Infrasound of cosmic origin in the atmosphere

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It is shown that solar wind turbulence can excite sound waves in the lower atmosphere with periods ranging from 0.5 to 3 min. The expected amplitude is 2–10 μbar.

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A sound wave, excited in the magnetosphere and propagating into the lower atmosphere, will undergo amplitude amplification. At altitudes $h > h_1$ (where h_1 is determined by the equality of the sound v_s and Alfvén v_a velocities, $h_1 \simeq 120$ km[1]), the sound wave corresponds to fast magnetosonic waves. The phase velocity of the sound v_a in this case varies from $\sim 10^6$ m/s in the magnetosphere to $v_s \simeq 300$ m/s at an altitude h_1. Because of the change in the phase velocity, the energy density of the wave increases[2] approximately by 3.5 orders of magnitude. At altitudes $h < h_1$, the atmosphere is nearly isothermal and, here, the energy density of the sound wave does not vary with altitude, but the amplitude of the pressure oscillations Δp increases, while the amplitude of the velocity oscillations Δv decreases with increasing density ρ according to the law[3]

$$\Delta p \propto \sqrt{\rho}\,; \qquad \Delta v \propto 1/\sqrt{\rho}\,. \tag{1}$$

The density of the atmosphere at the altitude h_1 is approximately eight orders of magnitude lower than the density in the layers near the surface[1] and, correspondingly, the amplitude of the pressure increases approximately by four orders of magnitude as the sound wave propagates from the altitude h_1 to the earth's surface.

The basic restrictions on the range of frequencies of waves reaching the earth's surface are related to propagation in the zone $h \lesssim h_1$. Waves with frequencies $\omega < \omega_0$, where

$$\omega_0 = v_S/h_0\,; \quad \text{and} \quad h_0 = (3/5)(v_S^2/g)\,; \tag{2}$$

here h_0 is the equivalent height of the atmosphere, and g is the acceleration of gravity, cannot propagate in an isothermal atmosphere. For the earth's atmosphere, $v_s \simeq 300$ m/s, $h_0 \simeq 7$ km, and $\omega_0 \simeq 0.03$ s^{-1}.

The second restriction is related to the damping of the waves. An estimate shows that damping is related primarily to the magnetic viscosity ν_m of the ionosphere near the altitude h_1. The damping constant has the form[2]

$$\gamma = \frac{1}{2}\,\frac{v_a^2}{v_a^2 + v_S^2}\,\frac{\tilde{\omega}\,\omega^2}{\tilde{\omega}^2 + \omega^2}\,; \qquad \tilde{\omega} = \frac{v_a^2 + v_S^2}{\nu_m}\,. \tag{3}$$

Damping attenuates waves with frequencies $\omega > \omega_1 \simeq 0.2\ s^{-1}$. The frequency ω_1 depends on the electron concentration N_e and on disturbed days can increase by several factors.

Thus, sound waves excited in the magnetosphere can reach the earth's surface in a comparatively narrow range of frequencies, which corresponds to periods ranging from 3 to 0.5 min.

The mechanism for excitation of a magnetosonic wave in the magnetosphere is as follows. A shock wave arises in the solar wind when this wind interacts with the earth's magnetosphere. After passage of the shock wave front, the solar-wind plasma is compressed and, in addition,[4]

$$\rho_0 v_0^2 = B_1^2 / 8\pi , \quad (4)$$

where ρ_0 and v_0 are the density and velocity of the plasma before the shock and B_1 is the intensity of the magnetic field after the shock. Density variations $\Delta \rho_0$ in the solar wind lead to pressure variations and, correspondingly, to variations in the magnetic field ΔB_1:

$$\Delta B_1 \simeq \Delta \rho_0 B_1 / \rho_0 . \quad (5)$$

The magnetic field disturbances then propagate in the form of magnetosonic waves. The energy flux density of the waves is

