To explanation of the phenomenon of spatial-temporal modulation of the intensity of light pillars from ground-based light sources

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The phenomenon of spatial and temporal modulation of intensity of light pillars, observed in high latitudes simultaneously with Earth magnetic field perturbations and aurora flames, is attributed to the ice particle orientation under influence of electromagnetic radio waves, generated in the ionosphere.

The phenomenon, which manifests itself in the form of periodically brightness-modulated light pillar from a ground-based source, was described in Ref. 1, but had not received yet a satisfactory explanation. We hope that this work makes up for the deficiency.

Light pillars are often observed in frosty winter nights. The reason of their origination is light reflection from crystalline ice particles, the orientation of flat faces of which is close to horizontal. This is the reason of formation of sun pillars as well. Quite many works are devoted to description of these phenomena.[2–4] The possibility of brightness modulation along the pillar length due to vertical stratification of ice aerosol is not excluded. However, the modulation in this case is a sufficiently fuzzy random function, characteristic for aerosol layers.

A peculiarity of the phenomenon [Ref. 1, Fig. 2] is a clearly pronounced periodical structure of the pillar in the form of alternation of light and dark dashes (Fig. 1). Their angular dimensions increase with the height. The number of light spots in the photo can be approximately estimated as 40. It is impossible to determine their exact number, since they merge in one line near the light source.

An important peculiarity of such phenomena is the fact that they are observed in Norilsk (about 70°N) and never in Yakutsk (61°N). Perturbations of the Earth magnetic field along with Polar aurora took place during observations of the phenomenon. The light brightness of pillars changed simultaneously with aurora flames and had a diverse character, i.e., observers saw changes either in brightness of the entire pillar or of its part, or noted the "running striations mode" (according to the author's terminology). Just the last case is fixed in Fig. 1.

Analyzing all the above facts, we presumed that the periodic modulation of light pillar brightness was caused by the interference of incident and reflected electromagnetic waves. The underlying surface was a snow-covered frozen ground, i.e., the dielectric with losses; and the dielectric is inhomogeneous along the wave vector. Therefore, when reflecting, phase shifts can depend on the frequency, and there can appear conditions for origination of wave packets at different moments and in different spatial intervals. This forms the "running striations phenomenon."

Fig. 1. Stratified halo. Photo by L.N. Popov.

To estimate the phenomenon, presume that the incident electromagnetic wave is monochromatic, and

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standing waves can be formed during its reflection from the Earth's surface. In the electric vector antinode, ice crystals of large diameters are horizontally oriented (along the vector **E** of the incident wave). Frequencies of generated waves can essentially differ at different moments, therefore, the half-wavelength can include either the visible length of the pillar or its part; or many half-wavelengths can cover the visible length of the pillar. Then, a system of equidistant layers of oriented particles is to be formed at an invariable frequency. Their reflectance is higher than the reflectance of particles in nodes of standing waves.

The photo[1] allows approximate estimation of the mean half-wavelength and, hence, estimation of the frequency range of electromagnetic oscillations. A frequency of about 70–90 MHz answers to the above situation. For the entire visible part of the pillar was covered by the half-wavelength, the frequency should be of several MHz. The relative dielectric permittivity for ice is 4.7 at the above frequencies. Correspondingly, the reflectivity for amplitude R at normal incidence is 0.37. We take this value as the reflectivity of the frozen ground.

The field strength, represented by a superposition of incident $E_0\sin(\omega t - kh)$ and reflected $RE_0\sin(\omega t + kh + \delta)$ plane waves, can be written as

$$E(h,t) = (1-R)E_0 \sin(\omega t - kh) + \\ + 2RE_0 \cos\left(kh + \frac{\delta}{2}\right)\sin\left(\omega t + \frac{\delta}{2}\right), \quad (1)$$

where E_0 is the amplitude of the incident wave; k is the wave vector collinear to the vertical direction h; δ is the phase shift at reflection.

The second member in the right part of Eq. (1) is a standing wave; the amplitude of oscillations in its antinodes is equal to double amplitude of the reflected wave and is zero in the nodes. Since $R \neq 1$, the amplitude of oscillations in the nodes of the standing wave is 0.63 E_0 and $1.37E_0$ in antinodes.

