MASS INPUT INTO AND OUTPUT FROM THE METEORITIC COMPLEX

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ABSTRACT. Direct observations have established the size distribution of interplanetary meteoroids at 1 AU as well as the dependence of the spatial density with respect to the distance from the sun. After evaluating the consequences of mutual collisions and the effect of radiation pressure the following conclusions can be drawn: 1. Catastrophic collisions dominate the lifetimes of meteoroids with masses $m \gtrsim 10^{-5}$g. About 10 tons per second are lost within 1 AU (mostly in form of 10^{-4}g to 10^{-1}g particles). Under steady state conditions these meteor sized particles have to be replenished by other sources, e.g. comets. 2. After being crushed by collisions 70 to 85% of this mass will be in form of particles with masses $10^{-10}\text{g} \lesssim m \lesssim 10^{-5}$g. Part of these "zodiacal light" particles (about 0.3 tons per second) are transported by the Poynting Robertson effect towards the sun where they will evaporate. However, since the collisional production of these intermediate sized particles exceeds their losses this population is presently not in equilibrium. 3. 15 to 30% of the collisional fragments have masses $m \lesssim 10^{-10}$g. Most of these small particles will be injected into hyperbolic orbits by radiation pressure (β-meteoroids).

1. INTRODUCTION

Mutual collisions between interplanetary meteoroids, the Poynting Robertson effect, and radiation pressure ejection of small meteoroids give rise to some interesting consequences which are here examined. From lunar crater statistics and satellite data, the size distribution and flux of micrometeoroids at 1 AU distance are derived. We evaluate the relative rates of destruction and production of grains by mutual collisions and the operation of other processes that determine the stability of the interplanetary meteoritic population. From the comparison of collisional and radiation pressure effects conclusions are drawn on the present state of the meteoritic complex. Especially the mass input into and the mass output from three different mass intervals (meteor sized particles, zodiacal light particles and β-meteoroids) of the meteoritic cloud are discussed. A more detailed description of the methods employed

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is given by Grün et al. (1984).

2. INTERPLANETARY METEOROID FLUX

Information on the interplanetary meteoroid flux is obtained from lunar crater statistics, in situ spacecraft measurements, meteor and zodiacal light observations. Grün et al. (1984) derive a flux model with the following characteristics:
Meteor observations (for a summary see Whipple, 1967) lead to a dependency of the cumulative flux on the meteoroid mass m according to $m^{-1.34}$ for masses 10^{-5}g $\lesssim$ m $\lesssim$ 10^2 g. The flux of smaller particles down to mass m $\sim$ 10^{-10}g is characterized by the size distribution of lunar microcraters (e.g. Morrison and Zinner, 1977). The absolute calibration of the fluxes at masses 10^{-7}g and $6\text{x}10^{-7}$g is obtained from measurements of the Pegasus satellite (Naumann, 1966). At m = 10^{-13}g and 10^{-12}g fluxes have been derived from the HEOS 2 experiment (Grün and Zook, 1980). These fluxes are below most lunar microcrater fluxes because the latter are dominated by secondary ejecta cratering (Zook et al., 1984) for particle masses m $\lesssim$ 10^{-10}g. In the mass range 10^{-14}g $\lesssim$ m $\lesssim$ 10^{-9}g the slope of the cumulative meteoroid flux is $\sim$ -0.36. The flux of smaller particles (m $\lesssim$ 10^{-14}g) has been calculated from a collisional model assuming that all fragments of this size range which are produced inside 1 AU are pushed out of the solar system by radiation pressure and become β-meteoroids.
This interplanetary flux leads to a spatial mass density at 1 AU of $\sim$ 10^{-16}g/m³, where most mass per logarithmic mass interval is in meteoroids of masses 10^{-6}g to 10^{-4}g. Measurements of the zodiacal light (Leinert et al., 1981) provide the radial dependence of the spatial number density n of interplanetary meteoroids: n $\sim$ $r^{-1.3}$. The determination of the color of the zodiacal light (Pitz et al., 1979) shows some reddening compared to the solar spectral flux. This observation is compatible with the characteristics of the flux curve, i.e. most cross-sectional area per logarithmic mass interval originates from particles of masses 10^{-8}g to 10^{-5}g. The total cross-sectional area of the interplanetary meteoroid cloud at 1 AU is $5\text{x}10^{-19}$m²/m³.

3. COLLISIONAL MODEL

The rate of catastrophic collisions is calculated using the size distribution described above. Further ingredients of the collisional model are:
- the effective mutual collision speed at 1 AU is 20 km/s and it varies with r as $r^{-0.5}$.
- the dependence of rupture energy upon particle size is given by Gault et al. (1972).
- the mass distribution of the fragments is taken from Fujiwara et al. (1977).

