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Progress in Explaining the Mysterious Sounds Produced by Very Large Meteor Fireballs

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Abstract — Strange sounds, heard simultaneously with the sighting of brilliant meteor fireballs many tens of kilometers distant, have been an enigma for more than two centuries. The term "electrophonic sounds" is now widely used to describe them and distinguish them from the normal sonic effects heard after the fireball has passed by. A physically viable explanation for meteor fireball electrophonic sounds has been developed and verified by observation and experiment. The history of this neglected branch of meteor science is presented in some detail, drawing attention to the difficulties which stood in the way of a solution until fairly recently.

Introduction

The entry into the atmosphere of a large meteor fireball is one of the most awesome natural phenomena that a human being can witness without being greatly endangered. The largest and most spectacular meteor fireballs are very rare events, and few people ever see one during their lifetime. For about ten percent (Lamar and Romig, 1964) of those who do witness a very luminous meteor fireball, the mental impression is heightened by strange swishing, hissing and popping noises coincident with its passage across the sky. Such sounds are quite anomalous in that they imply acoustic propagation at the speed of light. This anomaly was first recognized more than two centuries ago, and has defied explanation until quite recently. It is the purpose of this essay to relate the long history of observation of anomalous sounds from bright meteor fireballs, and to recount the course of events which led to a viable physical solution of the mystery.

But first, terminology. For reasons that will emerge, the anomalous sounds heard to accompany the flight of a meteor fireball will from here onwards be called electrophonic sounds to differentiate them from the acoustically propagated booms and rumbles which are heard from seconds to minutes after the light of the fireball has extinguished. Electrophonic sounds should not be confused with the electrophonic effect, otherwise known as electrophonic hearing, which relates to the sensation of hearing arising from the passage of an electric current of suitable magnitude and frequency through the body (Adrian, 1977; Walker, 1988). Also, in the interests of brevity, the word bolide will be used in lieu of "large, bright meteor fireball", since that is its accepted meaning.

History

The first lucid account of electrophonic sounds related to the flight of a bolide originated from China in 817 A. D. At the same time as it was seen, the bolide made "a noise like a flock of cranes in flight" (Astapovich, 1951; LaPaz, 1958). It is very probable that electrophonic sounds were heard in more ancient times. Some of the celestial noises mentioned in the writings of early authors such as Hesiod and in the Christian Bible (for example Acts 2:2) may well have been electrophonic of bolide origin.

There is no doubt about the electrophonic effects of a large bolide seen over England on the 19th of March, 1719. Edmund Halley (1719) reported some eye-witnesses "hearing it hiss as it went along, as if it had been very near at hand," but he dismissed such claims as "the effect of pure fantasy." This rejection is related to Halley's realization, by careful triangulation from many observations, that "they abundantly evince the height thereof to have exceeded 60 English miles", which is far too distant for sound waves to arrive instantly. Halley was one of the first to show that meteors occur at a great height compared to most other atmospheric phenomena and that their velocity was "incredible", being "above 300 such miles in a minute."

During the next half century there were two further accounts of electrophonic bolides in the Philosophical Transactions of the Royal Society (Short, 1740 and Pringle, 1759) and another drawing attention to what now would seem to be electrophonic sounds emitted by an intense auroral display (Derham, 1727).

In the year 1783 a spectacular bolide passed over Scotland, eastern England and part of Europe (for a recent evaluation of this event and its importance to meteor astronomy, see Beech, 1989). Many reports of electrophonic sounds were gathered by the Secretary of the Royal Society, Thomas Blagdon (1784). Blagdon, a former army surgeon who was quite familiar with the delay between the flash and the boom of distant artillery, was, like Halley, perplexed by the simultaneous perception of hissing sounds with the visual appearance of a bolide more than 50 miles distant. He was so convinced of the veracity of the witnesses that he did not reject the anomaly and decided that he "would leave it as a point to be cleared up by future observers." Again, following Halley, Blagdon did a disservice to the subject by suggesting that the sound perception may be psychological through "an affrighted imagination." These conclusions, by eminent men, bedeviled studies of electrophonic sounds for two centuries.

It must be realized that the views of Halley and Blagdon were circumscribed by the limits of existing scientific knowledge: by 1784, Coulomb had not yet discovered the fundamental law of electrostatics, and a further century was to elapse before Hertz demonstrated the existence of radio waves.

