TRAVELING IONOSPHERIC DISTURBANCES—A REVIEW

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Traveling ionospheric disturbances (TID's) represent one form of large-scale irregularities in electron density. They were discovered in the 'forties [1–3]. Attention was first given to their horizontal movement, which was usually in the form of a wave which traveled large distances without much change of shape. Later [4, 5], with more frequent sounding of the F layer, vertical motions were also observed. We shall discuss both types of movement in this review. It is possible that in both cases we are really considering the same process, and that the difference lies only in the method of observation.

Section 1 gives a short review of the methods of recording TID's and discusses the morphology of these disturbances and their connection with other geophysical phenomena. The theoretical interpretation is developed in sections 2 and 3, mainly in terms of the ionospheric propagation of internal gravity waves. This approach was first suggested by Martin [6], and has since been developed in detail by Hines [7]. Finally, in section 4, we deal with a number of unsolved problems and formulate some of the questions which still need to be answered for a more complete understanding of the nature of TID's.

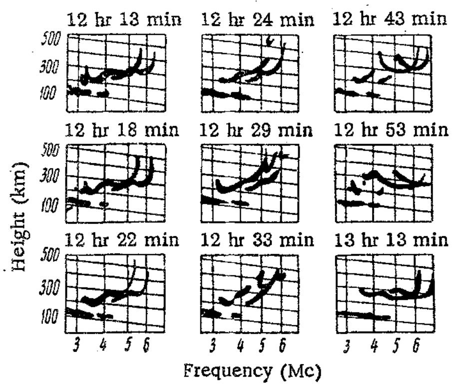

Fig. 1. Height versus frequency, h'(*f*), curves in the presence of a TID. The time of sounding is indicated on the ionograms. The first three diagrams show the state of the ionosphere before the disturbance appeared.

1. METHODS OF OBSERVATION AND PRINCIPAL CHARACTERISTICS OF TRAVELING DISTURBANCES

There is a variety of methods of investigating TID's and we shall only mention the most important ones.

The most common approach is to study ionograms taken at close time intervals (1 or 2 minutes at most). Typical results indicating the presence of a TID are shown in Fig. 1 [8]. The first appearance of the disturbance is accompanied by a cusp-like distortion

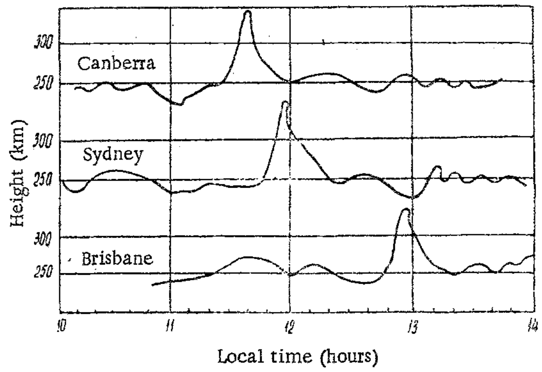

Fig. 2. Variation in height of reflection h'(t) for 5.8 Mc signals at three separated stations during the passage of a TID.

near the F layer critical frequency f_0F (see the ionograms taken at 12 hours 24 minutes and later). Usually, (Fig. 1) the changes in the ordinary and extraordinary wave traces occur at different times. An anomalous peak then appears (ionogram at 12 hours 43 minutes) and moves down towards the lower frequencies. Sometimes the arrival of the disturbance in the E region is accompanied by the appearance of an E_s layer or by an increase in its reflection coefficient [9].

Although this picture is the typical one, it should be noted that exceptions do occur. There is evidence [10] that the anomalies on the ionogram sometimes start in the E-region and move towards higher frequencies. Other types of distortion are also found—for example, the presence of double reflection heights (satellite traces) which occurs on night-time ionograms [8, 11–13].

The analysis of results from a single station gives information mainly on vertical movements.* The term "vertically traveling disturbances" is often used. However, this nomenclature must not be taken to imply that there is no horizontal component of motion.

The horizontal movement of irregularities can be studied from ionograms taken at suitably separated stations [14]. For this purpose, fixed-frequency sounding, in which the change of reflection height h' with time t is measured, is a very convenient method [15].

*Horizontal movements can be found from the time difference in the occurrence of disturbances on the ordinary and extraordinary traces.

Figure 2 shows h'(t) vertical sounding curves from three stations. Similar variations in h' occur at all three places, but there is an obvious time-shift in their appearance. From the values of these time-shifts and the known distance between the stations, the horizontal velocity of the disturbances can be found. We shall not give diagrams illustrating other types of h'(t) curves here since a classification of TID's from h'(t) variations can be found in [16].

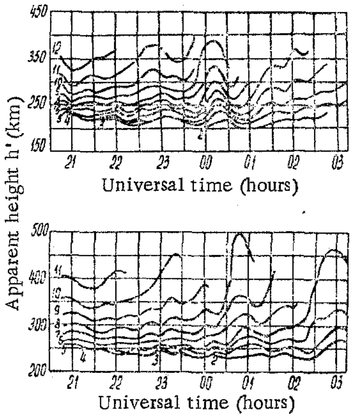

Fig. 3. Typical picture of the changes in apparent height h'(t) of reflection at fixed requencies during the passage of TID's. The numbers on the curves indicate the sounding frequencies in Mc. The upper diagram is for Boulder and the lower one for White Sands.

We note in passing that some authors connect the magnitude of the deviations in the reflection height Δh' with the vertical size of the corresponding TID [17]. It should be remembered, however, that Δh' characterizes the amplitude and not the size of the disturbance.

Measurements of h' in the presence of TID's can be made simultaneously on a number of frequencies. An example of such recordings obtained at Boulder (40°N, 105°W) and White Sands (32°N, 106°W) is shown in Fig. 3 [18]. In these measurements, both normal and oblique incidence can be used. The frequencies f can be either above or below f_0F. If the transmitters have a high frequency stability ($\Delta f/f \leqslant 10^{-10}$ in 24 hours), the Doppler method can be used to determine the motion of the irregularities [18, 19]. Additional evidence on TID's from fixed-frequency sounding can be obtained by correlation analysis of signals received at separated points. This method can give an estimate of the vertical size and degree of anisotropy of the irregularities [20–23].

An important addition to the methods described is the use of radio-astronomy observations [24–27]. From changes in the angle of arrival and intensity of waves, from discrete sources, and from the movement of the diffraction pattern on the ground, it is possible to estimate the horizontal dimensions, the relative magnitude ΔN/N, and the speed of motion of the irregularities. Certain assumptions have to be made about the height of the irregular layer [28]. Some observations are described in [29].

TID's have also been detected from topside sounding observations made by the Allouette satellite [30]. Characteristic slanting traces have been found on ionograms taken above the F_2 peak at times when typical TID's have been seen on the bottomside results.

Naturally, the most useful and effective approach is to employ a variety of different observing methods at the same time. This has recently become fairly popular [18, 31].

From the use of multiple techniques and the establishment of systematic observations, a great deal of experimental material has now been accumulated and a number of the principal features of TID's may be taken as being reliably established.

The magnitude of the relative deviation in electron density ΔN/N varies from a few tenths of one per cent to a few per cent for weak disturbances and reaches 10–20% for severe TID's [18]. In exceptional cases it is possible to find ΔN/N ~ 85%. Figure 4 shows ΔN/N in per cent as a function of height and time [32]. The left-hand diagram represents the N(h) profile for the undisturbed ionosphere. The contours of constant N were derived from high-frequency (430 Mc) signals back-scattered from the moving irregularities.

