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Anomalous Sounds from the Entry of Meteor Fireballs

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Sometimes very bright meteors known as fireballs are heard before they are seen. This apparent violation of the normal mechanisms of acoustic propagation has been a long-standing problem in meteoritics. According to Romig and Lamar (*1*), the problem was recognized almost 200 years ago by Sir Charles Blagdon (*2*), Secretary of the Royal Society of London. He collected reports of a large fireball and was perplexed by the simultaneous observations of hissing sounds heard as the fireball passed more than 50 miles from the observers. He was so convinced of the veracity of the observations that he would not reject the anomaly and decided that he "would leave it as a point to be cleared up by future observers." It must be stressed that these anomalous sounds are not to be confused with the normal acoustic phenomena—sonic booms and rumbles—which travel at normal velocities and are heard some time after the fireball has passed the observer.

Summary. A very bright fireball observed over New South Wales in 1978 produced anomalous sounds clearly audible to some of the observers. An investigation of the phenomenon indicates that bright fireballs radiate considerable electromagnetic energy in the very-low-frequency (VLF) region of the spectrum. A mechanism for the production of VLF emissions from the highly energetic wake turbulence of the fireball is proposed. Trials with human subjects revealed a very extended range of thresholds for the perception of electrically excited sounds among a sample population, particularly when the VLF electric field excites surface acoustic waves in surrounding objects. This fact, together with variable propagation effects and local conditions, can account for the sporadic distribution of reports of anomalous sounds from fireballs and auroras.

An interesting summary of all of the effects produced by infalling meteorites has been published by LaPaz (*3*), and many more recent instances have been cataloged by Romig and Lamar (*4*). Psychological explanations of the sounds were questioned long ago by Udden (*5*), whose detailed study of observations of the Texas fireball of October 1917 led him to ask if the sounds could be due to some form of electric energy. In his text on meteoritics, Nininger (*6*) drew attention to instances where the sensation of sound quite clearly preceded visual observation of fireballs and rejected opinions denying the existence of a physical phenomenon. Ingalls (*7*) quoted in full a specific account of noises produced by a large fireball which was observed by a geophysicist, B. W. Hapke, and his wife near Ithaca, New York, in 1960. Hapke 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 directly from the meteor or from all around us."

The search for a physical explanation of these sounds has led to some bizarre suggestions, such as Khan's (*8*) hypothesis that the sounds are produced in the immediate vicinity of the observer by matter associated with the meteor and traveling at a similar speed. Much more defensible is the suggestion by Hughes (*9*) that "Considerable radiation must be produced by the fireball in regions of the electromagnetic spectrum other than the visual and this could provide a possible explanation." Such radiation has not yet been identified in association with a fireball, but this is not very surprising since, as Hughes points out, "anomalous noise seems to be associated with brighter fireballs (average magnitude −13) which are rare objects indeed."

Not only are the anomalous sounds rarely produced, but their perception threshold varies rather widely among the population. Such was the case with a recent large fireball event in Australia.

Observational Data

In the early morning of 7 April 1978 a large fireball of visual magnitude −16 passed over the east coast of New South Wales, Australia, including the metropolitan area of the city of Sydney, and was seen by hundreds of witnesses.

At an early stage, it became evident that any resulting meteorite or meteorites would have descended into the sea approximately 70 kilometers offshore. However, one-third of the eyewitness reports described anomalous sounds coincident with the passage of the fireball. These prompted a more extensive investigation, including personal onsite interviews.

Most of the reports of anomalous sounds bear a close resemblance to those quoted by Romig and Lamar (*4*). They strongly suggest that the passage of a fireball generates a real physiological sensation in many, but not all, observers, which is manifest only when the fireball is a large one. Otherwise such reports would be much more frequent. The reality of the effect is supported by three of the reports where the perception of a strange sound clearly preceded visual identification of the fireball.

The fireball itself exhibited no unusual features. It is quite normal for a large fireball to explode, as most of the observers noted. This occurs when the at-

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mospheric retarding force exceeds the crushing strength of the meteoritic material (*10*), and at this moment the fireball is normally close to maximum brilliance.

There were no reports of radio interference, fading, or blackouts at the time of the fireball. Also, no reports of abnormal signals in telephone or telex circuits were received, probably because any disturbances would pass unnoticed at such an early hour. The lack of independent electrical or electronic detection of electromagnetic radiation from the fireball is unfortunate but not unusual. Almost all of the many reports summarized by Romig and Lamar (*4*) have a similar lack.