Over the intervening period there were a number of inconclusive reports of electrophonic sounds from bolides and similar hissing noises from very bright aurorae. The great Leonid meteor shower of November 13th, 1833, gave rise to many reports of sounds accompanying some of the largest meteors. Denison

Olmsted (1834, 1835), Professor of Mathematics and Natural Philosophy at Yale, gathered many reports and wrote, "The sounds supposed to have been heard by a few observers, are ... represented either as a *hissing noise*, like the rushing of a sky rocket, or as slight explosions like the bursting of the same bodies. These comparisons occur too uniformly, and in too many instances, to permit us to suppose that they were either imaginary or derived from extraneous sources."

About a year after Hertz' experiment, a letter to *Nature* from Samuel Sexton (1885) drew attention to the similarity of sizzling, hissing and buzzing sounds to the affliction of *tinnitus aurium*, suggesting this to be the explanation for auroral sounds.

Even when electric fields and radio waves became well understood, the solution to the problem of instantaneous sounds from bolides remained elusive. The only evidence was anecdotal and the incidence of the sounds remained highly capricious, being sometimes heard by only one or two members of a group of eye-witnesses in close proximity to each other. This feature of the electrophonic bolide sounds, together with their simultaneity with a visual event tens to hundreds of kilometers away, undoubtedly led respected meteor observers such as W. F. Denning (1903) to uphold Halley and Blagdon's judgement, despite the existence of a number of reports suggesting otherwise, such as "While walking in my garden my attention was attracted by a distant hissing sound, and on looking up I saw the meteor" (quoted in Denning, 1903).

Although "W. F. Denning was one of those rare amateur astronomers who achieved world-wide respect and fame in several areas of astronomy ... he is probably best remembered today for his work in the field of meteor astronomy" (Beech, 1990). Therefore Denning's conclusion that "hissing and similar noises ... may be dismissed as imaginary," and is an "observational illusion" (1907) carried considerable weight among meteor scientists. He later likened auroral sounds with electrophonic sounds from meteors, stating, "They are either imaginative or due to causes not directly connected with the phenomena observed" (Denning, 1915).

Such was the climate of opinion when a spectacular bolide lit up the night sky of almost the entire State of Texas on the first of October, 1917. Engineering Professor J. A. Udden of the University of Texas gathered more than 60 reports of the event with the intention of locating its impact point somewhere in central Texas. He noted that "Several parties who saw the bright body at a distance of about 200 miles (320 km) or less, report hearing a swishing or buzzing sound, which seems to have been simultaneous with the appearance of the light." After analyzing nine reports of these sounds, he concluded (1917a), "If these observations are not subjective, the cause of the sound may perhaps be sought in either waves that, on meeting the earth, or objects attached to the earth, such as plants or artificial structures, are in part dissipated by being transformed into waves of sound in the air." His very apt conclusion was evidently prompted by one of the observers who "seems to refer this sound to objects attached to the ground" (Udden, 1917b).

Udden's perceptive hypothesis was not readily tested because of the rarity of electrophonic bolides at any given location. Every few years a report of an electrophonic bolide would appear in a scientific journal and, without first-hand experience of the event, all a meteor scientist could do was to gather and collate such reports. One such was Udden's fellow American, C. C. Wylie, Professor of Mathematics and Astronomy at the University of Iowa, who wrote an article "Sounds from Meteors" in Popular *Astronomy* (1932). In it, Wylie asserted "The explanation is without doubt psychological."

In following Denning rather than Udden, Wylie was undoubtedly influenced by his earlier investigation of the large bolide seen over central Illinois in July 1929. He concluded his summary of that event (Wylie, 1929) with the paragraph "Many letters report a swishing or hissing sound. Some report other noises; but we often have from the same community a definite report that no sound was audible to some one sitting on a porch where everything was quiet. Further, there is no mention of an appreciable interval of time between the appearance of the meteor and the hearing of the sound. In all cases the interval should have been minutes. Hence, none of these sounds can be accepted as from the meteor."

Later, Wylie (1939) embellished his case by lumping electrophonic bolides with other, better founded, examples of psychological errors affecting meteor reports from the general public. He also claimed that persons knowing that a meteor must be fifty or more miles away never report hearing such sounds.

The negative opinions of acknowledged meteor experts such as Denning and Wylie led many meteor scientists to shun the subject of electrophonic bolides. Among the exceptions was H. H. Nininger (1939), one of the first prominent meteor scientists to begin "to regard the matter as a problem in physics rather than psychology" and to "finally become convinced of the reality of such sound where the environment of the observer is favorable." Nininger based his view on the "Many cases (that) are on record where the informants insist that the sound attracted them from behind or within buildings, and, in some instances of daylight meteors, the sound was commented upon before any light was seen or known about."

