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Radiation of Ultra Low Frequency Electromagnetic Waves from Atmosphere under the Influence of Strong Shock Waves

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We present preliminary results from the experimental investigation of the response of the atmosphere due to the impact of powerful shock waves. The response is evidenced as ultra low frequency electromagnetic wave radiation at frequency of 2–5 kHz and in duration of 3–7 s. We hypothesize that this radiation appears due to the following process: the shock wave ionizes the neutral particles in the air and these charged and neutral particles continue their vertical motion, which forms in the trail of the shock wave. Such motion can cause the cyclotron-like radiation measured.

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Several researchers have presented ground-based observations of electromagnetic emissions observed during seismic events.[1−3] During these events, two types of emissions are observed. First, precursor emissions occur between a few days and a few hours before earthquakes, in a frequency range from one hundredth of a Hz up to several MHz. Secondly, emissions observed after the shock are generally attributed to the propagation of acoustic gravity waves. Hypotheses concerning the mechanism for the generation of precursor emissions are also valid after the shock when the Earth's crust returns to an equilibrium state. The emissions can propagate up to the ionosphere, and observations made with low-altitude satellites have shown an increase in the intensity of ULF/ELF/VLF waves above seismic regions.[4] In contrast to the ground-based experiments, satellite experiments can cover most of the Earth's seismic zones, and any statistical studies become meaningful due to the much larger number of recorded events.

In recent years, many investigations have been particularly relevant to the modeling and understanding of the ionospheric response. These investigations have shown that the intense acoustic waves generated at the Earth's surface influence the ionosphere, and the ionosphere responds to these perturbations in different ways.

Galperin and Hayakawa[5] reported an experiment to examine the effect of a shock wave produced by a surface explosion (in one experiment 300 T of trinitrotoluene was used). When the shock wave reached a defined altitude, i.e., where conditions prevail for electric discharge in the 'wave front–ionosphere' gap, electromagnetic oscillations resulting from the wave were detected on board of a satellite. To explain the electromagnetic perturbations in the ionosphere, a hypothesis was advanced[5,6] about the electric discharge between the front of the shock wave and the ionosphere. The shock wave from the surface explosion rises to altitudes where conditions for electric discharge are met. The crucial point in the proposed hypothesis is the assumption that electrical conductivity at the shock front exceeds that of the surrounding environment. According to this model, the ascending electric discharges may be initiated not only by storm lightning, but also by intense acoustic waves in the atmosphere.

For our ground-based experiments, we employed an acoustic gun that is used in anti-hail installations (Fig. 1) as the shock wave generator. An explosion of a propane-butane-air mixture in the combustion chamber forms shock waves. The Mach number of the shock wave is $M \approx 3.25$ and the wave's beam width angle is $\alpha \approx 26°$.[7]

For determination of electromagnetic emissions in the ULF range, we fabricated a multiband antenna attached to an amplifier and an analyzer. The temporal and frequency response of the atmosphere due to the shock wave can be divided into three regions:[8] (1) ULF electromagnetic wave radiation with frequency of 2–5 kHz and duration of 3–7 s; (2) very wide-band and short-duration (0.1 ms) electromagnetic wave radiation; and (3) low-frequency chirp with a duration of a few milliseconds.

In this work, we discuss only the first region in more detail. Immediately after the shot, ULF electromagnetic radiation is observed for a duration of

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a few seconds (3–7 s) and during this time the frequency first quickly increases and then stays constant or slowly decreases (Fig. 2). The radiation frequency and radiation evolution are very similar to the sound wave's frequency and evolution that were generated by the shock wave (Fig. 3).[8,9] Due to the fact that ULF radiation is detected directly after the shot (see Fig. 2) and after taking into account the fact that the shock wave's velocity is 1000–1200 m/s, it could be deduced that ULF radiation is observed to be up to 7–10 km. This means that our observations are related to processes occurring up to 7–10 km.

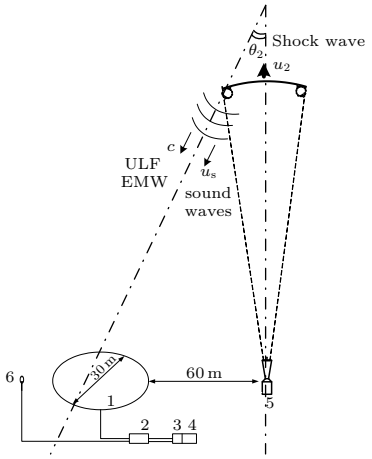


Fig. 1. Experimental scheme. Here u_2 and u_s are the velocities of the source (shock wave) relative to the environment and speed of propagation of sound in the environment, respectively; and θ_2 is the angle formed between the source (shock wave) velocity vector and the vector directed from the detector to the source. (1) Antenna for receiving ELF electromagnetic waves; (2) amplifier for sound frequency; (3) ADC; (4) laptop; (5) acoustic gun; and (6) microphone.

