Available online at www.sciencedirect.com
ScienceDirect
Advances in Space Research 56 (2015) 333–340
ADVANCES IN SPACE RESEARCH
(a COSPAR publication)
www.elsevier.com/locate/asr

Dynamics of IGW and traveling ionospheric disturbances in regions with sharp gradients of the ionospheric parameters ☆

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Received 12 November 2014; received in revised form 31 March 2015; accepted 1 April 2015
Available online 11 April 2015

Abstract

The dynamics of the 2D solitary nonlinear internal gravity waves (IGW), as well as traveling ionospheric disturbances (TID) of the electron density excited by them at heights of the ionosphere F-region, for conditions close to those of the F-layer assuming that the source of initial perturbation has the pulse character is studied analytically and numerically. On a level with general case the rather interesting applications when the sharp gradients of the ionospheric parameters are the functions of space coordinates and time, namely the IGW and TID dynamics in the frontal regions of the solar terminator and solar eclipse are considered. The results obtained describe the dynamical structure, evolution and transformation of the IGW and TID at heights of the ionosphere F-layer including its strongly heterogeneous regions.

Keywords: Internal gravity waves; Solitons; TID; Ionosphere; Solar terminator; Solar eclipse

1. Introduction

Structure and dynamics of internal gravity waves (IGW) and associated traveling ionospheric disturbances (TID) are extensively studied for more than forty years (Heisler, 1959; Hunsucker, 1982, 1987; Hocke and Schlegel, 1996). Despite extensive observations involving numerous various technics such as, e.g., vertical and slanted ionospheric as well as satellite sounding (Belashova et al., 1990) and recently developed imaging technique using multipoint GPS networks (Tsugawa et al., 2006), the associated theory is less developed.

To solve the wide range of problems associated with wave perturbations at the ionospheric F-layer heights, it is necessary to take into account essential factors such as the middle- and large-scale traveling ionospheric disturbances (TID). TID directly affect variability of the ionospheric parameters as well as those of the Earth's ionosphere waveguide. One of the most convenient approaches to these problems is to study TID dynamics in terms of the internal gravity waves (IGW) (Belashov and Vladimirov, 2005). Of special interest are the IGW solitons as traveling in the F-layer stable large-scale wave formations, caused by various reasons such as the isolated magnetic substorms, solar terminator and solar eclipse (Belashova and Belashov, 2006), seismo-volcanic processes, and high-power artificial explosions (Belashov and Vladimirov, 2005; Belashova and Belashov, 2006). Here we first investigate the dynamics of the solitary nonlinear IGW (as well as TID excited by them at the heights of

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☆ This paper has been presented at 40th COSPAR Scientific Assembly 2014, August 3, 2014, Moscow, Russia, C2.2-4-14.

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http://dx.doi.org/10.1016/j.asr.2015.04.008
0273-1177/

the ionosphere's F-region) for conditions close to those of the F-layer, by omitting the physical nature of the sources, but assuming that it has the pulse character (more details about excitation of the pulse disturbances by various physical sources are given below as well as in the references listed above). Then we consider applications of the obtained results to the problems of the generation of IGW in the regions with sharp gradients of the ionospheric parameters such as electron density, temperature, scale heights for the ions and neutral particles etc. As particular cases we consider the frontal regions of the solar terminator and solar eclipse. To confirm our conclusions we result some results of natural radiophysical experiments in the end.

2. IGW solitons and TID of electron density

For the isothermal model of Earth's atmosphere, we take into account $k_\perp^2 \ll k_y^2$, and $|Hk_x| \ll 1$ in the linear approximation, and expanding in k up to the fifth order, write the dispersion law as (Belashov and Vladimirov, 2005)

$$\omega = Vk_x\left\{1+\frac{k_y^2}{2k_x^2}\pm\frac{(\gamma-2)^2}{\gamma^2}H^2k_x^2\left[2+\frac{(\gamma-2)^2}{\gamma^2}\varepsilon H^2k_x^2\right]\pm H^2k_z^2\right\} \tag{1}$$

