Global Electrophonic Fireball Survey: a review of witness reports - I.

D. Vinković, S. Garaj, P. L. Lim, D. Kovačić, G. Zgrablić, Ž. Andreić

Despite more than 300 years since its first scientific description, the phenomenon of electrophonic sounds from meteors is still eluding complete physical explanation. According to the accepted knowledge, the sound itself is created by strong electric fields on the ground induced by the meteor. Nonetheless, there is no convincing theory that can fully explain how a meteor can generate such a strong electric field. Extreme rareness of the phenomenon has prevented a substantial experimental work so far; thus, consequently, it remains on the margins of scientific interest. This is quite unfortunate since these electric fields suggest existence of a highly complex electromagnetic coupling and charge dynamics between the meteors and the ionosphere. Therefore, the existing theoretical work relies mostly on the witness reports. The Global Electrophonic Fireball Survey (GEFS) is the first systematic survey of witness reports of these sounds with a standardized questionnaire designed exclusively for this phenomenon. Here we present the overall picture of the phenomenon that emerged after almost 100 reports collected by GEFS. It becomes clear now that the lower meteor brightness limit is about -2^m, suggesting a bias in the existing electrophonic sounds catalogues toward brighter meteors. In contrast to the current belief that such low brightness electrophonic meteors produce transient sounds, we find that they can also produce sustained sounds. The current theories can not accommodate these results. We revive the old idea that the electrophonic sounds can be created by the *corona discharge* mechanism, in addition to the existing prevalent suggestion of resonant vibration of objects on the ground.

1. Introduction

Audible sounds from meteors can be divided into two groups: *normal* and *anomalous* (*electrophonic*) sounds. Normal sounds are acoustic waves produced either by a hypersonic shock front or by a terminal burst and they propagate at the speed of sound. Hence they display a noticeable time delay between the visual appearance of the meteor and an audible detection on the ground. In contrast, anomalous sounds lack this time delay, which means that the light and the sound are observed simultaneously. The exact mechanism of their production by a meteor is still not known due to the extreme rareness of this phenomenon.

The first written record of distinction between the normal and anomalous sounds dates back to the 17th century. Even though the concept of electromagnetic (EM) waves was unknown at that time, almost instantaneous propagation of the anomalous sounds over a large distance was suspected to be somehow connected to the "electric matter". Nevertheless, the existence and reality of anomalous sounds was often denied by scientists, especially when the real nature of meteors was discovered in the 19th century. Since then, these sounds have been mainly ignored by the scientific community, despite the persistent emergence of witness accounts. Consequently, the anomalous meteor sounds have become the oldest unexplained astronomical phenomenon.

Over the years, scarce theoretical research has managed to establish a connection between the EM waves and anomalous sounds. In the first extensive study of these sounds, Romig & Lamar (1963) concluded that these sounds are most probably similar to the *brontophonic sounds* (simultaneous with, or slightly preceding, the lightning stroke) and *aurora sounds* (another poorly studied phenomenon — sounds simultaneous with bright auroras). They concluded that the sound is created by *corona discharge* on sharp conductors, including plant leaves. Keay (1980) narrowed the frequency region for these EM waves to the ELF/VLF (between 30Hz and 3kHz) region. He also conducted experiments on human subjects and concluded that the ELF/VLF electric fields are capable of entangling ordinary objects around the observer, from metals to dielectrics, into a resonant vibration which then produces a sound in the same frequency range as the EM waves (Keay & Ostwald 1991). This has become a widely accepted theory and the corona discharge mechanism has been mainly forgotten.

The term “electrophonic sound” was used for the first time in 1937 as a description for sensation of a sound caused by electrical current through the head (Stevens 1937). A few years later the term “electrophonic bolide” entered meteor astronomy as a description of a bright meteor accompanied by anomalous sound (Dravert 1940).

All this, however, merely moved the problem from how to create a sound to how to create a strong ELF/VLF radiation from a meteor. Sound can be created from the ELF/VLF waves only if the electric field at the ground is of at least several hundred V/m. Considering the large distance between the observers on the ground and a meteor, the electric fields in the vicinity of the meteor should be many magnitudes larger than on the ground (due to distance square dependence for frequencies of kHz and higher and approximately exponential dependence on distance for lower frequencies) (Wang, Tuan & Silverman 1984). This problem has been studied theoretically by several authors (for an older review see Bronshten 1991) (Beech & Foschini 1999), including Keay (1980). Nonetheless, the first instrumental recording of the electrophonic sounds combined with a video and VLF observations during the 1998 Leonids showed that none of the existing theories can explain the data (Zgrablić et al 2002).

Even though all these theories have been based solely on witness reports, there has been no attempt to collect them with a standardized questionnaire. The existing catalogues of electrophonic sound reports (Romig & Lamar 1963 , Kaznev 1994, Keay 1993a) are usually extracted from other sources, mainly from the fireball catalogues, and then statistically analyzed. Considering how little we understand the nature behind this phenomenon, the witness reports are still a valuable source of information. Two years ago, we initiated the Global Electrophonic Fireball Survey (GEFS) to collect these reports in a standardized form (Vinković et al 2000). After receiving almost 100 reports, we present here a review of the collected data. Some reports of special interest (such as the Leonids or meteors with complete trajectory) are presented in more details. Due to the limited space in the journal, we can not present the complete reports, but they can be accessed at the GEFS web-page *http://www.gefsproject.org* or obtained from us by a request.

2. Statistical analysis of the reported electrophonic sounds

Witness reports were collected by the following methods: through the on-line HTML data submission form, e-mail using a text version of the form, or informal e-mails. All of them were transformed into the standardized survey form described by Vinković et al (2000). A single report often includes more than one person. Before we started preparing this review, we received 91 reports of electrophonic meteors.

The reports are designated as **GEFSYYYY_MM_DD_NN**, where YYYY_MM_DD is the date of the electrophonic event (year, month, day) and NN is numeration in a case of more than one event in a day. We consider one location as one event, no matter how many observers are involved. If the auditory perception of electrophonic sounds does not differ among observers, they will have more or less the same psychophysical reaction regarding the sound description when exposed simultaneously to the same sound. Therefore the sound is considered as one event instead of being interpreted as several events based on the perception of multiple observers.