The real height distribution N(h) in the ionosphere can be derived from ionograms. Thus the distortion in the contours of constant N throughout the ionosphere during the passage of a TID can be obtained. Figure 5 shows the results of one such analysis [33]. The abscissa represents horizontal distance D rather than time t ($D = v_h t$, where v_h is the horizontal velocity of the disturbance).

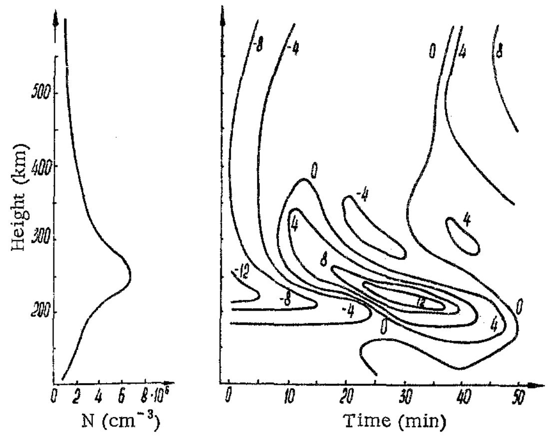

Fig. 4. Contours of equal relative deviation in electron density ΔN/N for a TID (right-hand diagram) plotted against height and time. Constructed from 430 Mc back-scatter data taken at Puerto Rico. The numbers indicate the value of ΔN/N in per cent. The left-hand diagram shows the normal electron density profile.

The quasi-periods T for TID's lie between 10 minutes and several hours. The most frequently occurring values are 20–30 minutes [34]. The duration

τ for small T corresponds to a few periods: for T of the order of one hour or more, $\tau \simeq T$ [18, 29].

The scale size λ_h, which defines the periodicity in a horizontal direction, varies from several hundred kilometers to 1000 km and more. It is more difficult to derive the vertical structure size. We might take $\lambda_v = v_v T$, where v_v is the vertical component of velocity. From ionograms, the apparent velocity $\tilde{v}_v$ is of the order of 40–100 m · sec^{-1} [14, 35–37]. Occasionally higher values occur, and in individual cases it is possible to find $\tilde{v}_v = 300$ m · sec^{-1} [5]. The virtual height on ionograms is always greater than the true height, so that the real vertical velocity is less than $\tilde{v}_v$ (by a factor of about 1.5–2). If we assume that both the horizontal and vertical displacements are the result of the same process, we can take T ~ 20–30 min. Thus if $v_v \sim 20$–50 m · sec^{-1}, we obtain a rough estimate of $\lambda_v \simeq 50$–100 km. Thus as a rule the vertical size of TID's must be smaller than the horizontal size,

$$\lambda_v \ll \lambda_h . \tag{1.1}$$

However, this inequality may be only marginally satisfied. In some cases it is probable that $\lambda_v \lesssim \lambda_h$.

It was pointed out above that the vertical dimension is sometimes taken to be the value of Δh, which determines the amplitude of the deformation of a plane of constant N corresponding to the reflection of a given radio frequency [38]. This definition of vertical scale gives values of $\Delta h \lesssim 5$–15 km—smaller than the previous estimates of λ_v.

References [23, 39] contain information on the form of large-scale ionospheric disturbances connected with TID's. The most important and well-founded conclusion is that the orientation is in the direction of the geomagnetic field H_0. Further evidence for this anisotropy is to be found in [29, 30, 32].

There is a considerable spread in the values of the horizontal velocities of TID's—from 50 m · sec^{-1} to 300–400 m · sec^{-1} [40–43]. Most commonly, $v_h \sim$ ~ 150 m · sec^{-1}. The prevailing direction is towards the part of the ionosphere illuminated by the sun: from north to south in the northern hemisphere and in the opposite direction in the southern [8]. In some cases an east-west component is observed, whose direction reverses in the course of 24 hours [42–46]. The vertical velocity has already been discussed: in the majority of cases it is directed downwards.

TID's are most often observed in the winter months during the day time [8, 47]. The frequency of occurrence decreases sharply from day to night (winter to summer) [48–50].

TID observations from widely spaced stations show that single disturbances can often travel distances of several thousand kilometers without significant change of amplitude [51]. The width of the wave-front can be of a similar order of magnitude.

It has already been mentioned, in the discussion of TID effects on ionograms, that when the disturbance reaches the E region, a sporadic E_s layer is formed. If the layer already exists, the TID can produce an increase in the ionization density and a corresponding rise in the reflectivity. However, it has not been possible to discover a one-to-one connection between TID's and E_s [9].

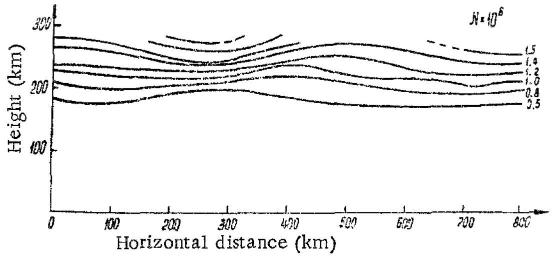

Fig. 5. Distortion of constant electron density contours caused by a TID. The lines of equal electron number density N (cm^{-3}) are constructed from a series of real height distributions N(h) obtained from ionograms.

Traveling disturbances are not recorded at high latitudes [52], possibly because of the strong turbulence in the polar ionosphere which makes it difficult to detect them. There are indications that the disturbances do not occur inside the narrow equatorial belt covered by the electrojet. This idea needs further confirmation since TID's are not infrequently recorded at sub-equatorial stations [33].

An analysis of data from systematic observations shows that there is practically no connection between the appearance of TID's and magnetic activity. There is an indication [50] that the occurrence increases with solar activity. Some TID's are thought to be connected with the onset of photo-ionization in the F region [13].

Finally, in this section, we must emphasize the value of comparing TID processes with certain phenomena which appear when artificial irregularities are created by the deposition of chemical substances into the ionosphere during explosions, etc. [53–56]. Ionization clouds with certain controlled properties are produced in these experiments and the ionograms taken on the ground are found to have much in common with those observed during TID's.

2. THE NATURE OF THE WAVE PROCESSES INVOLVED

The discovery of TID's presented the theoreticians with the problem of explaining the possibility of large-scale wavelike ionospheric irregularities in electron density. In a weakly ionized gas where $N_m \gg N$ (N_m is the molecular concentration), two types of disturbance can, sometimes somewhat arbitrarily, be distinguished. The first is connected with motion of the plasma and depends mainly on the parameters of the ionized constituent. The neutral component is only slightly disturbed and its principal effect is to deform the plasma oscillations. The second type of disturbance is connected mainly with the neutral component, and the plasma part of the gas does not to a first approximation affect the bodily motion of the medium.

We begin by considering the plasma type. We are interested here only in low-frequency waves (with $\omega = 2\pi f \leqslant 10^{-3}\ \mathrm{sec}^{-1}$), in a plasma which is situated in an external geomagnetic field H_0. We limit ourselves to the case in which the waves are infrasonic and weakly attenuated.

