

The Structure of Planetary Waves in the Auroral Region Upper Atmosphere¹

Y. T. CHIU AND J. M. STRAUS

Space Physics Laboratory, The Aerospace Corporation, El Segundo, Calif. 90245

(Manuscript received 26 September 1973, in revised form 30 January 1974)

ABSTRACT

Invoking recent satellite observations of the planetary-scale variations of auroral forms, as well as direct satellite observation of polar upper atmospheric winds during magnetic storms, we suggest that substorms may be a source of planetary waves of frequency intermediate between the Rossby and acoustic-gravity regimes. The zonal wavenumber of such waves is approximately 3-6; therefore, their propagation is strongly affected by the Coriolis force. Interpretation of worldwide traveling ionospheric disturbances in terms of meridional propagation of these waves is discussed.

1. Introduction

The dynamics of the upper stratosphere, and perhaps the lower thermosphere as well, have been shown to be strongly affected by the interaction of mean zonal winds with planetary Rossby waves (Charney and Drazin, 1961; Newell and Dickinson, 1967; Finger *et al.*, 1966; Dickinson, 1968; Matsuno, 1970). Clearly, a source of Rossby waves in the stratosphere would be that associated with large-scale tropospheric weather systems. However, if a second source of such planetary- or synoptic-scale waves were to exist, then it would be of considerable interest to workers concerned with upper atmospheric dynamics. In particular, if such a second source of neutral atmospheric waves were related to geomagnetic activity, and if such waves were of the proper dimensions to interact with the upper atmospheric circulation, then they may act as the initiating perturbations to trigger latent aerodynamic instabilities in the upper atmosphere.

In this paper, we would like to suggest, by invoking recent satellite observations of planetary-scale variations of auroral forms (Morse *et al.*, 1973), as well as direct satellite observations of polar upper atmospheric winds during magnetic storms (Feess, 1968; Chiu, 1972), that auroral substorms may be a source of planetary waves in the 100-km altitude region. It is understood that numerous observations of ionospheric and atmospheric disturbances associated with geomagnetic activity have been reported from time to time; however, upon examination, most of these are either in the high altitude regions (~ 350 km) or of such local nature that the lateral extent of the disturbance cannot

be ascertained. As a result, our discussion of observations and our theoretical efforts will be focused on the zonal and meridional structure and dispersion of such planetary waves in the spherical rotating upper atmosphere. Since our primary purpose is to consider the possible existence of these waves from available observations and to suggest possible observations to study the wave characteristics, discussions of their possible interaction with upper atmospheric circulation systems will be deferred until more observational evidence is available. Further, our theoretical investigation will be limited to consideration of wave characteristics essential to establishing the existence of such waves. Detailed features such as propagation in realistic atmospheres with zonal wind shears (Dickinson, 1968) and effects of non-linearity (Einaudi, 1969; Chiu, 1970) will be ignored.

Traveling ionospheric disturbances occurring in the 200-800 km altitude region have been observed for many years (Thome, 1968; Davis and daRosa, 1969). Well-correlated ionospheric disturbances of ~ 2000 km horizontal scale and of $\sim 1-2$ hr periods have been observed to propagate from the auroral zone at speeds of ~ 500 m sec⁻¹. These disturbances have been interpreted generically as due to the passage of gravity waves. Since the horizontal scale and wave speed are so large, being reminiscent of long waves in the ocean, at least two intriguing questions must be raised. First, since aurorae occur at the 100-km level, it would be of interest to ask if these high-altitude ionospheric disturbances may be related to variations of the low-altitude aurorae and associated neutral disturbances. Second, if such large-scale disturbances were indeed neutral waves, then it would be of interest to investigate the effects of sphericity and the latitude variation

¹ This work was conducted under U. S. Air Force Space and Missile Systems Organization (SAMSO) Contract F04701-73-C-0074.