Nininger had earlier (1934) proposed "that there may be, in connection with meteors, ethereal as well as aerial propagation of sound." In his later paper he revealed, "In 1934, Mr. Elmer R. Weaver of the U. S. Bureau of Standards suggested to me in conversation that possibly ether waves are transformed into sound waves upon striking objects in the environment of the observer." Nininger went on to report that it is a matter of common knowledge among radio engineers that many different kinds of object, in the vicinity of powerful radio transmitters, serve as receivers, "sometimes giving out very good reproductions of programs which were being broadcast." In these instances the radio signals were being rectified by the objects in order to demodulate and produce the audible sounds. Similar speculations involving microwave and millimeter-wave energy were presented by Anyzeski (1946).

Weaver's hypothesis came tantalizingly close to success: it was not accepted for want of evidence of radio signals from even the largest bolides. Nor had he been explicit about his suggested transformation process, so the subject remained open to speculation.

Returning now to the problem of nomenclature, Nininger (1939) proposed "that 'ethereal' be used as a designation for sound produced by the natural transformation of ether waves into audible sound" suggesting that he, too, must have been close to realizing how such sounds may be heard. Soon after, in 1940, Professor Peter Dravert, of Omsk University, introduced the term 'electrophonic fireball' (Bronshten, private communication) and this quite rapidly became the accepted practice in describing such events.

Barringer and Hart (1949), in discussing the mechanism of sounds from meteors, were unimpressed by psychological arguments. After summarizing the "mass of data" available, they concluded that "a meteor's audible accompaniment can scarcely be dismissed as a product of the imagination of the visual observers." They presumed that such sounds were carried by radio waves and estimated that a large bolide could easily dissipate energy at the rate of several gigawatts. Of this high level of energy, the thermal radio wave component was far too weak leading them to consider that the light of the bolide might be modulated at audio frequencies. This, of course, led to severe problems of generation and detection mechanisms quite unknown to science. They retreated to suggesting that the ionized wake of the bolide "may reasonably be expected to give off radiation of the intragalactic type," probably alluding to the early discoveries in radio astronomy of hissing signals of extra-terrestrial origin.

Barringer and Hart's suggestion was taken up in a serious way by Hawkins (1958a, b), who conducted a search for radio emissions from meteors at several frequencies, namely 475, 218 and 30 MHz and also at 1 Hz using a magnetometer. The meteors Hawkins observed had visual magnitudes between -1 and +5. He concluded "Thus it is probably true to state that meteors do not emit radio noise within the frequency range 1 Hz - 500 MHz above the limits of sensitivity of these measurements. Meteors therefore show a surprisingly low efficiency in converting kinetic to radio energy."

In the meantime, the problem of electrophonic bolides was under scrutiny in the Soviet Union. The most notable work was undertaken by Professor I. S. Astapovich, who compiled an extensive catalog of electrophonic bolides and drew several important conclusions from his detailed investigations (Astapovich, 1958): only bolides brighter than -9 absolute visual magnitude produce sustained electrophonic sounds; the majority of reports noted that the bolide trajectories had very small inclinations to the horizontal; and, since all of the bolides were observed at mid-latitudes, their low inclinations meant that they were moving at a large angle to the earth's magnetic field lines. Other Soviet scientists noted that the sharp crack or "peal" sometimes heard is always associated with the disintegration and detonation of the bolide. They considered these sounds to be a purely psychological effect, but accepted the physical reality of other electrophonic sounds from bolides (see Romig and Lamar, 1963, p. 53). The controversy over the nature of electrophonic sounds was contested as strongly among Soviet meteor scientists as it was in Western countries: Academician B. Yu. Levin supporting the psychological explanation, while Astapovich, an ardent defender of the reality of electrophonic sounds, argued in favour of a physical explanation (Bronshten, personal communication).

In a review article, the experienced meteoriticist L. LaPaz (1958) observed that opinion had turned strongly towards accepting with Udden the objective reality of anomalous meteoritic sounds. He attributed this as a possible result of the "ever-increasing amount of prompt, first-hand interrogation of numerous witnesses of large fireball falls" and noted that "several attempts have been made to give rational explanation of their cause."

Such was the situation when the United States Department of Defense decided that the matter should be examined, not least because it was well known from the literature on the subject that Soviet scientists were actively investigating naturally occurring electrophonic phenomena. A contract was awarded to the Rand Corporation, which assigned Mary Romig and Donald Lamar to the work. Their "study was motivated by the possibility that a better understanding of these phenomena will lead to new techniques for determining the size, nature and path of any large body entering the earth's atmosphere" (Romig and Lamar, 1963).