For the frequency values indicated above the following conditions will always be well satisfied:

$$\omega \ll \Omega_H, \quad \omega \ll \omega_{0i}, \tag{2.1}$$

where $\Omega_H = eH_0/Mc$ is the gyrofrequency and $\omega_{0i} = (4\pi e^2 N/M)^{1/2}$ is the ion Langmuir frequency (M is the mass of the ions, which are taken to be of one kind and singly ionized, e is the absolute value of the charge on the electron, and c is the velocity of light in a vacuum). Conditions (2.1) severely restrict the possible choice of waves. Both electromagnetic and plasma waves are automatically excluded since for these the motion of ions is unimportant.

Magnetohydrodynamic waves fall in the range defined by (2.1). For $\omega \simeq 10^{-3}\ \mathrm{sec}^{-1}$ and in the F region, we have

$$\omega^2 \gg \nu_{im}^2 \frac{N^2}{N_m^2}, \tag{2.2}$$

where ν_{im} is the effective collision frequency of ions with molecules, and N_m is the molecular density. Thus for a wave propagated along the direction of the field H_0, the complex refractive index is given by [57]

$$\tilde{n}^2 = \frac{4\pi c^2 MN}{H_0^2} - i\frac{4\pi c^2 MN}{H_0^2}\frac{\nu_{im}}{\omega}. \tag{2.3}$$

Here we are dealing with plasma-type disturbances (the density of the ionic component occurs in (2.3) as $\rho_i = NM$). In the ionosphere where $\nu_{im} \gg \omega$,* it follows from (2.3) that the waves will be strongly attenuated. Similar results are obtained in practice whatever the direction of the wave vector k in relation to H_0. It can easily be shown from the dispersion equation for waves in a magnetoactive plasma, and from expressions for the components of the dielectric constant tensor ([57], p. 121), that for one type of magnetohydrodynamic wave Eq. (2.3) is true for any direction of k. For the other type (Alfven waves) it is only necessary to replace H_0 by $H_0 \cos\alpha$, where α is the angle between the vectors k and H_0. This is not strictly true if $\alpha \simeq \pi/2$, when certain singularities occur, but this does not concern us here.

We therefore conclude that it is impossible to connect TID's with magnetohydrodynamic waves.

There is another type of wave which can exist in the F region. In the presence of a drift arising under the action of the electric fields and of the field H_0, the motion of irregularities can be related to certain waves for which [59]

$$\omega \simeq (\boldsymbol{k}\boldsymbol{u}_{i0}),$$

where u_{i0} is the ordered velocity of the ions. The phase velocities of these waves can be similar to the propagation speeds of TID's. However, these waves are strongly attenuated in the ionosphere unless the direction of motion is strictly perpendicular to the magnetic field H_0. Thus the prevailing direction of motion would be $\alpha \simeq \pi/2$. But it is clear from section 1 that this is not what is observed. This argument and others lead to the conclusion that the drift mechanism is not applicable.

It should be noted that in [60, 61] yet another type of wave is invoked to explain TID's. If the Alfven velocity $v_A = H_0/(4\pi NM)^{1/2}$ is so great that $v_A \gg C_{0i}$, where C_{0i} is the ion sonic velocity, when collisions are neglected $\omega/k = C_{0i}\cos\alpha$ [61]. For fairly small values of $\cos\alpha$, the phase velocity of these waves may be much less than C_{0i} and corresponds to the speeds of traveling disturbances. However, it is well known that in an isothermal plasma these waves are strongly attenuated due to the Cerenkov mechanism [62]. The inclusion of collision effects can lead to an even greater attenuation.

It follows from the above analysis that plasma-type waves are not applicable to the present problem. Greater success can be achieved by studying wave processes in the neutral gas. The disturbances in the ionospheric plasma can then be considered as caused by the interaction of the charged particles with the neutral background.

One of the most convincing mechanisms is that based on a relationship between the appearance of TID's and the excitation of internal gravity waves [7]. There are a number of papers devoted to the properties of this type of wave [7, 63–66]. We shall now consider the principal characteristics of internal waves, assuming that they are propagated through a conducting medium in the presence of the geomagnetic field H_0. We start from the linearized equations of magnetohydrodynamics for a weakly ionized gas* [57, 67],

$$\rho_0\left[\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}_0\nabla)\boldsymbol{u} + (\boldsymbol{u}\nabla)\boldsymbol{u}_0\right] = -\nabla p + \rho\boldsymbol{g} + \eta\Delta\boldsymbol{u} + (\eta/3 + \zeta)\,\mathrm{grad}\,\mathrm{div}\,\boldsymbol{u} + \frac{1}{c}[\boldsymbol{j}\boldsymbol{H}_0]; \tag{2.4}$$

$$\frac{\partial \rho}{\partial t} + \mathrm{div}(\rho_0\boldsymbol{u} + \rho\boldsymbol{u}_0) = 0; \tag{2.5}$$

$$T\rho_0\left[\frac{\partial S}{\partial t} + (\boldsymbol{u}_0\nabla)S\right] = \mathrm{div}(\varkappa\nabla T). \tag{2.6}$$

* In the F region, the collision frequency ν_{im} varies with height from roughly 50 sec^{-1} to 1 sec^{-1}. We recall that $\omega \leqslant 10^{-3}\ \mathrm{sec}^{-1}$.

*It is assumed that $N_m \gg N$. Thus to a first approximation no distinction is made between the values of p, ρ, and other parameters for the neutral component and for the entire medium.

In these equations and elsewhere, undisturbed values of parameters are denoted by the subscript '0'; disturbed values bear no subscript. The notation is as follows: ρ is the density of the gas, p is the pressure, S is the entropy, T is the temperature, u is the velocity, η and ζ are the first and second coefficients of viscosity, and δ is the thermal conductivity. The velocity $u_0 \neq 0$ in the presence of drift. To this system of equations must be added the relationship for the current density j; this is written in the form of a generalization of Ohm's law to the case of anisotropic media:

$$\frac{m\omega_H}{e^2N}\frac{[jH_0]}{H_0} + j/\sigma - \frac{1}{\sigma_\perp}\frac{(jH_0)H_0}{H_0^2} = E + \frac{1}{c}[uH_0], \quad (2.7)$$

where E is the electric field, m is the mass of the electron, $\omega_H = eH_0/mc$ is the electron gyrofrequency, $\frac{1}{\sigma} = \frac{1}{\sigma_\parallel} + \frac{1}{\sigma_\perp}$, and $\sigma_\parallel$ and $\sigma_\perp$ are the longitudinal and transverse conductivities.

In studying the propagation of internal waves in the ionosphere, we must remember that these waves are only weakly absorbed. We can then to a first approximation ignore dissipative processes. We can also, as a rule, put $u_0 = 0$ and neglect the effect of the geomagnetic field. If there is no heat conduction, Eq. (2.6) corresponds to adiabatic conditions. When $\delta = 0$ and $u_0 = 0$, we can use in place of (2.6) the equivalent equation $\frac{\partial p}{\partial t} + (u\nabla)p_0 = C_0^2\left[\frac{\partial \rho}{\partial t} + (u\nabla)\rho_0\right]$, where C_0 is the adiabatic speed of sound.

