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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 (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. The 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 the sixties and seventies several studies 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 the past years, these two terms were often used as synonymous in meteor physics, even though they indicate two different states of 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, to our knowledge, no one continued his studies. Only in 1999 the question of collective oscillations in meteoric plasma was taken up again (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. 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 useful new 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 weakens 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, where there is total reflection; type II, where binary collisions allow the propagation. The division 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 the potassium ion, which is the chemical element with the lowest ionization energy. In addition, recent studies show that potassium seems to be much more important in the evolution of meteors than previ-

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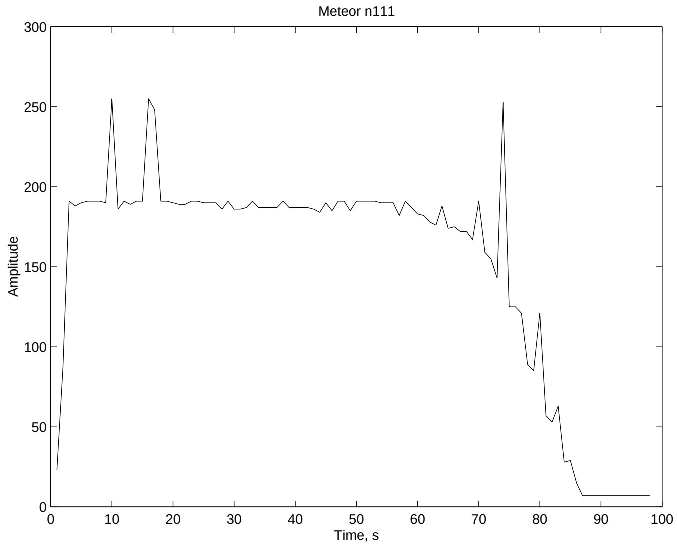

Fig. 1. Example of overdense type I echo.

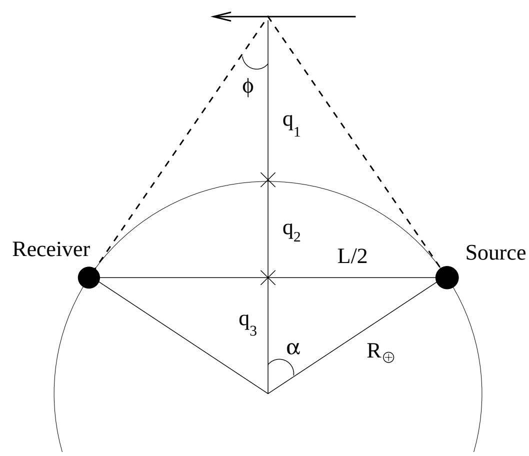

Fig. 2. Forward–scatter reflection geometry and height calculation (plot not in scale)

ously thought (von Zahn et al. 1999). With this assumption, the division between overdense echoes occurs at about 10^{17} m^{-3}. It is worth noting that this boundary can be moved by considering other elements. But the calculation of particle distribution and evolution in a meteoric plasma will be the 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 Paper I. Here we want to present a statistical sample of several meteor showers, for which we have calculated the height. The data will be discussed and compared with available data in literature.

2. A simple formula for meteor height

We recall briefly how to calculate the meteor height, as described in Paper I. First, we have to take into account that the plasma does not have 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 the 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:

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

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:

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

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

$$\boldsymbol{k} = \boldsymbol{\beta} + i\boldsymbol{\alpha} \quad (3)$$

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 $a = -20\alpha l \log e$, where l is the path of the wave into the plasma:

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

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

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

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

The Eq. (5) 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 trasmitter and receiver. Strictly speaking, Eq. (5) 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:

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

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

Therefore, we can calculate the meteor height by considering the geometry of Fig. 2. We can see that:

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

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

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

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

$$q_1 \approx \frac{L}{2}\left(\frac{1}{\tan\phi} - \frac{L}{4R_\oplus}\right) \quad (9)$$

where $L = 2R_\oplus \sin\alpha$. The angle α 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 the foci (Forsyth & Vogan 1955). This condition is fulfilled at 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 in 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.

