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Instrumental recording of electrophonic sounds from Leonid fireballs

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[1] Electrophonic meteor sounds, heard simultaneously with the meteor appearance, are a longstanding problem due to their nonintuitive nature. Previous investigations have been undermined by lack of instrumental recordings. Here we present the first instrumental detection of electrophonic sounds obtained during the observation of 1998 Leonids from Mongolia. Two Leonid fireballs of brightness -6.5^m and -12^m produced short, low-frequency sounds, which were simultaneously recorded by microphones in a special setup and heard by different observers. Simultaneous measurements of electromagnetic ELF/VLF radiation above 500 Hz did not reveal any signal correlated to the electrophonic event. The lack of signal was explained by the low frequency of electrophones. We show that physical characteristics of Leonid electrophones cannot be completely explained by existing theories and that further theoretical refinement and observational work is needed. Finally, we tentatively suggest the possibility of stronger than expected coupling of fireballs with atmospheric charge dynamics and ionosphere. *INDEX TERMS:* 6245 Planetology: Solar System Objects: Meteors; 2435 Ionosphere: Ionospheric disturbances; 6929 Radio Science: Ionospheric physics (2409); 2411 Ionosphere: Electric fields (2712); *KEYWORDS:* meteors, Leonids, electrophonic sounds, ELF/VLF, ionosphere disturbances

1. Introduction

[2] Meteor appearance is, in some occasions, accompanied by a sound event on the ground. Acoustic effects of the meteors can be divided into two distinct groups: normal sounds (e.g. hypersonic booms) and electrophonic sounds (anomalous sounds or electrophones). The normal sound is an acoustic wave generated by the meteor airburst in the lower atmosphere, which propagates at the speed of sound. For this reason it is heard a few minutes after the appearance of the meteor. Electrophonic sounds lack retardation effects and are generally heard simultaneously with the meteor's appearance. These sounds, therefore, cannot be explained by an ordinary acoustic propagation. Normal sounds have been extensively studied for several decades, yielding established methods of the infrasonic detection of bright meteors (fireballs) [*Ceplecha et al.*, 1998]. In contrast, electrophonic sounds have been scarcely studied due to their nonintuitive nature and extreme rareness of the phenomenon [*Keay and Ceplecha*, 1994].

[3] Reports of electrophonic sounds from meteors have a long history and can be recognized in the old Sumerian, Arabian and Chinese chronicles. In 1676, Geminian Montanari was the first to recognize the anomaly between a real distance to the fireball and a distance required by the sound to be heard at the same time (cited in the work of *Halley* [1714]). Since then, many more witness reports were revealed and have been analyzed in a number of extensive catalogues [e.g., *Kaznev*, 1994; *Keay*, 1994; *Romig and Lamar*, 1963]. Many observers heard sounds even before they saw the fireball or they heard the noise inside a house. Accordingly, the phenomenon has been firmly accepted as physically real (for more discussion on this matter, see *Keay* [1980a]).

[4] Today, the physical explanation of electrophonic sounds infers an emission of the electromagnetic (EM) waves from a fireball with the frequency of audible sound (20 Hz to 20 kHz, ELF/VLF spectral region). These waves reach the observer without notable retardation. Consequently, the sound is created by coupling the electromagnetic energy at audio frequencies with objects on the ground, capable of suitable coherent vibration. This conclusion is consistent with the witness accounts, in which the reported sound is heard from a specific object in the vicinity of the observer or from the surroundings (see cited catalogues).

[5] Fireballs are rare events and phenomenological study suggests that only a small fraction of fireballs will be able to produce electrophonic sounds [*Keay and Ceplecha*, 1994]. Even when produced, the electrophones are in many occasions masked by man-made background noise. It is not

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surprising that an electrophonic sound is a once in a lifetime event and has not been recorded before. An exceptionally high activity ("storm") of the Leonid meteor shower was expected over East Asia on the night of November 17/18 1998 [*Jenniskens*, 1996]. Witness reports from previous Leonid storms suggested that the 1998 Leonid shower could be a very good opportunity to study electrophonic sounds [*Garaj*, 1999]. To take advantage of this rare event and to collect a significant sample of fireballs, we organized an expedition to Mongolia, lasting from 10 November until 24 November. The goals of the campaign were to examine the physical existence of the electrophonic sounds, to collect strong evidence for the ELF/VLF emission from meteors and to check the possible correlation between these two effects.

[6] Until now, the main setback in the full evaluation of the electrophonic phenomenon was the lack of instrumental detection of the electrophonic sounds, even though some researchers reported detection of VLF emission from the meteors [*Keay*, 1992a; *Beech et al.*, 1995; *Garaj et al.*, 1999; *Price and Blum*, 1998]. Here we report the first instrumental detection of electrophonic sounds combined with video observation of meteor and witness reports.

[7] Witness reports of electrophonic sounds from Leonids are briefly discussed in section 2. Special attention is given to the electrophonic sounds from the 1998 Leonids, reports of which were also collected. In section 3 we review the theoretical background of the electrophonic phenomenon and instrumental detection of the low-frequency emission from meteors. Observational details and instrumental setup for detection of electrophones is discussed in section 4. The results are presented in section 5. The discussion in given in section 6, where we make an effort to get a quantitative insight and comparison with existing theories. Finally, the conclusion is given in section 7.

