

Letter to the Editor

A space charge model for electrophonic bursters

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Abstract. The sounds accompanying electrophonic burster meteors are characteristically described as being akin to short duration “pops” and staccato-like “clicks”. As a phenomenon distinct from the enduring electrophonic sounds that occasionally accompany the passage and ablation of large meteoroids in the Earth’s lower atmosphere, the bursters have proved stubbornly difficult to explain. A straightforward calculation demonstrates that in contradistinction to the enduring electrophonic sounds, the electrophonic bursters are not generated as a consequence of interactions between the meteoroid ablation plasma and the Earth’s geomagnetic field. Here we present a novel and hitherto unrecorded model for the generation of short-duration pulses in an observer’s local electrostatic field. Our model is developed according to the generation of a strong electric field across a shock wave propagating in a plasma. In this sense, the electrophonic bursters are associated with the catastrophic disruption of large meteoroids in the Earth’s atmosphere. We develop an equation for the description of the electric field strength in terms of the electron temperature and the electron volume density. Also, by linking the electron line density to a meteor’s absolute visual magnitude, we obtain a lower limit to the visual magnitude of electrophonic burster meteors of $M_v \approx -6.6$, in good agreement with the available observations.

Key words: meteors, meteoroids – plasmas – shock waves

1. Introduction

While Electrophonic meteor sounds have been widely reported throughout recorded history, they are, none-the-less, a poorly observed phenomena (Keay & Cepelcha, 1994). By this we mean that the accounts of electrophonic sounds are mostly anecdotal and secondary. To our knowledge only two electrophonic meteors have ever been recorded instrumentally. These are the fireball events of 1981, August 13th as reported by T. Watanabe and co-authors in Japan (see Keay, 1993 for details) and 1993, August 11th as reported by Beech et al. (1995).

Expressed in terms of two broadly divided classes, electrophonic sounds are either of the short duration, or burst type in which a sharp “click” of “pop” is reported, or of the sustained

type in which a temporally extended “rushing” or “crackling” sound is heard (Keay, 1992). For brevity and phenomenological reasons we shall call the short duration electrophonic sounds “bursters”. The essential characteristics of the electrophonic bursters are their short durations, $\tau \approx 1$ s, and their piquant impression on the human auditory system.

It is not presently possible to draw any clear statistical inferences from the available data on electrophonic sounds. This is due primarily to the fact that it is the local transduction conditions that dictate whether or not an electrophonic sound will be heard (Keay, 1980, 1993). A fireball that some observers report as being electrophonic may be “silent” to other near-by witnesses simply because the environmental conditions have changed. Also, personal “in-field” experience has revealed that unsuspecting public observers often fail, at least initially, to mention that they heard an associated sound when describing a fireball event, thinking that the sounds were either an illusory or irrelevant coincidences. All this being said, the literature survey conducted by Kaznev (1994) revealed that from a total of 888 electrophonic meteor events some 76 (8.5%) would qualify for membership in our burster category. The survey by Keay (1992) indicates that 31 (10%) out of the 301 events considered would qualify as bursters. We note also that both of the instrumentally observed electrophonic meteors fall into the short duration burster class. The observations also indicate that electrophonic burster meteors must be very bright. Indeed, the 1981, August 13th electrophonic fireball event recorded in Japan had an estimated visual magnitude of -6 , while the fireball of the 1993, August 11th had an estimated visual magnitude of -10 .

Keay (1980) and Bronshten (1983) have developed a robust theory to explain the extended “rushing” or “crackling” electrophonic sounds. The key physical mechanism identified in the production of these sounds is the freezing-in and “twisting” of the geomagnetic field in the turbulent wake behind a large meteoroid. In this mechanism it is the release of the strain energy in the geomagnetic field that produces very low frequency (VLF) radio waves and these, depending upon the local environmental conditions, are transduced into audible sounds. The generation of a VLF radio wave signal will proceed provided that the Reynolds number in the meteor ablation column is greater than 10^6 (i.e., the ablation column is turbulent) and that the magnetic

Reynolds number is concomitantly greater than unity. Irrespective of the environmental surroundings, if the Reynolds number conditions are satisfied, then an appropriately designed receiver should detect the VLF radio signal. These conditions can be useful in order to evaluate the dimension of the meteoroid (Beech, 1998).

