Mem. S.A.It. Suppl. Vol. 11, 89

Memorie della
Supplementi

Study of the Interaction of Micrometeoroids with Earth's Atmosphere

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Abstract. Submillimetric micrometeoroids dominates the annual extraterrestrial mass flux toward the Earth. Indeed these bodies show an unexpected ability to survive the interaction with the terrestrial atmosphere. In this work it is suggested a new general numerical model for the micrometeoroids-atmosphere interaction: this is the first step of a more extended study (Aiello et al , 2005) that includes also experiments for the next few years in laboratories as well in atmosphere (microsatellites or balloon-borne experiments).

1. Introduction

Micrometeoroids (MMs) with dimensions between 50 e 500 μm represent the absolute majority in the Solar System minor bodies population at a distance of 1 AU from the Sun (Grün et al , 1985). and in the flux of extra-terrestrial matter that enter the Earth's atmosphere in 1 year (40000 ± 20000 ton/y Love & Brownlee (1993)).

Furthermore, MMs show an unexpected ability to survive to the interaction with the atmosphere, as demonstrated the the large number ($\sim 10^5$) of micrometeorites recovered in Antarctica during the last 20 years (Engrand & Maurette , 1998). Many of the recovered samples show a degree of alteration less than expected: indeed, on the basis of numerical models proposed up to now to describe the passage of MMs in our atmosphere, we expect that only a minor part of these bodies could survive or reach the Earth surface without melting: 1% according to Brownlee (1985), 10% for Love & Brownlee (1991).

A further reason of interest for these objects is the possibility that they could have been in part responsible, if not even indispensable, for the emergence of life on Earth. MMs are rich in C and N, and the distributions of these elements observed in micrometeorites suggest they are bound together in an organic material. Thus, MMs may have been the dominant source of organic carbon on the primitive Earth (Matrajt et al , 2003). Moreover, the evaluations of the total amount of N, Ne, H_2O and CO_2 released by MMs in the atmosphere during the ~100 My of the so-called *sterilization* period (about 4.4 Gy ago), justify the idea that MMs did play a major role in the formation of

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terrestrial atmosphere and oceans (Maurette et al , 2000, 2001).

The possible role of MM as conveyors of amino acids and nucleo-bases is less clear. Thus far only one amino acid, α-amino isobutyric acid, has been found in one of the MM Antarctic samples (Matrajt et al , 2003). The absence of amino acids in the other samples may be due to the heating they experienced during atmospheric entry when the MMs temperature reaches values at which organic species sublimate or decompose. On the other hand experiments have demonstrated that sublimation could be an important mechanism in the survival of organic compounds in MMs during the atmospheric entry (Glavin & Bada , 2001).

In the light of the considerations above it seems to us that the processes occurring during the passage of MMS trough the atmosphere are worthy of a detailed investigation. This implies that we have to consider a lot of physical processes, different from one another but complementary at the same time. The complexity of a comprehensive treatment appear to be the reason why a general and detailed model of the MMs-atmosphere interaction has not yet been realized. Indeed a common property of the studies found in literature is that they analyze every time only one of the physical processes that determine the fate of a MM.

Therefore our idea is to approach this problem in a global way, including in our analysis the processes that can be the most important and highlighting how the same phenomenon can be affected by different mechanisms.

2. The model: properties of atmosphere and MMs

We treat MMs as spheres, with radius a_{MM} and transverse section S. MMs diameters are assumed to be between 10 μm and 1 mm. The upper limit of 1 mm is due to the hypothesis of isothermal MMs, i.e. we assume that a MM reach at every moment in his flight a uniform temperature T_{MM}. The inferior limit of 10 μm follows from the emission properties of these bodies: namely, in order to characterize MMs with a constant emissivity their dimensions must be larger than the wavelength of the emitted and adsorbed radiation. Since a MM generally adsorbs VIS - UV radiation (200 - 800 nm) and emits IR radiation with $\lambda \approx 3$ μm (at temperatures of ~1000 K), a_{MM} is restricted to 5 μm.

The MMs density ρ_{MM} is assumed to be constant, with values 3000, 1000 and 300 kg/m^3: these are close to those measured in carbonaceous condrites (meteorites that have the most similar composition to MMs; Norton (2002)). Similar values are adopted in some recent models (Campbell-Brown & Koschny , 2004; Rogers et al , 2005). For MMs structure and composition, being impossible to reproduce their peculiar characteristics, we assumed that they are composed entirely of graphite (C).