2. Witness Reports of the Electrophones From Leonids

[8] A breakthrough in understanding the origin of the meteors happened after the great Leonid meteor storm of 1833. From an extensive collection of witness reports, Dension Olmsted was able to study a correlation between the meteors and various natural phenomena, including the electrophonic sounds [*Olmsted*, 1834]. For our investigations, the electrophonic reports of a special interest are:"-. . .slight explosions, which usually resembled the noise of a child's pop-gun. . . The meteors which afforded these sounds. . .passed below the tops of the trees. . .giving a 'pop' just before they reached the trees. . .". We heard and recorded similar electrophonic sounds from the Leonids in 1998.

[9] During the Leonid fireball night in 1998, various electrophonic sounds were reported. In addition to the sounds heard and recorded by our team, we collected several other reports from Europe and the United States. The reported sounds, listed in Table 1, resemble the reports of electrophonic sounds from 1833. *Drummond et al.* [2000] suggest that the sounds heard by three members of their team might have been enhanced by objects close to the observers (a roof with metal railing and a nearby tower).

[10] Apart from the Leonids' storms of 1833, 1966, and 1998, the reports of electrophonic sounds originating from Leonids have been very rare. The statistical analysis of the electrophonic fireball catalogues until the 1990s by *Kaznev* [1994] do not show any increase of the electrophonic reports during the month of November. The month of August, for example, has a significantly larger proportion of the electrophonic reports. This may be attributed to the Perseid meteor shower. Alternatively, the peak in electrophones reports can be explained by the fact that more people are outdoors in August. In the most recent electrophonic catalogue [*Keay*, 1994] there is only one report that may be due to a Leonid meteor (16 November 1990, "faint hissing/sizzling noise," Texas, USA).

[11] We would like to stress awareness among the meteor observers and stress the importance of the electrophones. Such awareness may have yielded more reports and some information may not been lost or forgotten. To collect as many witness accounts as possible in a consistent manner, we established the Global Electrophonic Fireball Survey [*Vinković et al.*, 2000, also see http://gefs.ccs.uky.edu/] at the University of Kentucky. Aiming at the worldwide reach of the Internet, the project is compensating for the extreme rareness of the phenomenon.

3. VLF Emission From Meteors and Theoretical Investigations

[12] The possibility of sound production by dielectric materials exposed to electromagnetic radiation has been investigated by *Keay* [1980a] and by *Keay and Ostwald* [1991]. The conclusion is that the EM-to-sound conversion coefficient is critically dependent on the type and the geometry of dielectric material and on the atmospheric conditions.

[13] It has also been recognized that electrophonic sounds can be divided into two clearly distinctive groups. The electrophonic sounds of the first group (type 1, hereafter) appear as prolonged-duration, "whooshing" and "cracking" sounds [*Keay*, 1993]. They are associated with slow, extremely bright meteors. The electrophonic sounds of the other group (type 2, hereafter) are short-duration, deep "pops" and higher pitched "clicks" and they are linked to faster bolides, not necessary as bright as type 1 bolides.

[14] The question of the generation mechanism of low-frequency electromagnetic radiation from meteors is non-trivial. The most accepted theory of meteor ELF/VLF emission was introduced by *Keay* [1980a] and theoretically refined by *Bronshten* [1983] (KB theory hereafter). The EM waves are produced by trapping and tangling of the Earth's magnetic field in the turbulent plasma wake of an ablating meteoroid. The main prerequisite of the theory is that the meteor plasma should enter the turbulent flow regime. This means that the theory is applicable only for slow and luminous bolides (absolute magnitude brighter than -12^m), which are penetrating deep into the atmosphere (below heights of 20 km), i.e., type 1 electrophones.

[15] In order to explain type 2 electrophones, *Keay* [1992b] suggested a refinement to his theory in which the VLF radio burst is produced by explosive disintegration of a fireball. According to this theory, even the meteors dimmer then -6^m are capable of producing electrophones. Recently, an alternative theory to explain type 2 electrophones was

Table 1. Witness Reports of the Electrophonic Sounds During the 1998 Leonids Collected by the Global Electrophonic Fireball Survey[a]

No.	Time, UT	Sound	Duration, s	Witness	Meteor Magnitude
1	1933:12.1 (16 Nov.)	pop-like	0.12 ± 0.01	2	-6.5 ± 0.5
2	2028:25.2 (16 Nov.)	pop-like	0.074 ± 0.004	6	-12 ± 1
3	≈0400:00 (17 Nov.)	"whoosh"	≈1	1	≈−10
4	unknown (16/17 Nov.)	crackling	1 − 2	1	≈−5
5	≈0700:00 (17 Nov.)	sizzling (white noise)	≈3	1	"light up the whole sky"
6	≈0900:00 (17 Nov.)	sizzling, "like bacon frying"	≈1	3	−2

[a] From [*Vinkovic et al.* 2000, also see http://gefs.ccs.uky.edu/]. Report 1 and 2 belong to our group. Electrophonic event 6 is also described by *Drummon et al.* [2000].

suggested by *Beech and Foschini* [1999]. The theory proposes that the charge separation takes place during the airburst of the meteoroid due to propagating shock wave through ionized meteor plasma. Rapid and strong electric fields are produced by the charge separation and they produce low-frequency EM radiation.

