On the meteor height from forward scatter radio observations

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Abstract. It is known from theory that, by means of a plasma physics approach, it is possible to obtain a simple formula to calculate the approximate height of a meteor\textsuperscript{1} (Foschini, 1999). This formula can be used in case of forward scatter of radio waves and has the advantage that it does not depend on the diffusion coefficient. On the other hand, it is possible to apply the formula to a particular type of meteor only (overdense meteor type I), which is a small fraction of the total number observed. We have carried out a statistical analysis of several radio echoes from meteor showers recorded during last years by a radio observer located in Belgium. Results are compared and discussed with those obtained with other methods and available in literature.

Key words: meteors, meteoroids – plasmas – scattering

1. Introduction

A meteoroid enters the Earth’s atmosphere at hypersonic speed and it collides with air molecules. The high kinetic energy involved in the process determine the transformation of a solid body into a plasma, which can scatter radio waves and can emit light (meteor).

During sixties and seventies several works investigated the formation and evolution of the meteor, with particular attention to diffusion, in order to study mesospheric winds. A complete review of standard meteor science can be found in Ceplecha et al. (1998). However, there are still some aspects not well understood about the physical properties of a meteor, specifically whether it is an ionized gas or a plasma. During past years, these two appellatives were often used as synonymous in meteor physics, even though they indicate two different states of the matter. In some studies, such as those about diffusion, specific plasma properties are taken into account (e.g. ambipolar diffusion); however in other studies, such as about radiowave scattering, the meteor is simply considered a long narrow column of ionized gas.

This can appear as a futile debate, but it hides important concepts. Specifically, a plasma has collective properties (e.g. Langmuir frequency) that an ionized gas has not.

A first attempt to study the meteor as a plasma was carried out by Herlofson (1951). He investigated the proper oscillations in the meteor and their interaction with radio waves. But, at our knowledge, none continued his studies. Only in 1999 the question of collective oscillations in meteoric plasma was reprised (Foschini 1999). Perhaps, this gap may be explained by taking into account that, according to purposes of meteor astronomy, it was sufficient to use the approximation of the long narrow cylinder.

However, the meteoric plasma is something more complex than a reflecting rod and it is necessary to study it. There are several types of oscillations and instabilities, which can interact with radio waves. The scattering is not the only process: for example, fluctuations from equilibrium may lead to transformation of waves (longitudinal to transverse and vice versa). The question is: are such processes present in a meteoric plasma?

We think that the study of plasma collective oscillations may give new useful tools to understand the physics of meteors. Some basic concepts about meteoric plasma were settled in a previous paper (Foschini 1999), thereafter called Paper I. According to the theory exposed there, radio echoes can be divided into two classes and two subclasses. Then we have underdense and overdense echoes, according to whether the Langmuir frequency is higher or lower than the radio wave frequency. Overdense echoes totally reflect electromagnetic waves, but the presence of binary collisions among ions and electrons weaken the collective oscillations of the plasma, allowing the propagation of the waves, even though with strong attenuation. Therefore, we can divide the overdense echoes into two subclasses: type I, when there is total reflection; type II, when binary collisions allow the propagation. The division be-

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between overdense type I and II depends on the electron–ion collision frequency, which in turn depends on electron density and ion cross section. In Paper I, for the sake of simplicity, we considered potassium ion, that is the chemical element with lower ionization energy. In addition, recent studies show that potassium seems to be much more important in the evolution of meteor than previously thought. This is because it has a lower ionization energy compared to other elements. But the calculation of particle distribution and evolution in a meteoric plasma will be object of other papers.

The overdense type I echoes derive from total reflection of radio waves (see Fig. 1 for an example). This allows us to calculate the height of the meteor in an easy way, as shown in the Paper I. Here we want to present a statistical sample of several meteor showers, for which we have calculated the height. Data will be discussed and compared with available data in literature.

2. A simple formula for meteor height

We shortly recall how to calculate the meteor height, as described in Paper I. First, we have to take into account that the plasma has not a definite boundary and then, the incident electromagnetic wave penetrates a little into it before reaching the density necessary to allow total reflection. We can consider this something similar to skin effect in metals.

