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The electrical effects of micrometeoroids entering the terrestrial atmosphere at different speeds†

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Abstract. Micrometeoroids entering the terrestrial atmosphere lead to two important related electrical effects. One is the electrification of the upper atmosphere along their paths and the other is the electrical charging of the micrometeoroids themselves. In this brief note we will emphasize the central role of the initial encounter speed of the incoming micrometeoroid, showing how it changes the altitude profiles of electron production and electrical charging, not just quantitatively but also qualitatively. We will discuss the underlying reasons for this, as well as their importance in meteor studies.

1. Introduction

Ever since Ernst J. Öpik (1958) ushered in the physical study of meteor flight in the atmosphere over a half-century ago with his classic monograph, there have been numerous studies of the dynamics and thermodynamics of micrometeoroids entering the earth's atmosphere (e.g. see Bronshten 1983; Williams and Murad 2002). As these bodies encounter the increasingly dense atmosphere during their flight, they are simultaneously decelerated and heated by atmospheric friction, which in turn could lead to their partial or complete ablation. The dynamic and thermal histories of these bodies along their paths have been calculated using the equations of continuity of mass, momentum, and energy. These studies have also calculated the ionization of the atmosphere along the meteoroid's path due to energetic collision between the fast-moving ablated meteoroid molecules and the ambient atmospheric molecules; this ionization has been the main source of detection of small micrometeoroids via radar scattering by the electrons.

2. Electrical charging and electron production

The scope of these earlier studies was extended by Sorasio et al. (2001) and by Mendis et al. (2005) by adding a fourth equation: that of the continuity of the surface electric charge to study the history of the surface electric potential along

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the micrometeoroid's path. In these papers, the authors considered not only the grain charging by collection of the ambient plasma, but also the role of thermionic electron emission. This had two immediate consequences. Because the micrometeoroids could heat up sufficiently to emit electrons thermionically even before they were hot enough to ablate, they could provide another source of electrons, higher up in the atmosphere. Also, due to the dominance of thermionic electron emission over ambient plasma collection, in the mid-range of its flight, the micrometeoroid could change its charge polarity from negative to positive, and back again to negative along its path.

Another important contribution to meteor physics, which greatly increased the altitude range of atmospheric ionization, was due to Brosch et al. (2001). Öpik (1958) had already shown that physical sputtering was an important source of mass loss for high-speed meteoroids and provided semi-empirical formulae for the sputtering yield for iron and stony meteoroids, which he claimed to be in satisfactory agreement with available experimental data. These indicated that sputtering was important for iron meteoroids moving with speeds $\geq$42 km s^{-1}, and for stony meteoroids moving with speeds $\geq$51 km s^{-1}. The important point is that in these cases, the fast-moving sputtered meteoroid molecules would collide with the ambient atmospheric molecules and produce atmospheric ionization, just as in the case of ablated meteoroid molecules that we discussed earlier. All earlier studies, including ours, neglected this effect because they dealt with lower meteoroid speeds, where sputtering was unimportant. In fact, we largely restricted the initial speeds of micrometeoroids in our studies to the 'average' value of 30 km s^{-1}, while also considering lower initial speeds to show the difference between the effects of average 'cometary' micrometeoroids and slow-moving 'asteroidal' ones.

The first quantitative study of the role of sputtering in fast meteoroids was that of Brosch et al. (2001), referred to earlier. These authors considered relatively large (initial radius of 20 cm) meteoroids of two types, one composed of silicate and the other of water ice, each entering the atmosphere with the high initial speed of 71 km s^{-1}, corresponding to members of the Leonid meteor shower. For silicates they used a constant sputtering yield γ (the number of meteoroid molecules sputtered per impacting atmospheric molecule) = 2 and for water ice they adopted $\gamma = 22$. They found that sputtering-associated electron production was by far the dominant one at higher altitudes, and in the process also extended the range of atmospheric ionization to significantly higher altitudes. Very recently, we (Mendis and Maravilla 2009) added sputtering to our earlier model (Mendis et al. 2005), taking into account the velocity dependence of the yield, as opposed to a constant one as assumed by Brosch et al. (2001), and ran it for an initial speed of entry of 60 km s^{-1}. Continuing to use the 'free-molecular domain' approach, we used a much smaller initial size (40 μm, corresponding to a small micrometeoroid, instead of the large value of 20 cm, used by previous authors). Even with this smaller value, the altitude range of atmospheric ionization was increased over twofold, with the sputtering-associated process for electron production dominating both the ablation-associated process and the thermionic process.

The main goal of this recent paper (Mendis and Maravilla 2009) was to compare the altitude profile of the electron production rate by this fast (60 km s^{-1}) 'cometary' micrometeoroid with those of an 'average' (30 m s^{-1}) cometary micrometeoroid as well as a slow-moving (12.5 km s^{-1}) 'asteroidal' one, and show that they differ not just quantitatively, but also qualitatively.