[16] Many of the early works in theoretical modeling of ELF/VLF emission from fireballs were done in the former Soviet Union and are not readily available to an international reader. Although many of the models were oversimplified, they can give insight into the problem. Some other charge separation mechanisms have been described in the literature and revised by *Bronshten* [1991]. He has also considered a possibility of the charging of a meteoroid during the ablation in the atmosphere. Subsequent laboratory experiments with objects moving at hypersonic velocities have revealed the formation of electric charges on these objects and a charge separation in their wakes [see *Serov and Yarov*, 1996, and references therein].

[17] In previous years, there have been many attempts to directly detect low-frequency radiation from meteors. During the 1960s, attempts to detect the magnetic micropulsations from meteors were performed, but without conclusive results [*Jenkins*, 1966; *Hawkins*, 1958]. The first positive report of a VLF signal correlated to a meteor was given by Watanabe et al. [see *Keay*, 1992a, 1992b]. A short pulse (<0.2 *s*) of low-frequency EM radiation was associated with a -6^m Perseid fireball. The following investigation done by *Andreić et al.* [1993] did not reveal any meteor-correlated ELF/VLF emission partially because no meteor brighter than -2^m was observed during the measurements. Afterward, *Beech et al.* [1995] reported a VLF signal attributed to a -11^m Perseid fireball. Recently, reports of meteor VLF emission during 1998 Leonids were presented by our group [*Garaj et al.*, 1999], and for 1999 Leonids by *Price and Blum* [1998].

4. Instrumental Setup

[18] The observational site was placed in a remote desert-like plain, located 20 km away from Ulaan Baatar (Mongolia), far away from any human activity and thus with minimal background ELF/VLF and audio noise. The surrounding area was relatively flat, snow covered, and without any trace of vegetation. The only distinctive features were two drum-like tents (Mongolian "ger"), which were used as a base camp. During the observations no other human or animal presence was detected.

[19] The humidity was extremely low. Temperature during the observations was $(-27 \pm 3)°$C, measured 1 m above the ground. The sky condition was very good with visual limiting star magnitude of $+6^m$ or better. Neither strong winds nor other interfering weather events were detected during the night of the detection of the electrophonic sounds.

[20] The observational setup consisted of wide field video camera, two VLF receivers, two microphones in a special setup and a visual observation post. Two locally grounded VLF receivers with whip antennas were placed 50 m from each other, 30 m from the visual observing place. An acoustically isolated electret microphone ("electrophonic" microphone hereafter) with special setup (electrophonic channel hereafter) was placed 20 m from the observing place. Another electret microphone, without any special setup ("open" channel hereafter), was placed near the observing site to record the observers' comments and to monitor the environmental sounds. During the design of the experiment, special care was given to the durability and portability of the equipment due to the expected harsh environmental observation conditions. Time correlation was recognized to be of crucial importance and thus included in the design of the observational setup. All recordings were mutually time-synchronized within 0.04 *s* of accuracy. The absolute time synchronization was achieved by recording the time signal from a Taskent radio station (frequencies 5, 10, and 15 MHz) simultaneously at each recording unit. A sensitive and extremely durable monochrome CCD video camera (model DMK2002E, DBS GmbH, Germany; sampling rate: 25 *frames*/*s*) was used with a wide-angle lens for 55% sky coverage. The limiting magnitude of the video setup was 0^m. The video signal was recorded with a VHS video recorder (VCR; model Panasonic AG-6400) together with simultaneous recording of four audio channels, thus providing a precise relative time correlation. During the observations, the signal from the CCD camera was controlled with a portable monitor. To eliminate possible electromagnetic interference from AC power supplies, DC car batteries were used to supply power to the equipment. All the equipment was calibrated at the Department of Electroacoustics, Faculty of Electrical Engineering and Computing, University of Zagreb.

[21] To obtain the brightness of the meteors, we performed photometric analysis of the video records. A dark frame was created by averaging six frames taken 0.5 s before the meteor appearance. After subtraction of the dark frame, simple integration of remaining pixels at each

frame with the meteor was performed. Sources of errors in this procedure are due to selection of the outermost contour used for integration, due to the saturated pixels and due to comparison with the reference star. The last one was recognized as a principal source of error, because of the low signal to noise ratio (S/N) at the pixels covered by the reference star, placing the error estimate to $\pm 0.5^m$. The frame rate restricts the synchronization accuracy between different recording channels to 0.04 *s*.

[22] The frequency sensitivity of the VLF receivers is very good between 1–6 kHz (threshold $<10^{-3}$ V/m), falling sharply below 500 Hz and above 10 kHz. Two spatially separated sets of VLF receivers are highly desirable to exclude all local noise (artificial or natural). In contrast, global (natural or man-made) VLF noise could not be discarded by a separate set of antennas due to the large wavelength of monitored EM radiation. Usually, they can be distinguished by spectral analysis, but very precise time synchronization between the video and the VLF observations is needed to completely distinguish the meteor signal from the atmospheric noise. The signal from the first antenna was recorded on one of the VCR audio channels. A DAT recorder (model Sony PCM-M1) was used for recording the signal from the second antenna on one channel and the time synchronization signal on the second channel. Direct recording of the ELF/VLF signals on audio devices is standard procedure because the signals are of the same frequency as audible sounds.

