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A Debate over the Acquisition of an Electric Potential by a Meteoroid

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Abstract—The question raised in the title of this paper is considered in connection with the debate between A.P. Nevskii (1978, 1998) and A.Yu. Ol'khovatov (1997, 1998). The arguments and conclusions of the two parties of the debate are critically analyzed. It is shown that both Nevskii's conclusion about the enormous meteoroid–Earth potential differences and Ol'khovatov's opinion about their extremely low values are erroneous. A realistic estimate of the meteoroid charge and its potential relative to the Earth is given.

Recently, the problem raised in the title of this paper has been the subject of animated debate between A.P. Nevskii and A.Yu. Ol'khovatov. At the request of V.A. Bronshten, I have investigated this problem and reached the conclusions presented below.

THE COURSE AND ESSENCE OF THE DISPUTE

(1) Nevskii (1978) suggested the mechanism of electrization of a meteoroid as a result of thermionic emission due to heating during its flight through the atmosphere. Indeed, this mechanism deserves a serious analysis, but the main result, formula (22) of the above paper for the body potential

$$V = \Delta V \frac{R}{d}$$

is erroneous.

Here, ΔV is the potential difference between the body and the surrounding plasma, which is generally assumed to be neutral; R is the radius of the body or the plasma (they are close); and d is the Debye length of the plasma.

Some of Nevskii's results were uncritically perceived by Balklavs (1990) and Bronshten (1991, 2001).

(2) Ol'khovatov (1997) rightly doubted the validity of this formula, which yielded huge V. However, without discovering the true source of the error, Ol'khovatov attributed the following idea to Nevskii that the latter did not advance: the potential of a charged body increases if it is surrounded by an insulated conductor.

Having debunked the fallacy using a charged Christmas-tree decoration wrapped in insulated foil, Ol'khovatov himself made quite an ambiguous statement: $V = \Delta V$. If we scrupulously follow Ol'khovatov's analogy with Nevskii's model (the decoration is a charged meteorite, and the foil is plasma), then the potential difference between them ΔV and V are not exactly equal, by any means.

(3) Responding to Ol'khovatov's accusations that he does not understand the Gauss theorem, which solves the problem on the relationship between V and the charge Q of the entire system (body + plasma, decoration + foil), Nevskii (1998) rehabilitated himself in this respect.

In the course of the dispute, Nevskii (1998) explicitly formulated the idea that is key to the entire problem and that was implied in the paper of Nevskii (1978), if at all, in an extremely veiled form. Otherwise, Ol'khovatov would not attribute to the opponent an invented fault and, perhaps, would get to the true cause of the error. Here are these words: "if a negative charge is removed from a well-insulated body, then the body will be indefinitely charged positively…, its potential will also indefinitely increase…, reaching absolutely fantastic values".

(4) Here lies the crux of the matter. Deriving formula (22) for V, i.e., assuming that V and charge Q of the system were actually limited, Nevskii (1978) did not explicitly raise the question of the limitation mechanism. Solving the problem in terms of his model, Nevskii, of course, introduced a limitation, but did it implicitly and contrary to the nature of things; whence the incorrect result, formula (22). As regards Ol'khovatov (1997), this subject (what determines the "decoration" charge) was not touched upon at all.

Let us now get to the bottom of the problem.

WHAT IS THE ERROR OF NEVSKII?

In Nevskii's model, a meteoroid of radius R is surrounded by a postshock plasma layer and is heated by the plasma to a high electron temperature Θ. The body emits electrons with approximately the same temperature. The drop in potential $\Delta V \approx \Theta$ from the body to the plasma corresponds to the equilibrium of the electron fluxes between the body and the plasma. The drop in ΔV is assumed to occur in a sheet between the body and the plasma whose thickness is equal to the plasma Debye length d. All of the excess charge that came from the body is carried away from the plasma by the flow incident on the body. Thus, the conditionally spherical plasma sheet surrounding the body is assumed to be uncharged. Hence, according to the circuit of series-connected capacitors, "body–plasma" with plate gap d and "plasma sphere–ground," arises formula (22):

$$V = \Delta VR/d.$$

The error lies in the ungrounded and unjustified assumption that all of the potential drop between the body and the putative uncharged plasma shell occurs at a very thin sheet equal in thickness to the Debye length. This imposes a certain, very large charge Q on the "body + plasma" system, which is the source of the huge potential V. The above assumption leaves no freedom. Indeed, the field in the first capacitor is $E = \Delta V/d$, and the surface charge density on its "plates" is $q = \varepsilon_0 E$. The total positive charge on the surface of the body is

$$Q = 4\pi R^2 q = 4\pi\varepsilon_0 R^2 \Delta V/d.$$

This is the total charge of the entire "body + plasma" system, because the negative charge Q is concentrated on the plasma surface adjacent to the surface of the body and the charge Q is concentrated on the outer plasma surface. Having the positive charge Q, the system has a potential relative to the ground

$$V = Q/4\pi\varepsilon_0 R = \Delta VR/d.$$

In physical language, we deciphered the electrical circuit of the given model of series-connected capacitors with gap d between the "plates" of the first of them.