In this brief note we will extend this work to compare the altitude profiles of not only the electron production rates but also of electrical charging of the micrometeoroids entering the atmosphere at different initial speeds, and will also discuss their observational implications.

3. The model

The model equations (excluding the role of sputtering, valid for higher velocities) are given in Mendis et al. (2005) and the additional terms resulting from physical sputtering are included in Mendis and Maravilla (2009). So in the interest of conserving space in this brief note these will not be written out at length. Here we will offer a brief qualitative description of the processes included and the important model parameters.

As pointed out earlier, a micrometeoroid entering the earth's atmosphere is both decelerated and heated by atmospheric friction, which in turn leads to mass loss by ablation. The processes leading to mass loss are sublimation, spray (from the partially fused surface) and sputtering. While the source of heat input to the grain is atmospheric friction, the heat sinks are associated with sublimation, fusion, sputtering, thermionic electron emission, re-radiation and its internal heating. The electrical currents that are responsible for grain charging are the usual electron and ion collection currents and the one associated with thermionic emission of electrons. There is also another current (first introduced in Mendis et al. 2005), which they call the 'ablation current', which follows from the fact that the ablate from a charged surface also carries away a fraction of the surface charge. (This may be simply written as $I_a = Q/\tau$, where Q is the surface charge and $\tau = -A/\dot{A}$, with A being the surface area.)

The model is restricted to the free-molecular domain (i.e. the Knudsen number, $K_n = \ell/r > 1$) and is thus restricted to micrometeoroids typically smaller than about 1 mm in radius).

Also in all cases, so far, the authors have adopted the model atmosphere corresponding to the same location (21 h local time at San Diego, USA, on 6 January 1999), which restricts their consideration to the night side of the earth, thereby eliminating the need to consider photoemission.

4. The role of micrometeoroid entry speed on the electron production profile

The model of Mendis et al. (2005) allows for micrometeoroids entering the earth's atmosphere at different speeds and angles of entry. Once again, in the interest of brevity we will restrict ourselves to vertical entry as in Mendis and Maravilla (2009), and we will consider three 'stony' micrometeoroids each of initial radius 40 μm, entering the 'top' of the atmosphere with initial speeds of 60, 30 and 15 km s^{-1}, representing respectively fast and average (speed) cometary micrometeoroids and a slow asteroidal one.

The altitude profiles of electron production for the three cases are shown in Fig. 1. Each one represents the sum of electron production by all three processes we have mentioned. We will begin with the two profiles corresponding to the two lower initial speeds, since sputtering (which takes place only when the speed $\geq$50 km s^{-1}) plays no role there. Since thermionic electron emission turns on at a lower temperature

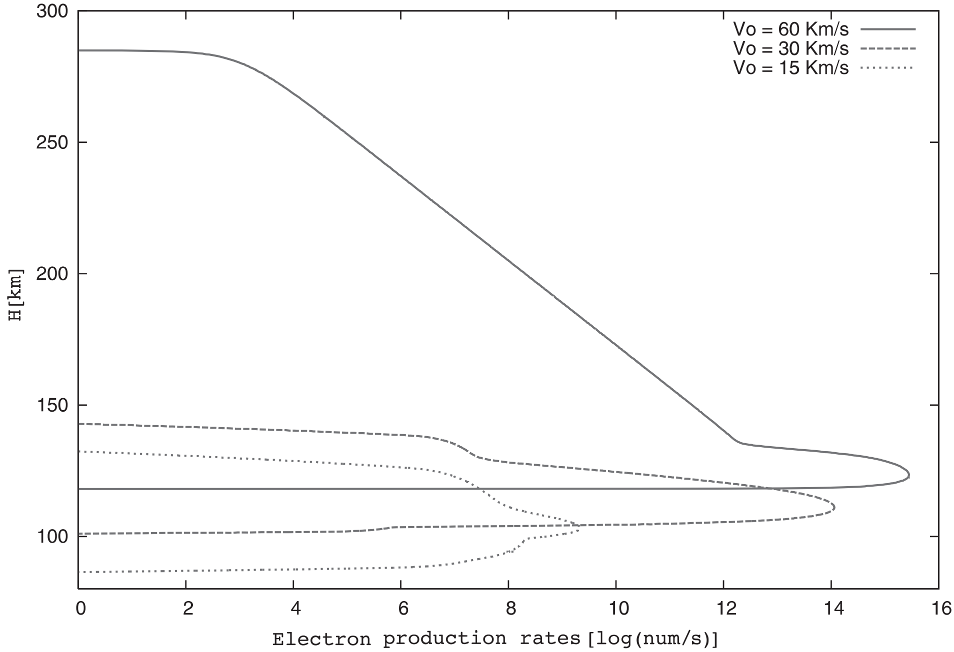

Figure 1. The altitude profile of the production rates of electrons by micrometeoroids, of initial radius 40 μm, entering the earth's atmosphere vertically, with three different initial speeds: $v_0 = 60$ km s^{-1} (corresponding to a 'fast cometary' micrometeoroid), $v_0 = 30$ km s^{-1} (corresponding to an 'average cometary' micrometeoroid) and $v_0 = 15$ km s^{-1} (corresponding to a 'slow asteroidal' micrometeoroid).