[23] Signals from the microphones were recorded at different VCR audio channels. The remaining VCR audio channel was used to record the time synchronization signal. Special care was taken to minimize the signal leakage between the channels in the recording devices and cables. The leakage was proven to be negligible. Another concern is the induction of the ELF/VLF signals in the long wires that connect the antennas and microphones with the recording equipment. To avoid this induction, coaxial Mogami Star Quad cables with appropriate grounding were used.

[24] The electrophonic microphone was placed in a box, acoustically insulated from the environment. A special setup for recording of the electrophonic sounds was used. According to the laboratory tests [*Keay and Ostwald*, 1991], good electrophonic transducers (sheets of paper and aluminum foil) were suspended inside the box. Thermal insulation proved to be very important in this extreme weather conditions since another (spare) electrophonic microphone unit failed to work properly due to very low temperatures. Acoustic insulation of the electrophonic microphones was checked at the observing site by intentionally producing loud sounds and comparing the recorded signals from the open and electrophonic microphones. The analysis shows that most of the sounds were completely attenuated by the acoustic insulation and distance. The low-frequency component (<100 Hz) of some of the sounds produced very close to the box was able to partially penetrate into the box with the electrophonic microphone. Nevertheless, the attenuation of these signals was about 30 dB, which is more than adequate for our purposes.

[25] The night before the maximum activity of Leonids, we had windy conditions; however, the electrophonic microphone did not pick up any significant noise from the wind. Since the night during the observation of the Leonids was almost windless, we can exclude the wind as a possible source of noise.

[26] During the observing sessions at any given time, at least two persons were observing visually and their comments were recorded on the open channel. To exclude fatigue and problems with extreme weather conditions, observers rotated every 30 min. These visual observations were important for determining a connection between the instrumental recordings and the witness reports, as they were previously intensively studied in the literature.

[27] Having in mind the extreme rareness of the phenomenon and necessity for the complete control of the detection conditions, strict a priori constrains for accepting a positive ELF/VLF detection and positive electrophonic detection were established. The minimal a priori constraints on the electrophonic signals are (1) the time correlation with the visual/video observation of the meteor; (2) simultaneous detection of the signal by spatially and acoustically separated sets of microphones; and (3) the electrophonic sound should be confirmed by more than one witness.

[28] An acceptable ELF/VLF meteoric signal should have (1) strong correlation with the video observation of the meteor; (2) simultaneous detection on spatially separated sets of VLF receivers; (3) no visible dispersion effects typical for atmospheric ELF/VLF noise; and (4) nonmonochromic spectral distribution. Strong time correlation with the fireball appearance is needed because the natural ELF/VLF spectrum is a strong source of interference and only precise time correlation with the meteor's light curve can provide conclusive evidence.

5. Results

[29] Although the Leonids did not show storm activity, they showed an exceptionally large number of very bright fireballs on the night of 16/17 November 1998 [*Brown and Arlt*, 2000]. Despite the relatively low overall meteor rate (around 150 meteors per hour) almost all of them were extremely bright fireballs. This was very favorable for our measurements, providing the fireball sample equivalent to many years of continuous observations during a normal meteor activity [*Ceplecha*, 1994].

[30] During the observational campaign, two distinctive electrophonic signals that fully satisfy the restrictive a priori constrains were detected. In the first case, a meteor fireball appeared on the eastern part of the sky at 19 hours 33 min 12.1 s UT, 16 November 1998, with an absolute magnitude of $M_V = -6.5^m \pm 0.5^m$. The complete trajectory was recorded on video. The meteor path had an angle of 54° to the horizon and was about 55° above it. Two visual observers saw the meteor and independently reported hearing a short duration "pop"-like sound. On both open and electrophonic channels, an electrophonic signal was recorded with almost the same duration and spectral distribution. The signal lasted for (0.12 ± 0.01) s, and it was recorded (0.70 ± 0.05) s earlier than the meteor light maximum (Figure 1). No ELF/VLF signal was detected during the electrophonic event. The calibration of the microphones yields an electrophonic sound intensity of 75 dB sound pressure level (SPL) on the open channel and 50 dB SPL on the electrophonic channel, with most of the spectral weight below 250 Hz (Figure 3a).