The Earth atmosphere properties (density and neutral components concentrations profiles), are taken from the MSIS-E-90 model (Hedin , 1991) The atmospheric properties determine also how a MM moves in the atmosphere: because the mean free path of an atmospheric particle, at heights between 60 and 200 km (those of interest in this work), is always bigger than the MM radius, we apply the *free molecular flow* regime. In other words, a MM always interacts with single atmospheric atoms and molecules, and there isn't a gas layer that protects it from collisions.

3. The model equations

The two-dimensional MMs trajectory is described by the two coordinate h (height from the Earth surface) and z (angle with respect to the local vertical direction). The initial value of h is 200 km: above this height the atmosphere density is too low and the interaction is not effective. The initial value of v_{MM} is between 11.2 km/s and 72.8 km/s. Collisions with atmospheric atoms and molecules are the main mechanism by which the MMs velocity v_{MM} is determined. To evaluate this effect we neglect the thermal velocity of atmospheric particles (~370 m/s for T_{atm} = 160 K at h = 100 km) with respect to v_{MM}. Including also the Earth gravitational attraction, we obtain the following equation

$$\frac{dv_{MM}}{dt} = -\frac{\Gamma}{M_{MM}} S \rho_{atm} v_{MM}^2 + gcos(z)$$

where $\rho_{atm} = \rho_{atm}(h)$ is the atmospheric density, and Γ is the *drag coefficient*, that describes the momentum fraction effectively transferred to a MM in a single collision. Its value is between 0 and 2 (2 for elastic collisions) and we chose $\Gamma = 1$.

As a MM acquires energy from collisions with atmospheric particles its temperature raises. This causes the onset of processes like evaporation and fusion of the MM material, which determine a reduction of its mass and dimensions. It's reasonable to think that these processes begin as soon as a MM starts to acquire energy from atmosphere: for this reason we describe the rate of mass loss as a function of the MM temperature T_{MM}. To describe fusion we use a term proportional to the energy acquired by a MM, as suggested by Campbell-Brown & Koschny (2004), to account for the mass loss of melted layers when high temperature (~2000 K) are reached. Another process by which MMs lose mass is sputtering. In order to evaluate the amount of mass lost by sputtering, we must calculate the sputtering yield Y, for which we chose a semi-empirical formula suggested by Draine & Salpeter (1979). We assume that a MM can collide with 6 species of atmospheric particles: N_2, O, O_2, Ar, He, H. A critical parameter is the fraction η of incoming kinetic energy effectively used by sputtering. However its value remains an arbitrary one, due to the complexity of this process and the lack of works in which sputtering is studied together with ablation processes. We assume $\eta = 0.1$.

MMs acquire energy mainly by collisions with atmospheric atoms and molecules with a rate:

$$\frac{dE_{coll}}{dt} = \frac{\Lambda}{2} S \rho_{atm} v_{MM}^3.$$

Here Λ is the *heat transfer coefficient*: it describes the fraction of kinetic energy of an incoming particle that is effectively transferred to a MM. We assume $\Lambda = 1$. The energy absorbed by a MM causes an increase in its temperature and the emission of electromagnetic radiation, that is fundamental for the MMs thermal balance, unlike it happens for greater meteoroids. Then we have to consider the processes that cause the mass reduction of MMs: as already underlined by Love & Brownlee (1991), it is essential to include these terms in the energy balance to properly evaluate the MMs temperature evolution. Besides these, in the present work we introduce in the energy balance a new term for the energy used by sputtering. Another important feature of our model is that the contributions of fusion and evaporation are treated separately (Campbell-Brown & Koschny , 2004). This choice is essential to estimate their relative role in the MMs-atmosphere interaction, and it represents the first step to study the different alterations suffered by the MM structure. A last term is introduced in this work to consider the kinetic energy of the mass removed from MMs by ablation. In this case we assume that the melted and evaporated MM particles go away with a velocity determined by the MM temperature T_{MM} (Campbell-Brown & Koschny , 2004).