The geographical locations of the electrophonic meteors include: Australia, Belgium, Canada, Croatia, Denmark, England, Finland, France, Germany, Israel, Mexico, Mongolia, The Netherlands, Norway, Scotland, Singapore, Sweden, and the USA. The oldest event is from the year 1952. The complete trajectory is calculated in three occasions. It is interesting to note that 34 reports are associated with the Leonids and 7 with the Perseids. Among them, there is one very interesting account of numerous electrophonic sounds from the 1966 Leonids. In addition to the reports of electrophonic sounds from meteors, there are three reports of (most probably) aurora sounds (GEFS1964_11_00_02, GEFS2001_11_23_01 and GEFS2001_12_14_01) and one report of an electrophonic sound from the Space Shuttle reentry (mission STS-109) over central Texas (San Antonio). These four reports are not included in the analysis shown below.

Here we statistically evaluate the data for specific segments of the GEFS form. We would like to emphasize that most of the reports have very valuable information provided in the *additional remarks* section of the form.

2.1. Personal information

The GEFS reports are sometimes not submitted by the witnesses themselves, but rather by a person who collected various reports of sighted meteors and recognized reports of electrophonic sounds among them. Such reports are sources of the events with known meteor trajectory described in the next section; thus, the name of person who submitted the data is not necessarily the name listed under *personal information*. If the specific permission to use the witnesses' name as a reference to the submitted GEFS data was not obtained then their name is omitted. If one GEFS report contains several qualitatively different witness reports, the word "multiple" is used as personal information and the names (or initials) are provided in conjunction with their GEFS data. The level of meteor observing experience among the witnesses varies from *not experienced* to *highly experienced*. Most witnesses had never heard a sound from a meteor before, as expected.

2.2. Description of the observing site

The location of observing sites is usually described as a geographical feature, thus the given coordinates correspond to these features and are not precise. The meteorological conditions are described as *clear sky* and *calm* (windless or light breeze) in 84% of reports with provided weather conditions. This is not surprising since such conditions increase the possibility of spotting a meteor and noticing an unusual sound.

2.3. Details about the sound from the meteor

The exact month of the electrophonic event is provided in 73 reports but the day in only 47 (mainly because of very old events). The time is specified in 70 reports, usually an estimate of the hour, thus only 32 reports have specified minutes or better.

Descriptions of reported electrophonic sounds are matching descriptions in the existing electrophonic catalogs (e.g. Keay 1993a, Kaznev 1994). Keay (1993b) classified the electrophonic sounds into three groups: *smooth* (with 71% rate of occurrence), *staccato* (18%), and *sharp* (11%). This classification applied to the GEFS reports is shown in Table 1. Our rate of occurrence of smooth and staccato sounds is different, more than expected from Keay (1993b). This is probably due to different methods used for counting sound events.

In addition, some observers may not hear the sound or agree on its duration or direction. The reported duration of sounds varies from less than a second to more than 10 seconds. Sound is recognized as coming from *all directions* in 19 reports (27%), *no direction* in 10 (14%), and from *the meteor* in 41 (59%). Air is often mentioned as the direction or source of the sound. Three reports (GEFS1998_11_16_02, GEFS1998_11_17_04, GEFS2001_11_18_08) have an exact object identified as a possible sound source.

In 76 (84%) cases, the meteors were spotted simultaneously with their sound. Observers can not decide about a specific meteor that produced the sound in 8 (9%) cases because of high meteor activity. The electrophonic meteors were spotted prior to the sound in 2 (2%) cases, but the sounds did not exceed the duration of their meteor. In 5 (5%) reports, the meteors were spotted after the sound. In two of such cases (GEFS1972_00_00_01, GEFS1969_06_00_01), the electrophonic sound prompted the observers to look toward the sky.

Correlation of the sound with the meteor's light maximum reveals that: in 29 reports witnesses *can not decide*, 48 (76%) reports indicate *simultaneous* sound and light maximum, 6 (10%) reports indicate a sound *before*, and 9 (14%) *after* the light maximum (one report has two sounds with different correlations). Since some reports deal with multiple sounds with the same type of correlation, the percentages shown here suffer from large error bars.

Table 1 – *Phenomenological classification of electrophonic sounds. The percentage shows the rate of occurrence in the GEFS catalog. According to Keay (1993b), the sounds can be classified as* smooth, staccato, *and* sharp. *This classification would correlate the sound frequency and duration with the meteor ELF/VLF radiation of the same frequency and duration. In our study, we consider the possibility of corona discharge as a source of some electrophonic sounds and apply different classification according to two mechanisms of sound production:* vibration *or* discharge.

sound type	rate	sound description
		classification according to Keay (1993b)
smooth	40.5%	hissing, buzzing, whuss, whoosh, fizzing, bottle rocket, sjhh, pchiu, steam escaping from cooker, sss, swishing, voom, high-pitched whistle, whispering, sheewu
staccato	47.0%	rustling, crackling, wood burning, phtt - like electric arc, sizzling, white noise, shaking bulb with broken filament, zzz, firework, frying bacon, tzz, foam being ripped, like static, lit match, thrumming, small single engine 'Cesna' airplane, butter in hot pan, hot metal in water, cards being shuffled, ice breaking up, electric flutter
sharp	12.5%	pop, thwuck, tic, boom, whump, clap, kweik
		classification according to our study
vibration	51.3%	hissing, buzzing, fizzing, whuss, pop, thwuck, sjhh, tzz, bottle rocket, shaking bulb with broken filament, sss, tic, steam escaping from cooker high-pitched whistle, swishing, small single engine 'Cesna' airplane, whispering, thrumming, boom, whump, voom, sheewu, clap, kweik
discharge	48.7%	rustling, sizzling, whoosh, crackling, white noise, 'htt - like electric arc wood burning, firework, frying bacon, zzz, pchiu, foam being ripped, lit match, butter in hot pan, like static, hot metal in water, cards being shuffled, ice breaking up, electric flutter

In a case of one Perseid meteor, fading of the meteor's trail is described to correlate with the loudness of a sizzling sound that ended with a "pop" (GEFS1995_08_10_01).

Two out of 6 reports of sound before the light maximum are actually marked as 'can not decide', but their audio/video recordings show the sound preceding the final meteor flash (GEFS1998_11_17_04 and GEFS1998_11_17_05). This demonstrates that it is very hard for an observer to make such a time estimate. These two recordings belong to the 1998 Leonids and show that a meteor can induce an electrophonic sound when it has altitude of ∼100km (Zgrablić et al 2002).