With these assumptions we have calculated the collisional lifetimes of interplanetary meteoroids (Fig. 1). At 1 AU the lifetimes are shortest

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(10^4 years) for particles of mass 10^{-3}g to 1g. Both bigger and smaller particles have longer collisional lifetimes. For comparison we also show the Poynting Robertson lifetimes (Wyatt and Whipple, 1950). The efficiency factor used was that for olivine particles and the average initial eccentricity of the particle orbits at 1 AU is assumed to be 0.5. Collisions dominate the lifetimes of meteoroids with masses $m \gtrsim 10^{-5}$g. These large particles will not change their orbits significantly due to the Poynting Robertson effect before they are involved in a collision and fragmented into smaller particles. Only smaller particles will have their orbits circularized by the Poynting Robertson drag and will eventually spiral in towards the sun where they will evaporate. Using our collisional model the rate of catastrophic collisions is compared with the rate of production of fragments for logarithmic mass intervals in the range from 10^{-18}g to 10^2g. This comparison in terms of collisional loss and gain is shown in Fig. 2. We have also computed the radial loss due to the Poynting Robertson effect which is required in order to maintain a radial density distribution of $r^{-1.3}$. The result of this comparison is discussed in the next sections.

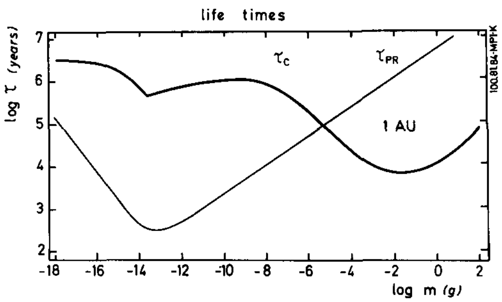

Fig. 1: Lifetimes of interplanetary meteoroids with respect to collisions τ_C and Poynting Robertson effect τ_{PR}. The sharp edge of the collisional lifetime at 10^{-14}g is caused by the artificial cut-off of the meteoroid distribution at $m = 10^{-18}$g.

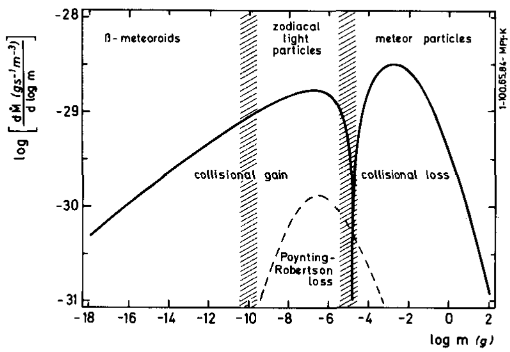

Fig. 2: Net mass loss and gain rates from collisions and transport losses due to Poynting Robertson effect at 1 AU. The total mass lost by collisions ($m \gtrsim 10^{-5}$g) and gained as fragments ($m \lesssim 10^{-5}$g) is 9×10^{-29}g/m³s. The Poynting Roberston effect requires a loss of only 4×10^{-30}g/m³s in order to maintain the spatial density $\sim r^{-1.3}$.

4. METEOR PARTICLES

Large meteor sized particles ($m \gtrsim 10^{-5}$g) are dominated by collisional fragmentation. Assuming a radial dependence according $r^{-1.3}$ and a filling factor $\varepsilon = 0.23$ (Leinert et al., 1983) then a total of 9 t/s

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is lost from this size range within 1 AU. This particle population would be depleted on a time scale of $\sim 10^4$ years without replenishment from cometary and asteroidal sources. Under steady state conditions most meteor particles are "young", i.e. they have not been fragmented by collisions and their initial orbits are not much altered by radiation pressure drag. Only planetary perturbations could distort the initial orbits significantly before the particles break up by catastrophic collisions. Observations of meteor streams support this finding.

5. ZODIACAL LIGHT PARTICLES

The optically active zodiacal light particles (10^{-10}g $\lesssim m \lesssim 10^{-5}$g) are dominated by radiation pressure drag and not by catastrophic disruption. Their lifetimes due to Poynting Robertson effect range from 10^5 years to 10^3 years for the smaller particles. However, many more particles are gained in this mass interval from collisional break-up of meteor-sized particles than are removed either by Poynting Robertson effect or by collisions. About 6 to 8 t/s of these particles are produced inside 1 AU. This compares to only ~ 0.3 t/s which are lost by the Poynting Robertson effect. This situation is not stable but the zodiacal light particle population increases in time (on a time scale of about 10^4 years at 1 AU). Time stability of this particle population can only be maintained if we have overestimated the meteoroid flux by more than a factor 10 or if the break-up laws which we have applied are not at all representative for interplanetary meteoroids. Both alternatives are not supported by the data.

6. β-METEOROIDS

Small particles are affected by radiation pressure (see e.g. Burns et al., 1979) which reduces the solar gravitational attraction. A small fragment particle which is generated by a collision between a larger parent meteoroid and another meteoroid will move on an unbound trajectory if its reduced potential energy (gravitation minus radiation pressure) is exceeded by its kinetic energy which is derived from the parent particle. This is especially effective at the perihelion of an eccentric parent particle's orbit, where the kinetic energy and the collision rate are highest. Since the eccentricities of the parent particles are significant even fragment particles of masses as large as $m \sim 10^{-10}$g can get on hyperbolic trajectories and become β-meteoroids (Zook and Berg, 1975). This direct injection of fragment particles into hyperbolic orbits is a very efficient loss mechanism since the time these particles spend in the inner solar system is only order of 100 days. Therefore, most particles of masses $m \lesssim 10^{-10}$g which are produced from the disruption of larger meteoroids can efficiently be removed by this effect. Hence we conclude that particle population is in time stability. About 1 to 3 t/s of β-meteoroids pass the Earth's orbit.

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