The mechanisms responsible for producing electrophonic bursters have not been as straightforward to annotate as those for the extended sounds. However, the inherent characteristics of burster events suggest that they relate to catastrophic rather than on-going events in the atmospheric ablation of a meteoroid. This phenomenological argument suggests an association between electrophonic bursters and meteor flares and terminal detonations.

2. The magnetic cavity model

A compelling “first guess” model for the generation of an electrophonic burster is the excavation of a cavity in the Earth’s magnetic field. This could be achieved by the propagation of a highly ionized blast wave into the static geomagnetic field, as shown by Karzas & Latter (1962) for nuclear airbursts. The energy density of the blast wave produced by the catastrophic disruption of an ablating meteoroid is typically much lower than that of a nuclear detonation. Indeed, as we show below, the energy required to excavate a magnetic cavity capable of producing an electrophonic burster is characteristic of that of an impacting asteroid, rather than a detonating meteoroid. To first order, the power radiated will be given by:

$$P = U_m \frac{4\pi}{3} R^3 \quad (1)$$

where U_m is the geomagnetic field energy density ($U_m = B^2/2\mu_0 \approx 10^{-3} \text{ J/m}^3$) and R is the radius of the cavity. The cavity radius is set according to the distance at which the conductivity drops below the level for magnetic field entrapment. Key (1980) has argued that human electrophonic hearing begins once the electrostatic field strength variations exceed 160 V/m (peak-to-peak). For a fireball to produce such a variation in the electrostatic field, at a distance of say 40 km, a power output of some $2 \times 10^{11} \text{ W}$ is required (assuming a dipolar radiation field). In order to produce the required amount of power on the typical burster time scale, the detonating meteoroid would have to excavate a cavity of radius 37 km in about one second. In order to produce such a large cavity the detonating meteoroid would have to deposit a very large amount of energy into the expanding blast wave. Indeed, as we show below, an unreasonably large amount of energy is required. From Taylor (1950a, 1950b) we find that the propagation speed V [km/s] of a blast wave will be of order

$$V = 4.13 \times 10^{-6} \left(\frac{E}{\rho t^3} \right)^{1/5} \quad (2)$$

where ρ is the atmospheric density at the detonation height [kg/m^3] and E is the energy deposited by the detonating meteoroid [J]. Assuming a detonation height of 30 km, we have

$\rho \approx 0.02 \text{ kg/m}^3$ and $E \approx 10^{33} \text{ J}$. Clearly, the required energy deposition in the magnetic cavity model is unrealistically high. Indeed, it is characteristic of that expected from a large impacting asteroid rather than a large meteoroid. In this respect, we need to look for other burster generation mechanisms. In the section below we present a novel model for the production of electrophonic bursters, building our arguments upon the fact that meteoroids enter the Earth’s atmosphere at hypersonic velocities.

3. Space charge separation by shock waves

When a meteoroid enters the Earth’s atmosphere it moves at hypersonic speeds, that is with Mach number greater than 5. Hence, behind the bow shock the effect of ionization becomes very important (for a brief description of hypersonic flow around a meteoroid see Foschini, 1999a and references therein). Other effects, such as ablation, contribute to enhance the presence of charged particles in the fluid around the meteoroid (for a review see Cepelcha et al., 1998). Moreover, the presence in meteoroids of alkaline and alkaline-earth metals, which easily ionize, results in the rapid formation of a plasma sheet around the meteoroid body (see Foschini, 1999b).

When the meteoroid is large enough to create an energetic airburst, the shock wave propagates in the plasma. Owing to the presence of large gradients of pressure, temperature and other quantities, across the shock, and taking into account the very different masses of electrons and ions, there is a strong diffusion of the electron gas with respect to the ion gas. However, the diffusion in a plasma is quite different from the diffusion in a neutral gas, because a small change in the charge neutrality gives rise to a strong electric field, which in turn tends to restore the neutrality and to prevent further diffusion.