The same two 1998 Leonids were also monitored with ELF/VLF radio receivers and there was no electric ELF/VLF signal above 500 Hz during these two electrophonic events. However, such signals were detected from other Leonid meteors during the same observational campaign (Garaj et al 1999). This result is basically confirmed by Shawn E. Korgan from the NASA INSPIRE Team I-01 (GEFS2001_11_18_08). He was recording the atmospheric VLF activity when he heard electrophonic sounds from meteors. The recordings did not show any VLF activity correlated with the sound events. This is consistent with the detection of geomagnetic disturbances below 10 Hz detected during the reentry of an artificial satellite accompanied by electrophonic sounds (Verveer, Bland & Bevan 2000) and with the electric field disturbances below several hundreds of Hz correlated with the activity of 2001 Leonids (Trautner et al 2002).

In 8 occasions, the observers associated meteor fragmentation with an electrophonic sound. Six of these are very transient in duration: "pop", "boom", and "crack". This suggests a sudden

Table 2 – *Distribution of the electrophonic meteor magnitudes. The rate of occurrence derived by Kaznev (1994) is also given. It has been argued by other authors that the low brightness meteors can not produce sustained electrophonic sounds, thus we also show the sound descriptions.*

magnitude range	magnitude rate	rate by Kaznev	magnitude descriptions	sound descriptions
-1 to -5	36.8%	11.3%	-2 or more, not so bright to 2, max -2 to -3, -1 with -3 end flare, -1 in twilight, bright, clearly visible, bright at Sirius, twice Sirius	crackling, sizzling like bacon frying, sizzling “sss”, soft hissing, hissing followed by a crack, ffffffffp, short burst of static, short sharp crack, broken filament shaking in blub, “thwuck”, pop, crackling, swoosh, woosh, high pitched whistle, fizzing with crackling, loud high-pitched hissing, faint hissing, crackled/hissed, pop
-5 to -10	41.3%	19.7%	very bright, -5 or so, -6.5±0.5*, -6 to -7, -5±1*, firework/flare, fireball, seen in evening, -8 to -10, brighter than Venus	“phtt” like electric arc, lit match, steam escaping from cooker, crackling fireworks, sizzling/crackling, “sSHheewwuu”, fizzing/hissing, swishing, hissing, crackling, whuss, pop, “sjhhhhh..”, hiss, sizzling ending with pop, single engine ”Cesna” airplane, like static/crackling, “sss” with a slight “zz”
brigther than -10	21.9%	69.0%	brighter than the full moon, like full moon, bright as moon, extremely bright, lit up the whole sky, lit up the ground, brightest ever seen, -12±1*, -15 to -20, -9 to -13	whistling with buzzing, whisper, sizzling, rustling like a rocket, wood on fire, white noise, thrumming, lit match, “sss” followed by pop, ”voom”, pop, whoosh like rustling, hissing/fizzing

*Absolute magnitude

release of large amounts of electric charge. Considering the mobility of electrons and ions, this burst of charge has to be either in excess of electrons or highly anisotropic (or both) in order to create a net long-range electric field. It remains a mystery, however, why this process does not happen, or at least not with the same energy scale, during any other similar meteor fragmentation in nature.

Another interesting unusual phenomenon related to an electrophonic fireball is reported in GEFS1977_09_00_01: a warm “puff of wind ... towards the end of the duration of the sound”. Similar tactile phenomena like “oscillations and shaking of the air” (Kaznev 1994) or “ oppression of air” (Romig & Lamar 1963) have been reported since the beginning of the history of electrophonic phenomenon. In 1719, Sir Edmund Halley dismissed “hearing [meteor’s] hiss” and “the warmth of its beams” as “the effect of fancy” (Halley 1719).

Appearance of smell simultaneously with a bright meteor has a similar history. There is one (GEFS1969_06_00_01) GEFS report mentioning a smell of sulphur, one of ozone (GEFS0000_11_00_02), and one of “lightning” (probably also ozone) (GEFS1998_08_12_01). Such phenomena have been documented in the electrophonic catalogs (Kaznev 1994). The smell of sulphur and onion was reported during the 1833 Leonids (Olmsted 1833). More recently, a "foul metallic, chemical or sulphurous odor" was reported to accompany the flight of the Tagish Lake meteorite in 2000 (Brown, ReVelle, & Hildebrand 2001). These phenomoena are even more rare than electrophonic sounds. The tactile sensations could be explained by vibrations of human hair in oscillatory electric fields (Carstensen 1986), while the smell comes from the ozone production (and some other chemicals) by corona discharge (Romig & Lamar 1963, Aubrecht, Stanek & Koller 2001). Nevertheless, these explanations remain a speculation since a comprehensive study of those phenomena has never been performed in the meteor astronomy.

2.4. Details about the meteor

Thirty eight reported meteors (events) are identified as *sporadic* (48%), 34 as *Leonids* (43%), 7 as *Perseids* (9%), and one as possible Delta-Aquarid. One of the Leonids is probably misidentified (GEFS1998_11_16_01) because the radiant was below the horizon at the time of the event. The range of electrophonic meteor magnitudes shown in Table 2 is of a special interest for theoretical work since it carries information about the energetics of electrophonic events. The range of magnitudes is divided into three groups: between -1^m and -5^m, between -5^m and -10^m, and -10^m or brighter. Sometimes it is not easy to make a magnitude estimate; thus, we provide their descriptions to show our method. The distribution is compared with the statistical results of Kaznev (1994) who had a sample of 71 electrophonic meteors with known magnitudes.

Our results are clearly different from Kaznev's distribution. Almost 80% of our meteors are not brighter than -10, compared to about 30% by Kaznev. This suggests that our survey is far less biased toward extremely bright meteors, in contrast to all other existing electrophonic catalogues. This is understandable because most of their electrophonic meteors were extracted from catalogues (or reports in the literature) of very bright fireballs. From the theoretical point of view, it is very interesting that the lower brightness limit for electrophonic meteors can be as low as approximately -2^m. One can argue that these meteors can have much brighter absolute magnitude, but their height above horizon clearly shows that this is not the case (one of them is also photographed, see next section). Keay (1992) (see also Keay 1994) argues, in the context of his theory, that electrophones from the -7^m or fainter meteors should be very transient in nature, lasting for a tenth of a second or so. Again, the reports shown in Table 2 demonstrate that this is not the case for many of such sounds.

