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ANOMALOUS SOUNDS AND ELECTROMAGNETIC EFFECTS ASSOCIATED WITH FIREBALL ENTRY

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The RAND Corporation
SANTA MONICA • CALIFORNIA

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PREFACE

The problem of the nature and origin of certain hissing sounds and electromagnetic effects associated with the passage of very bright meteors or fireballs has long been of interest to meteor astronomers. This Memorandum describes these effects and discusses their possible origin from the standpoint of atmospheric electricity and re-entry physics. This 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.

SUMMARY

Observers located as much as 300 km from the ground trace of bright fireballs have reported hearing swishing sounds simultaneously with the fireball passage. These sounds are anomalous because the geometry of fireball path and observer locations requires that the effect producing the sound sensation be propagated at the speed of light. The great number and striking similarity of these sound reports, which have appeared in the published literature for several centuries, are difficult to attribute to coincidence or psychological suggestion.

Sound-producing fireballs are extinguished at lower altitudes and are brighter than ordinary meteors. These fireballs deposit kinetic energy at altitudes below 30 km at rates on the order of at least 10^{16} ergs/sec. The description of the anomalous sounds as a hissing or crackling and rare reports of odors which may be ozone suggest that the sound is associated with electric discharges. Other electromagnetic disturbances occur during fireballs, such as deflection of compass needles, induction in long lines, and radio interference. Similar anomalous noises and electromagnetic effects have been observed during strong auroral displays and near lightning discharges.

The most plausible explanation of the anomalous sounds is that they are caused by electric discharges near the observer. These discharges may be the result of perturbation of the geopotential gradient by the fireball. It is also possible that the anomalous sounds are due to strong electromagnetic radiations from the fireball which are transduced by natural objects, perhaps even the human ear.

The two catalogs appended to this Memorandum contain examples of anomalous sounds and electrical disturbances and provide the basis for many of the conclusions reached herein.

ACKNOWLEDGMENTS

The authors wish to acknowledge the assistance given to them by members of the meteoritics profession who suggested items which should be included in the catalog; in particular, they are indebted to Lincoln LaPaz of the Institute of Meteoritics at the University of New Mexico and John Russell, Chairman of the Department of Astronomy at the University of Southern California. They are grateful to Richard McCrosky of the Smithsonian Astrophysical Observatory for his critical review of an early draft of this Memorandum and for discussions involving the fireball network. They would also like to acknowledge many valuable discussions with Peter P. Wegener of Yale University, a RAND consultant, who contributed a translation and interpretation of the Treysa fireball, as well as other items from the Astronomische Nachrichten. F. D. Drake of the National Radio Astronomy Observatory, Green Bank, West Virginia, kindly furnished copies of letters reporting anomalous sounds from the Virginia fireball of September 1, 1962.

CONTENTS

I. INTRODUCTION

An exceptionally bright meteor, or fireball, is a rare, unpredictable, spectacular event of short duration. Its flight through the atmosphere is accompanied by vivid visual and auditory phenomena. It is necessary to interview untrained observers to obtain information on the fireball trajectory and radiant and to locate any meteoritic debris. Their estimates of height, flight direction, and time can thus be adversely affected by the magnitude of unexpected stimuli. The fireball network being set up by the Smithsonian Astrophysical Observatory in the Midwest should obtain more reliable information in the future.

If a fireball explodes during flight, the position of the body at the time of the explosion can be estimated if the time interval between the light flash and the noise is known. This point usually coincides with the last visible light and hence provides a fix on the downrange area of possible meteoritic fall. Witnesses are often asked, therefore, if they heard any noises associated with the fireball. Low-frequency sounds such as detonations and shock waves (sonic booms) are the most common noises reported. Allowing for local winds and terrain, these sounds are always heard at the time, and with the intensity, appropriate to the observer's distance from the flight path. Some observers also describe a swishing or crackling sound heard simultaneously with the passage of the body. Since these persons are many kilometers from the flight path, the sound-producing effect must be transmitted at the speed of light. Considerable controversy has arisen concerning the reality of these anomalous sounds. Since we must rely for the most part on published information (which may not always be unbiased), it is impossible for us to prove that the anomalous sounds are real. Moreover, we cannot rule out the chance that the sounds were coincidental to the fireball. If, however, the sounds are indeed associated with the fireball, their simultaneity demands that some form of electromagnetic disturbance be involved. Such a disturbance could be due to passive radiation from the fireball or interaction of the fireball plasma with the geofields. It is of obvious interest to the field of re-entry physics that such a phenomenon be investigated.

This Memorandum presents the first part of such an investigation. Appendix A is a catalog of anomalous-sound observations. Appendix B is a translation of a catalog of Russian observations, prepared by Lyubarskiy.(1) Lyubarskiy's catalog is a revision and extension of a catalog compiled by Astapovich,(2) in which all reference to non-Russian and pre-twentieth-century observations has been deleted.

From these catalogs we are able to summarize the sensory and electromagnetic events surrounding a "typical" sound-producing fireball. In an attempt to understand the mechanism which produces the hissing sounds, we have reviewed information on the noises and electromagnetic disturbances associated with lightning, aurorae, and ordinary meteors. Previous theories of fireball sounds are also reviewed, and a promising mechanism is discussed briefly.

It will become evident throughout this Memorandum that further study is necessary to determine the physical environment of the fireball in flight. This includes the volume, extent, and conductivity of the plasma surrounding the fireball; the interaction of the plasma with the geofields; and the nature of the sound produced by corona discharges, its dependence on voltage gradient, and decay with distance.

II. FLIGHT CHARACTERISTICS OF SOUND-PRODUCING FIREBALLS

A schematic view of the flight path of a typical sound-producing fireball is shown in Fig. 1. The heights, velocities, path angles, and visual descriptions discussed below are the average values for the meteors listed in Appendix A.

Light is first produced when the body encounters the atmosphere at point A at an altitude h_1. There is always a large scatter in the values of h_1 for a given fireball, because observers are rarely looking at the sky and do not see the fireball until the light illuminates the surrounding area. Still others may have their vision obscured by nearby objects. Wylie(3) has pointed out that observers tend to extrapolate back up the trajectory and see a longer visible flight path than that actually existing; furthermore, the estimates of angular height are generally too high.(4) Wylie estimates the average altitude at point A as $h_1 = 80$ km. The average for the present catalog is $h_1 = 112$ km.

The meteor velocity at entry can vary from 11 km/sec to 72 km/sec for members of the solar system. Velocities obtained from observation are mean values, estimated by dividing the path length by the elapsed time. Since both these quantities are prone to error, fireball velocities are not reliable. We find, however, that there is no preferred velocity range for sound-producing fireballs; the catalog contains velocities as low as 8 km/sec for the Chant Procession and as high as 61 km/sec for the Missouri fireball of 1950. The average mean velocity is 24 km/sec.

The entry angle γ is usually fairly small for brilliant fireballs; the average value of γ for the fireballs listed in the catalogs is between 27 and 31 deg. The fireball proceeds along this flight path in essentially a straight line, becoming brighter as more kinetic energy is lost during penetration into the atmosphere. Sound-producing fireballs vary from -6 magnitude, which lights up the locality, to -20 magnitude. (The magnitude of the full moon is -12; that of the sun is -26.) Astapovich found an average magnitude of -18 for items

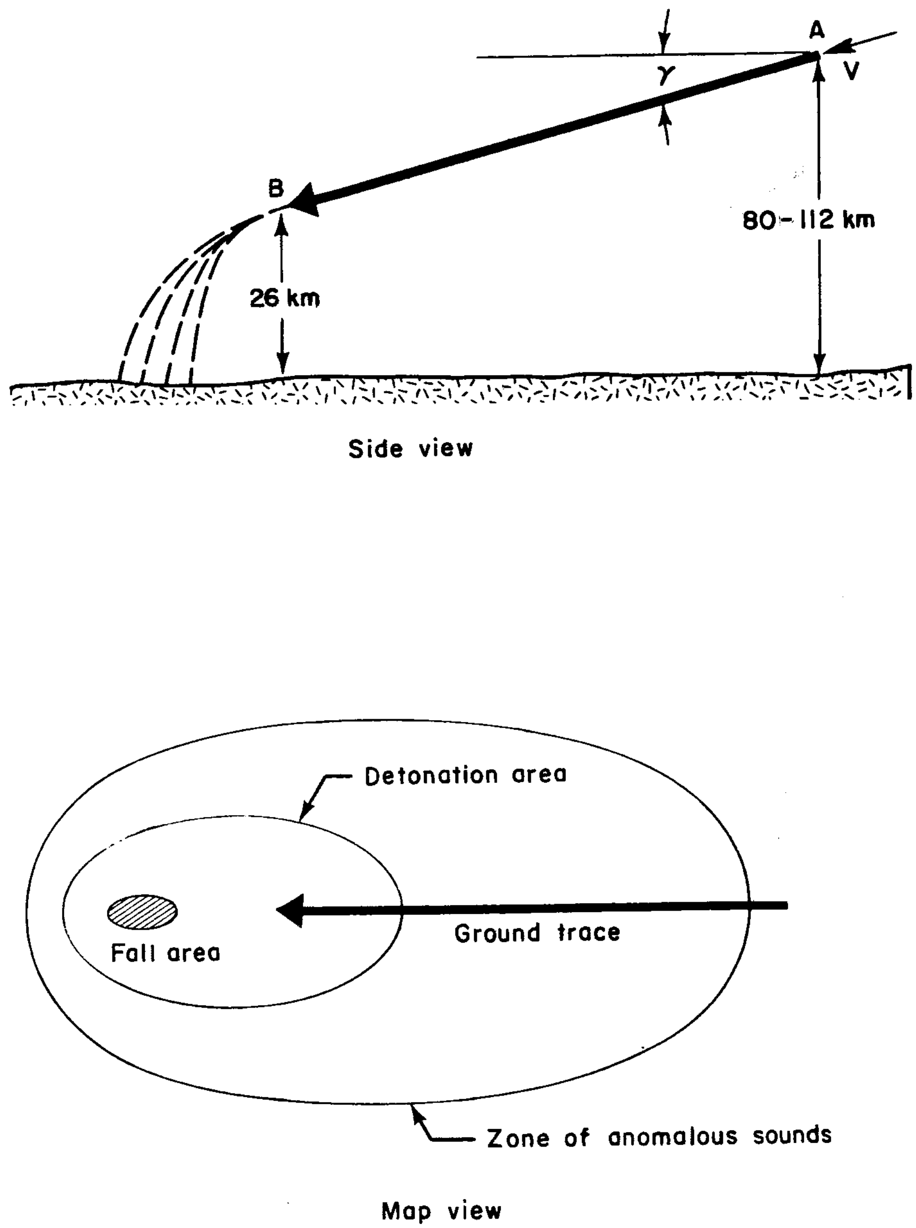

Fig. 1 —— Trajectory and distribution of sounds for a typical anomalous-sound-producing fireball

in his catalog.[2] The average brightness for the items of Appendix A is -13 magnitude.

Near the end of the luminous flight, fireballs often explode or flare up. The reasons for this are not clear; it could be due to internal stresses from heat, or to a sudden increase in dynamic pressure as the body reaches peak deceleration. Some sound-producing fireballs explode more than once, and the resulting fragments continue in flight. The average height of extinction for the sound-producing fireballs listed in Appendix A is 26 km. According to the Olivier catalog[5] the average extinction height for ordinary fireballs is 40 km, and a zeroth-magnitude meteor is extinguished at an altitude of 60 - 80 km.

At maximum brightness, sound-producing fireballs are predominantly blue or blue-white, which suggests that ultraviolet light is also being radiated. It is suspected that the far-ultraviolet radiation from the hot gas cap produces a large photoionization halo around a blunt shape during entry.[6] During the later stages of flight the radiation intensity usually diminishes, and the color gradually changes to red. In cases where the fireball flares or explodes, the light often disappears abruptly; in other cases, dark pieces have been seen falling.

About 67 per cent of the fireballs in the present catalog leave a smoky trail of ablated material. Some of the trails have endured long enough to be photographed.[7] Although Astapovich[2] concluded from his catalog that "most" sound-producing fireballs had trails, Lyubarskiy[1] shows only 38 per cent with trails in the revised catalog of Appendix B.

The fireballs listed in Appendix A have no preferential flight direction, although most (65 per cent) fly in a general east-west or west-east direction. Both Lyubarskiy and Astapovich found a strong tendency for flight from the south.