For an isothermal atmosphere, when the pressure p_0 and the density ρ_0 vary as $p_0, \rho_0 \sim \exp(-z/H)$ ($H = \varkappa T/Mg$ is the scale height, $\varkappa$ is Boltzmann's constant, and M is the molecular mass), the solution of (2.4)–(2.6) can be found by assuming that all the variables vary as $\exp(i\omega t - iK_x x - iK_z z)$. We then obtain the following dispersion equation [68]:

$$\omega^4 - C_0^2\omega^2(K_x^2 + K_z^2) + i\gamma g K_z \omega^2 + K_x^2 g^2(\gamma - 1) = 0. \quad (2.8)$$

We note that the speed of sound $C_0 = (\gamma g H)^{1/2}$ (γ is the ratio of the specific heats). If we take ω and K_x to be real ($K_x = k_x$), we can represent K_z as

$$K_z = k_z + i/2H, \quad (2.9)$$

where k_z is a real quantity. By using complex K_z, we can formally reduce the problem of the propagation of waves in a nonhomogeneous isothermal atmosphere to the case of a homogeneous medium. The imaginary part of (2.9) corresponds to an increase in the amplitude of waves with decreasing density ρ_0. The energy density $\rho_0 u^2$ remains constant with height. From (2.8) and (2.9) we obtain a relationship which involves only real quantities,

$$\omega^4 - \omega^2 C_0^2(k_x^2 + k_z^2 + 1/4H^2) + (\gamma - 1)g^2k_x^2 = 0. \quad (2.10)$$

Solving this for ω^2, we obtain

$$\omega^2 = \frac{C_0^2}{2}\Big\{k_z^2 + k_x^2 + 1/4H^2 \pm \left[(k_z^2 + k_x^2 + 1/4H^2)^2 - 4(\gamma - 1)g^2k_x^2/C_0^4\right]^{1/2}\Big\}. \quad (2.11)$$

In accordance with the terminology of [69], the plus sign in (2.11) corresponds to acoustic (sound) waves, and the minus sign to gravitational waves.

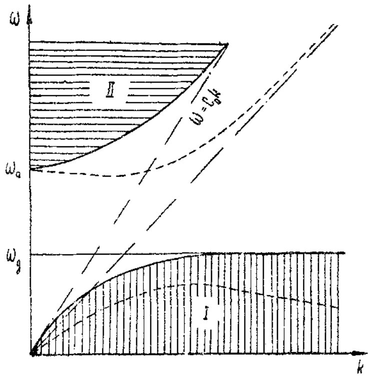

Fig. 6. Regions of possible propagation of internal gravity (I) and acoustic (II) waves in an isothermal atmosphere. The dashed lines indicate the shift in the boundaries ($k_z^2 = 0$) caused by the presence of a homogeneous horizontal shift (ku_0) > 0.

When $k_x = 0$ the dispersion equation describes sound waves propagated in a nonuniform atmosphere $\omega^2 = C_0^2k_z^2\left[1 + 1/4k_z^2H^2\right]$ [70]. In the outer limiting case, when the vector k is horizontal ($k_z = 0$), we obtain

$$k_x^2 = \frac{\omega^2}{C_0^2}\frac{\omega^2 - \omega_a^2}{\omega^2 - \omega_g^2}, \quad (2.12)$$

where

$$\omega_a^2 = \gamma^2 g^2/4C_0^2, \quad \omega_g^2 = (\gamma - 1)g^2/C_0^2.$$

Figure 6 shows the $\omega(k_x)$ relationship. The solid lines represent the curves for $k_z = 0$ (2.12). The shaded areas correspond to $k_z^2 > 0$, where vertical propagation of gravitational (region I) or sound (region II) waves takes place. In the nonshaded area $k_z^2 < 0$. In region II the phase velocities are supersonic, and in region I subsonic. For TID's, only gravitational waves are of interest.

It should be noted that these results can easily be generalized to include a drift velocity which is constant in time and space. It is only necessary in (2.10) to replace ω by $\omega - ku_0$ (for a horizontal wind, by $\omega - k_x u_{0x}$). The dashed line in Fig. 6 shows the change in the boundaries of the regions for $k_z^2 > 0$ when $k_x u_{0x} > 0$.

An important property of internal gravity waves is the existence of a limiting frequency ω_g, such that

$\omega < \omega_g$. This can be seen from the diagram. The frequency $\omega_g = \sqrt{\gamma - 1} g/C_0$ has already figured in (2.12). Since $\omega < \omega_g$, it follows that the period $T = 2\pi/\omega$ is restricted to $T > T_g$, where $T_g = 2\pi(\gamma H/(\gamma - 1)g)^{1/2}$.

In the F region where $H \sim 30$ km, $g = 10^3$ cm · sec^{-2} and $\gamma = 1.4$, we can estimate $T_g = 10$ min. It follows from the results of §1 that the periods of TID's satisfy the requirement $T > T_g$.

Equations (2.10) or (2.11) can be used to determine the phase velocity $v_p = \omega k/k^2$ and the group velocity $v_{gr} = \partial\omega/\partial k$. We can also find the velocity v'_{ph}, which characterizes the motion of the wave front in a horizontal direction: it is equal to $v'_{ph} = \omega/k_x$ [7]. In the general case, the equations for v_p and v_{gr} are rather cumbersome, and we will not give them in full. Considerable simplifications are possible when

$$k_z^2 \gg k_x^2; \tag{2.13}$$

$$k_z H \gg 1. \tag{2.14}$$

These conditions imply that the vertical wavelength λ_z is much smaller than λ_x (with $\lambda_x < 2\pi H$) or $2\pi H$ (with $\lambda_x > 2\pi H$). Under these conditions, we have

$$\omega = \omega_g k_x/k_z, \tag{2.15}$$

where

$$v_{gr\,x} = \omega_g/k_z, \quad v_{gr\,z} = -\omega_g k_x/k_z^2; \tag{2.16}$$

$$v_{p\,x} = \omega_g k_x^2/k_z^3, \quad v_{p\,z} = \omega_g k_x/k_z^2. \tag{2.17}$$

From these and (2.13) it follows that the phase velocity is almost vertical and the group velocity almost horizontal.

The calculation of v_p and v_{gr} in the presence of a homogeneous wind is given in [71, 72]. The general equations are rather cumbersome. In the approximation of (2.15), the velocity u_0 affects only the component v_{grx}, and

$$v_{gr\,x} = \frac{\omega_g}{k_z} + u_0 \qquad (k_x u_{0\,x} > 0). \tag{2.18}$$

The components of the phase velocity v_{px} and v_{pz} are increased by a factor $(1 + k_z u_0/\omega_g)$.

When Eq. (2.10) holds, the polarization of internal waves can be determined from the relationship

$$u_x/u_z = \frac{C_0^2 k_x K_z - i k_x g}{\omega^2 - C_0^2 k_x^2}, \tag{2.19}$$

whereas for low-frequency waves ($\omega \ll \omega_g$), when (2.15) is true,

$$\frac{u_x}{u_z} \simeq -\frac{K_z}{k_x} = -\frac{k_z + i/2H}{k_x} \simeq -k_z/k_x. \tag{2.20}$$

From (2.19) it can be seen that in general the waves are elliptically polarized and have a component of velocity transverse to k. In the rough approximation of (2.20) $k_x u_x \simeq -k_z u_z$, the polarization becomes linear and the transverse component of velocity is fairly small. The elliptical nature of the polarization and existence of a preferred direction (along the vector g) suggest an analogy between internal waves and electromagnetic waves in anisotropic media [72].

We will now discuss the effect of dissipative processes in order to establish the applicability of the adiabatic approximation, and to estimate the absorption of gravitational waves.