The velocity of meteors is described as *very slow* in 5 reports (6%), as *slow* in 38 reports (42%), as *fast* in 40 reports (45%), 5 as *very fast* (6%), and one meteor as *stationary* (1%). Meteor fragmentation is reported for 32 events (38%) and it did not occur in 53 events (62%). The distribution of meteor height above horizon, its azimuth, and angle between its path and horizon is shown in Table 3. For comparison, distribution from Kaznev (1994) is also shown. Our statistical sample is big enough to notice some interesting statistical averages.

The distribution of height above horizon of the electrophonic meteors from Kaznev peaks with about 45% in the 30-60^o region. Our survey shows only 30% of meteors in this region. However, 45% of our meteors are above 60^o, while Kaznev reports only 25%. Even though people tend to overestimate this angle, this mismatch is significant because such overestimates appear in both surveys and they are statistically averaged. This suggests that something else is responsible for shifting our distribution closer toward the zenith.

We propose two explanations. The first explanation is that a larger number of smaller meteors in our sample. Indeed, there is a slight increase in the angle for the -5^m to -10^m meteors compared to the -1^m to -5^m meteors, but the statistical uncertainty is too large for any conclusive differentiation. The second explanation is that smaller meteors can not produce a very strong EM signal. This would imply that they have to be closer to the observer, that is closer to the zenith. Since all of our meteors are bright enough to be visible from a large distance, this explanation seems plausible.

However, the azimuthal angle shows a very random distribution of observers around meteors. One quarter of meteors appear in each of four 90^o intervals, which is also noticeable in Kaznev's distribution. The angle between the meteor path and horizon also shows similarity to Kaznev's results, with approximately 50% of meteors with available data in the 0-30^o region, 25% in the 30-60^o region, and 25% over 60^o.

Table 3 – *Statistical analysis of the meteor path in the sky. An event represents one observing site. If an angle is not clear cut between two statistical regions (e.g 30° for the hight above horizon) then the event is counted as 0.5 in both adjacent regions, or 0.33 when spanning over three regions. The results are compared to the values by Kaznev (1994).*

	Angle (deg)	Events	Rate	Rate by Kaznev
Height above horizon	0-30	18.7	23.9%	31.6%
	30-60	23.8	30.6%	43.9%
	60-90	35.5	45.5%	24.5%
Azimuth	315-45(N)	14.3	25.6%	22.4%
	45-135(E)	15.3	27.4%	28.5%
	135-225(S)	15.8	28.3%	22.3%
	225-315(W)	10.5	18.8%	26.8%
Angle between the meteor path and horizon	0-30	25.7	52.4%	44.5%
	30-60	11.7	23.8%	32.5%
	60-90	11.7	23.8%	23.0%

3. Reports of special interest

A couple of reports attract special attention either because they have been extensively documented by observers or they deal with an interesting type of meteor. We present details about the electrophonic sounds from Leonids, a photo of one low brightness electrophonic meteor, and meteors with estimated trajectory. More about all these events can be found at the GEFS homepage.

3.1. Electrophonic sounds from Leonids

The Leonids, and meteors with similar properties like Perseids, are the biggest theoretical challenge in explaining the electrophonic phenomenon. Not only are there low magnitude electrophonic Leonids which disintegrate at altitudes above 80 km, but there are also sustained sounds from the Leonids. A sustained sound should last for a large fraction of a second in order to be perceived as such by the observer. After taking into account their high velocity, we see that the electrophonic signal can start at exceptionally high altitudes of ∼100 km. These altitudes have been also obtained by the instrumental recordings of electrophonic sounds from the 1998 Leonids (Zgrablić et al 2002).

Altogether there are 34 reports of sounds from the Leonids. One report is about the 1964 Leonids, two about 1966, one about 1989, 10 about 1998, one about 2000, 17 about 2001, and two are without a specific year. The sound duration is usually overestimated by the witnesses, thus durations of ∼3 seconds are not surprising. The sound description spans from high-frequency sounds like "hissing", "sizzling", "crackling", "fizz", "swoosh", or "white noise", to low-frequency sounds like "(deep) pop", "boom/popping", or "clap". The magnitudes range from as low as -2^m to "bright enough to light up the ground" or "the whole sky". One case of a -2^m meteor is also described in Drummond, Gardner & Kelley (2000) (GEFS1998_11_17_01).

Details about GEFS1998_11_17_04 and GEFS1998_11_17_05 are available in Zgrablic et al (2002). As already mentioned above, the VLF radio signal did not accompany these two electrophonic meteors, as it did not the meteors in GEFS2001_11_18_08.

The reports GEFS1966_11_17_01 and GEFS1966_11_17_02 represent the first documented report of electrophonic sounds known to us from the famous Leonid meteor storm of 1966. The first observation took place in Texas, USA, from about 5:30 a.m. until 7:00 a.m. local time, when the radiant was 70-80^o above the horizon. According to the witness Willis Jarrel Jr., "the sounds came intermittently from the beginning of the observation until the end". It was not possible to connect particular meteors with the sounds, except in one case of an extremely bright fireball. This demonstrates again the existence of low magnitude electrophonic Leonids. The sounds were lacking directionality.

They are described as "a velvet silky rustling sound like a lady walking in a pleated dress where the fabric rubs against itself" and "some sounded like a short distorted hiss, with a pronounced sibilant tone". These sounds had shorter duration than the one connected to the bright fireball and were described as similar to the other sounds but "lower in pitch and much more edgy and crackling". The witness notes that he has better than average hearing, which explains his experience of a large number of electrophonic sounds. The witness has also provided photos of the observation site (second-story open-air deck on a house). The photos and additional details about the event are available on the GEFS homepage.

He also notes that he woke up and went to a window for no reason, probably because of a "stimulus of some sort". Even though the existence of a "stimulus" sounds unrealistic, this is not a unique report of this sort (Kaznev 1994) and can not be ignored. Possible physical explanation could be that the witness was exposed to frequent bursts of strong electric fields, as implied by the large number of electrophonic sounds. According to laboratory experiments, animals, especially, and humans can be sensitive to the short pulses of electric fields (Buskirk, Frohlich & Latham 1981). Thus the reality of such "stimulus" remains an open question for future research.

The second observation of the 1966 Leonids was from Kansas, USA, from about 1:00 a.m. to 4:00 a.m. local time. The witness recalls hearing approximately 20 "noisy" meteors that night. They sounded like "an electric flutter or sizzle" with one half of a second duration. The magnitudes are described just as "all magnitudes".