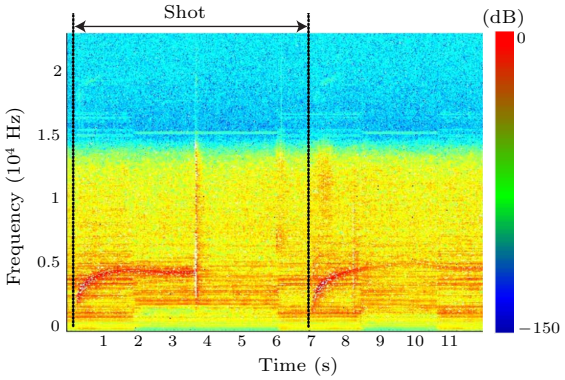


Fig. 2. Ultra low frequency electromagnetic wave radiation is observed after the shot.

We hypothesize that this radiation appears due to the following process: the shock wave ionizes the neutral particles in the air and these charged and neutral particles continue their vortical motion, which forms in the trail of a shock wave. Such motion can cause cyclotron-like radiation at the vortical frequency.[10]

As we know, the primary frequency of the synchrotron-like radiation of non-relativistic particles is equal to their rotation frequency ($\nu_0 = \nu_{el}$ at the fundamental $n = 1$; for harmonics with $n > 1$, the radiation intensity is essentially small). Hence, from Fig. 2 (see also Fig. 3) it can be deduced that the frequency of the vortical flow following the shock waves increases during a short period of time (0.5 s) then it becomes approximately constant.

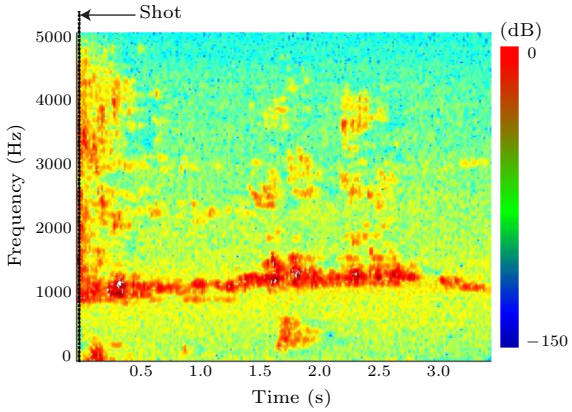


Fig. 3. Sound wave frequency and evolution generated from the shock wave.

Based on the observations, these vortical flows also produce acoustic waves with frequencies that are essentially lower (by 3–4 times) than the frequencies of the electromagnetic fields (see Fig. 3). This intriguing observation can be explained by considering the change in Doppler frequency that occurs during the detection of the acoustic waves. To show this, we begin with Doppler's famous relation

$$\nu = \frac{\nu_0 \cdot (1 + u_1 \cdot \cos\theta_1/u_s)}{1 + u_2 \cdot \cos\theta_2/u_s},$$

where ν is the frequency of the detected wave; ν_0 is the frequency of the source; u_s is the speed of propagation of sound in the environment; u_1 and u_2 are the velocities of the detector and the source relative to the environment, respectively; and θ_1 and θ_2 are the angles formed between the velocities and the vector that are directed from the detector to the source, respectively (see Fig. 1). During the observation period, $u_1 = 0$, $\theta_2 \approx 0$, and $u_2/u_s = M \approx 3$; therefore,

$$\nu \approx \frac{\nu_0}{1 + M} \approx \nu_{el}/4,$$

which is confirmed by comparing Figs. 2 and 3. An explanation for the short duration of the acoustic oscillations (∼3 s) can be made by considering the fact that the absorption of the acoustic waves in air is essentially stronger compared with the absorption of the electromagnetic fields.

The characteristic frequency ν_{eff} of synchrotron-like radiation from a relativistic particle with a Lorentz factor $\gamma = 1/\sqrt{1 - v^2/c^2}$ is of the order of

$\nu_{\rm el}\gamma^3$. In our case, the rotating particle (i.e., electron) is non-relativistic: $v \ll c$, and $\nu_{\rm eff} \cong \nu_{\rm el}$. Thus the radiation frequency and acoustic frequency are of the same order (Figs. 2 and 3).

In this manner, objects can be detected to move at supersonic speeds and leave a trace of ionized air.

In summary, the response of the atmosphere due to the impact of powerful shock waves is evidenced as ULF electromagnetic wave radiation with a frequency of 2–5 kHz and a duration of 3–7 s. We hypothesize that this radiation appears due to the following process: the shock wave ionizes the neutral particles in air and these charged and neutral particles continue their vortical motion, which forms in the trail of the shock wave. Such motion can cause the cyclotron-like radiation measured.

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