Romig and Lamar's 65-page unclassified report presented 88 references, a catalog of 41 anomalous-sound observations with seven detailed maps (their Appendix A), and a further catalog of 63 Russian observations (Appendix B). Their detailed study of the evidence available was, and still is, essential reading for any student of the subject. However they reached no firm conclusion on the physical mechanism for producing the sounds except to attribute them to an "electromagnetic disturbance," and recommended that "the properties of the plasma sheath and ionized wake should be the subject of further research." Romig and Lamar gave no indication of the generation process other than to state (without a reference) that "the presence of turbulence can greatly enhance normal plasma radiations." As Romig and Lamar's report was inconclusive, many meteor scientists continued to invoke the time-honored psychological explanation for electrophonic sounds from bolides.

At this point it is worth summarizing the difficulties which faced any investigator studying electrophonic sounds, specifically those from bolides:

1. They are rare. Few people have ever heard them, either from bolides, aurorae or lightning. Nor has anyone ever had the good fortune to have had a tape recorder in readiness to record them.
2. They are evidently capricious. Not all witnesses in a group may hear them.
3. Their propagation is instantaneous, implying transmission at the velocity of light, but no electromagnetic disturbance had been known to pro-

duce sound except for electrostatic brush discharges. Such discharges do not propagate over distances of up to 300 km.

4. No electromagnetic disturbance of sufficient magnitude had ever been detected from large bolides or aurorae.
5. The method of conversion of electromagnetic radiation into sound was quite obscure.
6. No physical mechanism was known for the production of strong electromagnetic radiation from bolides or aurorae.

This is where matters stood prior to the initial resolution of the problem published by the author in 1980 (Keay, 1980b).

The Great New South Wales Bolide of 1978

On the morning of 1978 April 7, the dark moonless night sky above eastern New South Wales became as bright as day when a large bolide arriving from the southwest passed over the city of Sydney and headed seaward past Newcastle (Keay, 1980a). Despite the early hour, ninety minutes before sunrise, hundreds of witnesses deluged the news media with telephoned sightings. The bolide reached a maximum brightness of at least -15 mag (absolute) and many observers were temporarily blinded by it.

As usual with such a bright bolide event, there were a number of reports of strange sounds heard while the bolide was in view. At first I rather fashionably dismissed these as a psychological effect, until persuaded otherwise by some clear examples of sounds being noted prior to any visual acquisition of the bolide or its light.

At Rose Bay, Sydney, 20 km from the ground track of the bolide, S. McGrath "Heard a bang before seeing the light. It was like a person in the next apartment slamming a door like a screen door: rather rattley but not loud." This witness had time to get to a window and watch the bolide recede and disappear.

At Edgecliff, Sydney, 20 km from the ground track, A. Hayes "Heard a noise like an express train or bus travelling at high speed. Next an electrical crackling sound, then our backyard was as light as day."

At Vales Point, 40 km from the ground track, J. Ireland "Heard a sound like an approaching vehicle and saw a flash of light (from behind his right shoulder) as everything was lit up like daylight."

At Kotara, Newcastle, 40 km from the ground track, N. Jones heard a noise like a "phut" when the bolide flared, but "It was not loud enough to wake anyone." However a friend standing by the door on the other side of their car heard nothing.

Other impressions of the sound simultaneous with the sighting were "a loud swishing noise"; "a humming sound like a transformer or distant siren"; "like steam hissing out of a railway engine for a count of about ten"; "a swishing sound like the onset of an unexpected high wind"; and "a low moaning, whooshing transcribable on a tape recorder." It is most unfortunate that a tape-recorder was not immediately available to the latter witness.

Publicity surrounding the 1978 bolide elicited recollections from witnesses of earlier bolides, who provided descriptions of simultaneous sounds quite similar to the above examples. It became clear to me that the psychological explanation was not realistic and a physical explanation had to be sought.

The Search for an Explanation of Electrophonic Sounds

Clearly, the transmission of energy from a bolide to the vicinity of an observer of electrophonic sounds must be by electromagnetic means. High electrostatic fields causing audible brush discharges may not be ruled out, but it is difficult for these alone to explain electrophonic sounds heard well over 100 km from the ground track of a bolide travelling at an altitude of only 30 or 40 km. Electrostatic fields produced by meteoroids entering the atmosphere vertically have been studied by Ivanov and Medvedev (1965) who showed that the induced potentials over distances of the order of the scale height may be several hundred volts for large meteoroids, hardly enough to cause electrophonic effects.