Sound-producing fireballs differ from ordinary fireballs and meteors in brightness and extinction altitude, which would imply that the solid bodies associated with these fireballs are larger than ordinary. Because they have a longer flight time and penetrate farther into the atmosphere, their kinetic energy is deposited at lower altitudes. For example, a Perseid meteor of -3 magnitude will lose kinetic energy at a rate of 2×10^{15} ergs/sec, but this is deposited at altitudes above 60 km in the ratio, heat: light: ionization = $10^4 : 10^2 : 10$, according to Greenhow and Hawkins.[8] The flight is in free-molecule flow; the brightness is proportional to the rate of mass loss, since it comes from direct impact of hypersonic air molecules with ejected surface material. Very little kinetic energy is lost due to drag.

On the other hand, because of its size and velocity, a fireball such as that produced by the Norton-Furnas meteorite will be in continuum flow during its luminous flight. The kinetic-energy loss is due primarily to drag. This meteorite is a blunt cone of elliptical cross section, with a volume of 0.334 m^3 and a mass of 1070 kg. Its average flight velocity was 9.25 km/sec.[9] If we assume that the size of the body at entry is the same as that of the final mass and use the average velocity, a conservative estimate for the rate of kinetic energy lost due to drag is 1.8×10^{12} ergs/sec at 50 km of altitude, and 10^{16} ergs/sec at 11 km, where an explosion occurred. The relative proportions of energy deposited in heat, light, and ionization are not known. The ratios given above for bright meteors should, however, be significantly altered because of the efficiency by which the shock wave can convert kinetic energy into heat and subsequent ionization. The ion concentration and conductivity of the plasma surrounding the fireball will be increased. The nature of the plasma is of primary importance in determining if interactions with the geofields or electromagnetic plasma radiations contribute to the anomalous sounds.

III. SOUNDS HEARD DURING A FIREBALL EVENT

One of the earliest recorded instances of anomalous sounds was found by Biot and Rémusat during the course of translating the Chinese chronicles of Ma-Tuan-Lin into French. Astapovich describes this noise reference as similar to that of a flock of geese in flight, heard simultaneously with the passage of a large fireball.[2] Although such instances of anomalous sound appear throughout early and medieval history, it is generally agreed that such evidence is subject to distortion by repetition and the passage of time. The reliability of documented evidence increased when meteoritics became an observational science midway in the nineteenth century. The growth of meteoritics as a science was aided by some phenomenal showers, which encouraged observation and dissemination of information. Both the Lyrid shower of 1803 and the Leonid shower of 1833 were descirbed in great detail,[10] primarily because the origin and nature of meteors were unknown.

At the beginning of the twentieth century, scientific investigation of fireballs was increased in an attempt to locate more of the associated meteoritic fall. The literature shows a corresponding increase in anomalous-sound reports. This was accompanied, however, by a growing tendency on the part of the investigator to disregard such sounds because they were seldom heard by "good" observers.[11] Furthermore, such sounds were inexplicable by the laws of sound propagation. We therefore find a decrease in detailed information of sound observations; i.e., the investigator will sometimes mention that such noises were heard, but the locations of observations relative to the flight path are generally not given. The incompleteness of the anomalous-sound reports and the possibility that such observations have even been omitted have severely hampered the present investigation.

Figure 1 shows the surface locations where the various sounds are hear during passage of a fireball, in relation to the flight path. The anomalous sounds, which appear to propagate at the speed of light, are heard in two general locations. The first type is heard simultaneously with the light, over the entire luminous trajectory. This sound is described as a hissing, swishing noise varying in intensity from a sizzling and spitting, similar to the noise made in arc welding, to the hiss made by plunging hot iron into water, and to a faint "sh-sh" or buzzing. The second type of anomalous sound is heard only by observers who are directly under the flight path at the time a fireball explodes. These sounds are described as sharp crackling and sputtering noises and as popping similar to gunfire.

The distribution of observers reporting the first type of anomalous sound is shown in Fig. 2 for those cases in Appendix A where the location was available. The positions in Fig. 2 are plotted relative to the direction and the end point of the trajectory. Because of the lack of data, it is not known whether or not the noise intensity is a function of distance. The scale of distances in Fig. 2 illustrates clearly that these sounds cannot be propagated at normal sonic velocities. Notice also that the reception of anomalous sounds is not directional in nature, with respect to either the flight path or end point, in this normalized plot. Maps in Appendix A illustrate the observer locations with respect to the actual trajectory for seven of the better-documented fireballs. Although the data are scarce, the maps indicate no predominant relationship among observer location, flight path, and local magnetic-field lines.

Because of insufficient data, it is impossible to discover any correlation between the observer's environment and the reception of anomalous sounds. For example, the weather conditions at the time of the fireball are rarely mentioned, except to indicate the extent of cloud cover. An exception to this is the detailed report by Olmsted of the Leonid shower of 1833.[10] Since many of the early observers believed the meteors to be some electrical phenomenon, similar to aurorae, they made measurements or took careful note of the local electric and magnetic conditions. Study of the letters reproduced by Olmsted shows that an unusual amount of static electricity was present at the time of the shower. The weather was very dry and cold, and silken clothes gave off sparks when rubbed; a gold-leaf electrometer could be charged merely by hand contact. Several cases of anomalous sounds were reported; whether the electrical conditions were a conse-

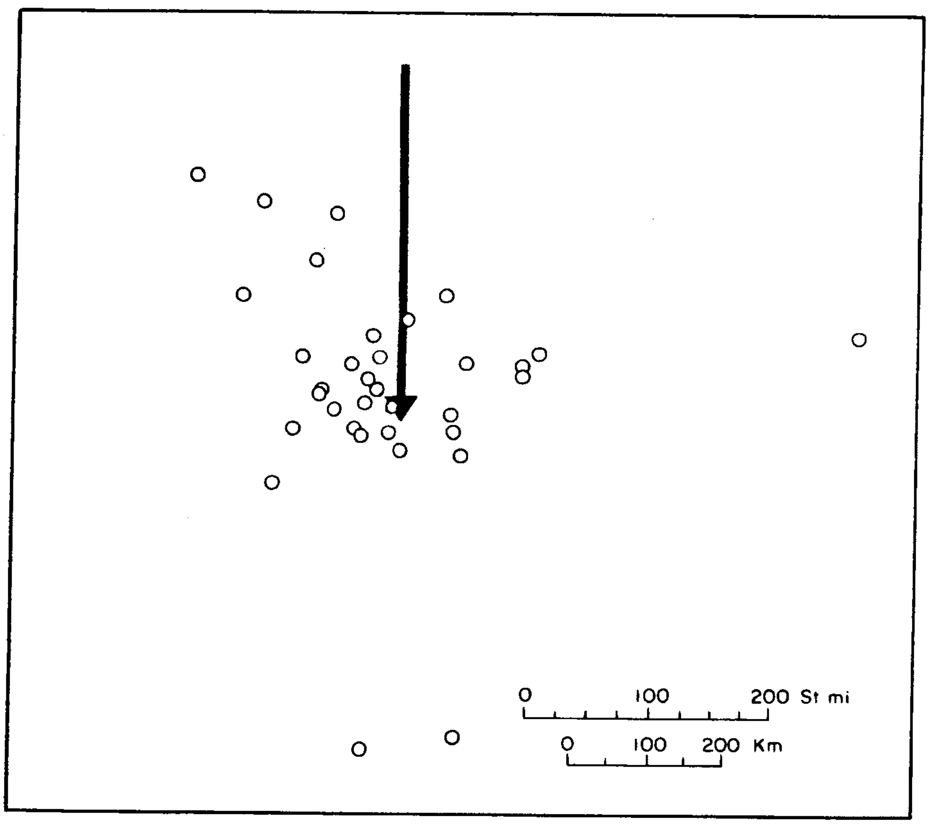

Fig. 2 —— Map view showing distribution of anomalous swishing sounds with respect to fireball path and end point for the sufficiently documented fireballs listed in Appendix A

quence of the shower, a necessity for hearing the sounds, or were a coincidence is not known.

People have heard anomalous sounds while inside buildings, as well as in the quiet countryside. Sometimes the sounds are so intense that they are heard over other noises. The sounds do not always appear to come from the fireball, for some astute observers have reported that the noise apparently originated from the surrounding vegetation. Dravert has called this type of anomalous sound "electrophonic."(2) He suspected that simultaneous sounds are associated with all meteorite-producing fireballs, only that not all observers heard them. In fact, he believed that it was probable that all fireballs which are extinguished at low altitudes produce some anomalous sounds.

Because of the speed at which the sound is received, it is obvious that in order for there to be a physical connection between the fireball and the noise, there must be an electrical phenomenon which is somehow transduced into sound. At the present time, there is no clear mechanism for the origin, propagation, and reception of the noises, although many theories have been proposed. In fact, it is not generally agreed that such sounds are real. For example, many people, unaware of the distance of the fireball, expect to hear a noise and seem ashamed to admit they did not.(11) Perhaps a good percentage of the observers reporting hissing noises did so because of this psychological suggestion.

On the other hand, there are many cases where observers claim that the hissing noise attracted their attention to the fireball. For example, Sellards(12) quotes one observer of the Texas meteor of June 23, 1928, as being stooped over, fastening the lower wire on a barbed-wire fence. He heard a whizzing like that of an airplane with the engine off. On looking up, he saw the flash of the meteor. Another observer was attracted by a "shhh" sound. A woman 24 km from the ground trace was lying in bed near a window and heard a whine at the time of passage. Nininger(4) discusses the case of an equipment dealer who, while indoors, heard a noise like an airplane in a steep bank and rushed out in time to see the fireball.

Instances have occurred where the second type of anomalous sounds has also called attention to the fireball. As an example, the Delaware County (Iowa) fireball of November 1909 appeared in late afternoon and passed between Manchester and Dyersville, Iowa. In both of these places the attention of observers was attracted skyward by the loud cracking noises which accompanied the flight.(13) An observer in Manchester stated explicitly the following time sequence for the sounds: "Just as the meteor passed over our heads we heard an awful cracking sound, and in about two minutes a loud roar and an awful sound like distant thunder."(13) Unfortunately, the fireball was not seen well enough to determine a trajectory.

Lyubarskiy(1) and the present authors question whether the second type of anomalous sound is truly anomalous. The noises may arise from multiple explosions and only appear to be simultaneous. If the body is undergoing continued fragmentation, an observer could hear one explosion and see another at the same time. Observers in the detonation area of the Kybunga fireball heard (1) a loud explosion, (2) a roll like thunder and a whistle like a rifle bullet, and (3) nine more explosions like a motorbike backfire, accompanied by puffs of smoke, which appeared to be simultaneous to the passage of the fireball.(14)

Furthermore, an observer located in the zone directly under the flight path at the time of explosion is subjected to unusually strong stimuli for a short time. It has been established that if a person is exposed to a sudden strong impulse such as a brilliant flash of light, he may experience a clearly audible internal noise of low frequency.(15) The intensity of the explosion could also cause some confusion as to the order of events, as well as a psychological compression of time, especially if the witness is not interviewed immediately.

None of these explanations, with the possible exception of multiple fragmentation, account for the cases where observers are alerted to the fireball by a cracking noise. These cases are included in the catalog, although there remains some doubt as to their true nature.

The other types of noise which accompany a fireball can be interpreted as being propagated at the velocity of sound. Observers in the detonation zone of Fig. 1 hear, after a suitable time interval, noises described as thunderclaps, cannon shots, or rumblings. These noises are detonation waves and are often followed by a roar which seems to move back up the trajectory. If the fireball is not seen, this can cause an 180-deg shift in the reported direction (see, e.g., Ref. 13). Wylie[11] suggests that this roar may in part be echoes from objects near the observer and multiple explosions. Such an apparent sound reversal in the flight direction may result if the meteor flight is supersonic; a similar phenomenon can occur during a low-altitude pass of a supersonic jet.

In the zone marked "fall area" in Fig. 1, observers sometimes speak of buzzing sounds. In some cases such noises are clearly caused by meteorites that are falling with subsonic velocity; witnesses have mentioned hearing the noise, then looking up to see dark shapes going past. For example, Wylie describes the fall of the Tilden (Illinois) meteorites: "Following the detonations, a roar like a tornado or earthquake rolled away...falling stones made a hum like an airplane flying high."[16] Notice here the reference to the roar following the detonations, as well as the time interval between the detonations and the noise of the falling stones.

In addition to light and sound, other sensory phenomena have been observed during fireball events which may have some bearing on the mechanism that produces anomalous sounds. Observers in the fall zone sometimes report smelling the odor of sulfur. It is unusual to find such reports from people distant from the fall area; however, Udden mentions that observers reported the sensation of heat, the odor of sulfur, and the odor of burning powder, and one commented that "it felt like a slight electric shock" as the fireball passed.[17] A group of four observers of the Leonid shower of 1833 reported that a number of slight explosions were heard (like a popgun). All four claimed the sounds were followed by a peculiar odor like sulfur or onions.[10] Astapovich attributes the smell of sulfur to ozone.[18] He cites many instances from the seventeenth to the nineteenth century in which witnesses noticed this odor and says that the phenomenon was observed in connection with the fireball of July 13, 1952, in the Voronezh region. Ozone and nitrous oxide are produced during electric corona discharges in air. These discharges are usually accompanied by hissing sounds caused by the breakdown of the surrounding air. When the voltage gradient increases so that the sparking potential is approached, crackling sounds are produced. This combination of sound and odor suggests that the anomalous fireball sounds may be produced by local electric discharges.