At a station near Woodville, New South Wales, 90 km from the fireball ground track, geomagnetic micropulsation recording equipment failed to register any signal in the frequency range 0 to 1.5 hertz at the time of the fireball, as evidenced by records kindly supplied by Fraser (*11*). This negative result is not too surprising because the theoretical magnitude of the perturbation of the geomagnetic field is in the range 10^{-11} to 10^{-13} tesla directly underneath the trail (*12-15*), which is comparable with the limiting sensitivity of the micropulsation recording equipment.

Fireball Energetics

A fireball of apparent visual magnitude -16 traveling at 20 km/sec at an altitude of 20 km is produced by a meteoroid mass of approximately 5 metric tons. This mass value is a best-fit estimate in rough agreement with the mass/luminosity relation published by Hughes (*16*), although it has more recently been pointed out by ReVelle (*17*) that there is a need to determine a more reliable mass/luminosity relation for the study of meteors, meteorites, and fireballs.

Assuming an effective meteoroid frontal area A equal to 1 square meter and taking the drag coefficient C_D to be unity, which is appropriate for a sphere moving at a velocity v of 20 km/sec at constant altitude where the air density ρ_a is 10^{-1} kilogram per cubic meter, the equation $E' = 1/2\ \rho_a C_D A\ v^3$ yields a rate of deposition of energy of 4×10^{11} watts at maximum.

Of this energy, upwards of 90 percent is carried away by the intense Mach 60 shock wave, the remainder being dissipated in the wake or lost as radiated energy. The latter may be estimated quite simply by treating the fireball as a blackbody with an emitting area of the order of 10 m^2. Although the stagnation temperature at the leading edge will be 25,000 K for such a fireball (*18*), the effective temperature T, based on excitation temperatures found from spectroscopic observations of fireballs by Ceplecha (*19*), will be closer to 6000 K. This gives a radiated power $P = \sigma A\ T^4$ (where σ is the Stefan-Boltzmann constant $= 5.67 \times 10^{-8}$ W m^{-2} K^{-4}) of the order of 10^9 W, which is less than 1 percent of the total energy deposition and will be neglected.

If we now conservatively assume that 2 percent of the total energy is dissipated in wake turbulence, the amount available to excite oscillations in the ionized plasma in the trail is of the order of 10^{10} W.

In an earlier search for radio noise from meteors, Hawkins (*20*) concluded that meteors show a surprisingly low efficiency in converting kinetic to radio energy. The meteors studied by Hawkins were no brighter than magnitude -1, whereas the 1978 fireball had a luminosity 10^6 times greater. This makes the absence of radio emission all the more surprising. Certainly a large amount of input energy is available, so the next problem is to identify the likely spectral range of any possible fireball radiation other than the thermal emission already considered.

Spectrum Constraints

In considering potential regions of the entire electromagnetic spectrum in which radiation may act as a carrier of the energy perceived as anomalous sounds, the first and most obvious step is elimination of all radiations on the ultraviolet side of the visible spectrum, since no ionization is produced beyond the immediate vicinity of the fireball, indicating that atmospheric absorption is complete. Energy radiated in the visible and infrared windows of the atmosphere cannot penetrate buildings and must also be eliminated, because two of the three people who reported hearing the fireball before seeing it were indoors at the time.