First, presume that particle orientation by the electromagnetic wave field results from interaction with the dipole moment induced in the particle by the same wave. The condition for appearance of the oriented moment of forces is the tensor character of polarization, which takes place in ice particles due to their non-sphericity. The problem of orientation in the electrostatic field is considered in detail in Ref. 5. A peculiarity of orientation by electromagnetic wave is the need in the wave-period averaging.[6] The phase shift between the filed strength and the dipole moment is taken into account automatically, since the difference of dielectric permittivity value for waves of the above frequencies from its value in a static field is just caused by the polarization delay.

When estimating the combined orienting action of aerodynamic and electromagnetic factors, the weather conditions for light pillar formation are to be considered. Usually the pillars are observed in conditions of the frosty calm weather, when water freezes out from air masses formed in previous relatively warm and humid period. The crystallization occurs in the surface layer just from vapor at a low absolute humidity of the winter air. Therefore, crystals have no time to become large. For estimation, we took large diameters (30 μm) both for plates and pillars at the ratio $d_{\max}/d_{\min} = 3$. The frosty calm weather is usually accompanied by the temperature inversion; therefore, the rate of energy dissipation was taken equal to 10^{-4} m^2/s^3.

Numerical assessments[5] compel us to reject the above model. The thing is that the effect of electric moment of forces becomes comparable with the action of aerodynamic moment at $E_0 \approx 10^4$ V/m. It is impossible to imagine wave generation with such amplitude; in this case, the Pointing vector should be equal approximately to 10^5 W/m^2. Waves with less amplitudes affect insignificantly against the background of the aerodynamic orientation. The reason is in the smallness of the dipole moment induced by the field. For example, a field of 1 V/m in strength produces a dipole moment of $1.2 \cdot 10^{-24}$ K·m in a pillar of 30 μm in length and 10 μm in diameter. Numerically, the maximum mechanical moment is equal to the same value, while the aerodynamic moment of forces is about 10^{-17} kg·m^2·s^{-2}.

Supposing that the phenomenon is caused by the electromagnetic effect of the system of standing waves on ice crystals, assume the following model.

As a working hypothesis, presume that particles have the constant dipole moment **p**. Imagine the following mechanism of its formation. If a positive aeron is captured at some moment of the crystal growth, then the surface, having grown later, has a positive polarization charge as well. This favors the capturing of a free negative charge on this surface. During further growing of the crystal, the polarization charge becomes negative and captures a free positive charge. Repetition of the process forms a chain of sign-altering charges, which has a significant dipole moment.

Even one odd pair of elementary charges in a pillar of 30 μm in length produces a dipole moment of about $4.8 \cdot 10^{-24}$ K·m, while the induced dipole moment is equal to $1.2 \cdot 10^{-24}$ K·m, as it was mentioned above.

The sign-altering moment of forces

$$\mathbf{M} = \mathbf{p} \times \mathbf{E}_0 e^{i\omega t} \quad (2)$$

affects a particle in the field of electromagnetic wave. To estimate the result of action of aerodynamic and electrical moments of forces, write the motion equation for a particle, the dipole moment of which is in the plane, including the vertical and the direction of vector $\mathbf{E_0}$ oscillations:

$$I\frac{d^2\theta}{dt^2}+\zeta\frac{d\theta}{dt}+\frac{1}{2}\lambda\rho u^2 V\sin 2\theta=-pE_0\sin\theta\cos(\omega t+\delta), \quad (3)$$

where I is the moment of inertia of the particle; ζ is the coefficient of viscous friction, $\text{kg}\cdot\text{m}^2\cdot\text{s}^{-1}$; λ is the form factor; ρ is the air density; u is the velocity of particle fall; V is the particle volume; p is the modulus of dipole moment. The third member in the left part is the aerodynamic moment of forces.[7] Here θ is counted from the horizontal direction, coinciding with the direction of the vector $\mathbf{E}_0$.

