Formation of Red Sprites

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Abstract—The properties of red sprites that are generated in the ionosphere at an altitude of 100 km are considered. A process that leads to the formation of such plasma objects is proposed. It is demonstrated that sprites are generated by acoustic waves that give rise to vortices and gas breakdown in the presence of strong gradients of gas temperature and electron density.

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A sprite represents a pulsed optical discharge with the dominant strong emission in the red spectral range that is generated in the ionosphere at an altitude of 80–100 km and propagates downwards to an altitude of 40 km [1, 2]. The sprites can exhibit cylindrical shapes or base-up conical shapes (Fig. 1) [2]. The transverse size of the sprites can reach several hundred meters. The emission duration ranges from several hundred microseconds to hundred milliseconds. The mean optical energy of the sprite per one event is about 50 kJ.

The sprite breakdown in the ionosphere is preceded by an unstable equilibrium state. Minor deviations (variations in a parameter) lead to the electrical breakdown.

The sprite images obtained in 1990 [3] have stimulated the research in this direction and numerous works have been published (see, for example, [4–15]). An important problem in the study of sprites is related to the process that gives rise to the effect.

One of the widely studied processes involves the effect of high-power thunderstorm lightnings [1, 2, 5]. However, the probability of such an effect is relatively low owing to the absence of thunderstorm lightnings at altitudes of 80–100 km. Nevertheless, lightnings can induce sprites due to another reason lying in the generation of acoustic waves. Below, we consider this effect in detail.

One of the important and interesting processes of aeronomy involves the influence of acoustic and impact waves on the effects in the upper atmosphere and ionosphere and the generation of sprites. Galperin and Hayakawa [16] present the experimental results related to ground explosions with up to 300 t of trinitrotoluene. In the experiments, shock waves reach certain altitudes and provide the conditions for the electric discharge between the shock wave and the ionosphere.

![Fig. 1. Photograph of a sprite.](image-url)
rotor drive power of 55 kW, the acoustic intensity at the horn exit was 160 dB.

Two acoustic emitters with a minor frequency unbalance were used to increase the penetration altitude in the atmosphere. A resonance frequency of about 24 Hz results from the nonlinear interaction of the acoustic waves in the atmosphere.

The responses related to the effect of the acoustic waves on the atmosphere were detected as optical signals and were recorded using a film with a sensitivity of 1000 units. The photographic recording was started prior to the acoustic action and was terminated with a delay of a few seconds relative to the termination of the acoustic action. In five (of ten) experiments, an increase in the airglow was induced by the acoustic action. The photometric analysis along the central line of the frames recorded prior to and after the action makes it possible to estimate the glow intensity. The experiments yield a significant increase in the airglow due to the acoustic action [13, 18].

The photographic recording of the airglow was supplemented with the measurements of the electromagnetic response at a frequency of 151 MHz. The electromagnetic waves were measured using an interferometer with two vertically oriented antennas. The measurements show that the electromagnetic signal increases due to the effect of the acoustic waves on the atmosphere [13, 18].

Note that the laboratory experiments in a gas-discharge tube with a variation in the acoustic intensity directed along the positive column yield the pulsed optical superluminescence [19–21]. This result is due to the vortex turbulent motion in the discharge in the presence of the radial gradient of the gas temperature inside the tube [22–24].

The study of the acoustic-wave propagation in the upper atmosphere can be found in [25, 26]. The model calculations show that the maximum velocity of particles in the acoustic wave is reached at an altitude of about 100 km regardless of the initial power and the initial angle of the acoustic beam. In addition, note the bending of the phase trajectory of the acoustic wave at this altitude, apparently, owing to the fact that the gas temperature and electron density sharply increase at $H \sim 100$ km [27]. Figure 2 shows the dependence of the air temperature on the altitude. Based on the above data, we can expect the vortex motion of gas resulting from the propagation of the acoustic waves at altitudes of 90–100 km, where the plasma formations (sprites) are created.

Acoustic waves can be generated in the lower atmosphere due to hurricanes, tsunamis, tornados, earthquakes, volcanoes, thunderstorm lightnings, and various (underground, ground, and above-ground) nuclear explosions.

Relatively frequent natural cataclysms generate high-power acoustic waves that propagate towards the ionosphere and significantly affect various atmospheric processes. When the acoustic waves propagate upward from dense atmospheric layers to layers with lower density, the high-frequency component is absorbed and the infrasound arrives in the ionosphere. At an altitude of 90–100 km, relatively strong gradients of the gas temperature and electron density [27] cause vortex motions in the presence of acoustic

![Fig. 2. Plot of the gas temperature vs. altitude.](image1)

![Fig. 3. Vertical distribution of the electron density in the ionosphere.](image2)