than ablation, thermionic emission dominates in the high-altitude range (∼143 km to 128 km) in the case of the micrometeoroid with an initial speed $v_0 = 30$ km s^{-1}. Electron production associated with ablation dominates below 128 km and reaches a maximum at ∼112 km when the micrometeoroid temperature has reached its maximum value (∼1544 K). As the micrometeoroid cools as it slows down (to a low terminal speed of ∼50 m s^{-1}, by which time its radius has shrunk to ∼3 μm), its temperature becomes too low for ablation. In the lowest portion of its trail where there is any electron production at all (i.e. between about 103 km and 101 km) it is entirely due to thermionic emission.

For the asteroidal micrometeoroid with $v_0 = 15$ km s^{-1}, thermionic electron emission is the dominant electron production process for most of its altitude range from turn-on at ∼132 km to turn-off at ∼85 km. Only in the narrow altitude range of about 10 km centered around 100 km does electron production by the ablation-associated process dominate. Incidentally, Mendis and Maravilla (2009) considered the case of an even slower asteroidal micrometeoroid with $v_0 = 12.5$ km s^{-1}. In that case electron emission by the thermionic process dominated over its entire altitude range from turn-on to turn-off.

The electron production profile for the fast micrometeoroid ($v_0 = 60$ km s^{-1}) is quite different, extending to much higher altitudes (≥250 km) than in the case of the lower-speed ones. This is due to sputtering, which dominates all the way down to about 132 km. Electron emission by the ablation-related process dominates only between ∼132 km and ∼120 km, by which time it has reached a temperature

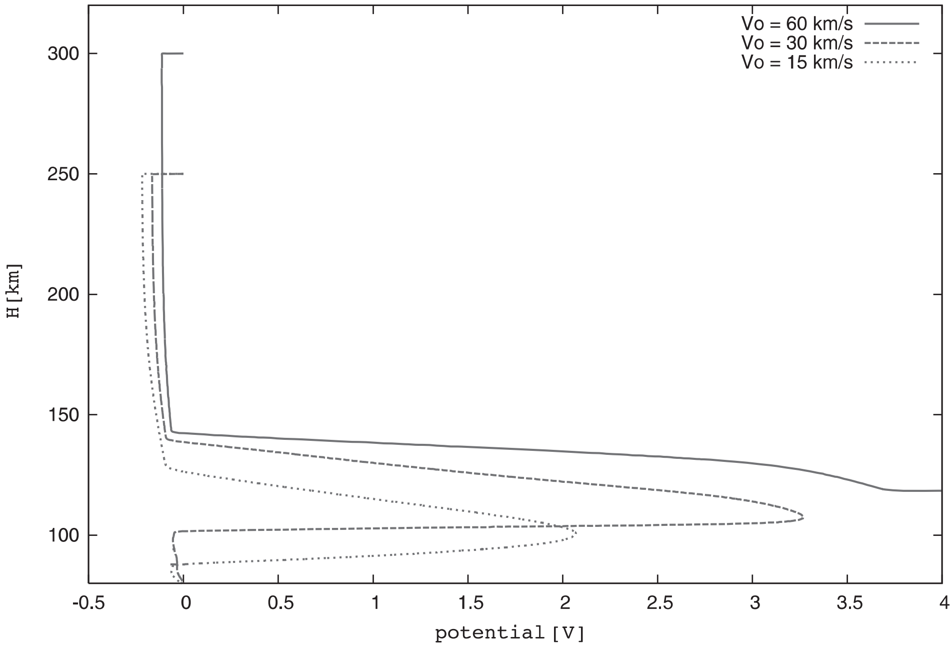

Figure 2. The altitude profiles of the electrical potential of micrometeoroids of initial radius 40 μm, entering the earth's atmosphere with three different initial speeds: $v_0 = 60$ km s^{-1}, $v_0 = 30$ km s^{-1} and $v_0 = 15$ km s^{-1}.

high enough (∼1700 K) to be completely ablated away, thereby shutting off all electron production processes simultaneously. There is some electron production by the thermionic process between about 145 km and 120 km, but it is completely dominated by the other two processes, and its signature is thus masked in the altitude profile of electron emission.