We can consider a simple geometry, as shown in Fig. 6 of Paper I, and then use the definition of the attenuation $a$ in decibel units:

$$ a = 10 \cdot \log \frac{|E_i|^2}{|E_r|^2} \ [\text{dB}] \ (1) $$

where subscripts $i$ and $r$ stand for incident and reflected wave.

From the solution of Maxwell’s equations we obtain that, for overdense meteors type I, the electric field is:

$$ E = E_0 e^{i(k \cdot r - \omega t)} \ (2) $$

where the wave vector in Eq. (2) has the form:

$$ k = \beta + i\alpha \ (3) $$

We refer to Paper I for explanation of symbols, even though they are commonly used in literature about electromagnetic fields.

We substitute Eqs. (2) and (3) in Eq. (1) and, taking into account that the amplitude of a totally reflected wave is equal to the amplitude of the incident wave, we can obtain an attenuation value of about $a = -20 \alpha \log e$, where $l$ is the path of the wave into the plasma:

$$ l = \frac{2\delta}{\cos \phi} \ (4) $$

where $\phi$ is the incidence angle and $\delta = 1/\alpha$ is the penetration depth. Then, Eq. (1) becomes:

$$ a = \frac{-40 \log e}{\cos \phi} \approx -17.36 \frac{e}{\cos \phi} = -17.36 \sec \phi \ [\text{dB}] \ (5) $$

In the case of overdense type I (total reflection) the attenuation is simply a function of the angle of incidence.

The Eq. (1) refers to an idealized case. When we deal with real meteors and radio waves, we have to take into account of several factors, i.e. antenna gains, losses in radio receiver and transmitter, atmospheric absorption, and the distance of reflecting point from transmitter and receiver. Strictly speaking, Eq. (1) can be considered as the “meteor cross section” in the radar equation.

We can consider common factors in radar theory, as described in Kingsley & Quegan (1992). By means of commonly used values for forward scatter radar, we obtain that the attenuation recorded with our receiver is:

$$ a = 20 \log V_R - 2 \ [\text{dB}] \ (6) $$

where $V_R$ is the received signal amplitude [V]. From the amplitude of the reflected wave, we can calculate the incidence angle with the Eq. (5).

Therefore, we can calculate the meteor height by considering the geometry of Fig. 3. We can see that:

$$ q_1 = \frac{L}{2 \tan \phi} - q_2 \ (7) $$

Taking into account that the Earth’s mean radius $R_\oplus$ is much larger than $L$, we can calculate $q_2$:

$$ q_2 = R_\oplus - q_3 = R_\oplus - \sqrt{R_\oplus^2 - (L/2)^2} \approx \frac{L^2}{8R_\oplus} \ (8) $$

$\therefore$
By substituting Eq. (8) in Eq. (7), we obtain the height of the reflection for an overdense meteor type I:

\[ q_1 \approx \frac{L}{2} \left( \frac{1}{\tan \phi} - \frac{L}{4R_S} \right) \]  

(9)

where \( L = 2R_S \sin \alpha \). The angle \( \alpha \) is the half angular distance between receiver and transmitter.

The distance \( L/2 \) plays an important role in the derivation of the above formula. Indeed, from a geometric point of view, the specular reflection in a forward scatter system occurs when the meteor trail lies along a tangent to an ellipsoidal surface, with the transmitter and the receiver stations in foci (Forsyth & Vogan 1955). This condition is fulfilled by different values of distances of the reflecting point from the source and from the receiver. If we do not know the path source–meteor–receiver, this introduces an uncertainty of about 40 km in the height of the reflecting point (for our system).