In addition to the report by Udden, the only other mention of heat is in connection with the Tunguska explosion in Siberia. The Tunguska event of June 30, 1908, was of such magnitude that it can hardly be considered an ordinary fireball. The trajectory, velocity, and origin of the explosion are unknown. It has been suggested that the explosion was due to a fireball or a comet,[19] and it was even speculated in the popular literature that the explosion was nuclear.[20] Intense heat was felt over a distance of 75 km. Anomalous sounds were heard in Keschma, over 100 km from the flight path.[21] The shock was traced as far as England, and the detonation was strong enough to be recorded on a seismograph at Irkutsk Observatory.[22] The geomagnetic field measured at the Observatory was disturbed two minutes after the explosion in much the same manner as by a nuclear burst.[23]

IV. ELECTROMAGNETIC DISTURBANCES DURING FIREBALL EVENTS

Astapovich calls the various electromagnetic phenomena observed during fireball passage "meteorelectric" and "meteormagnetic."[18] Electromagnetic effects could arise, for instance, if a net charge accumulated in the trail of the fireball. The charged trail could perturb the earth's electric field in much the same way as a thundercloud. Lightning, ball lightning, and St. Elmo's fire might be seen, and local discharges could occur on the vegetation. It is also possible that motion of the plasma around the fireball through the earth's magnetic field could induce ground currents which would cause perturbations in the magnetic field. Also, electromagnetic radiation could result from acceleration of charged particles in the trail. Each of these mechanisms could cause radio static and a variety of electromagnetic effects.

There is a paucity of evidence that meteorelectric disturbances occur during fireballs. Astapovich reports a few instances which he attributes to St. Elmo's fire or ball lightning: The first occurred during the fireball of November 29, 1662 (old calendar), near the village of Novye Ergi, in which "fire fell to the earth in many places and on the roads and dwellings like burning ropes, and people ran from it and it rolled after them..." On November 12, 1761, many people saw "fire around and near them" during the flight of a large fireball near Dijon, France. The Mazapil, Mexico, meteorite was accompanied by fine sparks: "the corral was bathed in luminescent light and there were small sparks in the air...which gradually disappeared."[18] In the first example the "fire" behaved like ball lightning, when it "rolled" after the people. The second item is so vague that the "fire" could be attributed to reflected light. In the third, a careful rereading of Farrington's original description of the Mazapil fall gives the impression that the sparks seen were remnants of the trail as the meteorite cooled during its fall at lower altitudes.[24] We know of no reports of lightning occurring simultaneously with the passage of a fireball.

Other electrical disturbances have been observed in more recent years. According to eyewitnesses of the Madrid fireball of February

10, 1896, the city's electric-light system lit up and went out during the flight; it occurred before the detonation and earth tremor.[18] A witness of the Kybunga fireball stated that "the fireball caused the electric wires on the front of our neighbor's house to burn out." This report was not corroborated by other observers.[14] LaPaz[25] gives another example of an electrical effect associated with the passage of an "exceedingly bright" fireball near Charleston, South Carolina, in 1954. Shortly before the meteor exploded, scatter occurred on the signal received at the local weather bureau from a radiosonde, a balloon-borne instrument which transmits weather information. The radiosonde was located at an altitude of 10.65 km, and the signal went out completely at the instant of explosion. A high-pitched noise was heard between the time of scatter and blackout. Krinov reported an electromagnetic effect associated with the Sikhote-Aline meteorite of 1947; an electrician on a telephone pole within 15 km of the fall zone received a strong electric shock from the wires at the instant of flash of the meteor.[26] One could hardly attribute this to pure coincidence, because the line was disconnected at the time the shock was felt. It is evident that the passage of the fireball coincided with a current induced in a long line. It is well-established that this type of induction occurs during strong auroral displays.[27] Astapovich asserts that the above example, the auroral disturbances, and sympathetic sparking during thunderstorms are analagous in effect.[18] The causes, however, must be different, for auroral disturbances are magnetically induced, and lightning is an electrostatic phenomenon.

Magnetic disturbances during fireball passage are difficult to detect; the observer is rarely prepared to make measurements, and the measuring instruments which are available are inadequate because of slow response time. Astapovich[18] has reported observations of compass-needle deflection during fireball passage. The most recent example summarized by Astapovich occurred in 1939, when two members of the Tiumensk Museum noted that the north end of a compass needle was deflected toward the east during the flight of a red fireball toward the northeast. After the fireball passed, the needle resumed its usual position.

Kalashnikov built a high-response induction magnometer in 1946 and began a series of systematic observations of the flux change during meteor showers.[28] The apparatus consisted of a 200-m-diameter loop and a coil of insulated wire of several dozen turns, attached to a fluxmeter which measured the induced current. The large area of the loop permitted detection of fluxes as small as 10^{-7} oersted. Measurements made during the Draconid maximum in 1946 showed that the shower caused a flux of 4×10^{-4} oersted; a distant lightning discharge, 10^{-6} oersted; and aurorae on the same date, 10^{-5} oersted. To obtain flux of 10^{-7} oersted, 0.5 per cent of the kinetic energy of a 1-g mass moving at 70 km/sec would have to be converted into field energy. Astapovich believes this is feasable, for this is close to the ionization energy created by a meteor.[18] To obtain a local electric discharge on the ground, or a deviation of the compass needle, at least 10^{6} times more field energy must be available. Although Kalashnikov observed a strong pulse from a visual meteor of -8 magnitude, the flux intensity was not given. The experiments indicated that meteors produce a radio noise at a frequency of 1 - 5 cps.[28]

The results of subsequent research are not conclusive. Hawkins has conducted similar experiments with more sensitive equipment and showed that there was no consistent radio emission from meteors of from +5 to -1 magnitude in the frequency range from 1 cps to 500 mc/sec. He suggested that the statistical correlation obtained by Kalashnikov between meteors and fluxmeter deflections was within the random scatter of the experiments.[29] On the other hand, Jenkins et al. reported increased nighttime magnetic activity[30] during several visual meteor showers. Recently Campbell found increased activity of magnetic micropulsations during the η Aquarid, δ Aquarid, and Perseid showers of 1958.[31] Campbell attributed the previous controversy to the fact that Hawkins made measurements close to natural sferics sources and the major fraction of pulses on his equipment was probably due to lightning. Kalashnikov and Jenkins operated in periods of minimum sferics noise.

The difficulty of distinguishing meteormagnetic phenomena from natural atmospheric noise also prevents a good correlation of radio disturbances with fireballs or meteor showers. Disturbances from industrial sources and static from lightning must also be considered. It is difficult to tell from the descriptions given by observers what kind of radio noise was heard. According to Astapovich, there is a difference between self-generated meteoritic noise and the signal received by reflection of a broadcast wave from the fireball. The former noises are certain crackling sounds noticed on a "clean" background. These are supposedly emitted by the meteor and trail. Doppler whistles are observed against normal broadcasting background and could be a result of reflection from the moving plasma.(18) On the other hand, if the fireball were generating an electromagnetic signal, Doppler shift would also be observed as a result of the fireball motion. Such a Doppler shift has been noted in the signals received from orbiting satellites.(32)

Radio noises described as a succession of short clicks were heard in Ashabad in 1944, at the end of visible flight of a fireball. These noises were sporadic and were received best in the long-to-medium-wavelength broadcast bands. There was some correlation with meteor brightness, but some faint meteors were "radioacoustic," while some brighter meteors were "mute." Astapovich attributes this lack of correlation to inhomogeneities of the atmosphere.(18) Millman and McKinley made a survey of 30-mc radar observations of meteors and observed that some bright meteors emitted a signal independent of transmitted radar pulses.(33) The frequency range of this emission, which may be related to the meteors, is not known at the present time.

Reports of very unusual radio noises occurring simultaneously with the passage of a fireball could be attributed to a Doppler effect. It is unlikely that static would account for the comment, "I heard a strange sound...over the radio. I have never heard a sound on the radio like it." Such an observation was made at the time of the Pennsylvania fireball of January 1931.(34) Crackling sounds were heard on radios during the fall of the Pervomaiskii Poselok meteorite on December 26, 1933, and during the Elenovka meteorite of October 17, 1951.(18) On March 24, 1933, a pilot, flying by radio beacon, noted an atmospheric roar at the time the Pasamonte fireball passed; a review of the literature on this fireball has, however, failed to substantiate this statement, which is not referenced by Astapovich.[18]

Astapovich estimates that several hundred kilowatts of power are emitted by the fireball sources of radio interference. A reception field of 10 - 100 μv/m is assumed, which would be heard only on receivers with a 10-kc or more bandwidth. This could account for the relatively few reported instances of radio interference. Wide variations in radio-interference reception could also be explained if the intensity of the effect was a function of the relative direction of the trajectory and local magnetic-field lines, i.e., if the emission was due to some magnetohydrodynamic process.

V. SOUNDS AND ELECTROMAGNETIC DISTURBANCES DURING AURORAE AND LIGHTNING DISCHARGES

The reality of auroral hiss is almost as controversial as the anomalous sounds associated with the passage of bright fireballs. Astapovich claims that their physical reality has been established conclusively and that they are even recorded on tape.(18) Unfortunately, no reference was cited for the tape recording.

Many field observations of auroral sound have been made. The sounds described are strikingly similar to those reported during the passage of bright fireballs. The following examples are typical of reports of these auroral noises:

1. A swishing or rustle, like that of a silken skirt moving back and forth,...very low, but plainly discernible.
2. Similar to those that accompany small static discharges.
3. Like the sound made when a couple of slices of good fat bacon are dropped in a red-hot pan.
4. They may attain a loudness comparable to that emitted by a high-tension electric current when charging a set of horngap lightning arrestors.
5. Quite audible swishing, crackling, rustling sounds.
6. Sounds similar to escaping steam, or air escaping from a tire.
7. Much like the swinging of an air hose with escaping air.
8. The noise of swishing similar to a lash of a whip being drawn through the air.
9. Sounds likened to a flock of birds flying close to one's head.
10. Not musical, it was a distinct tearing, ripping sound as when thin muslin is ripped or torn apart.

The intensity of auroral sounds varies from loud reports similar to rifle cracks to a fine crackling, resembling a hiss.(35)

Jelstrup observed a strong auroral display in which a pulsating aurora was accompanied by a "very curious faint whistling sound, distinctly undulatory, which seemed to follow exactly the vibrations of the aurora."(36) Static from the aurora interfered with time-signal measurements; the intensity of static bursts was larger than 100 mv/m. Størmer attributes these sounds to electrostatic discharges from the surroundings, which are caused by charge behavior in the aurora.(27) However, measurements of the potential gradient of the atmosphere reveal no appreciable change during auroral displays.(37)

During great aurorae, there are strong magnetic storms and consequent ground currents consisting mainly of rapid oscillations. The associated induced potential in long lines ranges from 300 - 400 mv/km to 50 - 60 v/km, depending on the intensity of the storm.(37) If a local discharge occurs, it appears from these data that it must be inductively generated by the fluctuating currents.

There would seem to be sufficient evidence in the description of noises and electrical effects on the ground to assume that the audible hissing noise is due to an electric discharge near the observer. Although it has been demonstrated that aurorae radiate electric noise at a frequency of 8 kc, with perhaps a 2-kc bandwidth, the field intensity is only 1 - 3 mv/m, which is 100 times less than the auroral static discussed above. Special equipment, consisting of a large vertical-loop antenna and a wide-band audioamplifier, is necessary to detect the signal which is transduced by a loudspeaker.(38,39) The sound of auroral electric hiss is similar to the noises described above; however, it is difficult to conceive of an efficient method of detection and rectification using natural objects, without very much greater signal strength.

Although we have pointed out the similarity of sounds observed from aurorae and fireballs, we cannot conclude that they are caused by the same physical mechanism. Assuming for the time being that the noise is due to local discharges, the method by which the discharge is generated may be quite different for aurorae and fireballs. Intense geomagnetic disturbances accompany aurorae, which occur at high latitudes, but there are only a few instances (see Section IV) where the geomagnetic disturbances associated with fireballs have been observed, and their intensity is unknown. Auroral phenomena occur at altitudes of 80 - 700 km, while the large luminous effects associated with fireballs take place at much lower altitudes. Finally, the velocities associated with the charged particles in the aurora are many orders of magnitude higher than those believed to exist in the fireball plasma.