Sustained electrophonic sounds accompany bolides in trajectories having very small inclinations (Romig and Lamar, 1963) rather than very steep or vertical paths. In the latter case, sounds of an electrophonic nature are generally of very brief duration.

The work of Hawkins, already referred to, was widely considered to rule out the generation of electromagnetic radiation by meteors, at least at the frequencies examined. However it seemed to me entirely plausible that very large meteors which penetrate low into the atmosphere — bolides — could excite plasma oscillations not possible with the smaller bodies at higher altitude which were observed by Hawkins.

A literature search disclosed instances where bolides produced no electromagnetic radiation at frequencies in the broadcast band and above, up to at least the microwave region of the spectrum (Keay, 1980b). On the other hand, the acoustic effects suggest that the electromagnetic energy may lie within the audible range from 100 to 10,000 Hz, in which case no rectification is needed to detect the signals: simple transduction suffices. There exists no observational evidence ruling out em radiation at frequencies in the ELF/VLF range, so energy transfer in this region of the spectrum was accepted as a working hypothesis, with transduction to acoustic energy taking place close to or within the hearing organs of some observers (Keay, 1979). The response to this idea was mixed: a prominent meteor scientist dismissed it with the words, "Or is this a more fruitful field for psychologists rather than physicists?" (anon., 1979).

At this point, it should be noted that Romig and Lamar (1963) did suggest "that the sound is electrically transmitted and transduced near the observer." Equality of frequency was not implied because they elsewhere employed the word transduction for examples where the em frequency did not lie in the audio frequency range. In a later paper, Romig and Lamar (1964) mentioned the possibility that "perhaps the electromagnetic waves act directly on the brain." But Lamar and Romig (1964) claimed (without references) that "There are also many individuals who report that the sounds seemed to have originated from surrounding objects rather than the fireball." Ingalls (1967) quotes a Cornell Radiophysicist, Dr. B. W. Hapke, who, with his wife, witnessed an electrophonic bolide. He stated, "The hissing and crackling noises were definitely associated with the meteor, although we cannot be sure whether or not they appeared to be coming from the meteor or from all around us."

Evidence for direct transduction of ELF/VLF em radiation into sound has been available from at least two sources. Lightning strokes emit em energy over a very broad spectrum and for many years instances of "vits," "clicks" (McAdie, 1928) "tearing noises" and "swishes" (Cave, 1926) preceding thunder have been reported. The latter are probably due to a rapid increase in the geoelectric field just prior to the discharge (Schonland, 1964), but the sharp sounds are usually coincident with the flash. Similar clicks are said to be heard at the instant of atmospheric nuclear weapon detonations from which the strong em pulse is well studied and known to peak at around 12 kHz (Johler and Morganstern, 1965).

The Electromagnetic Energy Generation Process

A large bolide sheds its kinetic energy at rates upwards of tens of gigawatts. Its luminous efficiency, a function of velocity and composition, is of the order of a few percent. Ionization is of the same order, while the remaining energy is mainly liberated as heat. The extremely high energy density residing in the plasma trail should excite all oscillatory modes possible, including those at frequencies in the audio range (ELF/VLF radiation). The problem is to discover a realistic generation mechanism. One possibility appeared to be through excitation of a hybrid-mode magnetohydrodynamic wave within the plasma of the bolide trail. For a typical ion density of 10^{23} m^{-3} at an altitude of 30 km, the plasma frequency is of the order of 10^{11} Hz, in the microwave region of the spectrum. Ion cyclotron oscillations in the Earth's magnetic field have a very low frequency, about 100 Hz, but they are prevented by the high collision frequency of at least 10^8 Hz.

Turning to the possibility of bulk oscillations in the trail plasma generating Alfven waves, the collision frequency at the above altitude in a fully ionized plasma at a temperature of 5500° K is found to be 1.5 x 10^{12} s^{-1}. This yields a conductivity

$$\sigma = \frac{e^2 n}{m_e v_c} = 7.5 \times 10^3 \,\mho\, \mathrm{m}^{-1} \tag{1}$$

Assuming an effective oscillating column length across the trail of 200 m, and taking, from the chosen altitude of 30 km, a typical value for the trail density of 2 x 10^{-2} kg m^{-3}, the Lundquist number, which determines the likelihood of magnetohydrodynamic wave generation (Alfven and Falthammar, 1963), is

$$Lu = \frac{BL\sigma}{2\pi^2}\sqrt{\frac{\mu_o}{\rho_p}} \approx 0.25 \tag{2}$$

This is quite insufficient, as it needs to be much greater than unity.