Incidentally, Nevskii explicitly formulated (not in the main paper (1978) but in the reply (1998)) the basic idea whose development led to the error: "it is plasma that provides the only mechanism of limiting the infinite increase of the potential… through… processes in the Debye sheet."

WHAT DETERMINES THE CHARGE OF THE SYSTEM?

The charge is determined neither by the internal interactions between parts of the system, as in the model of Nevskii (1978), nor by the processes at the plasma–body interface (in the Debye sheet). The charge of the system is determined by its interactions with the outside world, by how many electrons will the airflow carry away. The balance between the direct and reverse fluxes must be considered at the boundary between the entire system (i.e., plasma) and the ambient air medium rather than at the body–plasma interface.

In the absence of any flow, including convection even from the body that is strongly heated and that emits electrons, these electrons will not go far. The body will be charged to a positive potential large enough to hold around itself all of the emitted electrons. The "body + electronic shell" system will remain on the whole uncharged. In such a decoration with foil, Ol'khovatov's (1997) formula

$$V = \Delta V$$

will be valid.

The body's potential relative to the ground will be equal to the drop on the double layer, but this is not the case of a flying meteorite.

The balance between the electron fluxes at the body–plasma interface will be adjusted to the balance at the boundary with the ambient medium. The electron emission from the body will, probably, be sufficient to provide the removal of negative charge by the incident airflow.

Of course, constructing a theory replacing Nevskii's theory will require analyzing many effects; here, the difficulty with the geometry being two-dimensional will arise: a body in airflow. However, a rough estimate can be made by arbitrarily using a spherical model. Electrons are carried away from the surface of the plasma sphere; they escape forward, being more mobile than ions. Electrons are carried away by a flow with a velocity U of the order of the meteorite flight velocity. The system will lose electrons until the action of the remaining positive charge stops these losses due to the drawing of the electrons back into the system. For this purpose, the field E_s at the spherical plasma surface must provide a electron drawing velocity $\mu_e E_s$ equal to the removal velocity U (μ_e is the electron mobility).

Thus, the system's charge Q and its potential relative to the ground V are limited and determined by the condition

$$\mu_e E_s = U, \quad V = \frac{Q}{4\pi\varepsilon_0 R} = E_s R = \frac{UR}{\mu_e}.$$

This external condition transforms into the "internal" one, yielding, e.g., a distance Δx at which the plasma–body potential difference ΔV actually decreases.

Let us make a numerical estimate. Let a meteorite fly at an altitude $h = 18$ km, where the air pressure is $p = 0.1$ atm, at a velocity $U = 10$ km/s. For a rough estimate, we set $\mu_e = 10^3$ cm^2/(B c)/(V s), with an allowance made for all opposite effects: reduced pressure at altitude and shock compression and heating. Let $R = 1$ m. We obtain: $E_s = 1$ kV/cm, $V = 100$ kV, $Q = 10^{-5}$ C. If $h = 36$ km, $p = 10^{-2}$ atm, $U = 15$ km/s, we find $E_s = 10$ kV/cm, $V = 1.5$ MV, $Q = 1.5 \times 10^{-4}$ C.

IS A DISCHARGE BETWEEN A METEORITE AND THE GROUND POSSIBLE?

Ol'khovatov (1998) writes that a discharge between a meteoroid and the ground requires "a huge charge… tens or hundreds of thousands coulombs", and this "can be easily shown and was shown long ago." Whence does it follow? For instance, a lightning breaks down air at a charge of a thundercloud 15 C and a potential of

300 MV (at an effective cloud charge radius $R = 0.5$ km). For a meteoroid radius $R = 1$ m, even a charge $Q = 1$ C would produce a voltage $V = Q/(4\pi\varepsilon_0 R) = 10^4$ MV with a store of electric energy of the thundercloud. This would be quite sufficient for the spark breakdown of a multi-kilometer gap to the ground (Bazelyan and Raizer, 2001). However, the actual charge and potential of a meteorite is, probably, several orders of magnitude lower, and the possibility of a breakdown is problematic.

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