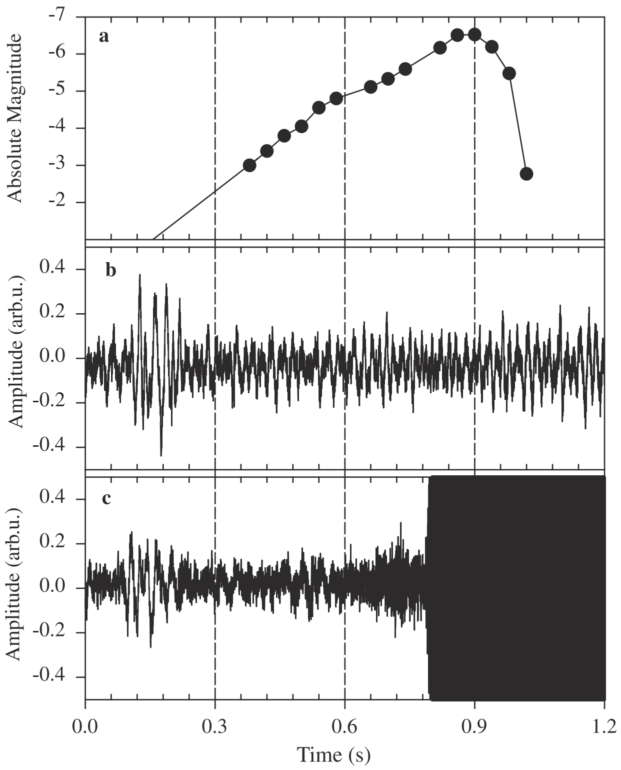

Figure 1. Recorded electrophonic sound from $M_v = -6.5^m \pm 0.5^m$ fireball: (a) the meteor brightness recorded by video; (b) the "electrophonic" channel; (c) the "open" channel. Amplitude is given in arbitrary units, time 0.0 s = 19 hours 33 min 12.0 s UT (16 November 1998) Saturation of the signal in the open channel is due to uncontrolled audio reactions from observers, but no signal leakage is visible on the electrophonic channel.

[31] Another, more emphasized electrophonic event was detected at 20 hours 28 min 25.2 s UT, 16 November 1998. A very bright Leonid fireball appeared on the northern part of the sky. Six people reported hearing a loud electrophonic sound, which was described as deep "pop." The fireball was spotted directly by three observers and its estimated visual brightness was $M_V = -12^m \pm 1^m$. Other witnesses, monitoring other parts of the sky, only heard the sound as the final flash of the fireball illuminated them.

[32] Electrophonic signal was recorded on the electrophonic and the open channels simultaneously (Figure 2). The signal lasted for $(0.074 \pm 0.004)s$ and it had significant spectral weight at very low frequencies, very similar to previous electrophone (Figure 3b). Maximum intensity was in the frequency range between 37 Hz and 44 Hz, both on the electrophonic and open channels. The signal/noise ratio on the electrophonic channel is 14 *dB*. On the open channel the noise was higher, but the signal was still very distinctive. Absolute sound intensity on the open channel was calculated to be 85 and 70 dB SPL on the electrophonic channel.

[33] The fireball was out of the field of view for the video camera, but recorded audio reactions from the observers are suggesting that the electrophonic effect was produced (0.6 ± 0.3) s earlier than the fireball's maximum brightness. Since this is a very tentative calculation, we will offer this only as a suggestion. Again, no coincidental ELF/VLF signal was detected. It is worth noting that the video signal shows unusual noise coincident with the electrophonic signal. We do not exclude the possibility that it was caused by a strong electrical disturbance.

[34] However, ELF/VLF signals were detected, for two other fireballs (published elsewhere, *Garaj et al.* [1999]). A sequence of short VLF pulses appeared simultaneously with the meteor's light maximum and the probability that this was an uncorrelated atmospheric noise is 1% or smaller. According to *Keay and Ostwald* [1991], the signals were too weak to create an electrophonic sound.

[35] We conclude that the detected electrophonic sounds are related to the meteors. Besides the fact that they satisfy the a priori criteria, several other factors corroborate the meteor origin. First, the experimental setup was designed to eliminate any incidental environmental sound. Second, the observational site was placed in an uninhabited area of Central Mongolia, devoid of life, any human or animal nocturnal activity, power lines, and AC electrical equipment of any sort. During the 10 days of the observational campaign, no environmental sound of such magnitude and especially of such appearance was heard or instrumentally recorded. Therefore the recording of an uncorrelated environmental sound coincidentally with the meteor appearance is extremely unlikely.

[36] To address any speculation that the recorded sounds were merely sonic booms from meteors, we point out that (1) a sonic boom is different in appearance and length than our short duration electrophonic signals; (2) Leonids are fast meteoroids with very low density and ablate high in the atmosphere, so they can not survive to altitudes below ~70 km [*Spurný et al.*, 2000] to produce an audible sonic boom (only infrasound from the Leonid's terminal explosion can reach the ground after >5 min [*ReVelle and Whitaker*, 1999]); (3) coincidental appearance of a meteor

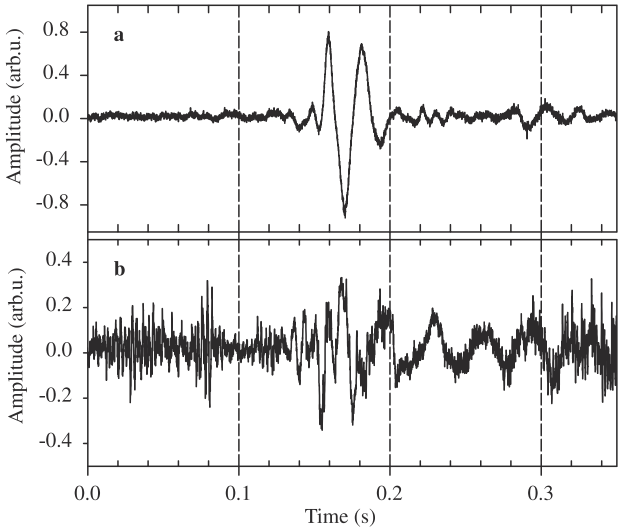

Figure 2. Recorded electrophonic sound from $M_v = -12^m \pm 1^m$ fireball: (a) the electrophonic channel, (b) the open channel. Amplitude is given in arbitrary units, time 0.0 s = 20 hours 28 min 25.0 s UT (16 November 1998).