Sounds associated with lightning discharges are called brontophonic (Greek: thundersound). These sounds have been compared to the hissing of a red-hot iron in water, the tearing of material, or the crackling when two conductors are brought together. They are either simultaneous with, or slightly preceding, the lightning, since they are produced by the leader strokes, and can be explained by an induced charge which appears at more than one point in the surroundings.[18] The extensive experiments of Wormell show that before the main lightning stroke there are predischarges in which the geopotential gradient can be negative near the lightning discharge and positive further away from it. These field anomalies enhance the possibility of breakdown.[40]

While these meteorological sounds are not as extensively documented as the auroral and fireball sounds, there are certain similarities in their quality and loudness. Furthermore, brontophonic sounds can be heard at a considerable distance from the lightning channel and before the thunderclap.[18] Astapovich uses this analogy to formulate a theory for the production of anomalous fireball sounds.

VI. THEORIES OF ANOMALOUS FIREBALL SOUNDS

The sound events which appear to be transmitted at the speed of light have been explained as (1) acoustical and related to the fireball, (2) acoustical but unrelated, (3) psychological and fictitious, (4) electromagnetically transmitted and rectified, and (5) electrostatic discharges.

A direct acoustical origin for the swishing noise was accepted in the nineteenth century, before the immense velocities and distances associated with fireballs were appreciated. Many of those reporting the hissing noise believed the fireball to be very near them; in fact, if they were scientifically educated, they utilized the fact that they heard the sound to deduce that it was nearby. The early Louisiana historian LePage du Pratz observed a meteor in the autumn of 1724 which "made itself heard by a whizzing sound like that of a large skyrocket."[(41)*] The brilliancy and the sound caused him to believe that it was "below the atmosphere." Galle attributed the "whizzing, like escaping steam" heard between the flash and the thunder of the Pultusk meteor to stones falling from the explosion.[(42)] He neglected atmospheric friction in calculating the time it took debris to fall. Khan proposed somewhat the same explanation; he believed the anomalous hissing noise was due to a continual influx of very friable material which resulted from the dissipation of the meteorites in flight. He argued that fine-grain dust could fall from the meteorite in four seconds, thus causing the impression of simultaneity of flash and sound during flight.[(43)] Recent studies on the high-altitude dispersion of particulate matter[(44)] disprove this conjecture, which, furthermore, does not explain the arrival of simultaneous sound at large distances from the flight path.

Wylie[(11)] suggested that wind whistling by objects, the hum of insects, and the sound of passing automobiles could all produce the swishing noise heard while the meteor is passing. The fact that many people could not specify for certain the direction of the noise substantiated Wylie's belief. Under this explanation the sound is real

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*The authors received this information in a private communication from D. H. Robey.

but unrelated to the fireball. This would explain why people in large cities hear anomalous sounds, while according to Wylie, people in the quiet countryside often do not.

Wylie[11] believed that such noises could also be psychological in origin. As a result of careful study of error sources in fireball observations, Wylie concluded that the average untrained observer was unreliable in his reports of altitude, time, and distance, especially if several days passed between the event and the interview. Coupled to this fact was Wylie's belief that

> Any real physical effect would be strongest near the path of the meteor. The fact that this is not observed and the evidence for this sound is far from conclusive makes it best to assume, at least tentatively, that this is not a real physical effect. This has been done by nearly all students of the subject. Kirkwood (Meteoritic Astronomy), Farrington (Meteorites) and Olivier (Meteors) all omit reference to these reports, although undoubtedly familiar with the fact that this type of sound is regularly reported.[11]*

Wylie also states that (1) intelligent, educated people never hear the noises, (2) in a group, not all people hear the noise, and (3) the sounds do not apparently come from the meteor.

The statement that any real physical effect must be strongest near its source is unusual for a scientist supposedly acquainted with radio (the article was published in 1932), since the effect is not achieved until the energy is transduced at the receiver. What is most alarming in the above quotation is the implication that information on anomalous noise was purposely omitted from scientific reports. It can only lead us to conclude that incidents of anomalous noise are more widespread than the present catalog would indicate.

If simultaneous sounds do accompany most bright fireballs, it is difficult and perhaps uncharitable to explain the paucity of reports only as the result of bias on the part of the investigators. Actually the number of reports will also be influenced by the frequency spectrum of the simultaneous sound and the receiving characteristics of the ear. The hearing range of individuals is tested by gradually increasing the strength of a signal at a certain frequency until it is heard.

*Underlined by the present authors.

A plot of the results for a number of frequencies reveals the lower limit of the individual's hearing range. If the sound amplitude is too high, a ticking sensation is felt in the ear. As ear damage may result from sounds above this amplitude, the threshold of feeling is the practical upper limit of the hearing range. Such tests[45] have revealed large individual differences in hearing ability, as indicated in Fig. 3. It should be noted that the range in hearing abilities is greatest for the high frequencies. A portion of this variability must be the result of differences in age, because the decrease in hearing ability with age is greater for the high frequencies,[45] as shown in Fig. 4.

If the sound generated as the result of the passage of a fireball were of high frequency, then only persons with exceptionally acute hearing would detect the sound. As the ability to hear high frequencies decreases with advancing age, it is possible that for some fireballs most of the individuals able to hear the sounds would be considered too young to be "qualified observers." For example, Olivier has reported an instance where only children claimed to have heard the sounds.[46] It is suggested that in the future, individuals who report hearing simultaneous sounds be given tests to determine whether their hearing is exceptionally good.

Reports that animals have sensed fireball events before human observers could be explained if the anomalous sounds were of high frequency. This is because animals, particularly dogs, are known to be able to hear higher frequencies than humans. A witness of the Kybunga daylight fireball said that the first indication he had of anything unusual was that the fowl suddenly became nervous and excited. He looked up to see the fireball come into view, and loud noises followed.[14] An observer of the Texas fireball of June 30, 1928, was attracted to the event by a dog which growled and barked. The observer then heard a hissing noise and turned to see the meteor.[12]

One of Wylie's arguments for a nonphysical origin--namely, that the sound apparently did not come from the meteor, but from nearby objects--suggests that the sound is electrically transmitted and transduced near the observer. Bunch,[47] in 1930, proposed that the

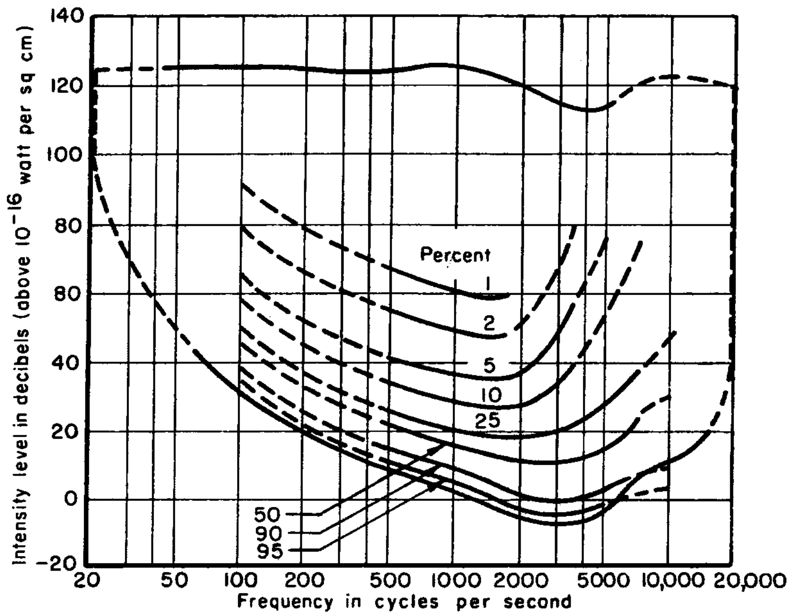


Fig. 3 — Contour lines above which lie a given percentage of thresholds for the age group 10-59, from Steinberg *et al.*[45]

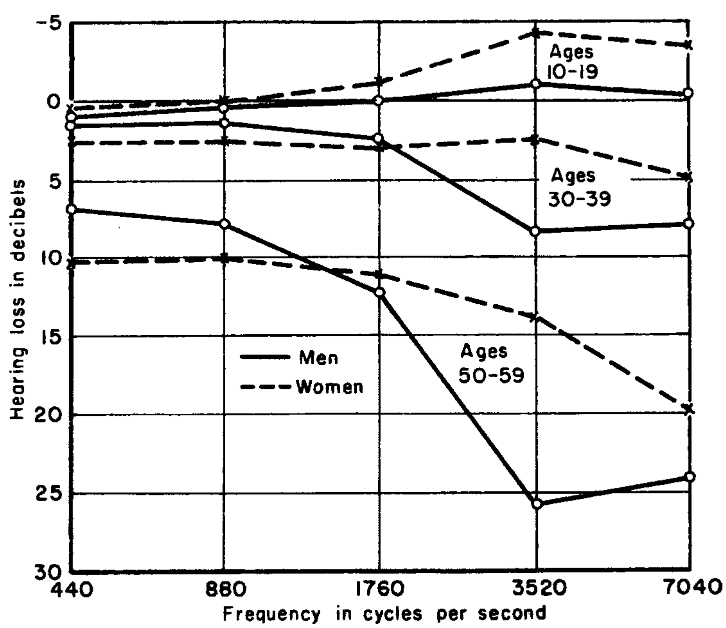


Fig. 4 — Mean hearing loss in db for men and women in different age groups, from Steinberg *et al.*[45]

disturbances which produce the anomalous sounds could be made audible with a radio. He suggested listening during showers for "meteor static" (see Section IV). Nininger,[48] in 1939, was also convinced of the reality of the anomalous sounds and suggested that they were the result of natural transformation of "ether waves" into ordinary sound by a suitable rectifier, such as a metallic object near the observer. He based his line of reasoning on the fact that near powerful radio transmitters many instances of sound due to unintentional rectification occur. There is some justification for this line of reasoning, for in many instances the observers of anomalous sounds were in or near metallic structures. On the other hand, several cases exist where the sound appeared to come from vegetable matter, which is not as likely to act as a transducer as would a barbed-wire fence.

Anyzeski[49] suggested that perhaps through some unknown physiological effect the ear can rectify electromagnetic waves itself. He pointed out the similarity between human ears and microwave plumbing. Actually, psychologists and physiologists have long been aware of just such electrophonic hearing. Stevens and Davis[50] describe an experiment where a high-frequency (100 kc) current modulated by a 400-cycle wave was passed through the head of an observer. The result was that the observer heard a 400-cycle tone. Stevens and Davis interpret this experiment as showing that the signal was rectified within the ear itself. If such a mechanism were the explanation for the simultaneous sound from meteors and aurora noise, it would have a great bearing on the type of instrumentation required to detect these "sounds." The signal might cause the sensation of sound in the ear with no corresponding wave motion of the air. Therefore, conventional microphones and recording equipment would be ineffective. We also must expect differences between individual abilities to "hear" electromagnetic waves.

Astapovich[18] suggested an electrostatic origin for the sounds, because the electrophonic phenomena associated with fireballs, aurorae, and close lightning discharges are all of the same order of loudness. If a lightning discharge occurs at a height of 5 km at a charge of 20 coulombs, then during the upper-atmosphere flight (500 - 200 km) of a fireball, a positive charge on the order of $10^4 - 10^5$ coulombs would be required for negative corona discharge on the ground. This discharge would be accompanied by hissing sounds, ozone formation, induction in communication lines, deflection of compass needles, and interference with radio reception. Thus, fireballs, in the model proposed by Astapovich, temporarily increase the local ionosphere charge by an amount equivalent to the full charge of the E layer (5×10^5 coulombs).

A similar electrostatic mechanism was proposed by Anyzeski,[(49)] who compared the fireball and shock wave to one plate of a condenser, the other plate being the earth. Fluctuations in the plate potential would cause noise, although the origin of the noise was not discussed. Anyzeski had several other suggestions for the production of the anomalous sounds, among them the proposal that the radio energy is emitted in the centimeter and millimeter wavelengths rather than at usual radio frequencies. This is the first reference to plasma oscillations, although the origin of the radio energy was not so specified.

Anyzeski also presented the following possible explanations: (1) high-energy elementary particles are generated during flight and create sound by water condensation on the ionized path of their trajectories, and (2) most of the energy produced by a fireball is in heat, and fluctuations in heat produce sound in surrounding vegetation.

