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ASTRONOMY AND ASTROPHYSICS

On the interaction of radio waves with meteoric plasma

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Abstract. In this paper, a meteoric plasma is analyzed from a physical viewpoint, with particular emphasis on its interaction with radio waves. The attention is drawn to some macroscopic characteristics of a meteoric plasma and it is shown that the electron–ion collision frequency is not negligible, as commonly thought.

Key words: scattering – plasmas – meteors, meteoroids

1. Introduction

When meteoroids enter the Earth's atmosphere, they create long and narrow trails of ionized gas, which can scatter radio waves. The meteor radio echo theory finds its roots in studies of the ionosphere made toward the end of the twenties (Skellet 1931). But only after the Second World War, and the development of military radar, the correlation between radio echoes and meteor trails became clear (Hey & Stewart 1946). The first experiments explicitly devoted to meteor studies were carried out by Pierce (1947), who observed Draconids during the night of 9 to 10 October 1946.

The first theories on the interaction of radio waves with meteors were due to Lovell & Clegg (1948), Kaiser & Closs (1952), Herlofson (1951). Thereafter, between 1950 and 1960, a lot of efforts in this field were undertaken, but after 1960 the interest quickly decayed. The state of knowledge was well exposed in a classical paper by Sugar (1964) and the book by McKinley (1961). Toward the end of the eighties, the advent of digital technology renewed the interest in forward–scattering as a useful tool for communication channels over the horizon (see Weitzen & Ralston 1988). Today, meteor radars are widely used, even by amateur astronomers, because of low cost (Jenniskens et al. 1997, Yrjölä & Jenniskens 1998).

Actually, the two main theories for radio echoes are due to Poulter & Baggaley (1977), who deal with back–scattering, and Jones & Jones (1990a, 1990b, 1991), who deal with forward–scattering. We can note that both theories *do not consider the meteor as a plasma*, but as a simply ionized gas, with a negligible collision frequency. This is an assumption quite common in work on radio echoes from meteors, except for Herlofson (1951), who first considered the meteor as a plasma.

Concerning the difference between back–scattering and forward–scattering, it is worth noting that the two systems use different types of radio waves. A forward–scattering radar uses a continuous sine wave, while a back–scattering one uses a pulsed wave. This influences the mathematical approach to the problem, but also physical theories. The pulse shape of the back–scattering radar can be represented by a sum of several components with different frequencies. It follows that, during the propagation, the various components tend to change phase with respect to one another, which leads to a change in shape of the pulse. The dispersion relation thus depends on the frequency and can be expressed in a Taylor series. A detailed treatment of the pulse propagation in dielectrics is not the subject of this paper: the interested reader can find useful mathematical tools in, for example, Oughstun & Sherman (1997). Here we want only to underline that we cannot simply consider the signal emitted by a back–scattering radar as sinusoidal: thus, the extension of the back–scattering echo theory to forward–scattering is not correct.

The purpose of this paper is to settle some basic concepts in meteor physics and we leave a "cook–book" approach to other articles. The interaction of sine waves (for the sake of simplicity) in the radio frequency range with meteoric plasma is investigated. We will see that the common assumption about meteors as a collisionless ionized gas does not have any physical ground.

2. Meteoric plasma

As a meteoroid enters the Earth's atmosphere, it collides with air molecules. At the heights where most meteors ablate, the mean free path of the air molecules is about $0.1-1$ m. On the other hand, common meteoroid dimensions are of the order of $10^{-3}-10^{-2}$ m. This means that there is no hydrodynamic flow around the meteoroid and single air molecules impact on the body. If we consider a meteoroid at a typical geocentric speed of 40 km/s, it can be found that air molecules impinge on the body with the same speed. The kinetic energy is about $1.3\cdot10^{-18}$ J (8 eV) per nucleon: a nitrogen molecule then has an energy of about $3.7\cdot10^{-17}$ J or 230 eV. The impact energy is readily transformed into heat, which makes atoms evaporate from the meteoroid. The collisions between free atoms and air molecules produce heat, light and ionization, i.e. a meteor. Since this transformation occurs throughout the flight, the meteoroid atoms are dispersed in a cylindrical channel along the path. The electron line density is proportional to initial mass of the meteoroid, because the air mass involved is negligible when compared to the meteoroid mass.