The assumption of adiabatic conditions is found in many papers. At the same time it is clear that rapid heat conduction would cause the processes to become isothermal and if $\gamma = 1$ gravitational waves would degenerate (only sound propagation would be possible). In this connection, it is of interest to discuss how far the adiabatic approach is justified. An analysis of this problem has shown that when $\delta \neq 0$, the quantity γ in (2.10) must be replaced by γ_{eff} [73], and

$$\gamma_{eff} = 1 + (\gamma - 1)\frac{\omega^2\tau^2}{1 + \omega^2\tau^2}, \tag{2.21}$$

where $\tau = \rho c_V/k^2\delta$ (c_V is the specific heat at constant volume). From (2.21) we obtain the condition for the processes to be adiabatic $\omega\tau \gg 1$: hence

$$\frac{v_p}{\gamma k \nu} \gg 1, \tag{2.22}$$

where ν is the kinematic viscosity. In going from (2.21) to (2.22) we have used the fact that $\nu\rho_0 c_V/\delta$ is of the order of unity [69]. Let us consider the F layer. Our estimates will necessarily be only qualitative since they are based on calculations [73] which ignore changes in ν or $\delta/\rho_0 c_V$ with height [74]. With $\gamma = 1.4$, $H = 30$ km, and $k_z H = 3$, we have for the phase velocity (2.17), $v_p \simeq 10^3$ cm · sec^{-1}. At a height of $h = 200$ km, $\nu \simeq 10^9$ cm · sec^{-1}, and at $h = 300$ km, $\nu \simeq 9 \cdot 10^9$ cm^2 · sec^{-1}; we thus conclude that in the first case inequality (2.22) is satisfied ($\nu_{eff} \simeq 1.32$), but that in the second, it is not.

Thermal conductivity is also important in that it leads to attenuation of internal waves. The absorption is of the same order as that produced by viscous effects. A detailed calculation is given in [69] of the attenuation for a viscosity ν and thermal conductivity $\chi = \delta/c_p\rho_0$ (c_p is the specific heat at constant pressure) which do not vary with height.

The following relationship has been derived for the decrement Γ of gravitational waves

$$\Gamma = \Big\{ H^{-1} g k_x^2 \left[(\gamma - 5/3)\nu + \nu_2\right] - C_0^2 K^4 \left[\nu/6 + \nu_2/2 - (2-\gamma)\chi/2\gamma\right] \Big\} \times \Big\{ 2\left[C_0^4 K^4 - 4(\gamma - 1) g^2 k^2\right]^{1/2} \Big\}^{-1} + \frac{K^2}{4}\left(\frac{7}{3}\nu + \nu_2 + \chi\right), \tag{2.23}$$

where

$$K^2 = k_x^2 + k_z^2 + 1/4H^2, \quad k^2 = k_x^2 + k_z^2,$$
$$\nu = \eta/\rho_0, \quad \nu_2 = \zeta/\rho_0.$$

The spatial attenuation is determined along the group path. The coefficient of energy absorption q for small attenuation is equal to

$$q = Q/v_{gr}E, \qquad (2.24)$$

where Q is the energy dissipated in 1 sec in unit volume, and E is the energy density associated with the wave. An expression for q is given in [69], where the most important special cases are considered. Numerical estimates of q show that gravitational waves with $\lambda \gg 4\pi H$ are not sensibly attenuated at heights of $h \simeq 100$ km ($q \simeq 5 \cdot 10^{-12}$ cm^{-1}). However, smaller scale waves are more effectively absorbed. Calculations [75] show that the dissipation of internal waves can make an important contribution to the thermal balance of the upper atmosphere, especially during magnetic storms.

It would undoubtedly be interesting to generalize the calculations of Γ (2.23) or q (2.24) [69] to include the height dependence of ν and χ. This would lead to more reliable estimates of the absorption. Two further points must also be borne in mind. For an unbounded isothermal atmosphere with no dissipation where the density $\rho_0(z)$ decreases with height, the amplitude of internal waves would increase as $A \sim \sim \rho_0^{1/2}$. The linearization of the hydrodynamic equations might then not be legitimate. If ν and χ are constant, it is scarcely possible to compensate for the increase in A. However, if they increase with height (as exp(z/H), say), then probably compensation would be adequate. The allowance for viscosity and thermal conductivity is also very important in connection with the rapid increase above the F_2 peak of the mean free path l_{mf}, which becomes comparable with the wavelength λ. Detailed calculations of the absorption with $\nu = \nu(z)$ and $\chi = \chi(z)$ do not yet exist. The problem is complicated by the fact that the solution of (2.4)–(2.6) cannot be found in the form of plane waves. Some results obtained by numerical analysis are given in [76].

Magnetohydrodynamic absorption (ohmic losses) can be important for large-scale disturbances. The problem has been considered in [77,78] for internal waves in the ionosphere; system (2.4)–(2.7) with $\eta = \zeta = \delta = = 0$ is taken as the starting point. Under the usual F-region conditions, the expression for the transverse current (2.7) takes the form $j_\perp = \sigma_\perp[uH_0]/c$ [77]. The initial equations can be reduced to

$$\frac{\partial^2 u}{\partial t^2} = C_0^2 \operatorname{grad}\operatorname{div} u - g\nabla u_z + (1-\gamma) g z_0 \operatorname{div} u + + \frac{\sigma_\perp}{\rho_0 c^2}\frac{\partial}{\partial t}[[uH_0]H_0], \qquad (2.25)$$

where z_0 is a unit vector along the z-axis. Use is made of the fact that the term with $\sigma_\perp$ in (2.25) can be considered as approximately independent of the height (over distances of the order of H). Variations with height would occur if $\sigma_\perp/\rho_0$ depended on the molecular concentration N_m. Since $\sigma_\perp = e^2 N\nu_{im}/M\Omega_H^2 \sim N_m(\nu_{im} \sim \sim N_m)$ and $\rho_0 = N_m M_m$ (M_m is the molecular mass), we conclude that the ratio $\sigma_\perp/\rho_0$ is independent of N_m. The variation of $\sigma_\perp$ with electron density N is of little importance since it is small even for distances considerably greater than H.

Using (2.25) and the group velocity equation (2.16), we can calculate the absorption coefficient q, remembering that $Q \simeq \sigma_\perp[uH_0]/c^2$ and $E = \rho_0 u^2$. We finally obtain [78] from (2.24) that

$$q = \frac{NM\nu_{im}}{N_m M_m} k_x \left[1 + \frac{k_x^2}{k_z^2} - \left(\cos\alpha - \frac{k_x}{k_z}\cos\beta\right)^2\right], \qquad (2.26)$$

where α and β are the angles between H_0 and the x- and z-axes.*

Estimates of the magnitude of q from characteristic TID data from middle latitudes lead to values of $q \sim 5 \cdot 10^{-9}$ cm^{-1}. This corresponds to distances $D = 1/q$, over which the disturbances travel without great attenuation, of $D \simeq 2000$ km. In [77], Eq. (2.26) is used to analyze the dependence of absorption on time of day and the direction of motion. We merely note here that absorption is minimal when the disturbance travels in a north-south direction.