3.2. Photo of a low magnitude electrophonic meteor

Electrophonic meteors with magnitudes as low as -2^m make a significant fraction of the electrophonic sound reports (see Table 2). Since they represent a challenge to the theoretical modeling of the phenomenon, here we present a photo of one of them.

The report GEFS1972_04_23_01 belongs to Eisse Pieter Bus from The Netherlands who was performing visual and photographic meteor observations on the night of April 22/23, 1972, at the Observatory of the University of Groningen at Roden. At 01:12:47UT, a -2^m meteor passed through the constellation of Corona Borealis. The meteor was photographed by the camera during a one minute exposure time (see Figure 1). Since Corona Borealis was $\sim$65^o above the horizon at that time, the absolute meteor magnitude was close to the estimated apparent -2^m.

The witness recalls hearing a cracking sound during the whole flight of the meteor in duration of $\sim$5 seconds. The sound did not have direction. "It was in the middle of [his] head like a sound in a stereo headphone". The meteor did not have a light maximum, but it showed "a wake that moved slowly from the left to the right (about 20^o to the left and right). Close behind this wake, but not connected, a persistent trail was visible with a lifetime of about 1 second". The witness emphasized that he has "seen hundreds of bright ... and very bright meteors but [he has] never heard a meteor with a sound nor [he has] seen a meteor with a wake again".

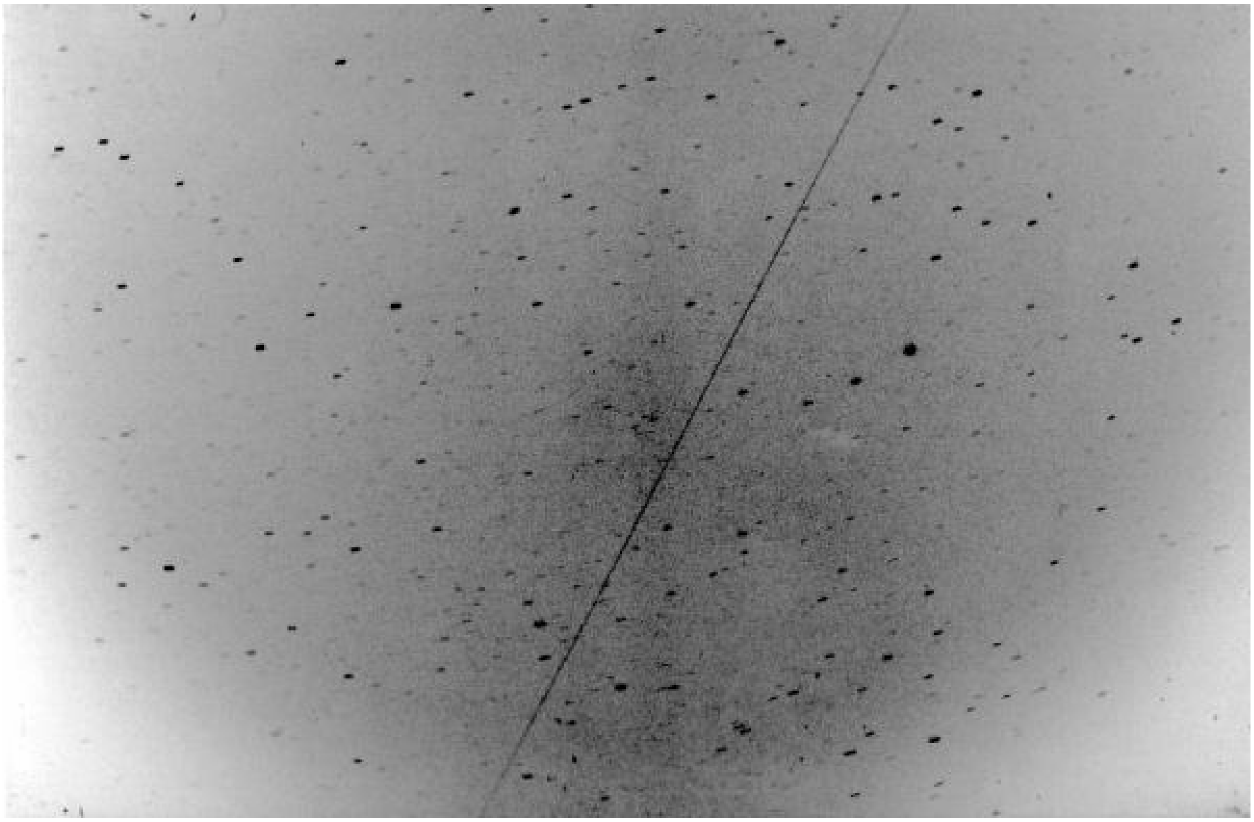

Figure 1 – *A -2^m electrophonic meteor on 23 April 1972, at 01:12:47UT photographed from the Observatory of the University of Groningen at Roden, The Netherlands. The meteor's direction is from South to North, the exposure time was 01:12:17UT - 01:13:17UT with Exa 1a 2.8/50 mm camera and Kodak-Tri-X film with 27° DIN. Courtesy of Eisse Pieter Bus.*

3.3. Fireball over north England, 9 January 2000

The witness reports of this event were collected by Alastair McBeath, who analyzed them and posted the results to the IMO-News e-mail list. All the information presented here are part of these results and published in McBeath (2000). The electrophonic event is cataloged as GEFS2000_01_09_01.

The fireball occured on 9 January 2000, over north England, UK, at around 01:56 UT. The estimated visible trajectory starts above Appleby in Cumbria (54°35'N, 02°30'W) and ends ~10 km offshore due east of Seaton Sluice, Northumberland (55°05'N, 01°15'W). The entry angle was 33±3° from the horizonal, which gives the atmospheric path length of approximately ~110 km, with the mean atmospheric velocity of 22±3 km/s. The estimated brightness was between -15^m and -20^m.

There was several reports of acoustic signals, one of which is recognized as an electrophonic sound. A whoosh sound, "like a rustling", was reported from an observer located on top of a hill called Eston Nab (54°33'30"N, 01°07'W), at the closest distance of approximately ~60 km south-east from the ground track. It is interesting that the noise was associated with the breaking up during the flight when "three large lumps, glowing like red-hot brick" separated off the main body, two of which were significantly smaller than the third.