After the escape, the first collisions of meteoroid atoms with air molecules take place at a distance of about one mean free path from the meteoroid path. It is useful to consider only the first collision to be important for ionization. This explains why the radio echo quickly rises to maximum amplitude and then slowly decays. At the moment of creation, all electrons are thus located inside a cylinder with a radius of about one mean free path.

It is possible to calculate the Debye length, a parameter that allows us to establish if the meteor is a plasma or simply an ionized gas. If the Debye length is small when compared with meteor characteristic dimensions, then it is possible to speak of *plasma*, i.e. a gas where the electrostatic energy exceeds the thermal energy. In this case, if the thermal energy produces deviations from charge neutrality, a strong electric field arises in order to restore the charge neutrality. On the other hand, if the meteor characteristic dimensions are small compared to the Debye length, this means that the thermal energy exceeds the electrostatic energy and there is no charge neutrality. In this case we have a simple ionized gas and we cannot speak of a plasma. It is important to underline the difference between a plasma and an ionized gas: a plasma has some macroscopic properties, such as the Langmuir frequency, which are absent in ionized gas.

As known, the Debye length is obtained by equating the thermal energy to the electrostatic energy and equals (see Mitchner & Kruger 1973):

$$\lambda_D = \sqrt{\frac{\epsilon_0 kT}{n_e e^2}}\ [\mathrm{m}] \qquad (1)$$

where ϵ_0 [F$\cdot$ m^{-1}] is the vacuum dielectric constant, k [J$\cdot$ K^{-1}] the Boltzmann constant, e [C] the elementary electric charge, T [K] the temperature and n_e [m^{-3}] the electron volume density. For the sake of simplicity, in this paper, the electron volume density is used, although in radar studies on meteors the electron line density is used. However, it is easy to obtain the electron line density noting that the meteor trail is like a long circular cylinder.

Common radio meteors are characterized by electron volume densities between 10^{11} m^{-3} and about 10^{20} m^{-3} (Sugar 1964) and temperatures between 1000 and 5000 K (Bronshten 1983, Borovička 1993, Borovička & Zamorano 1995). By substituting these values in Eq. (1) it is possible to calculate the maximum value of the Debye length, which is about 0.01 m. Comparing it to the lower value of the meteor initial radius (0.1 m), *it is possible to say that the meteor is a plasma and not an ionized gas*.

Since any slight distortion of the plasma from a condition of electrical neutrality gives rise to strong restoring forces, we have to consider how fast these forces act. Writing the equation of motion for the electrons, it is possible to find that they oscillate

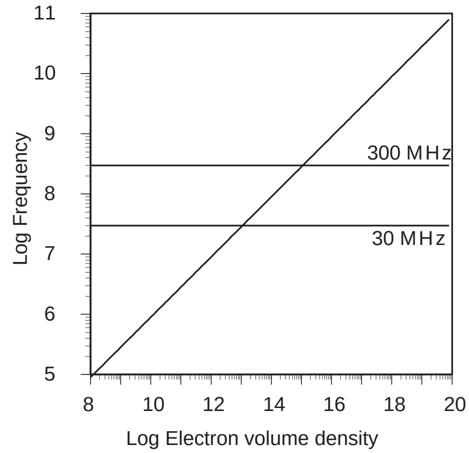

Fig. 1. Plasma frequency as a function of electron volume density. Typical radar frequencies are also shown for comparison. SI units are used.

with a characteristic angular frequency (see Mitchner & Kruger 1973):

$$\omega_p = \sqrt{\frac{n_e e^2}{\epsilon_0 m_e}}\ [\mathrm{s}^{-1}] \qquad (2)$$

where m_e [kg] is the electron mass. It is possible to calculate Eq. (2) for any type of charged particle, but as electrons move faster than ions, they give the main contribution to plasma frequency and other contributions can be neglected. The characteristic angular frequency is often called the Langmuir frequency.