Barringer and Hart[(51)] used the black-body-radiation formula to calculate the amount of energy present in the centimeter regime for a bright meteor with a black-body temperature of 3000°K. They found that the emitted power was on the order of microwatts. Even if the effective temperature were $50,000^{\circ}$K, the emitted power would be too small, especially if crude rectifiers like bushes, stoves, and fences transduced the signal. Barringer and Hart also suggested that fireballs emit radio-frequency-modulated light waves, which are transduced by some unknown photosensitive receiver on the ground.

It is evident that most of the theories discussed above suffer from the fact that the problem is not well defined. One must hypothesize a cause (at the fireball) to produce an effect (on the observer) when the effect itself is so tenuous that not all observers are aware of its existence. Furthermore, the hissing sounds associated with the effect can apparently be produced by several physically unrelated phenomena: fireballs, aurorae, and lightning.

However, the noises, the occasional odor of ozone, and the electromagnetic disturbances all indicate strongly that some form of corona discharge is involved. A corona discharge takes place in asymmetric fields, in which breakdown will occur at the highly stressed electrode with minimum influence of the other. The electric-field gradient can be either positive or negative. The discharge itself is accompanied by a hissing noise and the smell of ozone, due to the ionization of the air surrounding the stressed electrode. The discharge may be induced by either static, alternating, or impulsive fields. The voltage gradient at which breakdown occurs varies with the sign of the gradient, the material of the stressed electrode, and the conductivity and velocity of the air surrounding the electrode. It is estimated that a hissing noise will become audible, and the discharge luminous, at gradients of 10 - 15 kv/cm.(52) Both types of corona discharge are space-charge limited; the space-charge fields formed by the avalanche emissions of charges from the stressed electrode control the rate of emission and current flow in the gas.(53) In the laboratory, large fields of 30 - 50 kv/cm are necessary for breakdown at atmospheric pressure. Natural corona discharges are somewhat easier to obtain, because the atmospheric winds can remove ions and alter the space-charge field. For example, a small current from natural corona discharges from trees can be detected during stormy weather at a potential gradient of 600 - 1000 v/m. The average geopotential gradient at the earth's surface varies from about +100 to -100 v/m, rising to larger values during thunderstorms. Directly under a thundercloud, for example, the gradient can be as high as 5 - 280 kv/m.(54)

A negative point-to-plane discharge is accompanied by a bluish light and is accomplished by periodic cascading of electrons from the cathode. During initial stages, the frequency varies from 8 to 50 kc. The discharge is favorably influenced by weak ultraviolet light, which causes photoemission at the cathode. Too much light will choke the discharge by formation of negative ions in the air. The positive point-to-plane discharge is accompanied by a reddish glow, and is aperiodic, and the breakdown voltage is slightly higher than that for the negative point. Ultraviolet light does not enhance the breakdown.

A negative point-to-plane discharge could well be the source of the hissing noises accompanying the fireballs. This was pointed out by Astapovich(18) and was independently deduced by one of the authors (M.F.R.). We disagree with Astapovich in the particular form of the electric field causing the discharge. As mentioned earlier, Astapovich believes it is due to the enhancement of the D layer. Further, in the introduction to Chapter 28 of his book(18) he asserts that the fireball trail will have a net charge. Either of these will cause, if the charge density is large enough, induction on the ground and subsequent discharges.

These particular mechanisms can be rejected for several reasons. For instance, it is difficult to conceive of locally overcharging the D layer to the extent that discharges occur on the ground. If this occurred, more instances of radio anomalies would be apparent, and the electrical disturbances would be more widespread. Also, because of the magnitude of the Debye radius in the plasma, large charge densities cannot be sustained in the fireball trail except at altitudes above 200 km. Yet one of the outstanding differences between ordinary fireballs and sound-producing fireballs is the fact that the latter are extinguished at lower altitudes, and they have a longer lifetime.

Several mechanisms which could produce the anomalous sounds have not been explored adequately. The first is radiofrequency radiation from the fireball plasma itself. In order to determine the magnitude and frequency of such radiation, it is necessary to ascertain the plasma electron density and temperature, both of which involve detailed knowledge of the physical environment of the fireball during entry. Although we doubt that sufficient energy is generated by such radiations to cause discharges, the presence of turbulence can greatly enhance normal plasma radiations. The fireball trail will certainly be turbulent at low altitudes.

It is also possible that the ionized wake acts as a conductor in the earth's geofields. The wake could form a channel from the D layer to lower altitudes whose effectiveness would depend on the plasma electron density. If the atmosphere is considered to be one plate of a condenser, such a channel might affect the earth's electric field sufficiently to cause a discharge on the ground.

Both of the above hypotheses are independent of the way in which the sound is detected near the observer. There is still a reasonable doubt that the hissing sounds are a result of actual corona discharges; they may be electrophonic sounds heard by certain people under the influence of electromagnetic radiation.

VII. CONCLUSIONS

The simultaneous arrival of light and sound from some fireballs indicates that the sounds must be associated with an electromagnetic phenomenon. This Memorandum has shown that both electric and magnetic disturbances have occurred during the passage of bright fireballs; in some cases anomalous sounds were heard as well. That the electromagnetic disturbance is not coincidental, but is actually related to the fireball, is demonstrated by the induction of current into a disconnected telephone line during the flight of the Sikhote-Aline meteorite.[26]

The type of noise, an occasional smell of ozone, and the electromagnetic disturbances all suggest that a local corona discharge is responsible for the hissing noises reported by fireball observers. Similar noises heard during thunderstorms and aurorae have also been attributed to corona discharges. The similarity of ground effects, however, does not imply that the associated electromagnetic disturbance is the same for all three events. It has been established that strong fluctuations in the sign of the local electric-field gradient cause the thunderstorm discharge; on the other hand, no significant changes in the electric field are observed during strong aurorae.

In order to propose a realistic hypothesis for the origin of the electromagnetic disturbance accompanying the meteorite, it will be necessary to determine its physical environment during flight. In particular, the properties of the plasma sheath and ionized wake should be the subject of further research.

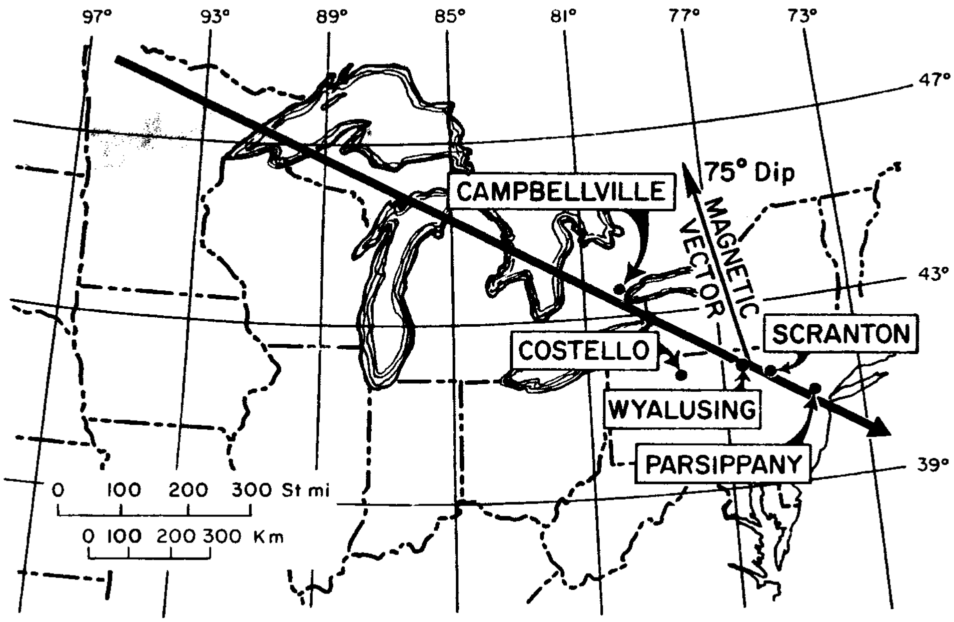
Appendix A

A CATALOG OF ANOMALOUS-SOUND OBSERVATIONS

The catalog presented in the following pages contains observations of anomalous sounds and radio interference for 42 fireballs. Most of these were obtained from the reports of the American Meteor Society in Popular Astronomy. The Astronomische Nachrichten and Ciel et Terre were also investigated for anomalous-sound reports. The latter journal contains only one account, of possible radio interference, during the years 1950 - 1963. The Astronomische Nachrichten has been published since 1823. The search covered all volumes from Vol. 1, 1823, to Vol. 286, 1962. The entries checked were Bolid, Feuerkugel, Meteor, Meteorit, and Sternschnuppen. (Most entries were found under the latter.) Only reports of clearly identifiable anomalous sounds are quoted here. No conjecture or theory was advanced in any of the papers.

Two Soviet fireballs are included because they were omitted from the Lyubarskiy catalog of Appendix B, although they are given prominent reference in the Soviet literature. Seven of the fireballs were referenced in such detail that the location is known for observers who heard anomalous sounds. These descriptions precede the main catalog and include maps showing the trace of the flight path and location of observers. The direction and dip of the magnetic-field lines for the time of fireball passage are shown at the end point of each trajectory. The names of the towns where anomalous hissing or whizzing sounds were reported are enclosed by rectangular borders.

CHANT PROCESSION, 2/9/13



From Mebane[55] and Chant[56]

ANOMALOUS SOUNDS

Wyalusing, Pa. "Several people heard a noise, apparently in the sky...it sounded like the exhaust of an aeroplane engine." (Newspaper report)

Scranton, Pa. "...heard a swish and saw some faintly colored things in the sky."[55]

Parsippany, N. J. A fireball appeared "as bright as an acetylene torch" which emitted a hiss "like a skyrocket."[55]

Costello, Pa. Attention was attracted to the sky by a noise like that of a jet plane.[55]

Campbellville, Ont. The procession passed overhead. The only sound heard was a faint whistling like that of bullets as they passed.[56]

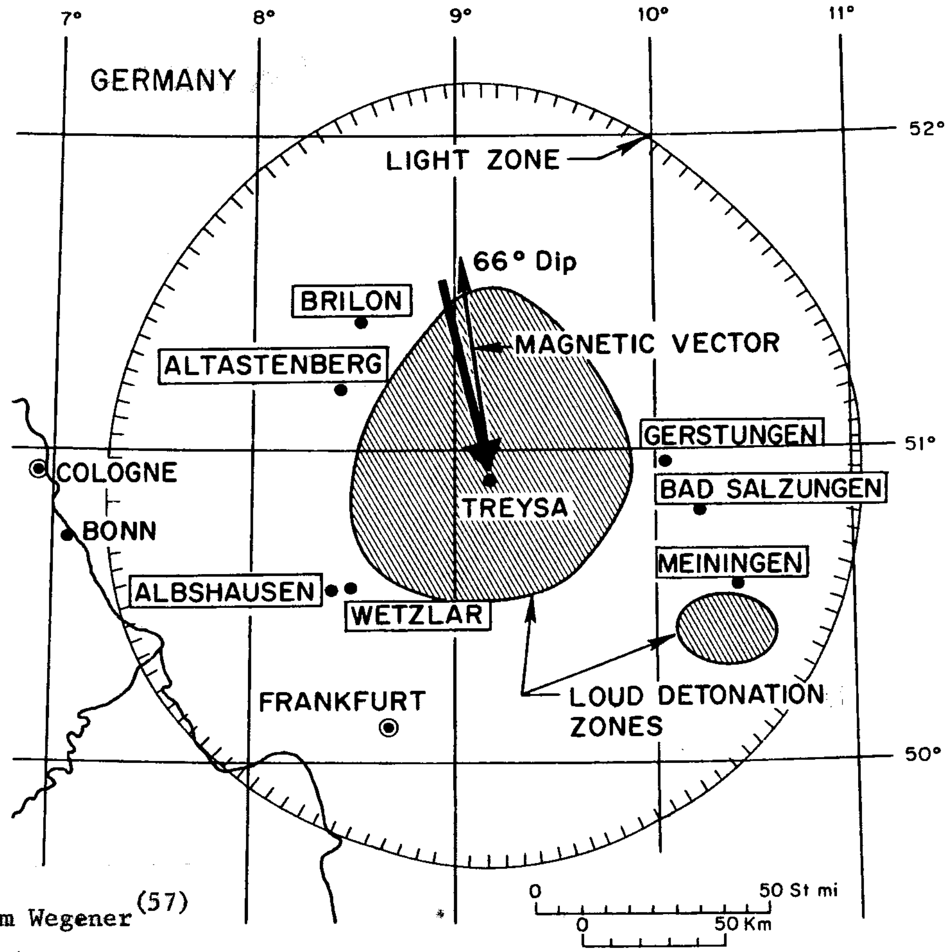
DESCRIPTION

Time: around 8:00 p.m. CST. The Chant Procession was an extraordinary display of large, slow fireballs which were seen from Saskatchewan to Bermuda. The orbit has still not been determined satisfactorily. Detonations occurred near Hamilton, Ont. From one to thirty objects seen. Estimated velocity, 11 km/sec.