$$H_S = W_S v_a = (1/4\pi)\Delta B_1^2 v_{a,1} = 2\left(\frac{\Delta \rho_0}{\rho_0}\right)^2 \rho_0 v_0^2 v_{a,1} , \quad (6)$$

where $v_{a,1}$ is the Alfvén velocity in the plasma after the shock. Assuming that in the region $\omega_0, \lesssim \omega \lesssim \omega_1$, $(\Delta \rho_0 / \rho_0)^2 = 0.1$,[5] $v_0 = 500$ km/s, and $v_{a,1} = 200$ km/s, we obtain $H_S \simeq 0.1$ erg/cm^2 s. If it is assumed that the flux density is constant along the path, then we obtain $W_S = H_S / v_s = 3 \times 10^{-6}$ erg/cm^3 at the earth's surface and, correspondingly, the relative amplitude of the pressure oscillations has the magnitude.

$$\Delta p / p = \sqrt{W_S / p} \simeq 2 \times 10^{-6} ; \quad (7)$$

i.e., the amplitude of the pressure oscillations is 2 μbar. However, this estimate is, apparently, too low due to the possible effect of focusing of wave energy, since the surface of the shock has a positive curvature and, in addition, waves cannot exit into the unperturbed solar wind. The grain in the flux density can attain magnitudes of the order of 100. Correspondingly, the amplitude of the pressure oscillations can reach magnitudes of $\Delta p = 10 - 20$ μbar.

The infrasound examined above, in principle, can also have a dynamic effect on the atmosphere. If on disturbed days the infrasound amplitude attains a magnitude of the order of 100 μbar, then the energy passing through the atmosphere over 5 days will be of the order of 0.01% of the thermal energy of the atmosphere. This figure agrees with the data in Ref. 6.

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New form of waves and solitons in a piezomagnetic antiferromagnet

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A new type of wave, which can arise in a plate made of a piezomagnetic antiferromagnet, is predicted. In these waves, the alternating magnetic field and the transverse (to the direction of propagation) displacement of the lattice differ from zero. It is shown that such a wave forms a soliton in the nonlinear limit.

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1. Waves that have not been previously studied and that are related to oscillations of the transverse displacements of the crystal lattice u and of the magnetic field H can be produced in a piezomagnetic antiferromagnet plate whose axis of easy magnetization (z axis) is parallel to the surface of the plate. These waves propagate along the surface of the plate in a direction normal to the axis of easy magnetization (x axis); the displacement of the lattice is oriented along the axis of easy magnetization. The wavelength k^{-1} is much greater than the thickness of the plate $2d$ and the propagation velocity is close to the velocity of transverse sound s. If the plate is bounded on one or both sides by a crystal whose magnetic permeability is much greater than that of the antiferromagnet μ (case A below), then a soliton, which is described by the Korteweig–de Vries equation and which transforms in the linear approximation into the wave indicated, can arise in the plate. The soliton cannot arise in a plate bounded by media whose permeabilities are lower than or comparable to the permeability of the plate (case B).

We shall limit our analysis to the magnetostatic approximation, when $H = \nabla\varphi$, and we shall examine the elastic and magnetic properties of the antiferromagnet (except for the piezomagnetic properties) in the approximation of an isotropic solid.

2. The system of equations that describe this problem is

$$\operatorname{div}(\mu H + 4\pi m^{\beta}) = 0, \tag{1}$$

$$\rho \ddot{u}_z = \frac{\partial}{\partial x_i}(\sigma_{iz} + \sigma_{iz}^{\beta}) \tag{2}$$

and the expression for the piezomagnetic part of the free energy density is

$$F^{\beta} = -\beta\left[\frac{\partial u_z}{\partial x}\frac{\partial \varphi}{\partial y} \pm \frac{\partial u_z}{\partial y}\frac{\partial \varphi}{\partial x}\right] \tag{3}$$