The global energy balance is hence described by the following expression:

$$\begin{aligned}(1-\eta)\frac{\Lambda}{2} S \rho_{atm} v_{MM}^3 &= \\ = c M_{MM} \frac{dT_{MM}}{dt} &+ 4\pi a_{MM}^2 \epsilon \sigma T_{MM}^4 + \\ + H_{ev} \left(\frac{dM_{MM}}{dt}\right)_{ev} &+ H_{fus} \left(\frac{dM_{MM}}{dt}\right)_{fus} + \\ + \frac{1}{2} \left(\frac{dM_{MM}}{dt}\right)_{abl} &\frac{3k_B T_{MM}}{\mu}.\end{aligned}$$

where $H_{ev} = 6.05 \cdot 10^6$ J/kg and $H_{fus} = 2.65 \cdot 10^5$ J/kg (Love & Brownlee , 1991) are the latent heats of evaporation and fusion, c is the MM specific heat.

4. Results

For the numerical integration of the described equations it was realized a proper code in IDL 6.3. The calculations were performed using an

RK4 method, to which we added an adaptive variable stepsize. As can be seen in fig. 1-A, a 100 μm radius MM that enter the atmosphere with v_{in} = 12 km/s, is able to survive and can reach the Earth surface with a final radius of ~20 μm. For higher values of the initial radius and velocity, however, MMs acquire more energy by collisions with atmospheric particles, so they reach higher temperature and also the mass loss increases.

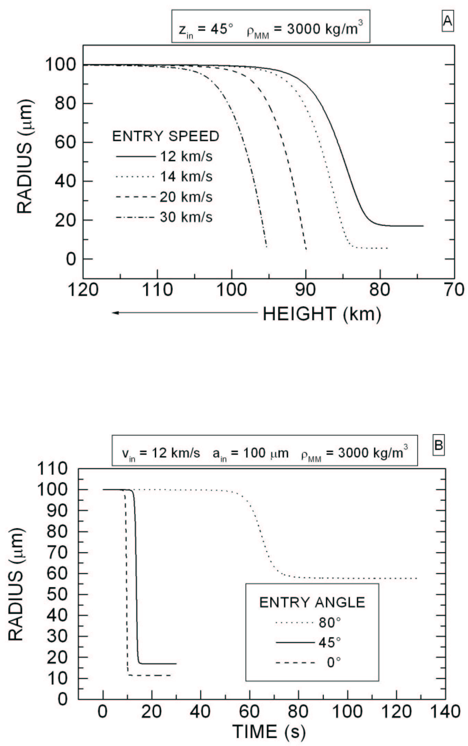


Fig. 1. MMs radius evolutions versus height or time for different values of the entry speed (A), and entry angle (B).

These effects are attenuated if we consider MMs that enter the atmosphere with great angles with respect to the vertical (fig. 1-B) or with a lesser density: when a MM has a trajectory far from the vertical direction, it reaches later and with smaller speed those atmospheric layers where the interaction is effective; with low density values (1000 or 300 kg/m^3) MMs are slowed down earlier, i.e. at higher height where the atmospheric density is low.

To understand which are the alterations suffered by MMs, and also to check whether the organic molecules they include can survive, we need to track the thermal evolution of MMs during the atmospheric passage. A typical temperature profile is shown in fig. 2 (solid line): the initial slight increment is followed by a rapid rise due to the arrive of the MM in atmospheric layers (h ~120 - 100 km) with high density. After the maximum value of about 1900 K, T_{MM} decreases very rapidly because the energy acquired by collisions is reduced, as the MM is slowed down and its dimensions decrease. Also from this figure is clear that for greater entry speeds the temperature increment is more rapid, and this implies a greater mass loss (in fact this MM doesn't survive, how can be seen from the truncated dotted line).

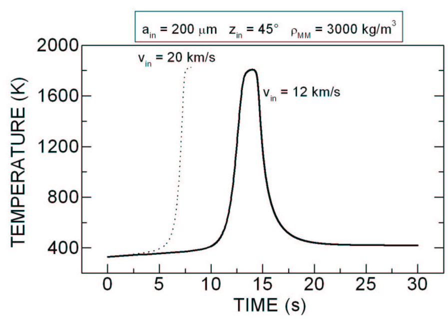
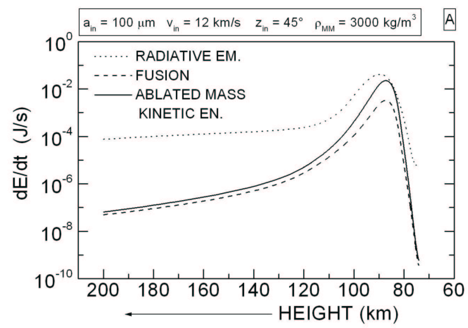


Fig. 2. Two possible temperature profiles of a MM crossing the Earth atmosphere.

