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Ionospheric effects of ground motion: The roles of magnetic field and nonlinearity

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ABSTRACT

Transformation of infrasound to magnetic sound upon propagation from ground level up to the ionosphere is considered. It is shown that upon entering the ionospheric layers at altitudes of order 150–170 km, the wave dynamics changes sharply. Nonlinear effects, including shock formation, are also considered. The shocks are typically formed in a relatively narrow range of altitudes, or not formed at all. Generalization of the model to a case of oblique propagation is briefly considered, and the effects of atmospheric profile variation and of finite plasma conductivity are estimated. Along with providing qualitative insight, the model gives some realistic estimates for waves generated by earthquakes.

1. Introduction

Observations of atmospheric motions due to infrasound generation by earthquakes began as early as the 1960s. Due to the rapid decrease in gas density with altitude, the corresponding velocities and displacements can reach at least dozens of m/s and dozens of meters, respectively. A summary of the earlier data can be found in, e.g., Blanc (1985) and Pokhotelov et al. (1995). In recent years, more detailed measurements of ionospheric motions induced by earthquakes have been performed with the use of ground radars and GPS systems (e.g., Calais and Minster, 1995; Artru et al., 2004; Iyemori et al., 2006; Liu et al., 2006). A similar ionospheric effect caused by tsunamis has also been observed and discussed (e.g., Artru et al., 2005; Occupini et al., 2006).

With regard to the theory, there exist numerous publications considering acoustic and acoustic-gravity waves without considering the effect of the Earth's magnetic field. Besides the classical models (Gossard and Hooke, 1975) and detailed calculations of the waves from localized sources such as explosions (e.g., Pokhotelov et al., 1995; Calais et al., 1998; Drobzheva and Krasnov, 2003; Kulichkov et al., 2004; Krasnov and Drobzheva, 2005), more general analytical and numerical results have been obtained for specific models of atmospheric profiles (e.g., Savina, 1996; Savina et al., 2006). Recently, numerical results have been obtained in relation to specific earthquakes and tsunamis and compared with observations (e.g., Artru et al., 2001; Occupini et al., 2006). In some publications (Drobzheva and Krasnov, 2003; Rapoport et al., 2004; Hobara and Parrot, 2005; Pokhotelov et al., 1995 and references therein), the effects of the acoustic and acoustic-gravity waves on electron density, geomagnetic field, and other characteristics of the ionospheric plasma have been estimated. Note that nonlinear magnetohydrodynamic effects have been discussed in relation to the heating of the solar corona by shock waves (e.g., Orta et al., 2003 and references therein).

The role of magnetohydrodynamic effects in the evolution of infrasound entering the ionized atmospheric layers from below has not yet been thoroughly studied. In the review paper by Pokhotelov et al. (1995) it is stated that the magnetic field is already important in the E-layer; in particular, the dissipation of Alfvén waves due to electron and ion conductivities was discussed; however,

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no connection with ground motion was considered. Koshevaya et al. (2001) presented results of numerical calculation of magnetic field perturbations due to transformation of acoustic waves into Alfvén and fast magnetoacoustic waves.

This article focuses on understanding of main changes in the linear and nonlinear dynamics of an infrasonic wave propagating upward from the ground to ionospheric levels, where it transforms into the fast magnetic sound which is the same wave mode as the non-magnetic infrasound excited at smaller altitudes within the geometry assumed below. To obtain insight, first we analyze upward propagation of a plane infrasound wave in a lossless exponential atmosphere in the presence of a homogeneous, obliquely directed magnetic field of the Earth. The solution utilizes explicitly the fact that near the ground magnetic effects are negligible. Another circumstance used here is that the wave behavior in the dense lower layers does not depend on their conductivity which allows us to apply magnetohydrodynamic equations with large conductivity to all levels. Here we do not consider internal gravity waves; this is justified for relatively short-period (up to 250–300 s) perturbations considered here.

Nonlinear propagation is analyzed to show that the magnetic effects radically change the rate of nonlinear distortion of a short wave and the condition of shock formation.

Then the case of oblique propagation is briefly considered, and the effects of non-isothermicity and finite conductivity are roughly estimated to demonstrate that many qualitative features of the infrasound transformation are not very sensitive to the details of the model. Finally, the main qualitative results are formulated and their relation to the observational data is briefly discussed.