One way to overcome this problem is to set up a third station, but if it is not possible, as in our case, we can reduce uncertainties by making heuristic considerations. Indeed, as explained by Forsyth & Vogan (1955), the forward scatter system is most sensitive to meteor trails which are nearly horizontal and directed along the transmission line. A meteor perpendicular to the source–receiver line gives an echo that is about five times lower than the case of parallel direction (Forsyth & Vogan 1955). Therefore, the choice of the reflecting point located closely to the middle of the transmission path appears to be reasonable and, as we shall see, is justified by facts.
not centered, but are located toward right. However, this seems to be an effect due to a low number of data. Indeed, the best fit for the observations, calculated with the $\chi^2$ test, is a gaussian distribution (therefore $\sigma$ is calculated with standard methods for this type of distribution). In Table 2 values of mean speed (Allen [1973] and height of overdense I meteor are shown.

4. Analysis and discussion

Data obtained here show that the mean height is independent from the entry speed of the meteoroids (see Table 2). On the other hand, it is known that the height depends on entry speed of meteoroids: for example, Greenhow & Lovell [1960] wrote that the highest speed sporadic meteors, moving at 60–70 km/s, ionize at a mean height of 100 km, whereas those with minimum speed (11.2 km/s) reach a mean height of 85 km.

The theory of radio meteor height was elaborated by Kaiser [1954a, b] and recently Belkovich et al. [1999] proposed some changes, in order to take into account the fragmentation. Kaiser found that the width of the height distribution depends on the atmospheric scale height and the mass distribution of incoming meteoroids. The mean height depends strongly on meteor speed, through two coefficients named $k_1$ and $k_2$, and depends also on the probability of ionization. Kaiser’s theory refers to the point of maximum ionization, but it is known that in experimental radio observations the height of reflecting point does not necessarily lie in the point of maximum ionization (Greenhow & Lovell [1960]).

If we observe a meteor shower with a given mean speed and mass distribution, the height distribution is related to the length of ionization curve. The point of maximum ionization corresponds to the most probable height. It is worth noting that Kaiser’s theory refers to underdense meteors. Only McKinley [1961] referred to overdense meteors and found no clear dependence on speed. Moreover, he found a two peaks distribution: the main peak is located at about 95 km, and the second one at 106 km.

We can try to explain the differences between our results and data available in literature. The first reason is that we try to analyse overdense meteors, while the large part of published data refer to underdense meteors. It is very interesting to note that for bright meteors, which are surely overdense, the radio height of maximum echo duration is well above the mean height of maximum light,
obtained from photographic data (Millman & McKinley 1963). On the other hand, the situation is reversed for faint meteors.

The reason for this difference is that overdense type I meteors reflect totally the incoming electromagnetic wave. Total reflection is allowed only when plasma frequency is higher than the radio frequency and the collision frequency in the plasma is negligible (see Paper I). These conditions are achieved independently from speed of incoming of meteoroid, but it depends on the mass and chemical composition of the body. Once an overdense type I meteor is created, the signal amplitude of the reflected wave remains constant until the collision frequency in the plasma or recombination and attachment processes subtract energy to the plasma frequency. We can say that collective properties of the plasma, which generate the long plateau of overdense type I meteor, “hide” in some way some properties of the incoming meteoroid.

Concerning the two peaks found by McKinley (1961), we note that our distributions show only the secondary peak. This can be explained by taking into account that while McKinley made no distinction between overdense meteors, we have considered only overdense type I meteors.

5. Concluding remarks

We have carried out an analysis of several overdense radio echoes, recorded during last years by a radio observer located in Belgium. We have analysed a particular class of overdense meteors (type I) and measured height distributions are in good agreement with previous results obtained by McKinley (1961), even though only for the secondary peak. We suppose that the first peak in McKinley’s work should be due to overdense type II meteors, while the secondary peak, recorded also by our system, appeared to be due to overdense type I meteors.

We think that collective properties of the meteoric plasma (Langmuir oscillations) hide some characteristics of the originary cosmic body, specifically there is no clear dependence on speed. Further study, mainly theoretical and able to take into account collective properties of plasma, are required to assess the particle dynamics in the meteor.

It should be noted that our studies were carried out with an amateur forward scatter system and we have no full control on it. Moreover, heuristic considerations were introduced in order to minimize uncertainties, but results showed that they were justified by facts. The agreement with previous works, with other techniques, supports our conclusions. The future availability of a full forward scatter system would be of great help in more detailed studies.

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