Equation (3) with zero right part describes particle motion in the absence of the field and perturbations induced by the Brownian motion and turbulence. At the same time, equation (3) describes pendulum motion with damping. Due to the mentioned perturbations, the particle comes out of the equilibrium position and the right part of Eq. (3) becomes non-zero. The equation requires numerical solution. However, to keep physical obviousness, let us consider a simplified variant.

Suppose that deviations from the equilibrium position are not very large ($\sin\theta \simeq \theta$,) and transform Eq. (3) to the following form:

$$\frac{d^2}{dt^2}\theta(t)+2a\frac{d}{dt}\theta(t)+\left[\Omega_0^2+\Omega^2\cos(\omega t+\delta)\right]\theta(t)=0, \quad (4)$$

where $a = \zeta/2I$; $\Omega_0 = \sqrt{\lambda\rho u^2 V/I}$; $\Omega = \sqrt{pE_0/I}$.

Designate the periodic function in square brackets as $\psi(t)$. It varies within the limits

$$(\Omega_0^2 - \Omega^2) \le \psi(t) \le (\Omega_0^2 + \Omega^2).$$

The following conditions are to be satisfied[8,9]:

1) if $a^2 \ge (\Omega_0^2 + \Omega^2)$, then each solution tends to zero at $t \to \infty$; (5a)

2) the same result is at $a^2 < (\Omega_0^2 + \Omega^2)$ and the condition

$$\int_0^{1/f}\psi(t)dt \le 4a\coth(a/f) \quad (5b)$$

holds, where $f = \omega/2\pi$ is the cyclic frequency.

The above-stated has a quite clear physical sense. Large values of the coefficient a indicate the dominance of viscous friction forces, at which the motion is nonperiodic. Though the moment of forces of electromagnetic wave action is of alternating character, the mean total orienting moment of forces turns out to be higher than in the absence of wave.

Under severely violated condition (5b), i.e., at sufficiently low frequency and large amplitude of electromagnetic wave, the oscillating mode with a small logarithmic decrement is possible, when a particle mechanically passes the position $\theta = 0$, where the acting moment of forces is zero.

Conduct the estimating for pillars of 30 μm in length and 10 μm in diameter. Let the air dynamic viscosity be equal to $3\cdot10^{-5}\,\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$. Equations for calculating the moment of inertia and the viscous friction coefficient, when rotating an oblong ellipsoid around the short axis, are given in Ref. 5.

The calculation gives the following values: $a^2=4\cdot10^4\,\text{s}^{-2}$ and $\Omega_0^2= 1.28\cdot10^3\,\text{s}^{-2}$. The electromagnetic wave noticeably affects the particle orientation, when Ω is comparable with Ω_0. When the electromagnetic wave amplitude is equal to 1 V/m, the equality $\Omega = \Omega_0$ holds provided the dipole moment is equal to $2.4\cdot10^{-17}\,\text{K}\cdot\text{m}$. The latter supposes the presence of a pair of opposite charges of $8\cdot10^{-13}\,\text{K}$. According to Ref. 10, such charges are quite real. At the above wave amplitude, the power density is $2.6\cdot10^{-3}\,\text{W/m}^2$. Note that this value is about one order of magnitude higher than the value of electromagnetic background within the 11.5–12.5 MHz frequency band, according to measurements under standard conditions (without aurora).[11]

In this case, the parameter a^2, characterizing viscous friction, one-order-of-magnitude exceeds $(\Omega_0^2 + \Omega^2)$, which answers nonperiodic motion toward the equilibrium position ($\theta = 0$). Condition (5a) is violated if dipole moment is two-order-of-magnitude higher, though condition (5b) fulfills in this case. It can be violated if a particle has a charge of about 10^{-8} K, which is virtually impossible. A 10-fold increase of particles size oscillations at $f \le 40$ Hz is possible at a particle charge of $8\cdot10^{-13}$ K and wave amplitude of 1 V/m.

As follows from the above-said, two types of electromagnetic wave effect on the intensity of light pillars are possible.

1. Presume that particles are large in size, about 300 μm and larger. Then, due to their aerodynamic orientation, conditions for light pillar formation arise. Under the effect of waves with frequencies of 10–100 Hz, particles begin to oscillate, thus partially or completely violating conditions for light pillar formation. Such intensity modulation evidently relates to the entire pillar length. The effect produced by standing waves is beyond the question here, since the wavelengths are equal to hundreds of kilometers.