3. Observations

The general principle of meteor observation by forward scattering of radio waves is the following: a VHF radio receiver (30–100 MHz) is located at a large distance (about 600–2000 km) from a transmitter at the same frequency. Direct radio communication is not possible, owing to the Earth's curvature, but the meteor allows the communication over the horizon, by reflecting the transmitted signal.

In this study, observations were carried out mainly by M. de Meyere. His radio receiver is located in Deurle, Belgium (longitude $3°37'$ E, latitude $51°00'$ N), while the transmitter is located in Sofia (Bulgary). It transmits radio signals at 66.50 MHz all through the day with 10 kW power. In this case, values of L and α are, respectively, 1751 km and $7.9°$.

The receiving station consists of a crossed Yagi antenna (4 elements), that is linked to a computer with a digital acquisition interface (150 samples per second, 8 bit resolution). Data are recorded and stored into a file.

Observations of several meteor shower were carried out during several years (see Table 1), with the total number of meteors recorded equal to 13401. The overdense I meteors are 131 (about 1% of the total) and the height distribution for analysed showers are shown in Figs. 3–6 (each bin is 1 km wide).

Table 1. Observed meteor showers. In the last column, the percentage indicates the number of overdense meteors type I compared with the total number of recorded meteors.

Shower	Years	Over. I meteor
Geminids	96-97	26 (1.1%)
Leonids	94-95-96-97-99	44 (0.6%)
Lyrids	95-96-97	41 (1.9%)
Quadrantids	95-98	20 (1.2%)

Table 2. Mean speed and height of overdense I meteor from several meteor showers.

Shower	V, km s^{-1}	$\bar{q}_1 \pm \sigma$, km
Geminids	36	101 ± 4
Leonids	72	101 ± 8
Lyrids	47	101 ± 6
Quadrantids	43	103 ± 3

Values in Table 1 refer to all echoes recorded during shower days. In order to evaluate also the sporadic background, we have analysed some days in February, without any shower. We have found a mean value for sporadic overdense type I meteors of about 0.2 meteor per hour, so that the contribution of the background can be considered negligible.

Measured heights are in the range between 70 and 110 km, in good agreement with typical meteor heights (60–110 km), even though a large part of meteors are in the range 95–110 km. The peaks of the distributions are not centered, but are located towards the right. However, this seems to be an effect due to the low number of data. Indeed, the best fit for the observations, calculated with the χ^2 test, is a gaussian distribution (therefore σ 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^{-1}, ionize at a mean height of 100 km, whereas those with minimum speed (11.2 km s^{-1}) 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 experi-

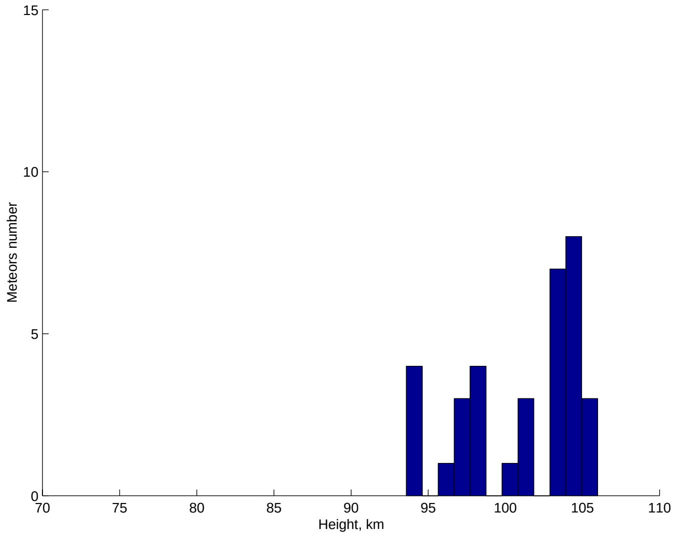

Fig. 3. Height distribution for Geminids meteor shower.