In order to estimate the order of magnitude of the electric field generated by a shock wave we refer to the book by Zel’dovich & Raizer (1967). For the sake of the simplicity we assume that the ions are singly ionized and, therefore, $n_e = n_i = n$, where n_e and n_i are the electron and ion volume density respectively. Let x be the dimension of the compression shock, that is the characteristic length along which macroscopic variables have strong changes. In this region, the shock wave generates a local difference $\delta n = n_i - n_e$ between the ion and electron densities. The electric field produced by the space charge $e \cdot \delta n$, where e is the elementary electric charge, can be calculated from Gauss’ law (we are interested in modulus only):

$$E = \frac{e \cdot \delta n \cdot x}{\epsilon_0} \quad (3)$$

and the potential difference across the shock will be $\delta\phi = Ex$. In the absence of other external fields (we can neglect the Earth’s magnetic field) the separation of ions and electrons is maintained by thermal motion only. Therefore the electron potential cannot exceed kT , where k is Boltzmann’s constant and T is the temperature. Therefore:

$$\delta\phi \approx kT \rightarrow \frac{\delta n}{n} \approx \frac{\epsilon_0 kT}{e^2 n x^2} = \frac{\lambda_D^2}{x^2} \quad (4)$$

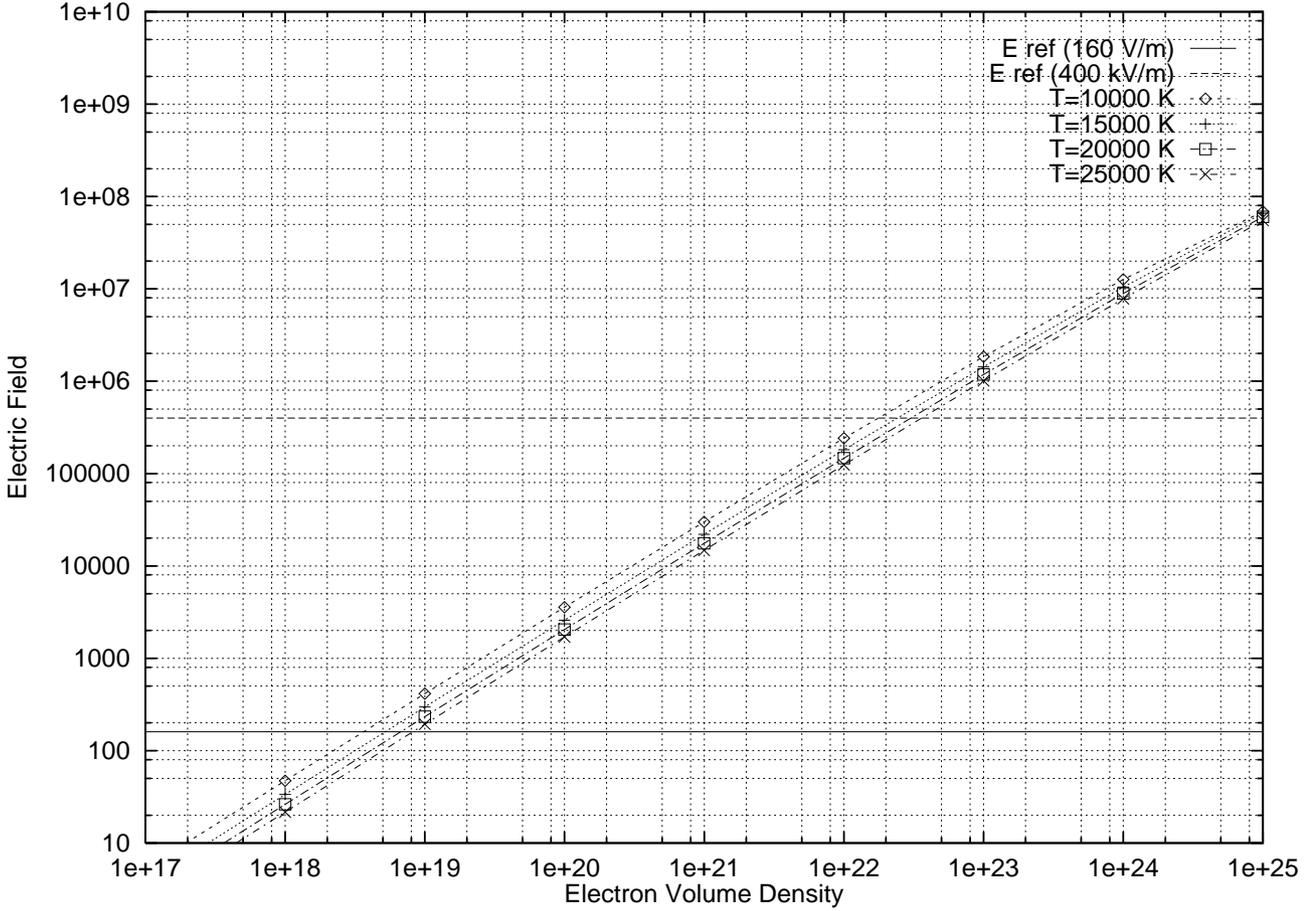


Fig. 1. The electric field generated by space charge separation in shock waves. The electric field value is in [V/m], while the electron volume density is in [m^{-3}]. Reference electric field of 160 V/m and 400 kV/m are also indicated (see text for details). Lines are plotted for several values of the temperature.

where λ_D is the Debye length, that establishes the characteristic dimension where the electrostatic force dominates over the thermal force. Eq. (4) shows that a strong separation of charges, that is $\delta n/n \approx 1$, occurs when the characteristic dimension of the shock is of the order of the Debye length.