where the second term in the right-hand side describes the diffraction divergence in the transverse direction of the wave propagation, the third and the fourth terms describe the dispersive effects of corresponding order, and the last term is the same in vertical direction; $V = 2\omega_g H$, $\omega_g = [(\gamma-1)g/\gamma H]^{1/2}$ is the Brunt–Väisälä frequency, H is the scale height of the neutral atmosphere, and $\varepsilon = -V/V_{\min}^{ph}$, where $V_{\min}^{ph}$ is the minimum phase velocity of the linear oscillations. In this case, taking into account the weak nonlinearity of the dimensionless function $u = u_z/ac$ which has a sense of vertical velocity of the neutral particles, $a = \exp(z/2H)$, $c = \sqrt{gH}$ and neglecting dissipative effects, from the hydrodynamic equations for the neutral gas we obtain the equation

$$\begin{aligned}&\partial_t u + ac\frac{2\gamma-1}{\gamma^2}u\partial_\xi u\\&\pm\frac{(\gamma-2)^2}{\gamma^2}VH^2\partial_\xi^3\left[2u+\frac{(\gamma-2)^2}{\gamma^2}\varepsilon H^2\partial_\xi^2 u\right]\\&=\frac{V}{2}\int_{-\infty}^{\xi}\partial_y^2 u\,d\xi\end{aligned} \tag{2}$$

which is written in the reference frame moving along the x-axis with the velocity V ($\xi = x - Vt$). The upper signs in (1) and (2) correspond to the positive wave dispersion, and the lower signs correspond to the negative one (without loss of generality we further assume that $V < 0$ and, as can be easily seen from (1), $\varepsilon < -1$). The obtained equation is the generalization of the Kadomtsev–Petviashvili equation (so-called Belashov–Karpman (BK) equation), for the first time it has been obtained in Belashov (1990), Karpman and Belashov (1991) and investigated in detail in a number of works (see Belashov and Vladimirov, 2005). It is written here for the velocity of the neutral component at the heights of the F-region with $\partial_z = 0$ without dissipation and describes the nonlinear IGW solitons and nonlinear wave packets, with the structure determined by both the coefficients and the function $u(0, \xi, y)$ corresponding to the initial condition, i.e., it depends on the sort of perturbation and accordingly the type of the source as well.

The structure of the solutions for the initial disturbance of the wave pulse type corresponding to various physical sources as, for example, the terrestrial and anthropogenic factors [as well as the "quasi-one-dimensional" sources of the global character, such as the solar terminator (ST) and solar eclipse (SE)], is described in detail in Belashov and Vladimirov (2005) and depends on ε. Indeed, the 2D solitons with the algebraic (for $\varepsilon \ll -1$) or the oscillating (in the direction of propagation, for $\varepsilon \leqslant -1$) asymptotics correspond to the upper sign in (2), whereas the dispersing wave packets and/or the 1D solitons which are stable in the case of the negative dispersion (Belashov and Vladimirov, 2005) correspond to the lower sign.

Let us consider the case of the upper sign in (1) and (2) and study the excitation by the IGW solitons of the middle- and large-scale TID for the conditions close to those in the F-layer. Considering the solitary IGW traveling at the near-to-horizontal angles, the continuity equation for the electron density in the F-layer is given by (Belashova and Belashov, 2006)

$$\begin{aligned}\partial_t N = {}&\partial_z\left[(\partial_z N + N/2H_i)D_0 e^{z/H_i} - u_z(1-e^{-\nu t'})N\sin I\cos I\right]\\&-\beta N + Q\end{aligned} \tag{3}$$

where $N(t, z)$ is the total electron density, $D_0\exp(z/H_i) = D_\alpha\sin^2 I$, D_α is the ambipolar diffusion coefficient, H_i is the scale height for ions, I is the magnetic inclination, $\beta = \beta_0\exp(-Pz/H_i)$ and Q are, respectively, the recombination rate and the ion production rate, the exponent $0 \leqslant P \leqslant 2$ characterizes the gas intermixing, $u_z = acu$ is the vertical component of the velocity of neutral particles, and $t' = t - t_0, t_0$ is the moment of the start of the neutral component's perturbation. Now we approximate the profile of the electron density at the height z for fixed time moment by $N = N_1\exp(z/H_i)$, $N_1 = N|_{z=0}$, and obtain that solution of (3) is given by (Belashov and Vladimirov, 2005)

$$N(u,t) = N(u,t_0)\exp[G(u,t)], \qquad G(u,t) = \int_{t_0}^{t} g(u,t)\,\mathrm{d}t \tag{4}$$