In the search for other possible generation mechanisms the production of the pulse of electromagnetic radiation from a nuclear explosion was investigated. Of the principal mechanisms discussed by Price (1974), those involving X- and gamma-radiation may be ruled out for bolides. But the third mechanism, involving the expulsion of the geomagnetic field from the ionized region surrounding the bolide, bears examination.

The ratio of thermal to magnetic energy per unit volume in the plasma sheath of the bolide is given by

$$\frac{3\mu_o\rho_p RT}{B^2 M} \approx 1.3\times 10^8 \tag{3}$$

where the molecular weight M is taken as the standard value of 29 and the strength of the geomagnetic field B is taken as 0.3 gamma (3×10^{-6} G). This indicates that the energy density in the sheath is 8 orders of magnitude greater than the geomagnetic field energy density and therefore the geomagnetic field is easily pushed aside by the bolide.

The geomagnetic field expelled from the plasma sheath surrounding a bolide leaks back into the trail plasma at a rate which may be estimated from skin depth considerations. It can be shown that the expelled field will penetrate the bolide trail plasma in a time no greater than

$$t_p = \frac{\mu_o \pi r_o^2}{2} \approx 5\times 10^{-3}\,\mathrm{s} \tag{4}$$

where r_0 is the initial trail radius which is taken as 1 meter for a magnitude -16 bolide and total ionization is assumed as an upper limit. This result indicates that the geomagnetic field can be expelled only from the first few tens of meters of the bolide trail. The power radiated amounts to no more than $u_m A v$, where **A** is the cross-sectional area of the plasma and v is the bolide velocity. This yields less than 100 watts for a bolide of magnitude -16, a consequence of the trail expansion expending most of its energy doing work against the ambient air pressure rather than against the geomagnetic field. Clearly, the mechanisms which operate to produce VLF radiation from a nuclear fireball are unimportant for a meteor fireball unless it is of comparable size and energy.

As indicated, the initial expulsion of the geomagnetic field is very temporary and the field leaks back into the plasma only a short distance behind the bolide body during the brief interval before the onset of wake turbulence. The re-established field is then controlled by plasma motion provided the magnetic Reynolds number ***Re,*** is well above unity.

Assuming the initial scale size of the turbulence L_p is of the order of the size of the bolide itself, around 1 meter in diameter, the velocity of the turbulent motion v, is one tenth of the velocity of the bolide, and the conductivity has the value given above, the magnetic Reynolds number is

$$R_m = \mu_o L_p v_p \approx 20 \tag{5}$$

This value is adequate for the transfer of the abundant turbulent wake energy into magnetic field energy for as long as the electrical conductivity remains high.

The turbulent motions in the wake have characteristic frequencies upwards of $v_p/2\pi L_p$, around 500 Hz, as energy is transferred to smaller eddies. The turbulence excites vibrations of the geomagnetic field giving rise to the emission of electromagnetic radiation in the ELF/VLF region of the spectrum. A major release of stored magnetic energy occurs when the conductivity falls, due to recombination or electron attachment as the plasma cools and the magnetic Reynolds number falls to less than unity. The twisted and tangled "magnetic spaghetti" then relaxes, releasing its strain energy as vibrations of the geomagnetic field within the earth-ionosphere cavity. These field vibrations have wavelengths of the order of 100 km, corresponding to an electromagnetic wave frequency of **3** kHz.

The above mechanism for the generation of electromagnetic radiation from large bolides is in accord with the observational finding that only very large bolides give rise to reports of electrophonic sounds. Astopovich (1958) claimed that only those bolides having an absolute visual magnitude brighter than -9 produce sustained electrophonic sounds. This empirical criterion has since been upheld by model calculations (Keay, 1992a) based on the need for the bolide to penetrate the atmosphere deeply enough to produce a turbulent wake (see, for example, ReVelle, 1979) in order for geomagnetic field trapping and scrambling to occur.

Soon after the development of the above bolide radiation mechanism by the author (Keay, 1980b) it was confirmed by Bronshten (1983a and b), who showed that a typical electrophonic bolide of magnitude -13 could generate well over a megawatt of radio power in the ELFIVLF region of the spectrum.

