the critical bursting angular velocity, ω_x, as indicated.

rotation periods at the time of creation by only considering their present distribution of rotations. We have hereby obtained further evidence for the soundness of the collisional model and the applicability of some of the inferences one can draw from such a simple "molecular chaos" approximation.

VI. Historical Note

In this section we shall very briefly discuss the possibility that asteroids may have significantly contributed to the zodiacal cloud in past times.

Because of collisions the asteroid belt is losing mass by the production of fragments sufficiently small to be expelled from the solar system by radiation pressure (Zook and Berg, 1975) or will spiral into the inner regions of the solar system because of the Poynting Robertson effect (Wyatt and Whipple, 1950). In addition to these processes, the asteroid belt is losing some of its members because of perturbations with Jupiter (Zimmerman and Wetherill, 1975).

It therefore is clear that there was more material in the asteroid belt in the past then is there now. The total initial mass of the asteroids in the asteroid belt has been estimated from about the same order of magnitude as its present mass (Dohnanyi, 1969) to about 3000 times its present mass (Chapman and Davis, 1975). Thus, if the cometary meteoroid population has been constant at its present level, the asteroidal contribution to interplanetary dust may well have dominated

https://doi.org/10.1017/S0252921100051708 Published online by Cambridge University Press

the particle population of the zodiacal cloud in earlier periods of the solar system.

The situation is, however, complicated by the fact that the population of cometary objects within the orbit of Jupiter may also have been much greater in the past (Wetherill, 1975, Whipple, 1975).

Until the past distribution of comets and asteroids is better known, it appears difficult to estimate the relative contribution of asteroidal material to the zodiacal cloud during the earlier period of the history of the solar system.

VII. Conclusion

The central conclusion reached here is that the contribution of comets to the small particle population in the zodiacal cloud dominates over the asteroidal contribution to it. The distriction between comets and asteroids is in many cases, however, not yet clear. We distinguish here between comets and asteroids somewhat arbitrarily on the basis of their orbital elements. Our conclusions will have to be reexamined if many of the earth and Mars crossing (Shoemaker et al., 1975) objects turn out to be asteroids that have escaped from the asteroid belt (Zimmerman and Wetherill, 1973).

The origin of asteroidal rotations is also considered, as a corollary to our discussion of the influence of collisions on the population of asteroidal fragments. It is found that the gross features of the distribution of asteroidal rotations can be explained if one assumes that the population of asteroids (whose spins have been measured) have reached steady state conditions under the effect of mutual inelastic collisions.

VIII. Acknowledgement

I am indebted to J. Schubart for helpful discussions.

I gratefully acknowledge that my visit to Heidelberg has been made possible by an Alexander von Humboldt Senior U.S. Scientist Award.

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