The Earth's magnetic field in the vicinity of the meteor is useful information for a future theoretical work. The magnetic field components (National Geophysical Data Center, The World Data Center for Solid Earth Geophysics, Boulder, http://www.ngdc.noaa.gov/seg/wdca/) on that day at location 55°N 02°W and 50 km altitude are Z=44,994 nT (vertical, direction down), H=17,181 nT (horizontal), with magnetic declination of 4°46'W (model IGRF2000). Variations from these values along the fireball path are ~1% or less.

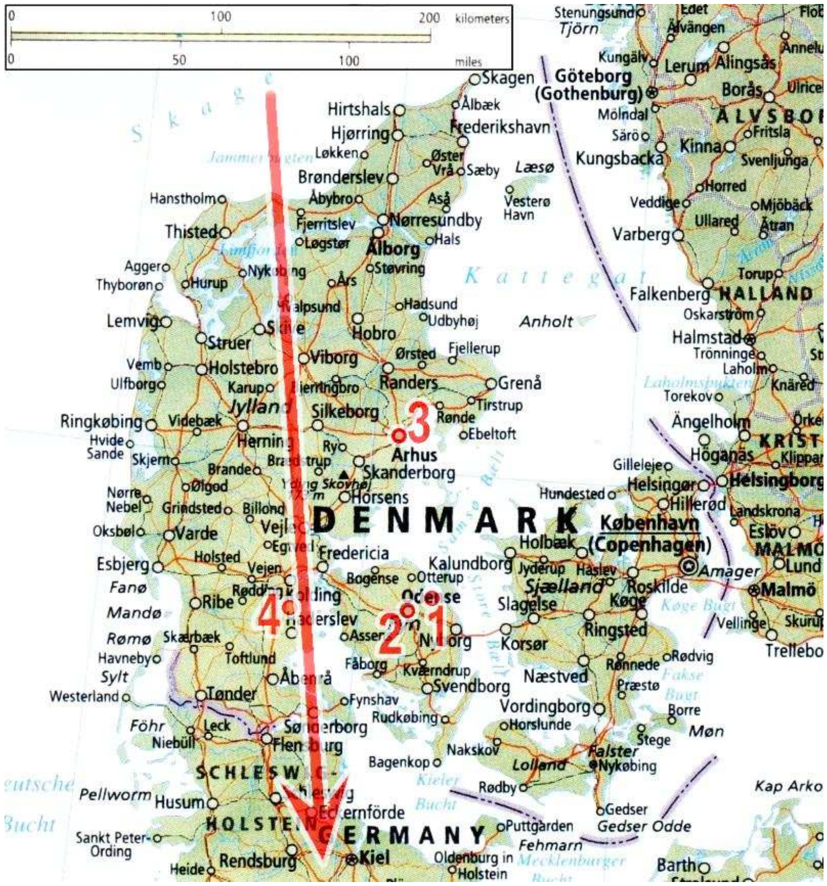

Figure 2 – *Electrophonic fireball over Denmark on 20 December 1999. The ground track is a rough estimate. The electrophonic sound events are marked by points and numbers. See text for their description and more details about the fireball. Courtesy of Holger Pedersen.*

3.4. Fireball over Denmark, 20 December 1999

The witness reports of this event were collected by the Tycho Brahe Planetarium, Copenhagen and provided to Holger Pedersen by its director Bjoern Franck Joergensen. The information presented here was obtained from a statement by the Planetarium and from the IMO-News e-mail list, where several e-mails related to the event were posted. Additional details about the electrophonic sound report were provided to the GEFS by Holger Pedersen and cataloged as GEFS1999_12_20_01.

The fireball occured on 20 December 1999, over Denmark, at around 19:15 UT. The exact trajectory is not determined. According to Lars Bakmann (Meteor Section Astronomical Society, Denmark) the meteor was passing zenith above Sønderborg (54°54'N, 09°47'E) with the azimuth of 170±20° (direction from the north to south). The azimuth favors larger angles, since the fireball was visible from Göteborg (Sweden) and the Oslo area (Norway). The trajectory was very shallow, often described as "almost parallel to the horizon". The altitude is uncertain. If the visible part of the flight started at an altitude of ∼110 km over the sea between Denmark and Norway and terminated at an altitude of ∼40 km above the region of the town Kiel in Germany, the ground track would be ∼400 km, and the angle of flight would be ∼10° with the horizontal. The mean atmospheric velocity was ∼10 km/s. All these numbers are rough estimates, including the meteor's magnitude of -5$\pm1^m$.

Five witnesses at four different locations reported acoustic signals recognized as electrophonic sounds:
(1) observer from Munkebo (55°27'N, 10°34'E) heard "a subdued, hissing sound ... (like) a boat which gently slides through water";
(2) observers from Odense (55°24'N, 10°23'E) heard a hissing sound when "a couple of small peaces detached";
(3) observer from Århus (56°09'N, 10°13'E) heard a faint hiss;
(4) and observer from Christiansfeld (55°21'N, 09°29'E) also heard a hiss.

The meteor ground track and location of electrophonic events is shown in Figure 2. The magnetic field components at 56°N 10°E and 50 km altitude are Z=45,700 nT (vertical, direction down), H=16,594 nT (horizontal), with magnetic declination of 0°01'E (model IGRF95).

3.5. Fireball over Croatia, 3 November 1997

The witness reports of this event were collected by Korado Korlević, Višnjan Observatory, Croatia, and the information presented here is the result of his analysis. When interviewing the witnesses (usually by phone), he recognized electrophonic sound events on several occasions and made a note about their location and the name of the observer but no other details. This fireball is cataloged as GEFS1997_11_03_01.