The most striking thing about these three altitude profiles for electron production in the atmosphere by the three micrometeoroids entering it at the three different speeds ($v_0 = 60$ km s^{-1}, $v_0 = 30$ km s^{-1} and $v_0 = 15$ km s^{-1}) is that they are different not just quantitatively, but also qualitatively.

5. The role of micrometeoroidal entry speed on the grain charge profile

The altitude profiles of electrostatic potential of the three micrometeoroids starting at different initial speeds are shown in Fig. 2.

The electrostatic potentials of the bodies with initial speeds of 30 km s^{-1} and 15 km s^{-1} (which are introduced to the atmosphere at an altitude of 250 km) are determined almost entirely by the plasma collection currents and the thermionic electron current, with only a small contribution by the ablation current. These bodies which begin with an arbitrary potential ($\varphi = 0$) quickly assume a small negative potential ($\varphi \approx -0.2$ V) corresponding to the electron temperature at that height. As they penetrate deeper into the increasingly dense atmosphere, they are heated by atmospheric friction, and thermionic electron emission, which depends on the grain temperature, begins to dominate and grains acquire significant positive

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potentials of a few volts. As the micrometeoroids penetrate even deeper into the atmosphere, their temperatures begin to decrease from their maximum values and eventually come into equilibrium with the radiative temperature of the atmosphere (which is the temperature of 'earth-shine' ∼200 K). At this point, their potentials (determined entirely by the ambient plasma) are very small and negative (~ -0.02 V). The reason for the temperature decrease is twofold. First, as the body decelerates due to atmospheric friction (which varies as v^2), atmospheric frictional heating (which varies as v^3) decreases. Also, as the body becomes sufficiently hot it begins to ablate and energy is utilized in this process. The reason that the potential of the fast ($v_0 = 30$ km s^{-1}) micrometeoroid decreases faster from its maximum value (∼3.3 V) and reaches a negative value higher up in the atmosphere, than the slower ($v_0 = 15$ km s^{-1}) one, is that it ablates much faster and at higher altitudes, leading to rapid ablation cooling. In fact, the ablation of the slower micrometeoroid is minimal and its eventual cooling is largely due to its slowing down by atmospheric friction.

The altitude potential of the fastest ($v_0 = 60$ km s^{-1}) micrometeoroid is seen to be rather different from those of the slower-moving ones. While it is seen to acquire a small negative potential high up in the atmosphere (soon after its injection with $\varphi = 0$) and then an increasingly positive potential as it penetrates into the lower atmosphere, the potential does not reach a maximum and turn around. The reason for this is that it reaches a high enough temperature to be completely ablated away at about ∼130 km, while the thermionic electron current is still the dominant one. So it is seen that, as in the case of electron production, the altitude profiles of electrostatic charging of the micrometeoroids entering the atmosphere at widely different speeds are different not just quantitatively, but qualitatively as well.

6. Conclusions

The central goal of this brief note has been to emphasize the differences (not just quantitative, but also qualitative) in the altitude profiles of the two electrical effects associated with different classes (defined by their initial speeds) of micrometeoroids entering our atmosphere. It was shown that their differences were a result of the different relative (altitude-dependent) importance of various physical processes, involved in both the electrical charging of the micrometeoroids and in the ionization of the atmosphere along their paths. We have emphasized the importance of two processes that have been included in meteor studies in more recent times. The first is thermionic emission, which has consequences for both effects. The second is physical sputtering from the micrometeoroids (which is important only for fast-moving ones). These sputtered molecules can then produce yet another source of electrons, even at higher altitudes, in the same way that ablated ones do at lower altitudes.

Some observational consequences of these processes have already been discussed. In particular, the role of thermionic emission has been invoked (Mendis et al. 2004) to explain the unexpected observation of a multi-layered region of fine dust (a positively charged thick upper layer and a negatively charged thin lower layer) near the tropical mesopause 30 min after local astronomical sunset (Gelinas et al. 1998). Also, a natural explanation for the observed difference between radar 'trail echoes' (associated with the electron trail left behind by the moving micrometeoroid) and the co-moving 'head echo' has been offered in terms of a thermionic electron sheath around the heated micrometeoroid (Mendis et al. 2005).

The altitude range of radar detection of meteoroids has been greatly extended by the new source of ionization associated with physical sputtering at high altitudes (Brosch et al. 2001). Indeed the qualitatively different composite altitude profiles for electron production, provided in this paper, can be used as a discriminant between the three classes of micrometeoroids (defined by initial entry speed) that we have considered.

We will conclude by pointing out that there is still a large discrepancy between the estimates of the mass influx of extraterrestrial material from radar observations and *in situ* dust measurements. A reliable understanding of the plasma production from meteoroids as functions of their mass and velocity, taking into account all relevant physical processes, is an important step toward resolving this issue. Consequently, we will need to pursue these studies further.

Acknowledgements

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