COMMENTS

The anomalous sounds reported in Ref. 55 were obtained in interviews made approximately 40 years after the event.

TREYSA, 4/3/16



From Wegener(57)

ANOMALOUS SOUNDS

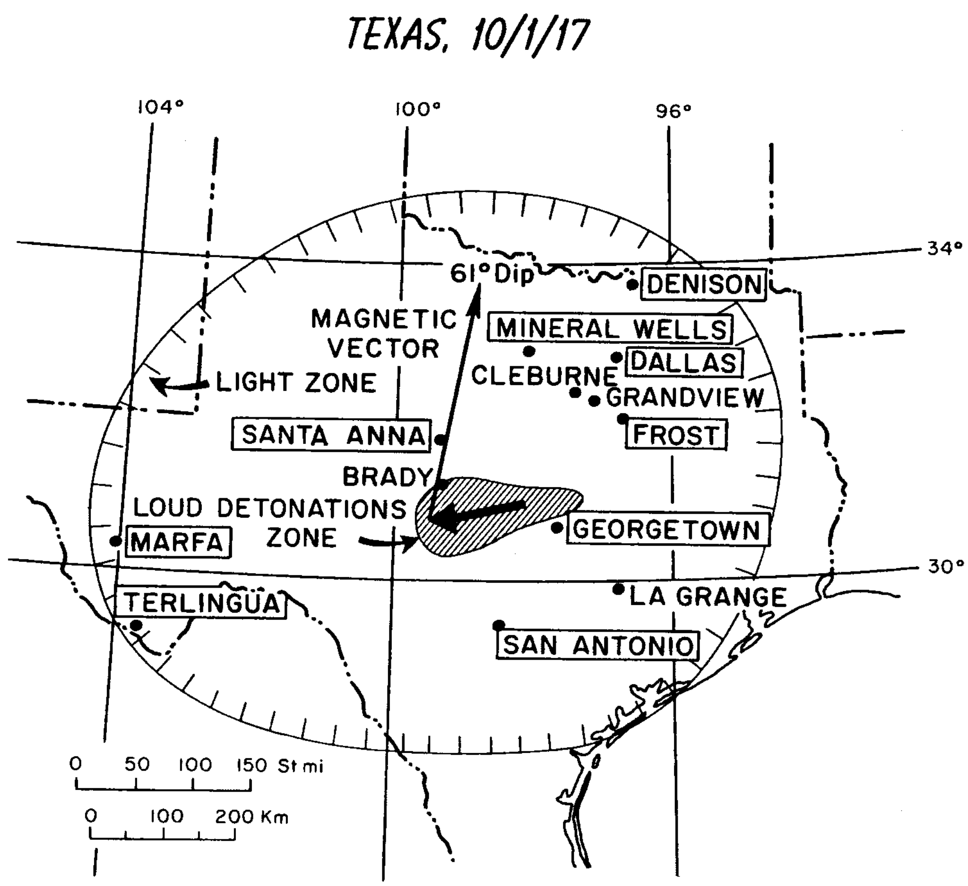
Observer No.

10. Girl. "...and a hissing could be heard in the air as long as the meteor was visible."
66. Meteorological observer. "The phenomenon was also accompanied by a hissing noise."
102. Innkeeper. "Suddenly with a swishing and hissing as if it passed closely by my ears, and a spraying of fire, it fell in the woods...I fetched the stone." (Observer unreliable--100 km from impact point.)
17. Young man with high-school education.
62. Meteorological observer.
59. Physician or M.D.
60. Civil servant with railroads.

} All these heard simultaneous hissing noises.

DESCRIPTION

Time: 3:30 p.m. A total mass of 63 kg fell from this meteor, seen in bright sunshine in a circular area of 135 km. Reddish light. No explosion. White trail.



From Udden (17)

ANOMALOUS SOUNDS

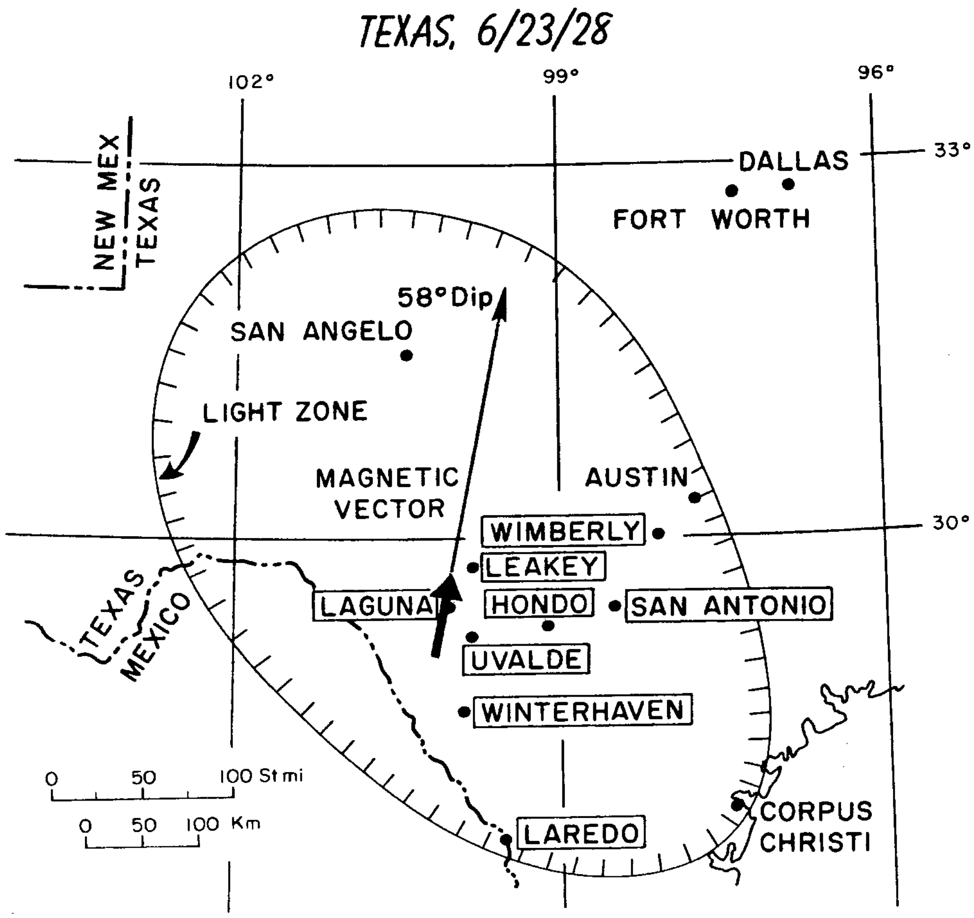
San Antonio. Four observers reported anomalous sounds. Described as "escaping steam" and "like the swish of a whip in the air." It seemed to come from the bushes or from the grass on the ground. Santa Anna. A spewing noise, like a small amount of powder. Reports of whizzing, hissing, whirring, and a faint buzzing at towns with names enclosed by rectangular outlines.

OTHER PHENOMENA

Grandview. Heat (felt a warm air).
Cleburne. Heat (felt it like a slight electric shock).
San Antonio. Odor of sulphur.
La Grange. Odor of burning powder.
Brady. Oppression of air (similar to automobile passing).

DESCRIPTION

Time: 10:30 p.m. Blue-white, sparkling train. The light was compared to lightning flash, quoted as "blinding" or equal to the sun. Two to five detonations.



From Sellards(12)

ANOMALOUS SOUNDS

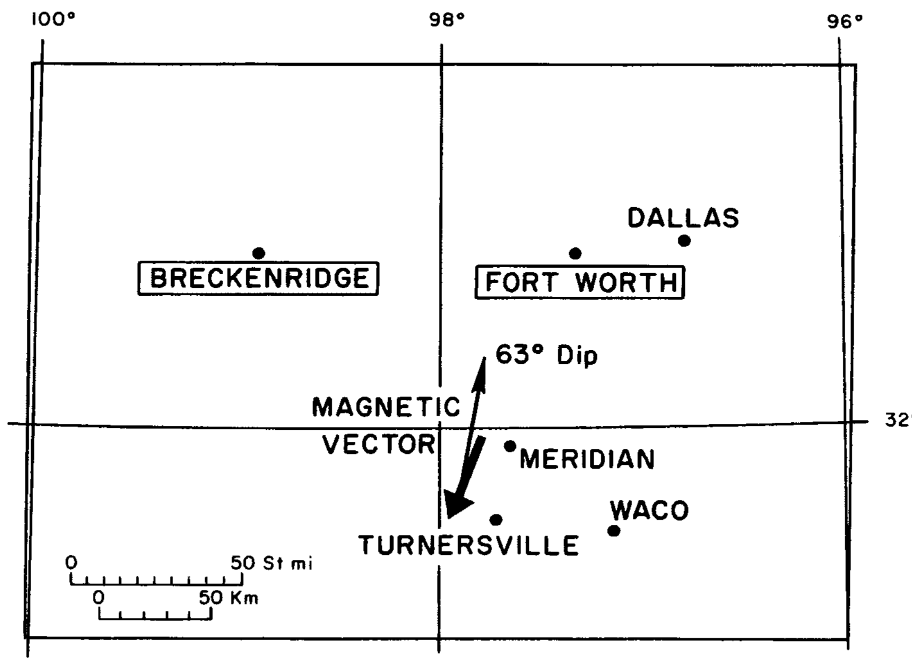
"Whining" noise reported at locations enclosed by rectangular outlines.

1. Repairing wire fence, stooped over fastening lower wire. Heard whizzing like airplane with engine off. On looking up, saw flash of meteor.
2. Attracted by "shhh" (Uvalde or San Antonio).
3. Sitting with back to NW (Uvalde or WinterHaven) and heard a hiss. Dog growled and barked before subject noticed meteor.
4. Uvalde lady heard whine while lying on bed near a north window. Whine continued after flash.
5. San Antonio observer heard a sizzling noise and looked up to see the object.

DESCRIPTION

Time: 4:40 p.m. Brief visible course. Very bright, visible in daylight. Trail lasted over an hour. Smoky white.

TEXAS, 8/8/28



From Olivier and Monnig[58]

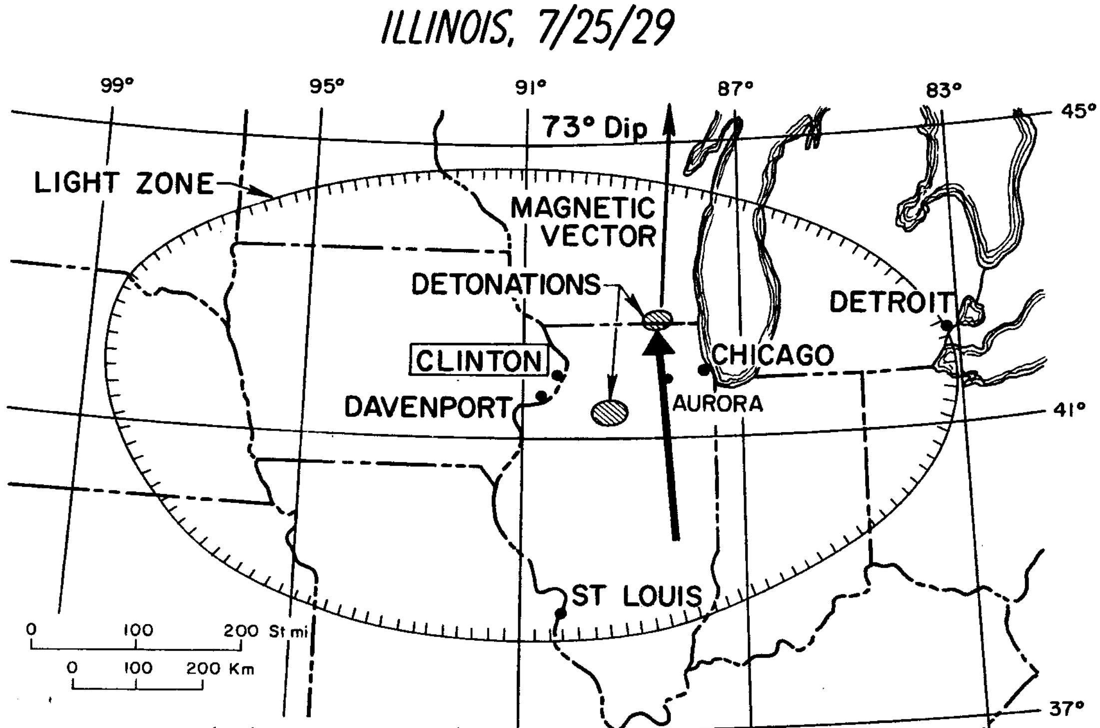
ANOMALOUS SOUNDS

Fort Worth. An astronomer heard a distinct and long drawn out "pop" just as the object appeared.