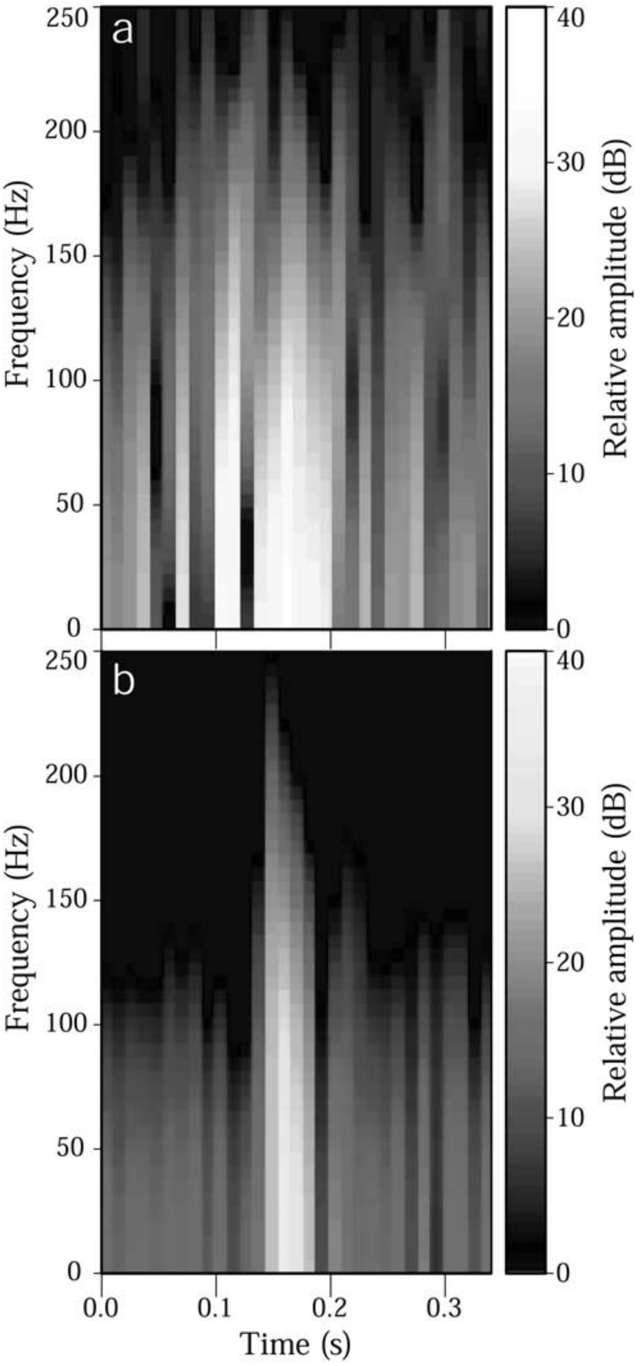

Figure 3. Spectral distribution of electrophonic channel signal for (a) electrophone from the -6.5^m fireball and (b) electrophone from the -12^m fireball. Both electrophones are very similar in appearance and spectral distribution. First signal has relatively smaller S/N due to lower signal intensity.

during the detection of sonic boom from another meteor would be improbable, even for such meteor rates.

6. Discussion

[37] During the 1833 Leonid meteor storm, some of the witnesses reported electrophonic sounds resembling deep "pops." Our detection of the electrophones from the 1998 Leonids resembles these reports. The sounds preceded the meteors' light maximum, which is also true for these types of sounds in 1833 (see section 2). The first electrophonic sound was detected when the meteor was at the altitude of ~110 km. The second electrophonic event was produced by the meteor at altitude of 85–115 km.

[38] The frequency range of the observed electrophonic sounds is 37–44 Hz and matches closely the observers' psychophysical response (deep, "pop" sound). For the mechanism of sound transduction from electric field, we expect the frequency of EM radiation to be very close to the frequency of electrophonic sound. This is probably the reason why we did not detect low-frequency EM radiation, because the receivers were completely insensitive for frequencies below 500 Hz. If we compare the intensities of the sound in the electrophonic box versus intensities at the open microphone with the sound-dumping coefficient of the box, we come to the conclusion that the sounds on the "electrophonic microphone" were produced inside the electrophonic box.

[39] According to the double station photographic observations of 1998 Leonids from China [*Betlem et al.*, 1999; *Spurný et al.*, 2000], the Leonid fireballs belong to the fireball group IIIB. These fireballs are very fragile, low-density objects and *Spurný et al.* [2000] derived the ablation coefficient of $\sigma = 0.16$ s^2 km^{-2} and density of $\rho_m = 0.7$ g cm^{-3} for a typical Leonid. The typical geocentric velocity of Leonids is v = 71 km/s. These values will be used in the following calculations.