Electrophonic sounds have been reported from bolides fainter than magnitude -9. The sounds are usually of brief duration coincident with flaring or an explosion. Under these circumstances the expansion of the plasma fireball, still travelling forward at high velocity, would create the turbulent conditions necessary for the generation of radio waves. Japanese observers (Watanabe, Okada and Suzuki, 1988) have succeeded in photographing a large Perseid meteor (a borderline bolide) which exploded and produced an electrophonic "phut" sound, while simultaneously from two other locations radio records were obtained (see Keay, 1992c). This was a remarkable feat given the rarity and random incidence of electrophonic bolides which makes it very difficult to record their radio emissions.

Turning now to other electrical and electromagnetic phenomena associated with meteor flight, Bronshten (1991) has conducted an exhaustive investigation of such effects, concluding that the problem is far from a solution. Many attempts have been made to investigate electric fields and currents in meteors and their trails without conclusive results. Claims that meteors can produce transient pulses in the geoelectric field (Hopwood, 1989) have not been independently verified.

The Electrophonic Sound Transduction Process

It is common knowledge that high electrostatic fields make dry hair stand on end. Human electrophonic hearing (the direct perception of electrostatic fields varying at audio frequencies) has been reported (Sommer and von Gierke, 1964) but the field strengths required are large: several kilovolts per meter. Tests undertaken in an anechoic chamber with 44 volunteers to check their response at frequencies of 1, 2, 4 and 8 kHz showed quite wide variability between subjects (Keay, 1980c). The findings of Sommer and von Gierke were confirmed for the least sensitive subjects. At the higher frequencies, 4 and 8 kHz, the greatest sensitivity was shown by three subjects (2 female) whose common characteristic was very loose or "frizzy" head hair. Their threshold peak-to-peak electric field strength was 160 V/m. Another subject (male) was found to be 3 to 4 db more sensitive at 2 and 4 kHz when wearing glasses.

These findings point towards external transduction near to the ears as being more effective than internal electrophonic hearing processes. This is borne out by Sommer and von Gierke's observation that it proved extremely difficult to eliminate direct acoustic radiation from the electrodes employed. This was also true in the above tests, which required acoustic insulation to suppress electrode sounds. Later it became clear that such electrically excited sounds were really those being sought! Interestingly, Ingalls (1967) alludes to the same problem in his similar tests, which "failed to produce effects which which could be attributed to other than normal aural paths from 20 to 20,000 Hz."

In the same anechoic chamber, tests were also conducted to check the ability of the volunteers to hear magnetic fields varying at audio frequencies. Up to peak magnetic fields approaching 0.1 mT (the maximum attainable with the equipment available) there was no significant response from any of the subjects.

Later, in another anechoic chamber, tests were conducted to test a number of mundane objects, including vegetation, for their ability to act as transducers

(Keay and Ostwald, 1991). Under electric fields of 400 kV m^{-1} peak-to-peak varying at 0.5, 1, 2 and 4 kHz, samples including aluminium cooking foil and typing paper produced sound levels in the 40 to 60 dB (SPL ref. 20 micronewton m^{-2}) range, while sprigs of casuarina pine and coastal myrtle produced from 10 to 25 dB (SPL). These represent minimal responses because the samples were not shaped or mounted in any special way to enhance their transduction ability. Of course, larger or more extensive amounts of the sample materials could be expected to produce similar sound levels at lower levels of electrical excitation. Furthermore, objects having resonant frequencies of vibration in the audio range would exhibit an enhanced response and color the sounds emitted.

From the above tests it is clear that for mundane objects, which may be close to observers of electrophonic fireballs, their transduction efficiencies may vary by ratios of more than 70 dB (power) accounting to some extent for the seemingly capricious incidence of reports of electrophonic sounds. This is borne out by the loudness range of witness reports, which span acoustic power levels (assuming the transduction occurs close to the observer) from as low as 20 dB (10^{-10} watt), "barely audible hissing"or "like a very faint sighing," to at least 80 or even 90 dB (10^{-3} watt). For example, from quite different locations, three independent witnesses of the 1986 fireball over the south-west region of Western Australia reported "a violent explosion," "very loud sounds" and "a roar" during the passage and about 90 seconds later all heard the sonic boom effects. A collection of over 100 electrophonic sound observations indicates that reports of faint sounds are far more common than loud sounds, suggesting that ambient noise levels mask electrophonic sounds in many instances.