Now, it is possible to understand the different behaviour of radio echoes. Already Kaiser & Closs (1952) noted a different behaviour of meteors due to electron line density. They introduced the names *underdense* and *overdense* to characterize meteors with electron line densities, respectively, below or above the value $2.4 \cdot 10^{14}$ m^{-1}. In underdense meteors, the electron density is sufficiently weak to allow the incident wave to propagate along the ionized gas and the scattering is done independently by each individual electron. On the other hand, when the meteor is overdense, the electron density is sufficient to reflect totally the incident wave. It has been usual to resort to a simple model in which the trail is regarded as a totally reflecting cylinder.

Now, comparing the electromagnetic wave frequency to the plasma frequency (Fig. 1) we can distinguish two regions depending on whether the plasma frequency is higher or lower than the radar frequency. In the first case, the charges in the plasma have sufficient time to rearrange themselves so as to shield the interior of the plasma from the electromagnetic field (overdense meteor). In the second case, since the radar frequency is higher than the plasma frequency, the incident wave can propagate along the plasma (underdense meteor). Moreover, space charges can appear.

Thus, a first method to distinguish underdense from overdense meteors, is by equating plasma frequency to radar frequency. We stress that this is valid for forward–scattering radar, which uses continuous waves, while back–scattering radar sees the meteors in a different way, because it uses short pulses.

3. General equations

In a plasma the magnetic induction $\boldsymbol{B}$ and the magnetic field strenght $\boldsymbol{H}$ are almost always treated by the same relationship as in free space. In order to account for polarizability associated with bound electrons of neutral particles and ions, it is necessary to calculate the dielectric constant of the plasma. However it is possible to see that, in the radar frequency range, the contribution due to polarizability is negligible. Then, the relation between the electric field strenght $\boldsymbol{E}$ and electric induction $\boldsymbol{D}$ can also be treated as in free space. The generalized Ohm law serves to relate $\boldsymbol{J}$ and $\boldsymbol{E}$:

$$\boldsymbol{J} = \sigma \boldsymbol{E} = \frac{n_e e^2}{m_e(\nu - i\omega)} \boldsymbol{E} \tag{3}$$

where ν [s^{-1}] is the mean collision frequency and σ [S$\cdot$ m^{-1}] is the electric conductivity. The meteoric plasma can be considered an isotropic medium since the electron gyrofrequency is much less than the radio wave frequency and thus the effect of the geomagnetic field can be neglected.

As stressed in Sect. 1, forward–scattering radars use continuous waves: taking into account that the time dependence of the electromagnetic field is $e^{-i\omega t}$, and using basic equations and standard identities, it is possible to combine Maxwell's equations in the following form:

$$\nabla^2 \boldsymbol{E} + (\omega^2 \mu_0 \epsilon_0 + i\omega\mu_0\sigma)\boldsymbol{E} = \nabla(\nabla \cdot \boldsymbol{E}) \tag{4}$$

$$\nabla^2 \boldsymbol{H} + (\omega^2 \mu_0 \epsilon_0 + i\omega\mu_0\sigma)\boldsymbol{H} = \nabla(\sigma - i\omega\epsilon_0) \times \boldsymbol{E} \tag{5}$$

These are equations for the electric and magnetic fields in a meteoric plasma. It must be noted that Eqs. (4) and (5) are useful in the underdense region, where there are space charges. On the other hand, in the overdense region, when the plasma frequency is higher than the radar frequency, charge neutrality is present and then the right side term of Eq. (4) vanishes, according to Gauss'law, when the net charge density is zero:

$$\nabla^2 \boldsymbol{E} + (\omega^2 \mu_0 \epsilon_0 + i\omega\mu_0\sigma)\boldsymbol{E} = 0 \tag{6}$$

The solutions of Eq. (6) are nonuniform harmonic plane waves of this type:

$$\boldsymbol{E} = \boldsymbol{E_0} e^{i(\boldsymbol{k}\cdot\boldsymbol{r} - \omega t)} \tag{7}$$

where the wave vector in Eq. (7) has the form:

$$\boldsymbol{k} = \boldsymbol{\beta} + i\boldsymbol{\alpha} \tag{8}$$

The two real vectors $\boldsymbol{\beta}$ and $\boldsymbol{\alpha}$ generally point in different directions. If we substitute Eqs. (7) and (8) in Eq. (6), it is possible to find that:

$$k^2 = \omega^2 \mu_0 \epsilon_0 + i\omega\mu_0\sigma \tag{9}$$

Taking into account Eqs. (2) and (3) and recalling that $\mu_0\epsilon_0 = c^{-2}$ (c: light velocity in vacuum), it is possible to rearrange Eq. (9):

$$k^2 = \frac{\omega^2}{c^2}\left\{1 - \frac{(\frac{\omega_p}{\omega})^2}{1 + (\frac{\nu}{\omega})^2} + i\left[\frac{(\frac{\omega_p}{\omega})^2(\frac{\nu}{\omega})}{1 + (\frac{\nu}{\omega})^2}\right]\right\}$$

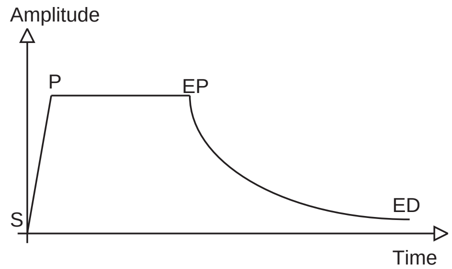

Fig. 2. Typical radio echo from a meteor trail. The dimensions are exaggerated. For an explanation of symbols, see text (Sect. 4).

$$= \frac{\omega^2}{c^2}(\kappa_R + i\kappa_I) \tag{10}$$

The quantity $\kappa = \kappa_R + i\kappa_I$ is often identified as the *complex dielectric constant* for the medium. From Eqs. (8) and (10), when vectors $\boldsymbol{\beta}$ and $\boldsymbol{\alpha}$ point to the same direction, it is possible to define the real numbers α and β as the *attenuation* and *phase* constants respectively:

$$\alpha = \frac{\omega}{c}\sqrt{\frac{|\kappa| - \kappa_R}{2}} \tag{11}$$

$$\beta = \frac{\omega}{c}\sqrt{\frac{|\kappa| + \kappa_R}{2}} \tag{12}$$

If the collision frequency is negligible, i.e. $\nu << \omega$, then Eq. (10) can be reduced to:

$$k^2 = \frac{\omega^2}{c^2}\left\{1 - (\frac{\omega_p}{\omega})^2\right\} \tag{13}$$

that is, the equation used until now. If $\omega > \omega_p$, then k is a real number and the incident wave propagates without attenuation. On the other hand, if $\omega < \omega_p$, then k is a purely imaginary number and the incident wave is totally reflected.

4. Collision frequency

In all work on the theory of radio echoes from meteor trails, the collision frequency is considered 2 or 3 orders of magnitude lower than the radar frequency (a detailed analysis of past radio echo theories can be found in Foschini 1997). This is the typical collision frequency of electrons with air molecules at the heights where meteors ablate. Work on collisions in meteor trails generally deals with ionization and excitation, in order to know processes during trail formation (Massey & Sida 1955, Sida 1969, Baggaley 1980). Other authors are interested in diffusion and thus study attachment, recombination and other chemical reactions between the atmosphere and meteoric plasma (Baggaley 1972, Baggaley & Cummack 1974, Baggaley 1980, Jones & Jones 1990c). In Fig. 2 a typical overdense radio echo from a meteor trail is plotted. When the "flat top" (P–EP) is reduced to zero, we have an underdense echo. Collision processes during the trail formation (from Start to Peak, S–P) are ionization and excitation, caused by air molecules impinging on the meteoroid. During echo decay, from End Peak (EP) to End Decay (ED), attachment and recombination are dominant processes, owing to the diffusion of the plasma in the surrounding atmosphere. During the *plateau* (P–EP) the trail can be considered in *local thermodynamic equilibrium*, when matter is in equilibrium with itself, but not with photons (Mitchner & Kruger 1973). The plasma in the trail is transparent to radiation at some optical frequencies, which escapes from the meteor and forms the light we observe.