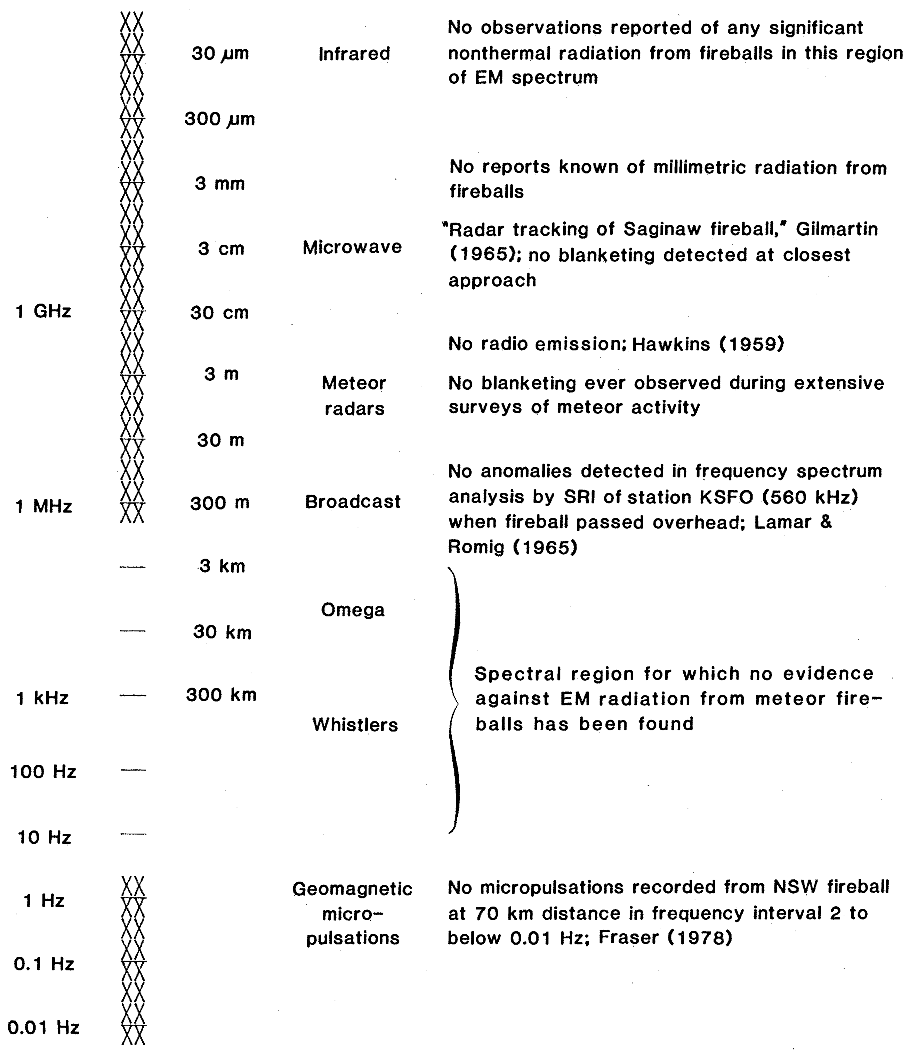

Fig. 1. Fireball electromagnetic (*EM*) radiation spectrum. Other abbreviations: *SRI*, Stanford Research Institute; *NSW*, New South Wales.

This leaves only radio energy. A diagram of the radio spectrum from the microwave region down to frequencies detectable on micropulsation recording equipment is shown in Fig. 1.

Emissions in the centimetric region may be eliminated by considering an interesting observation of the 1964 Saginaw (Texas) fireball reported by Gilmartin (*21*). This large fireball, from which a 100-kg meteorite was later recovered (*22*), was tracked with very high precision by a radar installation, which recorded the whole of its flight through the atmosphere. Following the disintegration of the fireball, the radar tracked three separate fragments for a further 3 seconds. There was no reported blanketing of the radar echo by noise emitted by the fireball plasma.

In the high-frequency (HF) and very-high-frequency (VHF) radio bands, extensive radar observations of meteor activity have failed to detect signals generated by meteors. In his search for such emissions, Hawkins (*20, 23*) obtained negative results at frequencies of 30, 218, and 475 megahertz. Following a Canadian meteor survey lasting more than 11 years, in which the 32-MHz radar observations were recorded on film, McIntosh (*24, 25*) reports that no fireball echoes exhibited any blanketing effect that could be attributed to electromagnetic radiation produced by the fireball. The same is true of the 69-MHz radar observations obtained over several years in the Southern Hemisphere meteor surveys conducted from New Zealand by Keay and Ellyett (*26*).

Lower in the radio spectrum, the AM broadcast band is the region most thoroughly monitored. In one of the reports of the 1978 New South Wales fireball, unusual sounds thought at first to be from a radio continued to be perceived after the radio was turned off. The same appears to be true of the 1963 San Francisco fireball described by Lamar and Romig (*27*), who cite three reports of anomalous sounds from a total of 65 reports. The 1963 fireball passed directly over radio station KSFO on 560 kilohertz, which was at the time being attentively monitored by a station engineer who was trying to identify an unrelated beeping signal later traced to accidental triggering of a time-marker oscillator. Spectrum analysis by the Stanford Research Institute of the monitor tape of the broadcast revealed no trace of a signal emanating from the fireball.