2. Presume that particles are small, about tens of microns. Therefore, their aerodynamic orientation does not produce conditions for bright light pillar formation. Domains with increased amplitude, traveling in space and producing the effect of "running striations," are resulted from the interference of incident and reflected electromagnetic waves. The increase in angular sizes of light dashes with height (see Fig. 1)[1] can be explained under assumption of deviation toward large frequencies.

Assess the effect of electromagnetic radiation on the orientation on the base of the distribution[5,7]

$$f(\theta) = \exp[\xi\cos 2\theta]/\pi I_0(\xi). \quad (6)$$

Here I_0 is the modified Bessel function of first type and zero order. The distribution parameter ξ in this case is

$$\xi(l,\varepsilon) = [\lambda\rho u^2(l)V + pE_0]/2\rho l^3\sqrt{\nu\varepsilon}, \quad (7)$$

where l is the pillar length; ε is the energy dissipation rate; ν is the kinematic viscosity of air.

Figure 2 shows the distribution of axes of rotation of oblong ellipsoids, imitating pillars, in the absence of electromagnetic waves and at two values of oscillating amplitude of the electric vector.

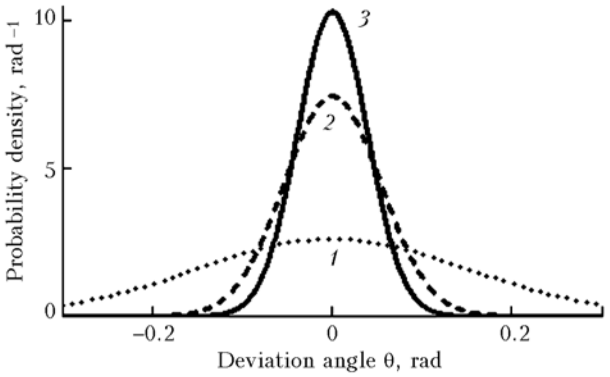

Fig. 2. The distribution of axes of rotation of oblong ellipsoids of 30 μm in length and 10 μm in diameter near the horizontal position at the amplitude of electromagnetic wave and in its absence: $E = 0$ (*1*); 0.63 (*2*); and 1.37 V/m (*3*).

The amplitudes relate to each other as the values in nodes and antinodes of the standing wave (1.37/0.63). The distribution sharpness essentially increases in antinodes. Much more particles occupy positions, in which large plane faces are horizontal. In addition, pillar axes acquire an azimuthal orientation in conditions of predominantly linear wave polarization. This could explain deviations of striation line from the vertical direction, seen in Fig. 1.

Conclusion

Two mechanisms of the effect of electromagnetic radiation, originating from magnetic perturbations in the atmosphere, on the ice particle orientation are considered.

The first variant of acting through the induced dipole moment requires too large radiation power. The variant of a constant dipole moment of particles of about 10^{-17} K·m presumes a noticeable effect on the particle orientation at a radiation power density of 10^{-3} W/m^2. The effect can be double. Low-frequency (10–10^2 Hz) oscillations can destroy orientation of sufficiently large (300 μm and larger) particles, resulted from aerodynamic forces, bringing them into oscillating state. In this case, a decrease in brightness of the entire light pillar is possible. At the same time, oscillations of the field with the above frequencies favor the orientation of small particles, since aerodynamic forces are insufficient for formation of the orientation, at which the bright light pillar appears.

Depending on the frequency, brightness of either the entire pillar or its part is modulated; or a quasiperiodic brightness structure is formed along the pillar. In the latter case, sufficiently rigid conditions should be fulfilled, namely, the presence of a large extra charge on particles, sufficiently high intensity of radio-waves within 10–100 m range, and, finally, their incidence to the Earth's surface should be close to normal, which favors the formation of wave packets. Seemingly, that is why such a rare phenomenon is observed only in high latitudes.

We did not plan in this work to describe in detail a particular phenomenon, presented in Ref. 1, because of a lack of initial data. This work is a quantitative illustration of a possible physical mechanism of the phenomenon, which has not been explained yet.

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