For a plasma in local thermodynamic equilibrium it is still possible to employ the Boltzmann and Saha equations (see Mitchner & Kruger 1973), even though complete thermodynamic equilibrium does not prevail. Now, thermal ionization becomes the main process and metals, with low ionization energy, drive this phase. It must be noted that in meteoroids there are some few per cent of alkaline and alkaline–earth metals, such as Na, K, Ca and Mg. These data are obtained from studies on meteorites (Mason 1971, Millman 1976, Wasson 1985) and on bright fireball spectra (Bronshten 1983, Borovička 1993, Borovička & Zamorano 1995). Because of their low ionization energy, at typical radar meteor temperatures (1000–5000 K), these metals easily ionize and thus, they are the main contributors to thermal ionization. A small percentage of one of these metals suffices to produce a huge amount of electrons.

In the calculation of collision frequency of electrons with other particles, it must be taken into account that, because of the electrostatic field, ions have a cross section larger than that of atoms and molecules. Thus, electron–ion collisions must be considered, and not electron–air molecule collisions, since the former are more frequent than any other.

Moreover, in calculating the electron–ion collision frequency we have considered potassium, because it has a low ionization energy (4.34 eV). This choice could be questionable because potassium is scarcely present in meteor spectra (Bronshten 1983) or even absent (Borovička 1993, Borovička & Zamorano 1995). However, this metal is present in almost all meteoritic specimens (Mason 1971) and other studies on meteor showers have reported its presence. Specifically Goldberg & Aikin (1973), using a rocket–borne ion mass spectrometer, detected the presence of potassium ion in β–Taurids. The absence of potassium in meteor spectra is due to the low efficiency of light emission processes in this type of atom: it is well known that the most intense spectral line of potassium is in the infrared range (766.49 nm). It is worth noting that also iron and sodium, two of the commonest elements in meteor spectra, could be absent in some cases (see Millman 1976). Therefore, we can consider a potassium percentage of about 1% of meteoroid mass.

It is very difficult to find experimental values for electron–ion collision cross sections of various species, in the temperature range of meteors. Experimental studies are mainly devoted to excitation and ionization cross sections, in order to compare results with data from spectra (Neff 1964, Boitnott & Savage 1970, 1971, 1972, Savage & Boitnott 1971). Rosa (1987) gives collision cross sections of K, K^+ and some atmospheric gases, such as O_2, in the temperature range from 2000 K to 3500 K. It is important to note that the K^+ cross section is about 3 (*three*) orders of magnitude larger than those of other species.

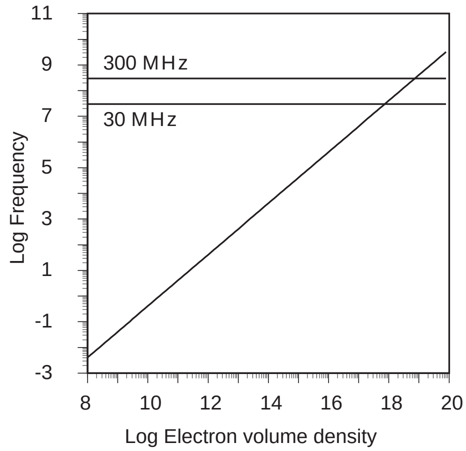

Fig. 3. Electron–potassium ions collision frequency as a function of electron density. Temperature 3000 K. Typical radar frequencies are also shown for comparison.

We have further supposed that only a single ionization is possible, i.e. we have a reaction such as:

$$K \leftrightarrow K^+ + e^- \qquad (14)$$

We would like to stress that we are only interested in the analysis of meteoric plasma in a steady state condition (during the *plateau*) and we do not actually consider echo decay (recombination and other chemical processes) or trail formation (collisional ionization and excitation). Thus, it is possible to use a simplified model of collision frequency (Mitchner & Kruger 1973), viz.:

$$\nu_{ei} = n_i v_{ei} Q_{ei} \qquad (15)$$

where Q_{ei} is the electron–ion collision cross section and v_{ei} is the electron mean velocity with respect to ions (it is assumed to be about equal to the electron mean thermal velocity), and n_i is the ion volume density. In our case, owing to Eq. (14), $n_i = n_e$.

Now, it is possible to observe that ν_{ei} cannot be negligible anymore, especially for a high electron volume density (Fig. 3). If we consider the contributions of other species, it is necessary to sum the various collision frequencies obtained using Eq. (15).

Now, in the overdense regime, we have to consider the dispersion relation in Eq. (10) and not in Eq. (13). It is worth noting that Eq. (13) is still valid in the underdense regime because only at high electron densities are the collisions not negligible.