The largest gradients in a plasma appear in the viscous compression shock, where the macroscopic variables undergo a large change on a scale length of the order of the mean free path of the charged particles:

$$x = l = \frac{v}{\nu_{ei}} \quad (5)$$

where v is the electron mean speed and ν_{ei} is the electron-ion collision frequency. In a plasma, the Maxwellian distribution speed is established quite quickly, even though there is a rather slow energy exchange between the electrons and ions. The effect is that there are two gases (electron gas and ion gas) with different temperatures, but both with Maxwellian distributions. We then consider the electron temperature as reference. The mean Maxwellian speed is:

$$v = \sqrt{\frac{8kT}{\pi m_e}} \quad (6)$$

where m_e is the electron rest mass.

Concerning the collision frequency, we can note that interactions between ions and electrons are more frequent than other interactions, owing to the electrostatic field. Particularly for high electron densities, such as during airbursts, ν_{ei} dominates over all other frequencies (Foschini, 1999b), so that we can consider the plasma as fully ionized. We can therefore use the following formula, valid for a singly ionized plasma (Mitchner & Kruger, 1973):

$$\nu_{ei} = n \frac{4\sqrt{2}\pi}{3} \sqrt{\left(\frac{m_e}{kT}\right)^3} \left(\frac{e^2}{4\pi\epsilon_0 m_e}\right)^2 \ln \Lambda \quad (7)$$

where $\ln \Lambda$ is the Coulomb logarithm. This equation is valid when $\ln \Lambda \gg 1$, that is under the condition that the gas is a plasma.

We can now obtain an expression for the electric field generated across a shock wave in a plasma. We have to substitute Eq. (6) and Eq. (7) in Eq. (5). We then have:

$$E = \frac{\delta\phi}{l} \approx \frac{kT}{el} = \frac{ne^3}{24kT\pi\epsilon_0^2} \ln \Lambda \quad (8)$$

Fig. 1 shows the electric field, calculated according to Eq. (8), versus the electron volume density for various temperatures. The reference electric field $E = 160$ V/m is also