Fireballs are known to cause interruptions to distant broadcasts, as reported for example by Folinsbee and Bayrock (*28*) in their study of the 1963 Peace River fireball. In this case, intense ionization due to the fireball in the E and D regions of the ionosphere caused the deep fade noted in the reception of a distant radio station, CJCA, on 930 kHz. A report many years ago by McKinley and Millman (*29*) of radar noise starting 1 second or so after strong meteor echoes has often been quoted (*4*). This was most likely due to forward scatter of signals from distant transmitters, again caused by the intense fireball ionization at high altitudes.

The only region of the radio spectrum for which convincing negative evidence of fireball emissions is not readily available is the very-low-frequency (VLF) region. A search of the literature pertaining to VLF emissions brought to light a paper by Johler and Morganstern (*30*) describing the propagation of an electromagnetic pulse originating from a nuclear explosion in the lower atmosphere. The greater part of the radiated radio energy from a nuclear explosion lies in the electromagnetic frequency range 5 to 20 kHz.

It is also pertinent to note that emissions of radio noise associated with auroras exhibit a power spectrum that peaks just above a low-frequency cutoff, which is usually around 2 to 6 kHz (*31*), and that there are countless reports, dating back to antiquity, of auroral displays being heard as well as seen (*32*).

Source Mechanism

In paraphrasing their study (*4*) of electromagnetic effects associated with fireball entry, Lamar and Romig (*33*) note: "There are two general explanations for anomalous sounds. The first possibility is that the fireball emits electromagnetic radiation which is somehow transduced into sound waves at the surface of the ground. The second possibility is that the passage of the fireball perturbs the Earth's electric field sufficiently to cause local electric discharges on the ground near the observer."

The latter mechanism was investigated by Ivanov and Medvedev (*34*), who obtained theoretical results indicating that electrostatic effects are produced by polarization of the ionized fireball trail, but the potential gradients produced are not significantly greater than ambient values. On the other hand, the generation of electromagnetic radiation by a meteor fireball has apparently escaped theoretical attention, and emission of energy in the VLF region of the spectrum has not been ruled out.

It is appropriate to remark that the extremely high-energy density in the turbulent wake of the fireball should excite all oscillatory modes possible in the ionization present. The scale of the turbulence will be comparable with the meteoroid diameter d, which, at an entry velocity v, will create new eddies at a rate v/d—in the present case 15,000 sec^{-1}. However, the collision frequency is too high and the geomagnetic field too weak to provide the charge separation necessary for appreciable electric dipole radiation near this or any other likely frequency, such as the ion cyclotron frequency.

Because of the high collision frequency, 6×10^{11} sec^{-1} at an altitude of 20 km, it is not profitable to seek a generation mechanism for meteor VLF emissions by examining the production of auroral radio noise, because it takes place in regions of the geomagnetic field where the collision frequency is very much lower (*35*).

As suggested by spectrum considerations already discussed, a parallel might be sought between electromagnetic emissions from a meteor fireball and the radio pulses produced by nuclear explosions in the atmosphere. For nuclear radio pulses three primary mechanisms have been recognized by Price (*36*), who comments, "A great deal of work on the generation of electromagnetic pulse by nuclear detonations, including the initial formulation of most of the generation mechanisms, remains available only in classified reports." Of the available unclassified material, Kompaneets (*37*) and Karzas and Latter (*38*) give a brief treatment outlining two ways in which a nuclear fireball interacting with the geomagnetic field will generate electromagnetic radiation. The first is through the intense current pulse of Compton electrons, and the second is by the expulsion of the geomagnetic field from the ionized region surrounding the fireball.

The meteor fireball lacks the radiation flux to support the first mechanism, but the hydrodynamic expulsion of the geomagnetic field bears examination. The geomagnetic energy density is given by $U_m = B^2/2\mu_0$, where B is the geomagnetic field and μ_0 is the permeability of free space; its value is normally 10^{-3} joule per cubic meter, which is six orders of magnitude lower than the thermal energy density in the fireball trail. When the ionization recombines, the expelled field collapses into its original volume, radiating the excess energy stored when the field was compressed outward. The energy release occurs randomly, with spectral components up to the eddy frequency.

From an approach based on skin depth

considerations, it can be shown that the expelled field will penetrate the fireball plasma in a time no greater than $t_p = \mu_0 e^2 n_0 r_0^2/2mv_c$, where n_0 and r_0 are the initial electron density and trail radius, respectively, ν_c is the collision frequency, and e and m are the charge and mass of the electron. Taking $r_0 = 1$ m and $n_0 = 10^{22}$ m^{-3}, assuming total ionization as an upper limit, we get $t_p \leq 3 \times 10^{-4}$ second, which means that the geomagnetic field can be expelled only from the first few meters at most of the trail of a magnitude -16 fireball. The power radiated amounts to no more than $U_m A v$, where A is the cross-sectional area of the plasma and v the fireball velocity, which yields a mere 40 W. Hence it is apparent that the mechanisms operating to produce VLF radiation from a nuclear fireball are insignificant for a meteor fireball unless it is of comparable dimensions.