(according to Ref. 1, the " + " sign is used for CoF_2, MnF_2, and FeF_2, while the " — " sign is used for $FeCO_3$; ρ is the density; m^{β} is the piezomagnetic magnetic moment; σ_{ik} and σ_{ik}^{β} are the elastic and piezomagnetic stress tensors). The boundary conditions are determined by the absence of external forces and by the usual conditions for the magnetic field and the induction. Analysis shows that only lattice displacements and a magnetic field symmetrical with respect to y are possible. It is possible to obtain solutions that are antisymmetric with respect to y, but only if

$$\Gamma kd \gg 1\ ;\quad \Gamma = 4\pi\beta^2\rho^{-1}s^{-2}. \tag{4}$$

Since[2] $\Gamma \simeq 10^{-4}$, the last inequality is not consistent with the condition of weak damping of waves $\nu k \ll s$, where ν is the coefficient of viscosity. Let us substitute u, $\varphi = u(y)$, and $\varphi(y)\exp(ikx - i\omega t)$:

$$\begin{cases} u = u_1 \operatorname{ch}\kappa y \\ \dot{\varphi} = \varphi_1 \operatorname{sh} k y + \varphi_2 \operatorname{sh}\kappa y \end{cases}, \tag{5}$$

$$\begin{cases} u = u_1 \cos\kappa y \\ \varphi = \varphi_1 \operatorname{sh} ky \end{cases} \tag{6}$$

for the upper and lower signs in (3), respectively. Thus, from (1)–(3), for both signs in (3), we find for case A,

$$\kappa = \sqrt{\frac{\Gamma}{\mu}}\, k\left[1 + \frac{(kd)^2}{2}\right],$$
$$\omega = ks\left[1 - (kd_0)^2\right], \quad d_0 = \sqrt{\frac{\Gamma}{\mu}}\,\frac{d}{2} \tag{7}$$

and for case B,

$$\kappa = \sqrt{\frac{\Gamma}{\mu}}\, k\left[1 - \frac{(kd)}{\mu}\right],$$
$$\omega = ks\left[1 + 2\,\frac{(kd_0)}{\mu}\right]. \tag{8}$$

As is evident from the dispersion equations, for $\Gamma kd \ll 1$ and $\nu k \ll s$, transverse displacement waves and magnetic field waves are possible.

3. In case A, from (7), after introducing for $|\partial u/\partial x| \ll 1$ an acoustic nonlinearity, we obtain, in accordance with Refs. 3 and 4, the Korteweig–de Vries equation

$$\frac{\partial u}{\partial t} s \frac{\partial u}{\partial x} + sd_0^2 \frac{\partial^3 u}{\partial x^3} - s \frac{\partial}{\partial x} \left(\frac{\partial u}{\partial x} \right)^2 = 0, \tag{9}$$

leading, with the usual zero conditions at infinity, to a soliton that moves with a velocity w,

$$u \sim \mathrm{ch}^{-2} \left(\sqrt{\frac{w-s}{s}} \, \frac{x - wt}{2d_0} \right).$$

The condition under which dissipation with respect to the two last terms in Eq. (9) can be ignored, taking into account that $\Gamma kd \ll 1$, $|ku| \ll 1$, and $w - s \ll s$, leads to the inequality

$$d \gg d_{max} = \frac{\nu}{s} \sqrt{\frac{\mu}{\Gamma}},$$

which is easily satisfied, since $d_{\max} \cong 10^{-3}$ cm.

Waves can be excited either by charged particles which pass through the plate with a velocity $v > s$ (but, $v - s \ll s$) along the axis of easy magnetization or by applying an external magnetic field $H_y = H_0 \cos(kx - \omega t)$. In this case, the displacement amplitude is of the order of $\beta H_0 (\rho \nu s k)^{-1}$.

The observation of the waves and of the soliton is facilitated by the presence of a magnetic field wave, which propagates in air along the surface of the plate (we note that for the soliton to exist, the opposite side of the plate must be bounded by a crystal with a high magnetic permeability).

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