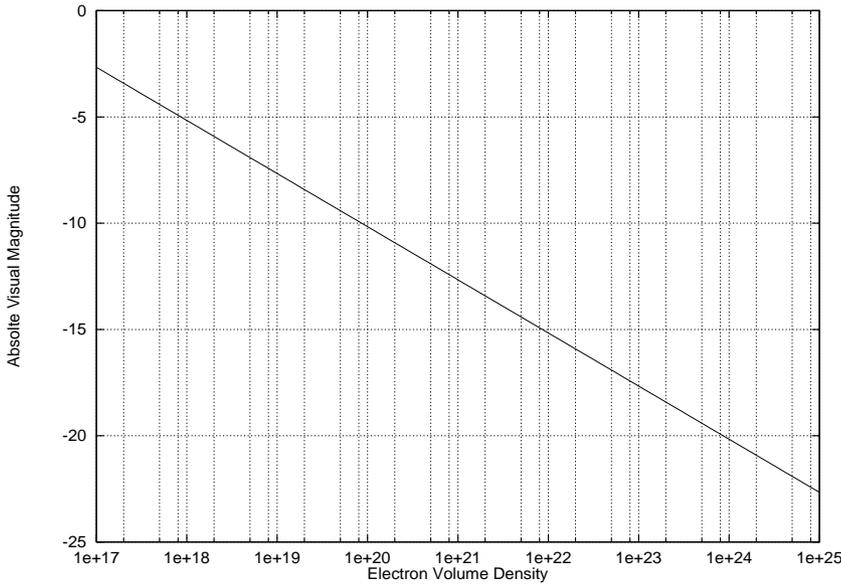


Fig. 2. Absolute visual magnitude as a function of electron volume density. The electron volume density value is in [m⁻³].

shown. We can note that we obtain the required field with $n \approx 4 \times 10^{18} \text{ m}^{-3}$ and $T = 10^4 \text{ K}$.

4. Discussion

For an evaluation of the absolute visual magnitude corresponding to a given electron volume density, we can use the formula cited by Allen (1973), valid for very bright bolides, and adapted for our purposes:

$$M_v = 35.5 - 2.5 \log \alpha_z - \delta M \quad (9)$$

where α_z is the electron line density [cm⁻¹] corrected for the zenith distance and δM is a correction factor depending on meteoroid speed. It is worth noting that meteoroid producing bolides are almost all of asteroidal origin (Jopek et al., 1995, Foschini et al., 1999), therefore we can consider $\delta M = 1.9$, that is the correction for a speed of 20 km/s. Moreover, we have to consider volume density instead of line density, therefore we have to insert a correction factor for α . Since we are only interested in the peak magnitude we consider the greatest electron volume density only, namely, the density appropriate to a circular cylinder with a radius equal to the initial train radius of about 1 m. We can neglect the zenith correction, owing to the fact that we are dealing with very bright bolides. Then, we obtain:

$$M_v = 35.5 - 2.5 \log(3.2 \times 10^{-3} \cdot n) - 1.9 \quad (10)$$

Now, we can calculate the minimum visual magnitude corresponding to the minimum electron volume density necessary to produce the required electric field. From Fig. 1 we have $n \approx 4 \times 10^{18} \text{ m}^{-3}$. Substituting this value in Eq. (10) we obtain $M_v \approx -6.6$. For the sake of simplicity we show in Fig. 2 the plot of M_v as a function of n , calculated according to Eq. (10). We specifically note that at an electron volume density of 10^{20} m^{-3} , an absolute visual magnitude of -10 is implied (see Fig. 2) and an electric field strength of about 2500 V/m is expected (see Fig. 1). These numbers are, in fact, in excellent agreement with

the measurements collected during the August 11th, 1993 fireball event, where the electric field strength was calculated to be greater than 2000 V/m (Beech et al., 1995).

The reference electric field of 160 V/m was obtained by Key (1980) by means of experiments with human beings. Later on, Key & Ostwald (1991) made some experiments in order to measure the acoustic response of several objects and materials by means of an applied electric field of 400 kV/m. If we consider this value as reference, the implied fireball magnitude is -16 .

5. Conclusions

In this Letter we have presented a novel and hitherto unreported model for the generation of short-duration electrophonic bursters. The model assumes the catastrophic disruption of a large meteoroid and the subsequent separation of electrons and ions by an energetic shock wave. Since meteoroids enter the Earth's atmosphere with hypersonic velocities, an airburst detonation results in the formation of a shock wave that propagates in the plasma boundary. As a result of the large temperature and pressure gradients across the shock, there is significant diffusion of the electron gas with respect to the ion gas, with the result that an electric field is produced by the space charge separation. It is the rapid variation in the electric field strength that results in the potential generation of electrophonic sounds.

At present the observations only afford one case (the August 11th, 1993 fireball event) in which actual measurements can be compared against the predictions. We are pleased to find, however, that in this one case there is an excellent agreement between the predicted electric field strength variation (as described by Eq. 8) and the measurements.

While our model was specifically developed to explain the electrophonic burster events, we note that the same basic mechanism may also operate with respect to producing extended electrophonic sounds. That is, if shock waves are produced within the hypersonic flow around a large ablating meteoroid, the space

charge separation mechanism can “run” in a temporally extended fashion. We hope to investigate this situation in future work.

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