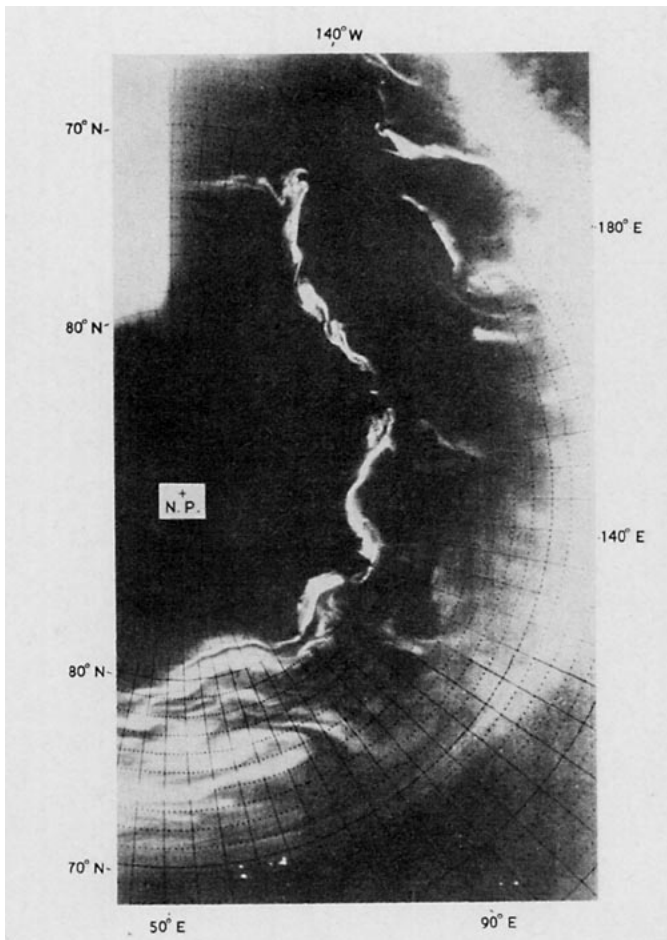


FIG. 1. An extensive auroral form observed by scanning radiometers on board a U. S. Air Force weather satellite near the north auroral zone at 1351 GMT 1 August 1972. The origin of the grid on the photograph is the north geographic pole. It is seen that, aside from small-scale variations of <100 km horizontal scale, the auroral form exhibits planetary-scale variations with zonal wave-number ~ 5 . The coherent extensiveness of the associated auroral heating is particularly significant. [Courtesy E. H. Rogers and D. F. Nelson, The Aerospace Corporation.]

of the Coriolis force on their propagation. These questions will be considered in some detail in this paper in order that the peculiar properties of these waves in the auroral region may be exploited for observational purposes. In this respect, it is perhaps relevant to note that, while meridional propagation of ionospheric disturbances has been studied thoroughly in the mid-latitude region, observations of the horizontal scale and propagation of such disturbances in the auroral region do not seem to be available.

Fig. 1 shows an extensive auroral form detected by scanning radiometers on board a U. S. Air Force weather satellite (Morse *et al.*, 1973). The most important feature revealed by this unique observation of planetary-scale auroral forms is that the aurora shows *coherent* spatial variations typical of a wave with zonal wavenumber 3 to 6. Since auroral substorms

show typical temporal variations of, say, 1–2 hr, these observations suggest clearly that auroral substorms, as a source of atmospheric heating in the vicinity of 100 km, must be rich in Fourier components of these zonal wavenumbers and wave periods. Indeed, there is theoretical reason to believe that such spatial and temporal variations of the aurora are related to waves in the auroral current (Hasegawa, 1970). Given the existence of such wave-like variations of auroral heating, it is reasonable to consider meridional and vertical propagation of such planetary waves, to lower latitudes and to higher altitudes, in the interpretation of traveling ionospheric disturbances.

Despite the observation of clearly wave-like variation of planetary-scale auroral heating, direct observations of the neutral wind field associated with such wave motion would be desirable in order to substantiate the suggested relation between the characteristics of auroral forms and traveling ionospheric disturbances. In short, are there *in-situ* satellite observations of upper atmospheric wind fields in the auroral region directly related to specific geomagnetic storms? In this regard, we wish to point out that the pattern of cross-track wind components, deduced from accelerometer and attitude control activity on board the 1967-50B satellite at altitudes between 150 and 220 km before and after the onset of a very large geomagnetic storm on 27 May 1967, are

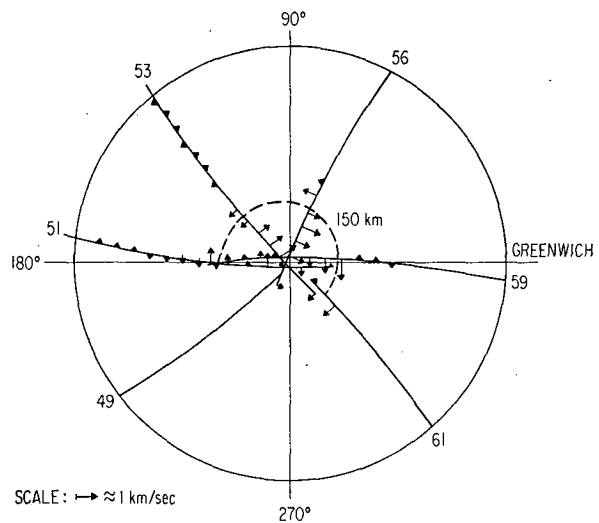


FIG. 2. Lower thermospheric winds deduced from accelerometer and attitude control activity on board the satellite 1967-50B on 27 May 1967 near the north geographic pole, the origin of the figure. The satellite paths are labelled by the orbit numbers (49–61) and the dashed curve indicates the locus of points for which the satellite altitude is 150 km. The polar plot shows the measurements for the Northern Hemisphere. The magnetic storm onset was at the 50th orbit. It is seen that well-organized wind components with a horizontal scale of ~ 2000 km seem to be associated with an extremely disturbed but stationary structure at the pole. These features are particularly well-illustrated on orbits 51, 53 and 59. It should be noted that both features are coherent and planetary in scale. (After Feess, 1968; for summary see also Chiu, 1972.)

of particular interest (Feess, 1968). Fig. 2 shows data from selected orbits in which well-organized cross-track wind variations were encountered. Although the major stationary structure near the pole may involve convective over-turning of the atmosphere (Chiu, 1972), the coherent wind variations of smaller magnitude, which change from orbit to orbit, are likely to be propagating waves of ~ 2000 km horizontal scale. These structures are particularly evident at or near satellite orbits 51 and 53.