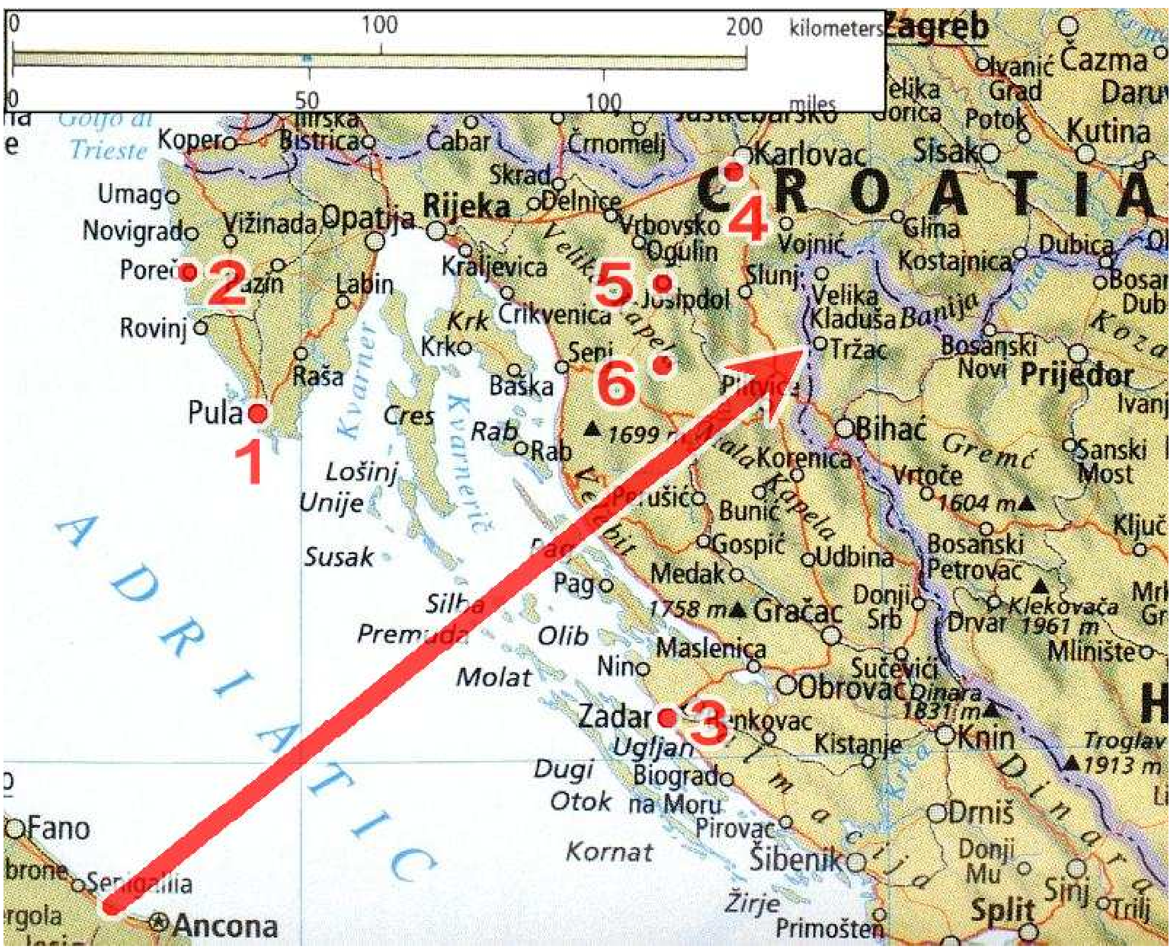

Figure 3 – *Electrophonic fireball over Croatia on 3 November 1997. The electrophonic sound events are marked by points and numbers. Their locations are:* **(1)** *Pula (44°52'N, 13°51'E),* **(2)** *Poreč (45°13'N, 13°36'E),* **(3)** *Zadar (44°07'N, 15°15'E),* **(4)** *Duga Resa (45°27'N, 15°30'E),* **(5)** *Josipdol (45°12'N, 15°17'E),* **(6)** *Dabar (44°57'N, 15°19'E). See text for more details about the fireball. Courtesy of Korado Korlević.*

The fireball occurred on 3 November 1997, over the Adriatic Sea and Croatia at 16:08:20 UT. The estimated visible trajectory starts over the Italian Adriatic coast (43°43'N, 13°13'E), close to Ancona, and ends over the border between Croatia (CRO) and Bosnia and Herzegovina (BH) (44°59'N, 15°45'E) at an altitude of 30-40 km. The angle between the trajectory and horizontal is $\sim$15° with $\sim$250 km of ground track. The meteor displayed multiple fragmentation over Velebit mountain. Fragments burned out quickly except for one of them which continued the flight parallel to the main body. The final fragmentation happened between Drežnik Grad (CRO) and Tržica (BH) with rapid deceleration (duration of the final flight was 3-4 seconds). The mean atmospheric velocity, excluding the final deceleration, was 20-25 km/s. Witnesses described the meteor as brighter than a full Moon.

The electrophonic sounds were reported from six different locations. The sounds are described as rustling or "like a rocket", but there are no details about particular events. The meteor ground path and locations of electrophonic events are shown in Figure 3. The magnetic field components at 44°N 14°E and 50 km altitudes are Z=39,522 nT (vertical, direction down) and H=22,618 nT (horizontal), with magnetic declination of 1°18'E (model IGRF95).

4. Conclusion

The analysis described in this study revealed two important facts: i) electrophonic sounds can appear even for meteors of a visual magnitude lower than previously thought, and ii) the estimated heights where electrophonic meteors enter the atmosphere can reach high values (even 100 km) which has implications on the theories of meteor ELF/VLF generation. From the theoretical standpoint, these new facts demonstrate that very little has changed since the early work in this field in the 1960's (Bronshten 1991).

Moreover, it has become widely accepted that the electrophonic sounds are created exclusively by vibration of ordinary objects exposed to the ELF/VLF electric fields, even though there are experiments which show corona discharge with the same value of electric fields. Thus, the catalogs like GEFS are still very useful and can be used for testing the existing theories.

The most important result, coming from the GEFS witness reports, is the lower limit on the magnitude of electrophonic meteors. The catalogues of electrophonic sounds studied so far have been observationally biased toward very bright fireballs, since such meteors are often individually studied and attract a lot of attention. The brightness limit often cited in the literature is about -10^m for sustained sounds and about -7^m for more transient sounds (Keay 1992, Beech & Foschini 1999). However, Kaznev's analysis of electrophonic meteors already pointed toward the existence of sounds from meteors of magnitude as low as -2^m. The GEFS reports show that such low brightness electrophonic meteors (dimmer than -7^m) really exist and represent a large fraction of the electrophonic sound events; moreover, they can produce sustained sounds instead of only transient sounds.

It is also important to notice that there are Leonids among these low brightness meteors. They ablate at very high altitudes, and sustained sounds from them indicate that the electrophonic effects may already start to appear at altitudes of about 100km. These are also altitudes of the beginning of nighttime ionosphere. This is consistent with the instrumental recording of the electrophonic sounds from the 1998 Leonids (Zgrablic at al 2002). An increase of height above the horizon of meteors in the GEFS reports, compared to Kaznev's results, could indicate that the EM effects from low brightness meteors are not as strong as from very bright fireballs. Presented examples of bright fireballs with the known trajectory show that the electrophonic sounds can be induced even at distances over 100km from the fireball's ground track.