Analysing the evolution, during the flight of a MM, of the terms that constitute the energy balance we can understand how those mechanisms contribute to determine the MMs fate. For the smallest ones is clear (fig. 3-A) that two very important quantities are the radiative emission and the kinetic energy of the ablated mass. The energy spent in these ways can't be used to reduce the MM mass, and so also these small bodies can survive. If instead we consider greater initial speeds and radii (fig. 3-B), these two mechanisms are no more able to avoid the MMs destruction, because is increased the role of the fusion process and also sputtering (due to the high MMs speed) contribute to the mass loss.



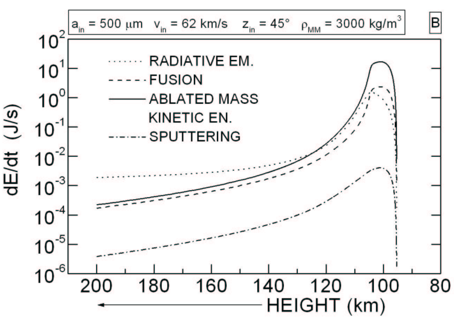


Fig. 3. Comparison between the principal terms of the energy balance. A): small MMs with low entry speed. B): MMs with higher entry speed and radius

5. Discussion

Very important for the ultimate fate of a MM in the atmosphere are the *drag coefficient* Γ and the *heat transfer coefficient* Λ, here both equals to 1. But these parameters are not exactly known, and very probably their value is not constant during the MMs flight (Campbell-Brown & Koschny , 2004). We have done simulations with $\Gamma \neq 1$ e $\Lambda \neq 1$. When Γ increases, MMs are slowed down more efficiently, so that they acquire less energy by collisions and they reach minor values of maximum temperature. A similar effect is due to values of $\Lambda < 1$: in this case decreases the energy transferred to a MM in an individual collision.

Equally important is the value of η, i.e. which fraction of the incoming energy we assume is spent by sputtering. With η=0.1, as in this work, even if the entry speed is very high (72 km/s) sputtering causes a negligible mass loss. If the value of η is taken equal to 0.9, the mass lost by sputtering is more than 2 orders of magnitude greater. But is very difficult to choose a value for η: theoretical (Sigmund , 1981) and experimental (Nakles , 2004) works treat sputtering in very detailed ways, but always as individual process, i.e. never in a situation similar to that of MMs, in which more than one mechanism is active at the same time.

Also the choices made for the characterization of physical processes can be decisive. To make an example, in this work results show that fusion is much more important than evaporation. This is probably due to the fact that the mass lost by evaporation depends on the MM temperature T_{MM}, while that lost by fusion is proportional to the incoming energy. Even more complex is the characterization of sputtering, in which there are several critical points (e.g. the sputtering yield dependence on the *projectiles* incidence angle, which particles are emitted from the *target*: atoms? molecules? both? See Tielens et al (1994)) and last but not least the speed at which these particles depart from the *target*. Coulson (2002), for example, suggests a sputtering treatment in which it causes an increment of a factor 11 in the momentum transferred to MMs by collisions, with consequent great decrease in the MMs speed and in all the other effects caused by the acquired energy.

6. Conclusions

The model described in this work is a first step to study the MMs-atmosphere interaction in a new way. The basic idea is to treat this problem in a comprehensive manner rather than to go deep into only one of its many aspects. Moreover it would be very helpful to study this problem in a multidisciplinary context, i.e. not only from a physical point of view, but also chemical and mineralogical (for the alteration that MMs can suffered crossing the atmosphere). And certainly it would be interesting, in the future, to analyze the biochemical aspects of this problem, to better understand the MMs role in the emergence of life on Earth.

Finally, an important property of this model is that is possible to apply it to atmospheres different from the terrestrial one, so that we can do a similar study for other planets and their moon (Mars, Venus, Titan) or also for the primordial Earth atmosphere.

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