2. Linear waves

The magnetohydrodynamic equations of a compressive gas in the presence of gravity can be written (in the CGS system) as (Landau et al., 2004, Sections 65–67)

$$\frac{\partial \mathbf{u}}{\partial t}+(\mathbf{u}\cdot\boldsymbol{\nabla})\mathbf{u}+\frac{1}{\rho}\nabla\left(p+\frac{H^2}{8\pi}\right)-\frac{1}{4\pi\rho}(\mathbf{H}\cdot\nabla)\mathbf{H}-\mathbf{g}=\mathbf{L}_1,$$
$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\mathbf{u})=0,$$
$$\frac{\partial p}{\partial t}+(\mathbf{u}\cdot\nabla)p+c_s^2\rho(\nabla\cdot\mathbf{u})=0,$$
$$\frac{\partial \mathbf{H}}{\partial t}+(\mathbf{u}\cdot\nabla)\mathbf{H}-(\mathbf{H}\cdot\nabla)\mathbf{u}+\mathbf{H}(\nabla\cdot\mathbf{u})=\mathbf{L}_2,$$
$$\nabla\cdot\mathbf{H}=\mathbf{0}. \tag{1}$$

Here $\mathbf{H}$ is the magnetic field, $\mathbf{u}$ is the gas velocity, ρ is the density, p is the pressure, c_s is the adiabatic sound speed, and $\mathbf{g}$ is the gravity acceleration. The terms $\mathbf{L}_1$ and $\mathbf{L}_2$ are responsible for dissipation: the former is for viscosity and thermal conductivity and the latter is for electric conductivity.

First consider a plane, linear magnetoacoustic wave propagating upward, along the vertical axis z, in a homogeneous, static magnetic field, $\mathbf{H}_0$, oriented obliquely in the (z,x) plane. Under this symmetry, $H_z=H_{z0}=\text{const}$. At this stage we also neglect dissipation. Formally this means, in particular, that the gas is ideally conducting, which is not valid for lower, dense layers of the atmosphere. However, in these layers the magnetic effects are negligible anyway; an estimate is given at the end of the paper. As a result, the set (1) allows us to describe transformation of a "purely" acoustic wave generated on the ground into the magnetic sound.

The perturbed variables are represented in the form of $p=p_0(z)+p'(z,t), \rho=R(z)[1+r(z,t)]$, and $H_x=H_{x0}+h(z,t)$. In the linear approximation, for a wave harmonic in time (varying as $\exp(-\mathrm{i}\omega t)$), we keep the same notation for the complex amplitudes (i.e., change $p'(z,t)\to p'(z)\exp(-\mathrm{i}\omega t)$, etc.). Then (in the absence of background wind) it follows from Eq. (1):

$$\frac{H_{x0}}{4\pi}\frac{dh}{dz}+\frac{dp'}{dz}+gR(z)r=\mathrm{i}\omega R(z)u,$$
$$\frac{H_{z0}}{4\pi}\frac{dh}{dz}=-\mathrm{i}\omega R(z)v,$$
$$\frac{du}{dz}-\alpha u=\mathrm{i}\omega r,$$
$$H_{x0}\frac{du}{dz}-H_{z0}\frac{dv}{dz}=\mathrm{i}\omega h,$$
$$c_s^2R(z)\frac{du}{dz}-gR(z)u=\mathrm{i}\omega p'. \tag{2}$$

Here u and v are, respectively, the z and x-components of the particle velocity amplitude, and $\alpha=-R^{-1}\,dR/dz>0$. We first consider an exponential model of atmosphere with $c_s=\text{const.}$ and $R(z)=R_0\exp(-\alpha z)$, and for estimates let $H_0=0.5\,\text{Oe}$, $c_s=340\,\text{m/s}$, $R_0=1.3\,\text{kg/m}^3$, and $\alpha^{-1}=8.5\,\text{km}$.

2.1. Short waves

As is known (e.g., Landau et al., 2004, Section 69), in a homogeneous medium, when both c_s and R are constants ($\alpha=0$), system (2) defines an Alfvén wave and two magnetoacoustic waves propagating at the respective speeds

$$C_A^2=\frac{H_0^2}{4\pi R},$$
$$C_\pm^2=\frac{1}{2}\left[c_s^2+\frac{H_0^2}{4\pi R}\pm\sqrt{\left(c_s^2+\frac{H_0^2}{4\pi R}\right)^2-\frac{c_s^2H_{z0}^2}{\pi R}}\right], \tag{3}$$

where subscripts + and − correspond to fast and slow magnetoacoustic waves, respectively, and $H_0^2=H_{x0}^2+H_{z0}^2$. At $H_0^2\to 0$ there remains only a fast wave which coincides with a non-magnetic sound wave, $C_+=c_s$. The same is true for $H_0\neq 0$ at large R, corresponding to the lower layers. At higher layers where R is small and c_s^2 is negligible, this wave becomes a fast wave with $C_+=H_0/\sqrt{4\pi R}$, which coincides with the Alfvén velocity. Hence, for the transition from the non-magnetic sound to the magnetoacoustic wave, under the symmetry assumed here, we consider the fast wave and further denote $C_+=C$.

Fig. 1 shows the dependence of C on altitude z for different directions of the static magnetic field (e.g., for