[40] Let us now investigate the electrophonic sounds in the framework of KB theory. In order for electrophonic sounds to be produced, it is critical to have a turbulent flow regime of meteor plasma, i.e., the Reynolds number $R_e = vD\rho/\mu$ has to exceed 10^6 (v is meteoroid's velocity, D is the meteoroid's diameter, ρ is the atmospheric density, and μ is the dynamic viscosity of the gas flow). From the single body ablation theory [e.g., *Ceplecha et al.*, 1998]) and the observed magnitudes and trajectories of our electrophonic meteors, we derived the initial diameter of $2.66^{+0.45}_{-0.37}$ cm (mass of $6.9^{+4.1}_{-2.5}$ g) for the first fireball and $13.6^{+4.7}_{-3.6}$ cm (mass of 919^{+1390}_{-553} g) for the second fireball. In addition to the single-body ablation theory, the 1976 U.S. Standard Atmosphere model was used instead of more crude approximations [*Beech*, 1998]. If the initial meteoroid diameter at infinity is D_0, then its diameter D at the altitude h is given by

$$D(h) = D_0 - \sqrt[3]{\frac{6}{\pi\rho_m}\frac{K\sigma v_0^2}{3\cos(z_r)}\int_h^\infty \rho(h)dh}, \qquad (1)$$

where K is the shape–density coefficient (for the Leonids $K\sigma = 3.0778 \times 10^{11}$ s^2 g$^{-2/3}$ [*Ceplecha and McCrosky*, 1976]), v_0 = 71 km/s is the meteoroid's velocity at infinity, and z_r is the zenithal entry angle ($z_r = 0°$ corresponds to a vertical trajectory). The value of R_e based on this approach is shown in Figure 4 for the entry angle of 0°. From the calculations, even larger initial size is needed for reaching the turbulent flow than the one proposed by *Beech* [1998]. According to our calculations, the Leonid's initial size has to be $D_0 > 200$ cm (mass ~3000 kg) to produce an electrophone in the framework of KB theory. Recent studies

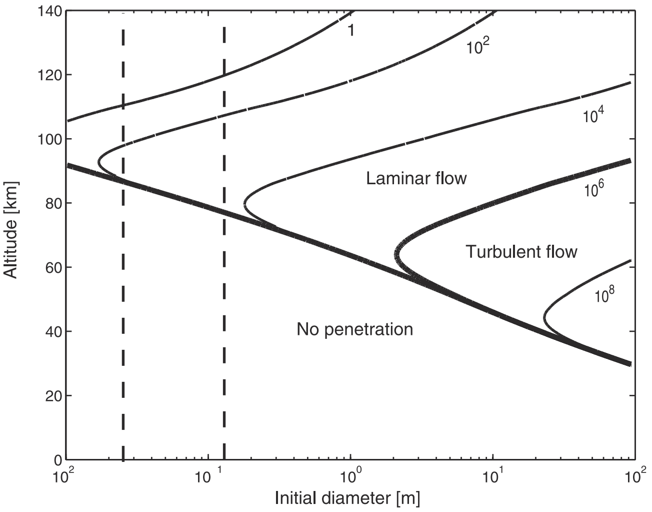

Figure 4. Calculated Reynolds number as a function of the meteor's initial diameter and altitude. Solid contours represent the lines of constant *Re*, whose values are marked on the graph. Bold lines are separating the region of laminar flow of meteor's plasma ($Re < 10^6$), the region of turbulent flow ($Re > 10^6$) and the region where a meteor does not penetrate. Dashed vertical lines specify initial diameters of our electrophonic fireballs. Calculation was done for zenithal entry angle $z_r = 0°$. In the case of larger angles, *Re* is further reduced due to $cos(z_r)$ factor in equation (1).

show that Leonids are more like "dustballs" [*Spurný et al.*, 2000] and single body ablation represents just the first-order approximation. A more exact calculation of Reynolds numbers will probably yield even higher required masses. Although the KB theory is very successful in explaining low-frequency EM emission from slow fireballs, it appears that it cannot be applied to Leonid meteors in general and that some refinements of the theory are required.

[41] *Beech and Foschini* [2001], however, applied EB theory to the Leonids. According to their calculations, our electrophonic meteors can be explained by EB theory, albeit only if they emit EM radiation at the moment of the airburst and by reaching altitudes below 90 km. This is not the case for our meteors and the certainty of our relative time synchronization comes from the fact that both video and audio data have been recorded in parallel on the same data storage medium (VCR). Furthermore, in the theory the internal electric field generated across the shock wave is taken to be the same as the electric field needed to produce electrophones on the ground. Due to multi–pole nature of the radiating system, the real electric field on the ground is most probably orders of magnitude smaller than the one taken by the authors. This inconsistency is largely underestimating minimal brightness of the electrophonic fireball coming from their calculations.

[42] Let us continue with a model–independent analysis. Starting from the detected sound intensity, we will deduce the required ELF/VLF radiation power from the meteor needed to produce the recorded sound intensity. The sound intensities of our electrophonic sounds were 75 dB SPL (85 dB SPL) for the first (second) electrophone. The corresponding sound intensity was 0.56×10^{-8} W/m^2 (1.78×10^{-8} W/m^2). According to the theoretical arguments of *Bronshten* [1983], the highest transduction coefficient (T_m) between the EM radiation and the sound is 0.1%. The more realistic value is probably orders of magnitude smaller than that, e.g., $T_m = 10^{-6} - 10^{-9}$ (calculated from references *Keay* [1980b] and *Keay and Ostwald* [1991]), and critically depends on the environmental transduction conditions. Thus the following calculation will give only lower limit estimate of the necessary ELF/VLF radiation power. Applying the geometrical calculations based on our video frames, we calculate that the meteors were ~130 km (~200 km) from the observing site at the time when they produced electrophones. In the approximation of spherical quasi-electrostatic wave propagation, the ratio of emitted ELF/VLF radio energy to total kinetic energy of the meteor is $8 \times 10^{-6} T_m^{-1}$ ($3 \times 10^{-7} T_m^{-1}$), and for the highest theoretical value of $T_m = 0.1\%$, it is 0.8% (0.03%). As emphasized before, for the experimentally measured values of T_m, the real ratio is probably greatly higher, maybe even exceeding 100%. Previously proposed theories are based on effects that are of second order in energy and can hardly explain such a high ratio.