5. Forward–scatter of radio waves from meteoric plasma

It is possible to define, from Eq. (10), a *critical electron density* in order to separate the underdense from the overdense regime and this occurs when:

$$1 - \frac{(\frac{\omega_p}{\omega})^2}{1 + (\frac{\nu}{\omega})^2} = 0 \qquad (16)$$

As an example, we can assume a mean temperature of 3000 K. If we consider the CNR radar facility (Cevolani et al. 1995), which has a radar frequency of

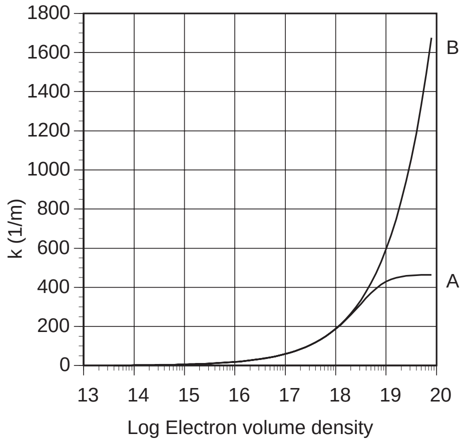

Fig. 4. Wave vector modulus as a function of electron density above critical value. Temperature 3000 K; Radar frequency 42.7 MHz. Line (A): with collisions; line (B): without collisions.

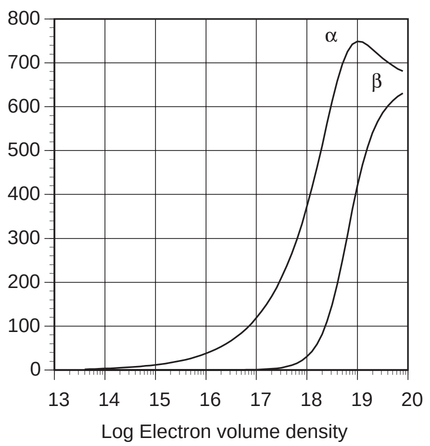

Fig. 5. Attenuation and phase constants, taking into account collision frequency, as a function of electron density above critical value. Temperature 3000 K; Radar frequency 42.7 MHz.

42.7 MHz, we obtain a critical electron density of $n_e \cong 2.3 \cdot 10^{13}\,\mathrm{m}^{-3}$. On the other hand, if we consider M. de Meyere's radar (see C. Steyaert, Radio Meteor Obs. Bulletin, ftp://charlie.luc.ac.be/pub/icaros/rmob/), which has a frequency of 66.51 MHz, we obtain a critical electron density of $n_e \cong 5.5 \cdot 10^{13}\ \mathrm{m}^{-3}$. Below this critical density (underdense meteors), the wave number is real and the incident wave propagates into the meteoric plasma with negligible attenuation. We obtain well–known results about underdense meteors. Above this value, waves which were previously excluded (see Eq. (13)), can now propagate, but are strongly attenuated (Figs. 4 and 5). From Fig. 5, it is possible to see that the presence of a collision frequency comparable with the radar frequency determines a rise of the real part of the wave vector modulus. Physically, this behaviour may be understood on the basis that collisions subtract energy from plasma oscillations, allowing the incident wave to penetrate, even if strongly attenuated.

We can observe two types and two sub–types of behaviour. We have two main classes of meteors, *overdense* and *underdense*, according to whether the plasma frequency is higher or lower than the radar frequency respectively, depending on the initial electron volume density. Moreover, overdense meteors are divided into two sub–classes (see Fig. 5): for an electron volume density between the critical density and about $10^{17}\ \mathrm{m}^{-3}$, the real part of the wave vector is negligible and the incident wave is totally reflected (*overdense I*). For a higher electron volume density, collisions allow the propagation of the incident wave, even if with a strong attenuation (*overdense II*).