Restrictions on the distance of propagation can also be obtained from the observational requirement that the packets of internal waves should not change very much in shape (see the experimental results in section 1). This means that the diffusion time of the quasi-monochromatic signal (gravity wave) τ must be much smaller than the life time T_1. For a homogeneous** anisotropic dispersive medium [57]

$$\tau = \sqrt{\pi\left(\frac{\partial^2 k}{\partial\omega^2} r\right)_{\omega=\omega_0}}, \qquad (2.27)$$

where ω_0 is the carrier frequency of a signal for which it is assumed that $\Delta\omega \ll \omega_0$. We determine the distance D over which significant distortion will appear by putting $\tau = T_1$. Evaluating τ from (2.27), we obtain [79]

$$D \simeq \left(\frac{T_1}{T_0}\right)^2 \lambda_x, \qquad (2.28)$$

where $T_0 = 2\pi/\omega_0$. If $T_1/T_0 = 2$–3 and $\lambda_x = 150$ km we find that $D \sim 600$–1500 km. We thus obtain distances of the same order as before (from considerations of magnetohydrodynamic absorption).

We will now discuss some characteristics of the propagation of gravitational waves in a nonisothermal atmosphere where $T = T(z)$ [80]. Even in the absence of dissipative processes system (2.4)–(2.6) no

*A similar relationship, differing only by a factor of 2, was obtained in [77] by another method. The calculation based on (2.24) is the more correct.

**We have already noted that the problem of internal waves in an isothermal atmosphere can in practice be reduced to the case of a homogeneous medium.

longer has plane-wave solutions. We therefore write the solution in the form $F(\omega, k_x, z)\exp[i(\omega t - k_x x)]$ and thus reduce the system to two first order differential equations for the variables div u and u_z [80].

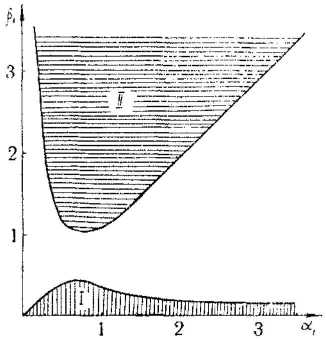

Fig. 7. Regions of possible propagation of internal gravity (I) and acoustic (II) waves in a nonisothermal atmosphere with a horizontal wind which varies with height.

These can be written in the dimensionless form

$$\frac{dY}{ds} = (\gamma/\alpha_1 - 1/\beta_1)\, Y \quad (\beta_1 - 1/\beta_1)\, X/\alpha_1; \qquad (2.29)$$

$$\frac{dX}{ds} = (1 - \alpha_1/\beta_1)\, Y + X/\beta_1, \qquad (2.30)$$

where

$$Y = \operatorname{div} \mathbf{u}/\Omega,\ X = k_x u_z/\Omega,\ s = k_x z,$$
$$\alpha_1 = \gamma H k_x,\ \beta_1 = \Omega^2/g k_x,\ \Omega = \omega - k_x u_{0x}(z).$$

When T and u_{0x} are independent of height, and Y, $X \simeq \exp(Qs)$, we obtain the dispersion equation

$$\alpha_1 Q^2 = \beta_1 + (\gamma - 1)/\beta_1 - \alpha_1 - \gamma^2/4\alpha_1, \qquad (2.31)$$

which reduces to (2.28) (where ω is replaced by $\Omega = \omega - k_x u_{0x}$). If the variations of T and u_{0x} with z are slow (α_1 and β_1 depend only weakly on s), the geometrical optics approximation can be used. This breaks down if Q = 0, when we obtain

$$\beta_1 + (\gamma - 1)/\beta_1 = \alpha_1 + \gamma^2/4\alpha_1. \qquad (2.32)$$

This relationship is illustrated in Fig. 7. The shaded regions I and II correspond to vertical propagation of acoustic and gravitational waves, respectively. In the unshaded part vertical propagation is impossible. It can easily be seen from Fig. 7 that even in the case in which the temperature increases linearly with height, waveguide propagation is possible.

In [80] quoted above, solutions are obtained describing the propagation of internal waves in the WKB approximation. The calculation is performed for both linear and exponential temperature profiles. The velocity u_0 is taken to be horizontal and independent of z. It is shown (for both T(z) distributions) that waveguide propagation of gravitational waves is possible with $v_{gr\,x} \leqslant \omega/k_x$.

When horizontal gradients of density ρ_0 and pressure p_0 occur, the theory of internal waves must be generalized to two dimensions. Suppose that p_0 and ρ_0 can be represented in the form

$$p_0,\ \rho_0 \sim \exp(-z/H)\, f(x), \qquad (2.33)$$

where the scale height H is taken as constant. Neglecting dissipative processes, we seek the solution of (2.4)–(2.6) in the form $\Phi(x)\exp(i\omega t - iK_z z)$ and arrive at the differential equation

$$\frac{d^2\Phi}{dx^2} + \frac{1}{f}\frac{df}{dx}(1 + b/a)\frac{d\Phi}{dx} + \left[\frac{\omega^2}{a}\frac{\rho_0}{p_0} + \frac{b}{a}\frac{1}{f}\frac{d^2 f}{dx^2}\right]\Phi = 0, \qquad (2.34)$$

where

$$a = \frac{\gamma\omega^2 - g(\gamma - 1)/H}{\omega^2 - (\gamma g/4H)(1 + 4k_z^2 H^2)},$$

$$b = \frac{\omega^2 + g(\gamma - 1)(ik_z - 1/2H)}{\omega^2 - (\gamma g/4H)(1 + 4k_z^2 H^2)}.$$

We recall that $K_z = k_z + i/2H$, where k_z is a real quantity. Making the change of variables $\Phi = \psi f^{-(a+b)/2a}$ we obtain the equation

$$\frac{d^2\psi}{dx^2} + \psi\left\{\frac{\omega^2}{a}\frac{\rho_0}{p_0} + \frac{b}{a}\frac{1}{f}\frac{d^2 f}{dx^2} - \frac{1}{2}\frac{d}{dx}\left(\frac{1}{f}\frac{df}{dx}\right)(1 + b/a) - \frac{1}{4}\left(\frac{1}{f}\frac{df}{dx}\right)^2 (1 + b/a)^2\right\} = 0. \qquad (2.35)$$

We can write the solution of this in the WKB approximation and investigate the possibility of waveguide propagation for particular forms of $f(x)$. A full analysis has not yet been carried out. The significance of the results would be enhanced if it could be shown that TID's exist which do not undergo large horizontal displacements. There is at present no experimental or theoretical evidence for this.

3. IRREGULARITIES IN ELECTRON DENSITY CAUSED BY INTERNAL WAVES. COMPARISON WITH OBSERVATION

In this section we shall discuss the nature of the ionospheric irregularities caused by internal waves. We shall then be able to some extent to compare the theoretical predictions with the experimental results.

The problem of the formation of irregularities involves a consideration of the collisions of electrons and ions with neutral particles. In addition, the effect of the earth's magnetic field H_0 and of the electric field E (arising from charge separation) must be taken into account.