However, the magnetic field reestablished in the fireball plasma will be controlled by the plasma motions provided the magnetic Reynolds number $R_m = \mu_0 L_p v_p \sigma$ is large compared with unity. Here L_p and v_p are scale length and velocity for the plasma motion, and the conductivity $\sigma = ne^2/m\nu_c$ is 5×10^2 mho/m in the plasma, where n is the instantaneous electron density. For a reasonable scale of turbulence in the wake, $R_m = 5$; although this is low, R_m becomes larger as the scale values are increased and is sufficient for the transfer of the abundant wake energy into magnetic field energy for as long as the electrical conductivity remains adequate. When the conductivity falls, due to recombination or electron attachment as the plasma cools, the twisted and extended magnetic "spaghetti" relaxes, releasing its strain energy as VLF fluctuations of the geomagnetic field.

The mechanism is in accord with the observational finding that only very large fireballs give rise to reports of anomalous sounds, because they are the only fireballs that penetrate the atmosphere to a low enough altitude to produce a turbulent boundary layer and wake (*17*). Furthermore, the magnetic Reynolds number is quadratically related to the size of the fireball through its dependence on both the scale length and velocity of the wake turbulence.

Anomalous Hearing

In the *Handbook of Sensory Physiology*, Simmons (*39*) remarks, "Probably no single topic about hearing has generated as much speculation and controversy as has electrical stimulation of the ear and of hearing." He then observes that "A certain confusion still exists today about what happens when an audio frequency current is applied in or near the ear, because there is more than one form of electrical hearing." Some of the more quantitative electrophonic experiments have been performed by Sommer and von Gierke (*40*), who exposed their subjects to both electrode and electrostatic stimulation over a range of frequencies from 100 Hz to 100 kHz. From the exposure of their subjects to electrostatic fields, Sommer and von Gierke obtained threshold data which indicated that electric field strengths exceeding 5×10^3 volts per meter are necessary for detection. Such field strengths are typical of the electromagnetic pulses from nuclear explosions rather than the VLF emissions from meteor fireballs.

Sommer and von Gierke noted that they had great difficulty in eliminating airborne artifacts when using large electrodes for electrostatic excitation of the head. They therefore abandoned the use of large electrodes. This distinction is irrelevant when considering anomalous meteor fireball or auroral sounds provided the causal agent is an electrostatic field variation. Indeed, it has often been suggested that such sounds are produced in the immediate vicinity of the observer by energy transmitted as an electromagnetic wave.

Turning to magnetic rather than electrical perception, some remarkable sensitivities have been reported for honey bees and pigeons, where responses to variations of 10 gammas and less than 70 gammas, respectively, have been described by Keeton *et al.* (*41*) (1 gamma = 10^{-9} T, or roughly 10^{-5} of the geomagnetic field). These results are in dispute (*42*), but in a review of the subject Ossenkopp and Barbeito (*43*) stated that "Magnetic fields have been shown to have a biological effect on a variety of life forms ranging from unicellular organisms to man." The field levels are generally of the same order of magnitude as the geomagnetic field or higher and rapid variations at VLF have not been deeply explored. However, at a somewhat lower frequency, Tucker and Schmitt (*44*) reported that in more than 30,000 trials on more than 200 persons exposed to 60-Hz alternating magnetic fields of 7.5 to 15×10^{-4} T root-mean-square, no real perception occurred.

In the light of these effects, both electric and magnetic, an opportunity was taken to conduct some tests with human volunteers exposed to electrostatic fields and magnetic fields, singly or crossed, varying at frequencies of 1, 2, 4, and 8 kHz and wideband noise. Purely acoustic tests, with a loudspeaker, were also conducted at the same frequencies. The magnetic field was generated by a large Helmholtz coil, which produced a maximum field of 10^{-4} T, 1.5 times the geomagnetic field. The electrostatic field was generated by a heavy electrode of effective area 4×10^{-2} m^2 suspended approximately 0.25 m above the subject. Direct acoustic radiation was attenuated more than 20 decibels by surrounding the electrode with a foam polystyrene enclosure and interposing a large sheet of the same foam material between the enclosure and the subject. Tests with and without earplugs indicated that the auditory effects were being produced electrostatically rather than acoustically, and tests with a sensitive sound-level meter indicated the presence of only very low levels of acoustic sound.