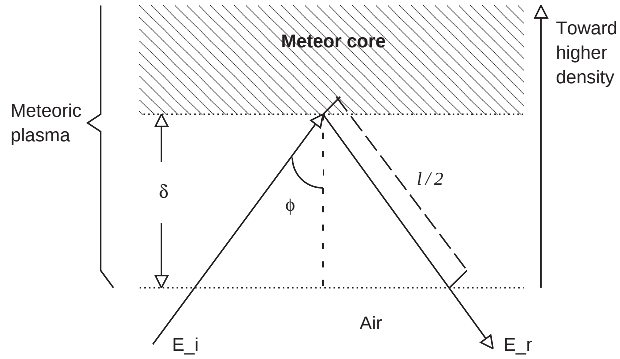

Fig. 6. Forward–scatter reflection geometry.

Total reflection, in the overdense I range, allows us to make some useful approximations in calculating the attenuation of radio waves after the forward–scattering. If the plasma had a definite boundary and a uniform electron density, then reflection at its surface would be simple because the gas would act as a dielectric with a complex dielectric constant. But a meteor trail does not have a definite boundary and thus, the incident wave penetrates a little into the plasma before reaching the density necessary to allow total reflection. Reflection occurs gradually, as in a mirage.

Taking into account this fact, it is possible to make some approximations. We can consider a simple geometry, as shown in Fig. 6, and then use the definition of the attenuation a in decibel units:

$$a = 10 \cdot \log \frac{|\boldsymbol{E_i}|^2}{|\boldsymbol{E_r}|^2}\ [\mathrm{dB}] \tag{17}$$

where subscripts i and r stand for incident and reflected wave. We substitute Eqs. (7) and (8) in Eq. (17) 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. From Fig. 6 we can see that:

$$l = \frac{2\delta}{\cos\phi} \tag{18}$$

where δ is the penetration depth and ϕ is the incidence angle. Now, if we consider something similar to the "skin effect" in metals, we have $\delta = 1/\alpha$. Then, Eq. (17) becomes:

$$a = \frac{-40 \log e}{\cos\phi} \cong \frac{-17.36}{\cos\phi} = -17.36 \sec\phi\ [\mathrm{dB}] \tag{19}$$

The attenuation is simply a function of the angle of incidence and this is compatible with results obtained by Forsyth & Vogan

(1955), who predicted an attenuation proportional to $\sec\phi$. It is necessary to stress that Eq. (19) is valid only for type I overdense meteors, where total reflection is allowed.

In order to make some comparison with experimental data, we can consider a sample of radio echoes obtained from the CNR forward–scattering radar facility (e.g. Foschini et al. 1995, Porubčan et al. 1995). Attenuation of reflected waves, in the overdense regime, ranges from -67 to -47 dB. By using the radar equation (Kingsley & Quegan 1992), attenuation values range from -155 to -125 dB, which gives a strong discrepancies with what is observed. To obtain from Eq. (19) the attenuation values requested, it is necessary to use incidence angles from 68° to 75°. This is a very good approximation because the CNR radar has the main beam with about 15° elevation angle: then 75° is just the complementary angle.

For overdense type I meteors, i.e. those with a *plateau*, Eq. (19) can be used to calculate the meteor height. Taking into account the CNR radar geometry (transmitter–receiver distance is about 700 km, see Cevolani et al. 1995), it is possible to obtain a range of overdense type I meteor heights from about 94 to 141 km. This is very important, because the height is obtained without taking into account the diffusion coefficient, which is very uncertain. This requires further investigations, which are currently being carried out.

6. Conclusions

In this paper, we settled some basic concepts in meteor physics. We have dealt with the interaction of sine waves, in the radio frequency range, with meteoric plasma. Attention is drawn to some macroscopic characteristics of a meteoric plasma and it is shown that the electron–ion collision frequency is not negligible, as commonly thought. It is possible to define two meteor classes (overdense and underdense) according to whether the plasma frequency is higher or lower than the radar frequency respectively. Overdense meteors are divided into two sub–classes (I and II), depending on the ratio between collision frequency and radar frequency.

Taking into account that the meteoric plasma does not have a definite boundary, a simple formula for the calculations of radio–wave attenuation after the forward–scattering is also presented. This formula allows us to calculate the meteor height, without taking into account the diffusion coefficient.

Further questions can be put: in this work, potassium ion is considered, but other studies can be carried out in order to know the impact of other alkaline and alkaline–earth metals, such as Na, Ca and Mg.

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