We can start from the set of quasi-hydrodynamic equations of motion for electrons and ions

$$\rho_e \frac{\partial \boldsymbol{u}_e}{\partial t} + \rho_e(\boldsymbol{u}_e\nabla)\boldsymbol{u}_e + \rho_e \nu_{em}(\boldsymbol{u}_e - \boldsymbol{u}) = -\nabla p_e + \rho_e \boldsymbol{g} - eN_e\boldsymbol{E} - \frac{eN_e}{c}[\boldsymbol{u}_e\boldsymbol{H}_0]; \tag{3.1}$$

$$\rho_i \frac{\partial \boldsymbol{u}_i}{\partial t} + \rho_i(\boldsymbol{u}_i\nabla)\boldsymbol{u}_i + \rho_i \nu_{im}(\boldsymbol{u}_i - \boldsymbol{u}) = -\nabla p_i + \rho_i \boldsymbol{g} + eN_i\boldsymbol{E} + \frac{eN_i}{c}[\boldsymbol{u}_i\boldsymbol{H}_0] \tag{3.2}$$

and the continuity equation

$$\frac{\partial \rho_e}{\partial t} + \operatorname{div}(\rho_e \boldsymbol{u}_e) = 0, \quad \frac{\partial \rho_i}{\partial t} + \operatorname{div}(\rho_i \boldsymbol{u}_i) = 0, \tag{3.3}$$

where u_e and u_i are the ordered velocities of electrons and ions, $\rho_e = mN_e$ and $\rho_i = MN_i$ are the densities, and N_e and N_i the particle densities, and ν_{em} is the effective collision frequency of electrons and molecules, the velocity of which is denoted by u. For the partial pressures p_e and p_i we have $p_e = N_e\varkappa T$ and $p_i = N_i\varkappa T$, where T_e and T_i are the electron and ion temperatures. Collisions between charged particles are neglected and no account is taken of the electron and ion viscosities which are of little importance in large-scale disturbances.

A considerable simplification is possible in the present case. The terms $\rho_e du_e/dt$ and $\rho_i du_i/dt$ can be omitted as they are small compared with $\rho_e \nu_{em} u_e$ and $\rho_i \nu_{im} u_i$. The plasma will be assumed to be isothermal ($T_e = T_i = T$) and quasi-neutral ($N_e = N_i = N$). Deviations from quasi-neutrality $(N_e - N_i)/N \sim (r_D/L)^2$ (r_D is the Debye radius and L is the characteristic length) must be very small for the disturbances we are considering. We therefore introduce the electric field $E = -\nabla\varphi$ which is necessary to prevent the appearance of space charges.

Under these conditions we can apply the usual F-region inequality $\Omega_H \gg \nu_{im}$ and obtain the following equation [81] from (3.1)–(3.3) for the excess electron density N' arising from neutral particle motion, *

$$\frac{\partial N'}{\partial t} - \frac{\partial}{\partial z'}\left(D\frac{\partial N'}{\partial t}\right) + g_{z'} \frac{\partial}{\partial z'}\left(\frac{N'}{\nu_{im}}\right) = -N_0\frac{\partial u_{z'}}{\partial z'}, \tag{3.4}$$

where $D = 2\varkappa T/M\nu_{im}$ is the ambipolar diffusion coefficient along H_0 (the z'-axis is taken in this direction).

Assuming an exponential variation of ν_{im} and ν_{em} with z, $\nu_{im} = \nu_{i0}\exp(-z/H)$ and $\nu_{em} = \nu_{e0}\exp(-z/H)$, and taking u to be caused by the passage of an internal wave ((2.10) and (2.19)), we obtain for N'

$$\exp(-z/H)\frac{\partial N'}{\partial t} - D_0\frac{\partial^2 N'}{\partial z'^2} - \left(\frac{D_0}{H} + g/\nu_{i0}\right)\frac{\partial N}{dz'} - (g/\nu_{i0})HN' = iN_0(k_x\cos\alpha + K_z\cos\gamma)u_{z0}[\cos\gamma - \cos\alpha(K_z/k_x)] \times \exp\{i\omega t - ik_x x - iK_z z\}. \tag{3.5}$$

In the coordinate system x, y, z, the field H_0 has components $H_0(\cos\alpha, \cos\beta, \cos\gamma)$. The level z = 0, corresponding to ν_{i0}, ν_{e0} and $D_0 = 2\varkappa T/M\nu_{i0}$, can be taken as being in the F region where the wave is propagated.

A full investigation of the solutions of (3.5) is rather difficult. Let us consider the simplified case in which the field H_0 is almost vertical. The axes z and z' can then be taken as being almost coincident and we are left with the coordinate system used in section 2.

We shall represent N'(z, t) in the form of the sum $N' = N_1(z, t) + N_2(z, t)$. The term $N_2(z, t)$ will correspond to the steady-state distribution of N' set up by a fairly long-acting "source"—$N_0\partial u_z/\partial z$—and it will vary like a wave with period T_0 and horizontal scale equal to that of the internal wave itself. The term $N_1(z, t)$ describes the setting up of the steady state after the source has been "switched on." An approximate estimate of the amplitude of N_2 gives [81]

$$\frac{|N_2|}{N_0} \simeq \frac{|u_{z0}|}{D_0 k_z}. \tag{3.6}$$

Taking $|N_2|/N_0 \simeq 0.1$ (in accordance with observations), for $D_0 \sim 10^9$ cm$^2\cdot$sec^{-1} and $k_z = 3\cdot 10^{-6}$cm^{-1} we find that $|u_{z0}| \simeq 8$ m $\cdot$ sec^{-1}. This value of velocity is very reasonable. A more detailed solution of the problem demands a knowledge of the incomplete gamma-function for complex arguments [78] and is complicated by the fact that tables of these do not exist.

In order to analyze the nature of N_1, it is necessary to know the characteristic solution of Eq. (3.5) without the right-hand side. We assume that the TID is localized in a layer of thickness L and that at the boundaries z = 0 and z = L, N' = 0. The solution of the homogeneous part of (3.5) can then be represented in the form [78]

$$N_1 = \exp(-z/2H) \times \sum_{n=1}^{\infty} \exp\left(-\frac{\lambda_n^2 D_0 t}{H}\right)[A(\lambda_n)\sin(\lambda_n\eta) - \operatorname{tg}(2\lambda_n)\cos(\lambda_n\eta)], \tag{3.7}$$

where

$$\lambda_n = n\pi/2(1-\delta),$$

$$\delta = \exp(-L/2H), \quad \eta = \exp(-z/2H).$$

*The condition $\Omega_H \gg \nu_{im}$ means that transverse diffusion, which is much smaller than the longitudinal, can be neglected. The relatively slow variations of the background N with height are not taken into account.

The constants $A(\lambda_n)$ are determined from the initial condition $N_1(z, 0) + N_2(z, 0) = 0$. The terms in (3.7) decay exponentially with time and the rate of decay increases with n. The maximum time for the establishment of the steady state corresponds to n = 1. Thus the time for the forced solution to predominate can be found from the relationship [78]

$$\tau_1 = \frac{4H^2(1-\delta)^2}{\pi^2 D_0}. \quad (3.8)$$

At heights of z = 250 km, we can take $D_0 \sim 7 \cdot 10^9$ $cm^2 sec^{-1}$ and H = 30 km. With $\delta = 0.1$ or $\delta = 0.5$, we obtain values of τ_1 equal to 7.5 or 2.5 min. For layers of greater thickness ($\delta \to 0$) $\tau_1 = 10$ min. Thus in the ionosphere internal waves can cause irregularities with periods T_0 greater than τ_1. We have $T \geqslant 10$ min. We note that periods T_0 for TID's (see section 1) are of the order of $T_0 \sim 20-30$ min. For these values $T_0 > \tau_g$ as required (in the F region $\tau_1 \sim \tau_g$). These estimates and the other considerations given above favor the interpretation of TID's in terms of gravity waves.