Breckenridge. An observer heard a "hissing or popping as the meteor appeared." It was accompanied by a "hissing or whirring noise."

DESCRIPTION

Time: 9:28 p.m. CST. Three to four times as bright as Jupiter; blue-white color. Left a trail, looking like ashes, for 6 sec. Trail color red-yellow. Left smoke ring at end. Ring expanded at velocity of 0.03 km/sec. One explosion noise at Turnersville.



From Wylie[59] and Olivier[60]

ANOMALOUS SOUNDS

"...Several persons in Clinton, Ia., reported this sound (of swishing), but a college professor of science, who observed it from the outskirts of Clinton, reported that everything was exceedingly quiet in his vicinity at the time the meteor fell, that he listened carefully and was sure the fall was accompanied by no sound. We may add that college professors have never reported to us that this sound was heard."[59]

"...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 someone 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."[59]

"There are a score or two (out of 200) observers who report simultaneous 'hissing sounds,' 'popping,' 'swishing,' 'sounds like a rocket,' etc. As many, if not most, were in large cities, suggestions may account for such reports."[60]

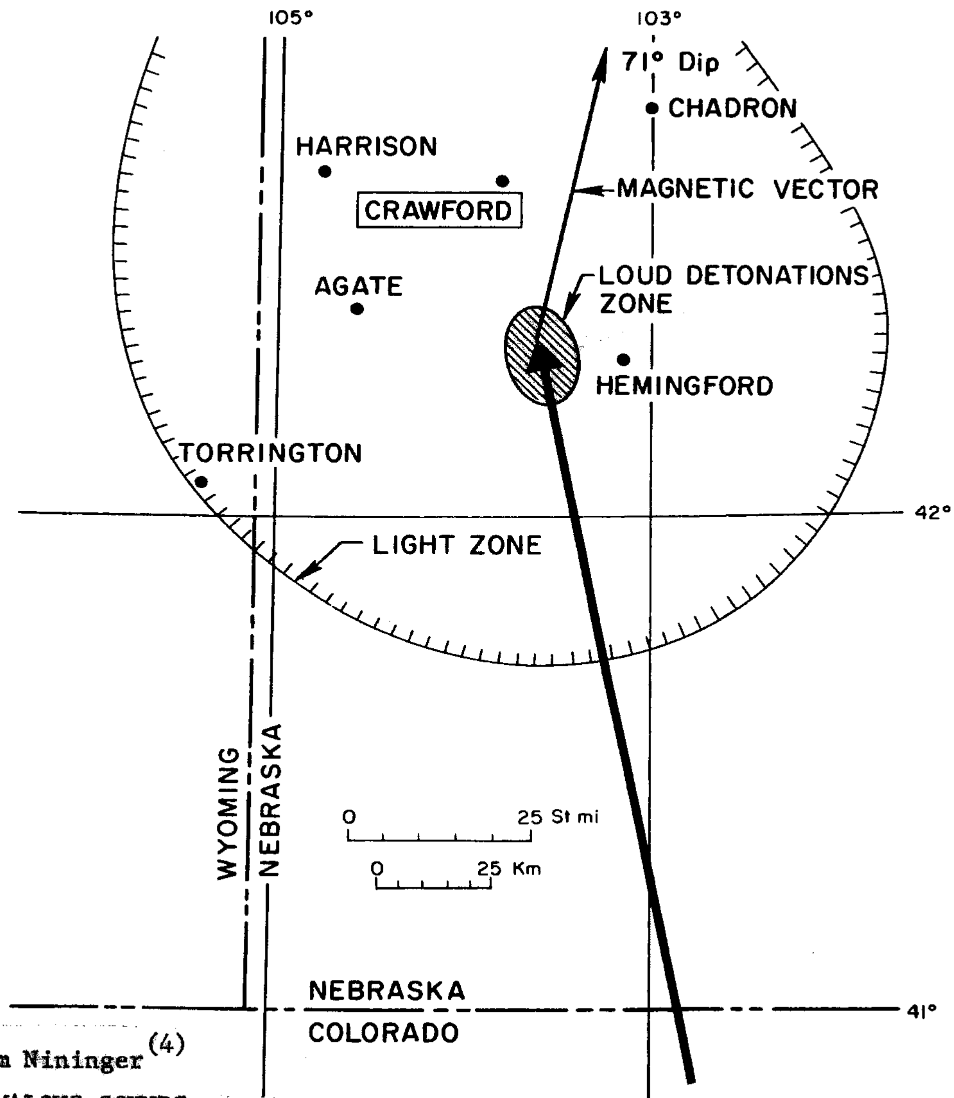
DESCRIPTION

Time: 9:46 p.m. CST. Exploded, no trail. Green-white. Estimated magnitude was -13.

COMMENTS

We suspect from Olivier's remarks that the other observers were in the Chicago or Davenport area.

NEBRASKA, 8/8/33



From Nininger(4)

ANOMALOUS SOUNDS

Crawford. Subject indoors, heard noise like airplane banking steeply. As he approached the door, the meteor came into view from southeast. Later investigation of time showed meteor was 160 km from location when noise was heard.

DESCRIPTION

Time: 10:30 a.m. Daylight, bright enough to be seen. Considerable detonations at Torrington, Chadron, Crawford, Harnson, Hemingford, Agate. Thirty stones recovered. Friable Howardite. Trail of light-grey smoke.

COMMENTS

Trace given on map was estimated by authors from description in Nininger's book.

CATALOG

Item	Time and Location	Description
1.	4/23/1803 Evening North Carolina, Virginia	Lyrid shower. "During...this remarkable phenomenon a hissing noise in the air was plainly heard, and several reports resembling discharge of a pistol" (Virginia). Four fishermen "distinctly heard a hissing in the air, but no reports" (North Carolina). (10)
2.	11/13/1833 4:00-6:00 a.m. Local time Connecticut, Virginia, Mississippi	Leonid shower. New Haven: four observers "heard a number of slight explosions--like that of a child's popgun, not unlike that of a fire-rocket." New Britain: a physician thought the fireball was accompanied by a noise "like the rushing of a skyrocket." Mississippi: "Some persons present affirmed that they heard a hissing noise on the fall of some of the largest (meteors)." Richmond, Va.: "a crackling sound accompanied" both fireballs. (10)
3.	1/30/1868 7:00 p.m. Local time Putusk, Poland	In the region of fall, the inhabitants related that, before the detonation itself, a whizzing, similar to that of escaping steam, was audible; at Solokow people sitting at home heard a whizzing, like escaping steam, between the flaring up and the thunder. (42)
4.	2/12/1875 10:20 p.m. Local time Iowa (Homestead)	Examination of the letters received show a number reporting this type (hissing or swishing) of sound. (11)
5.	9/14/1875 Evening England	While walking in the garden "my attention was attracted by a distant <u>hissing</u> sound, and looking up I saw the meteor." While standing in front of the house, saw the meteor; distinctly heard a "slight continued hissing as it rushed through the air." (61)
6.	8/7/1899 1:17 a.m. MST Colorado	"I though I heard it hiss as it went by." "We heard a loud rushing noise; looking up, we beheld a big ball of fire." (62)

Item	Time and Location	Description
7.	8/3/1905 8^h 55^m GMT Germany	"Two women in Offenback heard a distinct crackling while seeing the first red, then bluish meteor." (63)
8.	6/30/1908 0017^h 11^s GMT Tunguska, USSR	(Omitted from Lyubarskiy's catalog.) E. Sarychev of Kansk was at the river Kana (south of Kansk). First heard a noise like that of a flushed bird, passing from south to east towards Antsyr. A wave like a surge came up the river against the current. (Noted at other localities also.) A sharp clap was heard; then rumblings. (21)
9.	11/28/1909 Between 4:00 and 5:00 p.m. Iowa	Delaware County meteor. Cracking noises attracted attention skywards. (May not be anomalous.) (13)
10.	1/10/1913 22^h 50^m GMT Western Ukrainian SSR	"During the flight of the meteor one heard a tone which was similar to the rushing (Sausen) of the wind and which changed into crackling (Krachen) as from an automobile, all objects appeared to shiver (zittern). After the disappearance one heard an explosion, a little similar to a strong kettle drum beat." (64)
11.	3/9/1918 7^h 18^m MET Germany	"If we neglect those observations of sound phenomena such as crack (Krach), hiss (Zischen) and rush (Sausen) which were reported as occurring simultaneous to the light effects and therefore obviously depend on an illusion, there still remain a series of perceptions that are undoubtedly related to the fireball." (65)
12.	5/28/1922 10:28 p.m. Local time Virginia	No explosion noise, but some "sounds" or "swishing" noises were reported as heard within a few seconds. (66)
13.	12/19/1926 8:30 p.m. Local time Arizona	A hissing noise was heard simultaneously with the light. (67)

Item	Time and Location	Description
14.	1/2/1927 6:03 p.m. Local time Iowa	"Although many letters speak of a 'swishing sound' (presumably a psychological illusion) as the meteor went over, none of the letters indicate noticeable detonations." (68)
15.	10/16/1927 10:00 p.m. EST Maine	"A swishing sound, distinctly heard by persons on the streets, accompanied [the fireball]." (69)
16.	10/7/1928 9:40 p.m. CST Texas	"There is one report of the mooted 'swishing' sound, which the observer mentions first in narrating the circumstances of the fireball." (70)
17.	12/24/1928 17^h 56^m GMT Switzerland	"Brightness of head approximately like moon, discontinuous motion with repeated stronger light eruption, color blinding white, hissing noise audible, duration of visibility 4 sec." (71)
18.	1/22/1931 6:01 p.m. EST Pennsylvania	"...heard a strange sound that came over the radio. I have never heard a sound on the radio like it." The observer indicated the sound was simultaneous with the appearance of the fireball. (34)
19.	7/19/1932 2^h 35^m GMT Germany	"It is remarkable how many observers even under intense questioning claim to have heard a hissing noise even during flight. Noise like that of a rocket fired in the vicinity. Yes, some even claim to have been alerted by the noise to the appearance of the meteor. A few observers, however, emphasize the stillness of the flight." (72)
20.	8/10/1932 4:30 p.m. Local time Missouri	"It is a remarkable fact that two or three observers testify that their attention was first attracted to the meteor by a swishing sound and that they then looked up and saw it in flight." (Associated fall, the Archie meteorites.) (73)
21.	3/24/1933 5:04 a.m. MST New Mexico	"As with all of the meteors which the writer has investigated, there were many people who in this instance reported hearing a swishing or whining noise at the instant of the fireball's passage." (7)

Item	Time and Location	Description
22.	11/17/1933 5:07 p.m. PST Washington	"The simultaneous 'hissing' was heard as the meteor passed over certain people." (74)
23.	9/6/1934 8:00 p.m. Local time Kansas	A hissing noise was reported by an observer under the flight path; also by several witnesses in Oklahoma and Texas. (75)
24.	10/22/1935 5:12 p.m. EST New York	"Several, as usual, report that their attention was called to the meteor by a cracking or hissing sound." (76)
25.	2/15/1936 0^h 57^m MET Germany	There are nine reports of "hissing, rushing, sizzling, and crackling" simultaneous to the passage of the meteor. The meteor extinguished at a height of 46 km, and the people that heard these anomalous sounds were as much as 40 km from the ground trace. (77)
26.	4/12/1938 7:25 p.m. EST New York	"Four reports mention a 'hissing' or 'swishing sound' simultaneous with seeing it. Internal evidence would dismiss all but one of the latter as being due to what observers thought afterwards they should have heard and the impressions may be considered as illusory. The one exception is specific in saying attention was first called to the object by a sort of 'whizz.'" (78)
27.	11/4,5/1938 8:25 p.m. EST Vermont	"The only sound reported (by one or two out of ten) is within a few seconds, hence is probably illusory." (79)
28.	1/31/1940 5:55 p.m. EST New Jersey	Near New Egypt, New Jersey, observer returning home in car, radio playing, heard "terrific crackling noise" from radio and at the same time saw the meteor. (80)
29.	9/7/1941 4:30 p.m. Local time Australia	Peterborough: "On Sunday afternoon about 4:30 p.m. I was working in the yard. I was startled by a screaming noise and thinking it was a bullet I looked up and saw a huge meteor sailing

Item	Time and Location	Description
		through the sky...The meteor caused great disturbance to our all-electric wireless receiver and caused the electric wires on the ground of our neighbor's house to burn out..." (Electrical disturbances not corroborated by other observers.) Near the region of fall, at Blyth, Kybunga: cracks, backfiring, "flash and a whistle." At Blyth, the attention of one observer was drawn to the meteor by his fowls, who suddenly became wildly excited and ran in all directions. (14)
30.	3/7/1942 7:18 p.m. EST New York	"Again we have uncertain reports from a few who believe their attention was attracted to the fireball by hearing it, as they would a rocket." (81)
31.	9/1/1942 10:30 p.m. EST New Jersey	"Various sounds are reported. Most can be explained by other noises but as usual we find a few people saying that they heard a simultaneous 'hissing' or similar sound. A few will say that it was this which called their attention to the fireball." (82)
32.	8/18/1944 7:12 a.m. CST Ohio	"At places distant from the path we had some observers report a 'hissing' or 'swishing' simultaneous with the fireball...several say such an effect caused them to turn and see the meteor." (83)
33.	2/12/1947 10:30 a.m. Local time Sikhote-Aline (Primorskii Region, USSR)	(Omitted by Lyubarskiy.) Mechanic who was repairing disconnected telephone lines received an electrical shock at the time of passage. (26)
34.	2/18/1948 4:56 p.m. CST Kansas	A boy playing basketball heard a peculiar whistling or hissing noise; on looking up, he saw the ball of fire slanting earthwards. Associated meteorite: Furnas County. (84)
35.	10/26/1949 9:00 p.m. EST Pennsylvania	Buffalo, N. Y.: A low "sh-sh-sh" was heard at the time the light was seen. Frewsburg, N. Y.: A noise was heard in the sky and, on looking up, the light was seen.