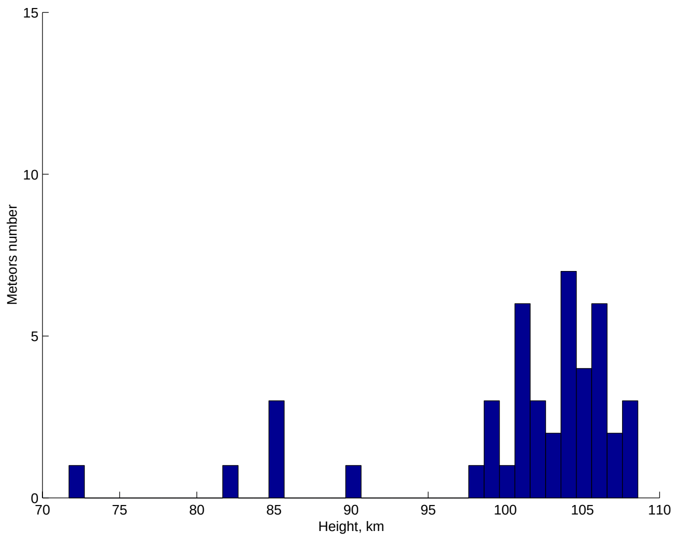

Fig. 4. Height distribution for Leonids meteor shower.

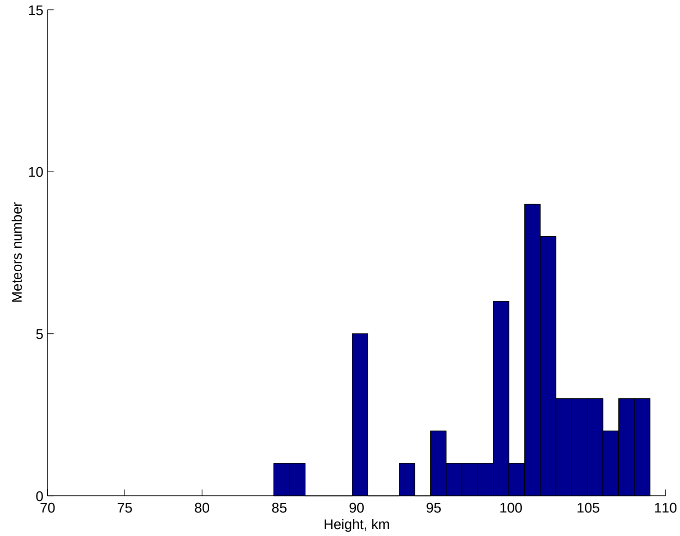

Fig. 5. Height distribution for Lyrids meteor shower.

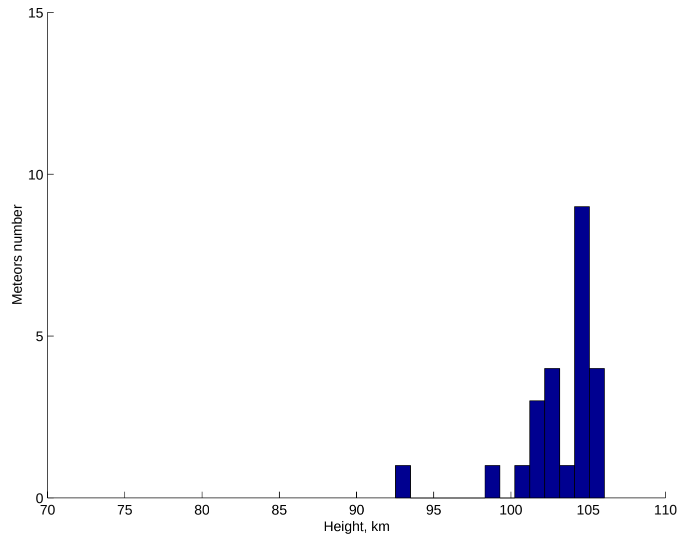

Fig. 6. Height distribution for Quadrantids meteor shower.

mental 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-peak distribution: the main peak is located at about 95 km, and the second at 106 km.

We can try to explain the differences between our results and the data available in literature. The first reason is that we try to analyse overdense meteors, while the majority of published data refers 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 independent of 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 the 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 the last years by a radio observer located in Belgium. We have analysed a particular class of overdense meteors (type I) and the 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 studies, 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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