The results of the tests on 44 subjects showed that magnetic fluctuations at the frequencies listed above were not perceived. However, the electrostatic responses were highly variable from subject to subject over and beyond the dynamic range of the equipment, which, in terms of power, extended more than three orders of magnitude. Peak-to-peak variations as low as 160 V/m (60 V/m root-mean-square) were perceived in the electrostatic field at frequencies of 4 and 8 kHz by the subjects with sharpest acuity. There was a fairly general, but certainly not proportional, relationship discernible between electrostatic and acoustic thresholds as a function of frequency. The full results of these tests will be published elsewhere, but the conclusions related to this study are that an electrostatic field of 160 V/m peak-to-peak amplitude, varying at upper audio frequencies, can be perceived by human subjects either by an electrophonic mechanism or by acoustic signals generated in the close vicinity of the ear by metal or dielectric objects vibrated by the field. Furthermore, the sensitivity of various individuals to electrostatically produced "sounds" varies by factors of at least 10^3 in terms of power, which helps to explain why only some individuals report hearing anomalous fireball sounds.

Conclusions

A peak-to-peak variation of 160 V/m in the **E** vector of an electromagnetic wave detected at a distance of 40 km from a fireball requires a total radiated power of 2×10^{10} W. However, this distance is of the same order as the wavelength of the

VLF radiation which is confined to the earth-ionosphere cavity and which has the effect of magnifying the effective power, provided absorption losses are not high. If the cavity effect and local conditions together act to concentrate the effective power in the vicinity of some observers, it should not be impossible to reconcile this power level with the amount of power available in the fireball wake. Also, if the generation of surface acoustic waves in the upper audible range by the varying electric field acting on objects close to the observer is as effective as laboratory trials suggest, it should be possible to reduce the power levels by a further factor of at least 10^2.

To confirm the existence of VLF emission from meteor fireballs, it will be desirable to compile and disseminate annual lists of fireballs (*45*). Each occurrence should be timed as accurately as possible to ensure positive identification of fireball events on the chart records of VLF receiving stations engaged on other work, such as whistler detection. VLF energy from a meteor fireball should propagate globally in the earth-ionosphere duct and have a distinctive time/frequency spectrum compared to lightning discharges or nuclear bomb detonations in the atmosphere. It seems more than likely that VLF receiving networks established for nuclear test monitoring must have already recorded many meteor fireballs, but they may not have been identified for want of fireball sighting data.

In 1 year only about 50 fireballs as large as the New South Wales fireball enter the earth's atmospehre, and of these fewer than three are observed and reported, the remainder being over the sea or unpopulated areas or behind clouds. From any given inhabited region such a fireball event will be seen on average at intervals of 30 to 100 years, depending on the cloud cover statistics of the region.

To sum up, it now appears to be certain that meteor fireballs are perceived aurally by a significant number of observers. The energy transfer appears to occur at very low frequencies in the upper audio range emitted by the fireball as electromagnetic radiation. Further work is now indicated to determine more precisely the mechanisms of electrostatic-to-acoustic transduction involved and the conversion of energy into VLF radiation from the energy of turbulence in the fireball wake.

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Suckling

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Among mammals, suckling is the only behavior that is universal and characteristic. Because of its vital importance for survival and its putative contribution to normal psychosexual development, suckling behavior has provided researchers with a rich source of theories and debates concerning the role of nature versus nurture in human behavior and the needs of the developing child. As the debates spent themselves, attention focused on the mechanisms that control suckling behavior, on its incidence and form of occurrence, on the events that precipitate and terminate it, on the way stress affects it, and on the way that suckling changes during the individual's development (*1*). Scientists and pediatricians alike became more sensitive to the pronounced individual variability among normal infants in the efficiency of suckling, and a number of investigators studied suckling in nonhuman primates (*2*) and other mammals (*3*) in search of general principles.

This effort revealed the multiple facets and functions of the suckling act. While the most obvious function of suckling is for the infant to obtain nutrients and fluids from the mother's milk, it has other vital functions as well. As a source of maternal contact, suckling seems to comfort the infant. For certain nonhuman mammals, it contributes to escape from predators. Some marsupial and rodent mothers (wood rats, for example) exploit their pups' tenacious grip

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