We shall now give a few further estimates which are based on this interpretation. The distance of propagation of TID's is determined by the smaller of two distances L_1 and L_2. Here L_1 is the distance over which absorption (for example, magnetohydrodynamic) leads to a noticeable reduction in amplitude. L_2 corresponds to the path length for which diffusion of the wave pulses occurs. Estimates of L_1 and L_2 from (2.26) and (2.28) lead to values of a few thousand kilometers. This is in agreement with experiment. We note that for magnetohydrodynamic absorption, L_1 is smallest, when $k_z \gg k_x$, for propagation along a meridian [77]. In practice this is found to be the prevailing direction of TID's. However, it is possible that this is due not to absorption but to other effects (for example, under wave excitation conditions).

One further estimate for D can be given. If a TID is in the form of a pulse, we can define D as

$$D = v_{gr\,x}\tau_2, \quad (3.9)$$

where τ_2 is the time taken for the pulse to pass right through the ionosphere,

$$\tau_2 = \Delta L / v_{gr\,z}. \quad (3.10)$$

It follows from (3.9) and (3.10) that $D = \Delta L v_{grx}/v_{grz}$. Since $k_z \gg k_x$ and $v_{grx} \gg v_{grz}$, $D \gg \Delta L$; this is in accordance with previous estimates.

A convenient fact in the interpretation of TID's in terms of internal waves is that the group velocity of these waves ($k_z \gg k_x$) is almost horizontal (see (2.16), (2.17)). Moreover, when $k_z \gg k_x$ the ratio $v_{gr}/v_p \sim$ $\sim k_z/k_x > 1$. It would seem that the various experiments measure not $v_p = \omega k/k^2$ but $v'_{px} = \omega/k_x$, which is of the order of the group velocity ($v'_{px} \sim v_{gr}$). Numerical estimates from (2.16), (2.17) show that the velocity of internal waves $v_{gr} \leqslant 10^4$ cm · sec^{-1} when $\gamma = 1.4$, $g = 10^3$ cm · sec^{-2}, $C_0 = 6 \cdot 10^4$ cm · · sec^{-1}. We recall that the actual speed of TID's varies between 30 and 300 m · sec^{-1}, and that there are measurements corresponding to $v_{gr}/v_p \sim 2$ [51].

In this connection, Hines [7] has suggested that the high velocity TID's are associated with internal waves for which $k_z \sim k_x$. In this case the dispersion equation differs from (2.15) and has the form

$$\omega^2 = \omega_g^2 \frac{k_x^2}{k_x^2 + k_z^2}. \quad (3.11)$$

This corresponds to waves for which $v_{gr} < v_p$. Thus the mechanism does not agree with experimental results on the relation between phase and group velocity.

We shall finally consider the connection between TID's and the formation of sporadic E. Wind shears [82–84] are nowadays accepted as the cause of E_s at middle latitudes. This point of view was first put forward by Whitehead [82] and has since received further development and confirmation.

It was noted as early as 1960 [7] that the appearance of wind shears could be connected with TID's. Mention was made in section 1 of the correlation between TID's and E_s. This correlation can quite easily be explained by the nature of the changes in the gas velocity u in internal waves. This has in fact been done in [88] where the formation of E_s is connected with turbulent motion of neutral particles during the passage of gravity waves.

4. CONCLUSIONS

Internal gravity waves can explain the principle features of TID's. However, two slightly different mechanisms have recently been discussed in the literature. One of these was suggested by Wickersham [89–91] and consists in the identification of TID's with certain modes of gravitational-acoustic waves in an atmospheric waveguide. Such waves were first suggested as an explanation of pressure oscillations observed at the earth's surface after nuclear explosions and volcanic eruptions [92–94].

The same name was given to pressure waves propagated in an atmospheric waveguide [95, 96]. The lower boundary of the waveguide is taken to be the earth's surface, and at some height z = L the isothermal semi-infinite space begins. In essence, gravitational acoustic waves are the same nature as those described in section 2 (see also [97]). The difference is that vertical propagation is restricted. This leads to a discrete spectrum. The atmospheric model adopted in this work has a realistic variation with height for temperature (one or two minima), molecular mass, gravity, and velocity of sound. A numerical solution is used to give the dispersion characteristics (variation of phase and group velocities with frequency) and also the distribution of energy with height. Wickersham identifies large-scale irregularities having translational speeds of 350–500 m · sec^{-1} and above with particular waveguide modes [89–91]. The basic criterion of this approach is the possibility of explaining theoretically the frequency of occurrence of TID's as a function of velocity.

A serious drawback in this mechanism is the presence of an upper limit for the period of gravitational-acoustic waves equal to about 15 minutes. This is in contradiction to the experimental observations on TID's. A more detailed criticism will be found in [98].

This difficulty has been overcome by Friedman [99] who has modified the conditions for the propagation of the gravitational-acoustic waves. The waveguide is not taken to be perfect but to have a certain leakage allowing a vertical transport of energy. As a result of this, the horizontal wave number becomes complex (even without absorption) $K_x = k_x + ik_x$. The solution is sought in the range of values of k_x', ω, ω/k_x, observed with TID's, i.e., $10^{-6}\,\text{km}^{-1} < k_x' < 10^{-3}\,\text{km}^{-1}$, $4 \cdot 10^{-4}\,\text{sec}^{-1} < \omega < 7 \cdot 10^{-3}\,\text{sec}^{-1}$, and $60\,\text{m} \cdot \text{sec}^{-1} < \omega/k_x < 800\,\text{m} \cdot \text{sec}^{-1}$. Numerical integration gives the group velocity $v_{gr} = d\omega/dk_x$, phase velocity $v_p' = \omega/k_x$, the vertical wave number (which varies with height), and other characteristics of the normal waves. An important fact is that as in all cases previously considered, the group velocity is less than $v_p' = \omega/k_x$. The waveguide model has not yet been completely developed.

It follows from all this that TID's can certainly be connected with the propagation of internal gravity waves in the ionosphere. All their principal features can be explained by this mechanism. The discrepancy between theory and experiment which exists in the question of group and phase (v_p') velocities can partly be explained by the difficulties in measuring these velocities.

At the same time it must be pointed out that a more detailed comparison of theory with experiment requires additional data and the solution of a number of problems. In particular, the question of the excitation of these waves is important [100, 101] and also their effect on the electron distribution in the ionosphere. It is of interest to investigate the properties of gravitational waves in two-dimensional inhomogeneous media and also to take into proper account the influence of viscosity and nonlinear effects in connection with the fact that in individual cases TID's with an almost two-to-one change in electron density are observed.

As regards experimental work, it is desirable to obtain data on the shape of large-scale irregularities, especially of their vertical structure and spatial localization. The latter is important in the choice of a model for the numerical method of analyzing internal waves. It is of no less interest to make direct measurements of the electron density N and neutral particle density N_m (or pressure p_m) in TID's with satellite or rocket sounders. There is little information on TID's at high latitudes or in the equatorial electrojet region: results need to be obtained on the variation of the distance of propagation with time of day and direction of motion.

Note added in proof. A number of papers connected with traveling disturbances appeared while the proofs for this review were being prepared. Some of them [103, 104] consider the problem of dissipation when the kinematic viscosity varies with height. References [105–107] are devoted to the generation of internal waves. In [108] the question of the connection of TID's with magnetic activity is again discussed. The results of observations of TID's at Tbilisi are published in [109].

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