[43] Any theoretical mechanism starting from meteor alone will have problems explaining this high efficiency of ELF/VLF production. Instead, let us suggest the possibility that the Leonids trigger other atmospheric phenomena that could, in conjunction with the meteor, lead to strong electromagnetic effect. With this approach, we are less limited by a meteor's size and energy. Laboratory experiments with objects moving at hypersonic velocities have revealed the formation of electric charges on these objects and a charge separation in their wakes [*Arsen'ev et al.*, 1989; *Serov and Yavor*, 1991; *Pilyugin and Baulin*, 1993; *Pilyugin*, 1994; *Serov and Yarov*, 1996]. Phenomenological interpretation of the process goes as follows. Since electrons from the plasma have a higher mobility than the ions, they are effectively charging the moving body. Due to their higher velocities and interaction with incoming flow, they accumulate in the nonviscous plasma wake. The positive charge is carried by the flow into the viscous zone immediately behind the body (stagnant zone). There it is stabilized due to the electrostatic interaction with the negatively charged body. The actual spatial charge distribution and charge dynamics is very complicated as the wake can be neutralized and polarized dynamically due to electron diffusion. The moving body, however, stays charged. Since these experiments were performed in the neutral atmosphere, the described process can be more complicated for the motion in the ionospheric plasma.

[44] The exceptionally large beginning heights of the 1998 Leonids [*Spurný et al.*, 2000] suggest that the charge separation can start very early during the flight of a Leonid meteoroid in the atmosphere. In this case, the acquired charge on the meteoroid and in its vicinity can be large enough to create unusual phenomena when the meteor enters the lower parts of the ionosphere (*E* layer) at ~110 km. Both of our electrophonic meteors produced electrophonic sounds approximately upon entering the *E* layer of ionosphere. Based on this, we are tentatively suggesting a possibility that the Leonids can trigger unidentified atmospheric phenomenon at the *E* layer boundary. Such phenomena could generate EM radiation burst energetic enough to produce the

electrophonic sound. One triggering effect of meteor was already demonstrated by *Suszcynsky et al.* [1999]. They recently observed a sprite phenomenon triggered by a meteor. Whatever the correct explanation of the electrophonic phenomenon is, interaction with the ionosphere cannot be ignored due to a large electric fields required by the electrophones.

[45] Apart from the reported electrophonic meteors, many more Leonid meteors of similar magnitude were observed which did not generate electrophonic sounds or detectable ELF/VLF emission. As all the Leonids have very similar physical characteristics, the question arises why all the fireballs did not produce electrophones. One of the reasons could be the following. In our theoretical analysis, the approximation of a point source of EM radiation and the spherical electromagnetic wave propagation was employed. This is not the case in the Earth's atmosphere due to the Earth-ionosphere waveguide. The far-field approximation of the ELF/VLF propagation in the waveguide is also not appropriate at the distances between the meteor and the site where the electrophonic sound is reported. Thus the correct solution should include a numerical calculation of the near-field configuration, which usually leads to complicated field profiles and polarization [*Yagitani et al.*, 1994]. The orientation of the emitter and its position relative to the ionosphere is then very important; i.e., the angle of meteor entrance in atmosphere and position of the observer could be of crucial importance.

7. Conclusion

[46] Our observations during the "fireball storm" on 16/17 November yielded the first instrumental detection of the electrophonic sounds from meteors. Two low-frequency "pop"-like electrophonic sounds (frequency dispersion below 250 Hz) were unambiguously attributed to the simultaneously observed meteors. They were recorded by two spatially and acoustically separated microphones and reported by two observers for the first electrophone and six for the second. The meteors' magnitudes derived from the video and visual observations are $-6.5^m \pm 0.5^m$ and $-12^m \pm 1^m$. Simultaneous ELF/VLF signals were not detected. This may be explained by the frequency response of our ELF/VLF receivers. These are insensitive to the frequencies below 500 Hz, and the recorded sounds imply a transduction from the ELF radio waves at frequencies below 250 Hz. An additional support for this conclusion are geomagnetic disturbances below 10 Hz detected recently during the reentry of an artificial satellite accompanied by electrophonic sounds [*Verveer et al.*, 2000].

[47] The discussion of the two theories of ELF/VLF emission from meteors demonstrates that neither of them can fully explain the detected electrophonic sounds from Leonids. The electrophonic sounds were not detected during the final flash of meteors but rather at the time of meteor crossing to the atmospheric *E* layer. We find that the radiated EM power from meteor alone is not large enough to produce electrophonic sounds. Having this in mind, we are tentatively noting that meteors may just trigger a more powerful atmospheric effect that in turn can produce EM bursts of sufficient power. This is supporting the emerging picture that the meteors can be more strongly coupled with atmospheric dynamics than previously supposed. The phenomenon of electrophonic sounds requires significantly more observational, laboratory, and theoretical study, since the existing understanding of the phenomenon is not completely satisfactory.

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