Item	Time and Location	Description
		Jamestown, N. Y.: One observer heard a crackling or sputtering at the same time the light was visible; another heard the sound in two seconds and an explosion later. Wyalusing, Pa.: Explosion was heard right away. Dubois, Pa.: One observer reported sounds in one second, another heard explosion immediately and sounds later (the latter may not be anomalous). (85)
36.	10/4/1950 5:20 p.m. CST Missouri	"Five other observers in assorted places report hissing, swishing, etc. But we find the ages of four are 11, 15, 13 and 13 respectively. Only the fifth is a grown person. While not denying (the noise)...in this case we consider the evidence so meager we need not discuss it further." (46)
37.	5/15/1954 11:22 p.m. PST California	"One report was obtained of sound heard at the same time that the fireball was seen. Although such ethereal sounds have been reported before, they are rare, and in this instance at least, probably psychological, since several observers disclaimed being able to hear anything during the time that the meteor was visible." (86)
38.	11/30/1954 10:45 p.m. EST South Carolina	Radiosonde signal scatter and blackout during meteor passage. A high-pitched noise at the receiver which may have been caused by shorting. (25)
39.	1/17/1955 $19^h\ 10^m$ GMT Netherlands	One observer said his attention was attracted to the meteor by a noise which appeared on the radio (1007 kc). (87)
40.	1/16/1961 6:00 p.m. PST California	"One Santa Barbara lady said she was attracted by a hissing sound which caused her to turn around and see the meteor." (88)
41.	9/1/1962 11:12 p.m. EST Virginia	"...from a distance it seemed to be rather long and glowing with a rumbling sound." "I heard a snapping sound and at the

Item	Time and Location	Description
		same time I observed a very bright and large meteor." "We don't recall any sound except maybe a swish." "There was a faint whizzing sound." "...a sizzling sound could be heard." "...similar to the sound produced by immersing something <u>very</u> hot in water." "I could hear the sizzling from it..." "Hissing noise made him look up."*

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*Excerpts from letters sent to F. D. Drake, National Radio Astronomy Observatory, Green Bank, West Virginia.

Appendix B

A CATALOG OF RUSSIAN OBSERVATIONS*

In the catalog of the Committee on Meteorites there are 94 reported observations of electrophonic bolides.** Some of these (57 in number) not appearing in the catalog of I. S. Astapovich(2) are given below. The remaining observations of electrophonic bolides in the catalog of the Committee on Meteorites are published in the above-mentioned catalog of I. S. Astapovich under Nos. 69, 75, 78, 80-83, 88, 89, 92, 94, 99-102, 106, 110, 112-118, 120, 124, 143, 146, 153, 156. In spite of the small number of observations in the catalog, they may be used, nevertheless, to make certain conclusions.

CATALOG OF ELECTROPHONIC BOLIDES

No.	Observation		Nature of the sounds (extracts from eyewitness accounts)
	Time	Region	
1	June-July, 1897	Chernigov Region	Aircraft noise, stream of explosions
2	Spring 1919	---	The bolide made a strange noise
3	December 1, 1907	Nizhegorod Region	A noise was heard in the air, followed by the sound of an impact
4	July 21, 1923	Pskov Region	Sounds like the buzzing of a dragonfly
5	November 5, 1923	Poltava	The fall was accompanied by a slight crack

*Part IV of Ref. 1, translated from the Russian by Jack Gallob, Trans-Slavic Associates.

**The word "bolide" (Greek: flaming spear) is used by the Soviet meteoriticists instead of "fireball."

No.	Observation		Nature of the sounds (extracts from eyewitness accounts)
	Time	Region	
6	December 8, 1923 1920 hours	Leningrad Region	The bolide made a dreadful noise and cracking sound The noise was so strong that a peasant was deafened
7	April 30, 1925 2130 hours	Moscow Region	A slight noise was heard
8	May 25, 1925 1300 hours	Molotov Region	Noise and cracking sound
9	September 24, 1925 2100 hours	Novgorod	Sharp, dry cracking sound
10	August 18, 1928 Evening	Siberia	A slight hissing was heard during the flight
11	February 2, 1932 1820 hours	Moscow	The sounds "zh-zh-zh" and "sooo" were heard
12	March 8, 1932 0800 hours	Western Siberia	The bolide made noise in flight
13	June 17, 1932 2223 hours	Astrakhan	Sounds like the noise of a rocket in flight
14	August 20, 1932 2130 hours	Moscow	The sounds were sharp and screeching
15	August 30, 1932	Moscow Region	The fall was accompanied by a weak cracking sound
16	October 2, 1933	Ural	The sound was like that of aircraft overhead
17	June 20, 1934	---	A powerful cracking sound and other noise were heard
18	April 12, 1935 1800 hours	---	The fall was accompanied by noise and rushing wind
19	May 29, 1935 1730 hours	Voronezh Region	A whistling sound was heard
20	July 30, 1935 0200 hours	Orel	The fall was accompanied by a cracking sound

No.	Observation		Nature of the sounds (extracts from eyewitness accounts)
	Time	Region	
21	August 8, 1935 0100 hours	Odessa	The fall was accompanied by a hissing sound
22	March 26, 1936	Krasnoyarsk Territory	The fall was accompanied by noise as the bolide appeared
23	June 13, 1936	---	A whistling was heard
24	November 29, 1936 0100 hours	Turukhansk Territory	A rumble like that of aircraft was heard
25	January 9, 1937 2203 hours	Mariyskaya ASSR	Hissing and whistling were heard
26	January 13, 1937	Pskov Region	The bolide burst into small sparks, omitting a noise like the crackling of lightning
27	May 3, 1937 1148 hours	Crimea	The bolide made a whistling noise in flight
28	May 5-10, 1937	Kursk Region	Noise was heard during flight
29	May 14, 1937 1510 hours	---	Whistling and hissing were heard, lasting for 10 sec
30	August 5, 1937 1600 hours	Vologda Region	Hissing was heard
31	December 12, 1937 1032 hours	---	A slight noise was heard, no shock
32	February 7, 1938 0130 hours	Tambov Region	Whistling and hissing were heard at beginning of flight, then shocks
33	February 15, 1938	Vologda Region	A hissing noise was heard
34	July 28, 1938 1135 hours	Orenburg Region	A crack was heard at the time of flight of the bolide
35	August 9, 1938 1415 hours	Stalinsk Region	Hissing was heard during flight
36	August 15, 1940 Noon	Arkhangelsk Region	A hissing was heard before the fall (2 or 3 sec)

No.	Observation		Nature of the sounds (extracts from eyewitness accounts)
	Time	Region	
37	October 30, 1940 1842 hours	Kharkov Region	A hissing was heard, no detonations
38	November 29, 1940 1600 hours	Arkhangelsk Region	The bolide flew low, a powerful noise was heard
39	December 16, 1940 0832 hours	Belorussian SSR	Hissing and howling noises were heard
40	December 24, 1940 0900 hours	---	Hissing was heard during flight
41	April 9, 1940 0230 hours	Molotov Region	Noise, hissing, cracking
42	May 4, 1941 0330 hours	Eastern Europe	Hissing was heard during fall
43	May 9, 1941 2320 hours	Karachayev Autonomous Region	The bolide moved with a barely audible whistling
44	June 23, 1941 0955 hours	Altay	The bolide made a quiet whistling noise
45	July 12, 1941 Night	Moscow Region	The flight was accompanied by a cracking sound
46	March 9, 1942 2045 hours	Khabarovsk Territory	The fall was accompanied by a noise like that of an airplane flying low with its engine shut off, and by cracking and hissing
47	December 30, 1942	---	A weak hissing was heard during flight
48	May 15, 1944 1530 hours	Krasnoyarsk Territory	Rumble like that of aircraft, cracking like that of ten pine trees when cut down and falling
49	May 8, 1945 2200 hours	Primorsk Maritime Territory	A sound like that of high-flying droning aircraft was heard, lasting several seconds
50	April 5, 1946 0100 hours	Rostov Region	Hissing was heard at the beginning of the flight

No.	Observation		Nature of the sounds (extracts from eyewitness accounts)
	Time	Region	
51	August 24, 1946 2043 hours	Dnepropetrovsk Region	Hissing was heard the entire flight time, with whistling at the beginning
52	April 6, 1947 1900 hours	---	Crackling and rustling were heard
53	March 6, 1948 2000 hours	Murmansk Region	Whistling was heard
54	March 10, 1948 2200 hours	Chelyabinsk Region	Hissing
55	March 16, 1948 1955 hours	Novosibirsk Region	Hissing
56	September 18, 1948 0215 hours	Kharkov Region	Sparks issued, with a hissing and cracking noise
57	September 28, 1948	Simferopol	A cracking sound 5 sec after detonation
58	October 21, 1948 2145 hours	Nikolayev	Slight hissing
59	November 22, 1948 2016 hours	Simferopol	Hissing
60	September 6, 1949 1728 hours	Ulyanovsk Region	Noise during flight
61	October 11, 1950	Novosibirsk Region	The bolide made noise and crackled during flight
62	October 31, 1950 evening	Ryazan Region	Cracking and whistling were heard
63	September 7, 1951 1900 hours	Moscow Region	Rustling sounds were heard during flight

All electrophonic bolides are very bright and almost always light up the area. As expected, no particular color is seen to predominate; there are 12 blue, 14 white, 12 yellow, 14 red bolides. A trail was seen in the case of 36 bolides.

In one instance the nature of the sounds was noted to change (as indicated by I. S. Astapovich[(2)] as well): "Hissing was heard the entire flight time, with whistling at the beginning" (August 24, 1946).

Observers usually describe the sounds of electrophonic bolides as rustling, hissing, whistling, rumbling--predominantly steady and prolonged sounds. In a great many cases, however, a peal or crack is also noted. As pointed out by L. A. Kulik, cracking is always associated with disintegration and detonation of the bolide. It is apparently a pseudo-electrophonic sound and is caused by the purely psychological effect of involuntary association with the picture of an explosion (e.g., Nos. 26, 56, and August 29, 1924: "A crack, as the bursting of a shell"; May 25, 1924: "A sound like bursting and hissing was heard with the emission of sparks"; February 27, 1925: "A cracking sound was heard as the bolide burned up"). As far as the rest of the electrophonic sounds are concerned, they are undoubtedly real.

Among the bolides indicated [in the catalog] thirteen bolides moved in the sector 300° - 60°, three in the sector 60° - 190°, eight in the sector 120° - 240°, and two in the sector 240° - 300°. I. S. Astapovich obtained figures in approximately the same proportion.[(2)] Consequently, 50 per cent of the bolides came from the south, as postulated by I. S. Astapovich, from the ecliptic, i.e., along inclined trajectories.

It is a characteristic fact that, except in those cases when the observer stood on the projection of the trajectory of the bolide and hence received the impression that the bolide was flying perpendicular to the horizon, through the zenith, the majority noted that the bolide trajectories were parallel to the horizon or had very small inclinations. The majority of the bolides with anomalous sounds probably actually have extended trajectories slightly inclined with respect to the surface of the earth. Since all of the bolides in the catalog of the Committee on Meteorites were observed in medium latitudes, this means that the bolides were moving at a large angle with the earth's magnetic-force lines.

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