Possibly Related Phenomena

Apart from the instantaneous sound occasionally heard to accompany a lightning stroke, as mentioned earlier, the phenomenon most obviously related to electrophonic sounds from bolides is the existence of many claims of sounds from very bright aurorae. Although their existence is hotly disputed by many auroral scientists, accounts of such sounds date back at least one thousand years (Dall'Olmo, 1980). The whole subject of auroral sounds has been exhaustively investigated by Silverman and Tuan (1973) who conclude "that the observational evidence supports the reality of auroral sounds and that the most likely source of these seems to be brush discharges, and that these are generated by aurorally associated electric fields." This was also the conclusion of a life-long student of such sounds, the late Professor C.A. Chant of Toronto (Keay, 1990). Very large electric fields of the order of 10 kV per meter from intense aurorae have been measured (Olson, 1971) but the equipment he used may well have been unable to rule out a large audio-frequency component of the field. Sixty years ago, Burton and Boardman (1933) reported bursts of VLF emission accompanying flashes of auroral light and there have been many similar observations since then proving that the polar regions of the

Earth are at times a very strong radio source with power levels in the gigawatt region (Gurnett, 1974). Four possible generation mechanisms have been proposed (Gurnett, 1978) and the subject is far from resolved.

An intriguing phenomenon, which may also result in the direct transduction of ELF/VLF electromagnetic energy into sound, is the correlation often reported between strong radio emissions and subsequent earthquakes (Corliss, 1983). A number of reports mentioning a "rushing" sound preceding earthquake shocks were gathered by Milne (1841). More recent accounts of such sounds may be lacking because of greater incidence of similar man-made artifacts reducing public alertness to sounds of seismic origin. However, audio frequency electromagnetic disturbances associated with earthquakes have been discussed in this journal (Parrot, 1990), while laboratory studies mentioned by Johnston (1987), and others, show that rock fractures generate electromagnetic signals. Cress and his coworkers (1987) recorded signals peaking in the range from 900 Hz to 5 kHz. Field studies conducted by O'Keefe and Thiel (1991) during large rock-blasting operations revealed a series of electrical pulses with a repetition frequency as high as 5 kHz and an amplitude of several volts. The substantially greater energy release in an earthquake could be expected to generate signals many orders of magnitude higher in amplitude. The connection has yet to be confirmed between these experimental observations and the alarm frequently exhibited by animals immediately prior to an earthquake and, of course, the sparse reports of earthquake sounds by human observers.

Lastly, a phenomenon which is almost certainly identical to the subject of this essay, was first reported when NASA space shuttles began landing in Florida (Keay, 1985). J. Oberg and D. Potter of the Johnson Space Center began receiving reports of people hearing a "swishing" sound as the shuttles re-entered the atmosphere over northern Texas and Oklahoma. Several attempts to record the sounds and the radio signals were thwarted by mission changes and the Challenger disaster. This quest has not yet succeeded, though the relative predictability of space shuttle re-entries makes the deployment of recording equipment more likely to be rewarded than for random bolide events. The destructive re-entry of large rocket stages also may produce electrophonic sounds: such a report was forthcoming from one of the witnesses (D. Deane of Townsville, QLD) to such an event over north Queensland on the early morning of 31 July 1992, when the Cosmos 2204 rocket reentered the atmosphere.

Conclusions

Physically acceptable explanations have now been found for each stage of the transfer of energy at luminal speed from a bolide to the ears of a witness. The explanations are, as yet, far from exhaustive, and there is ample scope for further investigations. In particular, there is need for a comprehensive treatment of the "magnetic spaghetti" radio generation mechanism taking turbulent plasma processes fully into account, and a need for thorough analysis of the acoustic response of mundane physical objects to impressed electrical stress.

The collection of high-quality observational data is an important priority. The difficulties of capturing records of bolide events are quite formidable given their rarity. Also important for correlation with synoptic ELF/VLF records are catalogs of electrophonic observations for which the times should be as accurate as possible. This has long been recognized by Russian meteor scientists who have now published five catalogs containing over 600 observations of electrophonic bolides (Bronshten, 1991). The only such catalog of Western origin is contained in Romig and Lamar's (1963) comprehensive study, although a new catalog containing more than one hundred entries has been assembled and is shortly to be published by the author in the WGN Report series of the International Meteor organization (Heerbaan 74, B-2530 Boechout, Belgium).

A limited search, with negative results, was conducted by Wang, Tuan and Silverman (1984) using data collected from a VLF monitoring station at Thule, Greenland. The distances from the bolide events were large and the frequencies examined were probably too high. There is a pressing need for better radio observations of bolides known to have been associated with confirmed reports of electrophonic sounds.

Lastly, it is essential for geo-scientists to take reports of audible phenomena more seriously in order that some progress can be made in identifying the physical mechanisms involved. The subject of electrophonic sounds from bolides is now considered respectable within the meteor science community (Keay, 1992b), and a similar shift in acceptance is now overdue within the communities of auroral and seismic scientists.

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