The results presented here are a big challenge for the theory. Any future work will require more expreimental/observational results and multidisciplinary research.

Acknowledgments

We thank the Center for Computational Sciences at the University of Kentucky and the Swiss Federal Institute of Technology Lausanne (EPFL) for providing technical support for GEFS. We are grateful to all the people who sent their witness reports to GEFS. We gratefully acknowledge the extensive data and materials provided by Eisse Pieter Bus, Alastair McBeath, Holger Pedersen, Korado Korlević, and Willis Jarrel Jr. We also thank Cora Allard and Helen Klarich for their assistance in preparing this paper.

References

[1] L. Aubrecht, Z. Stanek, J. Koller, "Corona discharge on coniferous trees - spruce and pine", Europhys. Lett. 53, 2001, pp. 304-309.

[2] M. Beech, L. Foschini, "A space charge model for electrophonic bursters", Astron. Astrophys. 345, 1999, pp. L27-L31.

[3] V.A. Bronshten, "Electrical and electromagnetic phenomena associated with the meteor flight", Sol. Syst. Res. 25, 1991, pp. 93-104.

[4] P. Brown, D.O. ReVelle, A.R. Hildebrand, "The Tagish Lake Meteorite Fall : Interpretation of Fireball Physical Characteristics", ESA SP-495, Proceedings of the Meteoroids 2001 conference, Ed. B. Warmbein, 2001, pp. 497-507.

[5] R.E. Buskirk, C. Frohlich, G.V. Latham, "Unusual animal behavior before earthquakes: a review of possible sensory mechanisms", Rev. Geophy. Space Phy. 19, 1981, pp. 247-270.

[6] E.L. Carstensen, "Biological effects of transmission line fields", Proceedings of a Special Symposium on Critical Emerging Issues in Biomedical Engineering, IEEE, Ed. C. J. Robinson and G. V. Kondraske, New York, 1986.

[7] P.L. Dravert, "Electrophonic bolides of Western Siberia", Byull. Tsentr. Komis. po Meteoram, Kometam i Asteroidam Astrosoveta, Akad. Nauk SSSR, 18, 1940, pp. 1-2.

[8] J.D. Drummond, C.S. Gardner, M.C. Kelley, "Catching a falling star", Sky&Telescope 99, June 2000, pp. 46-49.

[9] S. Garaj et al, "Observational detection of meteor-produced VLF electromagnetic radiation", FIZIKA 8, 1999, pp. 91-98.

[10] E. Halley, "An account of the extraordinary meteor seen all over England, on the 19th of march 1718/9. With a demonstration of the uncommon height thereof", Phil. Trans. Roy. Soc. London 30, 1719, pp. 978-990.

[11] V.Yu. Kaznev, "Observational characteristics of electrophonic bolides: statistical analysis", Sol. Syst. Res. 28, 1994, pp. 49-60.

[12] C.S.L. Keay, "Anomalous sounds from the entry of meteor fireballs", Science 210, 1980, pp. 11-15.

[13] C.S.L. Keay, "Electrophonic sounds from large meteor fireballs", Meteoritics 27, 1992, pp. 144-148.

[14] C.S.L. Keay, "Electrophonic Sounds Catalog", WGN Observational Report Series 6, 1993a, pp. 151-172.

[15] C.S.L. Keay, "Electrophonic Meteor Fireballs Require Further Study", Meteoroids and their parent bodies, Astronomical Inst., Slovak Acad. Sci., Bratislava, 1993b, Ed. J. Stohl and I.P. Williams, pp.315-318.

[16] C.S.L. Keay, "Audible fireballs and geophysical electrophonics", Proc. Astro. Soc. Australia 11, 1994, pp. 12-15.

[17] C.S.L. Keay, P.M. Ostwald, "A laboratory test of the production of electrophonic sounds", J. Acoust. Soc. Am. 89, 1991, pp. 1823-1824.

[18] A. McBeath, "SPA meteor section results: January-February 2000", WGN, Journal of the International Meteor Organization 28, 2000, pp. 232-236.

[19] D. Olmsted, "Observations on the meteors of Nov. 13th 1833", The Acoust. Soc. Am. 89, 1991, pp. 1823-1824.

[20] M.F. Romig, D.L. Lamar, "Anomalous sounds and electromagnetic effects associated with fireball entry", RAND Memo., RM-3724-ARPA, 1963.

[21] S.S. Stevens, "On hearing by electrical stimulation", J. Acoust. Soc. Am. 8, 1937, pp. 191-195.

[22] R. Trautner et al, "ULF-VLF Electric field measurements during the 2001 Leonid storm", Proc. ACM Berlin, 29 Jul - 02 Aug 2002, ESA-SP-500, submitted.

[23] A. Verveer, P.A. Bland, A.W.R. Bevan, "Electrophonic Sounds from the Reentry of the Molniya 1-67 Satellite over Australia: Confirmation of the Electromagnetic Link", Meteorit. Planet. Sci. 35 Suppl., 2000, pp. A163..

[24] D. Vinković et al, "Global Electrophonic Fireball Survey", WGN, Journal of the International Meteor Organization 28, 2000, pp. 48-53.

[25] D.Y. Wang, T.F. Tuan, S.M. Silverman, "A note on anomalous sounds from meteor fireballs and aurorae", J. Roy. Astron. Soc. Can. 78, 1984, pp. 145-150.

[26] G. Zgrablić et al, "Instrumental recording of electrophonic sounds from Leonid fireballs", J. Geophys. Res. - Space Phys. 107(A7), 10.1029/2001JA000310, 2002.

Authors' address

Dejan Vinković, Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506-0055, USA, e-mail: `dejan@pa.uky.edu`.

Slaven Garaj, I.G.A.- Département de Physique, Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne-EPFL, Switzerland.

Pey Lian Lim, Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506-0055, USA.

Damir Kovačić, Cognitive Neuroscience Sector, International School for Advanced Studies, SISSA, via Beirut 2-4, 34014 Trieste, Italy.

Goran Zgrablić, Institut de Physique de la Matiere Condensee, Universite de Lausanne, CH-1015 Lausanne, Switzerland.

Željko Andreić, Department of Materials Science, Thin Films Laboratory, Rudjer Bošković Institute, Bijenička 54, HR-10000 Zagreb, Croatia.