Clearly, in this extremely brief review of possible evidence indicating the existence of planetary-scale neutral waves in the 100-km region, we have ignored many excellent observations of atmospheric and ionospheric variations which do not bear as directly on the horizontal scale of these disturbances as the above. The ionospheric incoherent backscatter technique yields the most detailed information on ionospheric structure (Evans, 1972); however, until more observation stations are in coordinated operation, information relevant to the horizontal scale of substorm-related ionospheric disturbances appears to be unavailable. Satellite observations of atmospheric density show a great deal of promise in this regard; however, insofar as we can ascertain, analysis of density disturbances in terms of their spatial and temporal organization does not seem to be available. It is evident from the scanty observations cited above that the existence of substorm-related atmospheric waves of ~ 2000 km horizontal scale and of ~ 2 hr time period remains a conjecture. However, in view of the fact that planetary-scale waves in the 100-km region can interact readily with stable or unstable circulations of the mesosphere and thus exert influence on their dynamics, we feel that such a conjecture is an interesting one. While confirmation of the existence of such planetary-scale waves would require further simultaneous observations of auroral emissions, atmospheric density changes, and neutral wind fields by low-altitude satellites, we shall attempt to examine here the properties of such waves in order to delineate the difference between these waves and other smaller-scale atmospheric waves modes. From Figs. 1 and 2, it is clear that, if such disturbances are identified with waves, then their horizontal scales are sufficiently large that effects connected with sphericity and the variation of the Coriolis force with latitude would significantly influence the wave characteristics. In this regard, it must be noted that all such internal adiabatic atmospheric waves can, in a generic sense, be classified as "gravity waves"; therefore, our suggested interpretation of the above observations is not in direct conflict with the "gravity wave" interpretation. However, for the sake of clarity, adiabatic waves in a spherical rotating atmosphere may be more exactly classified according to the spectrum of frequency and wavenumber. At the higher frequency end of the spectrum are the classical acoustic-gravity waves for which all horizontal directions of propagation are indistinguishable. At the

lower frequency end of the spectrum, we have, on the other hand, the Rossby waves on which the influence of the latitude-dependent Coriolis force is so prevalent that only retrograde (westward) propagation is allowed. From the observations above, it seems that the planetary waves under consideration here probably lie somewhere between these two limits. It is in this sense that we draw a distinction between such waves and those in the acoustic-gravity regime.

2. Planetary waves in the upper atmosphere

In view of the possible planetary-wave interpretation of observations discussed in the previous section, it appears to us that, in order to establish their existence, it would be necessary to consider the detailed properties of such waves in conditions appropriate to the polar upper atmosphere so that the various waves modes may be distinguished by observations. The problem of free oscillations of a spherical, rotating, stratified atmosphere has been treated in various special situations and approximations by many authors (see, for example, Kuo, 1959; Eckart, 1960; Phillips, 1965; Lindzen, 1967; Longuet-Higgins, 1964, 1965). For most stratospheric applications (Charney and Drazin, 1961; Dickinson, 1968), considerations of planetary-scale waves are treated in terms of a purely horizontal streamfunction satisfying the equations of vorticity conservation and thermodynamics. Since the waves of major interest in stratospheric applications are in the Rossby regime, such an approach is most appropriate in that the high-frequency acoustic-gravity modes are automatically eliminated. For the present case, it is evident that such an approach cannot be taken for at least two reasons. First, the frequencies of large-scale traveling ionospheric disturbances and neutral wind systems considered in the previous section seem to be considerably higher than waves of the Rossby regime. Indeed, both the frequency and horizontal wavenumber of waves corresponding to the observations seem to be intermediate between the Rossby and acoustic-gravity regimes. Second, unlike tropospheric disturbances which are vertically evanescent, large-scale internal waves in the upper atmosphere may have vertical phase propagation. Therefore, it seems that the proper treatment of such waves in an isothermal atmosphere must be formulated in terms of the equations of adiabatic state, continuity, energy conservation, and three-dimensional momentum balance in a stratified rotating atmosphere. In such a treatment, the properties of the waves change continuously from westward propagating Rossby modes to high-frequency acoustic-gravity modes, although the perturbation equations are not amenable to exact analytic solution as in the case of the vorticity-thermodynamic approximation. On the other hand, since the formulation of the atmospheric perturbation equations is well known and since the treatment of the equations in spherical coordinates parallels that of Longuet-Higgins (1964, 1965) and of "tidal theory" (Lindzen,

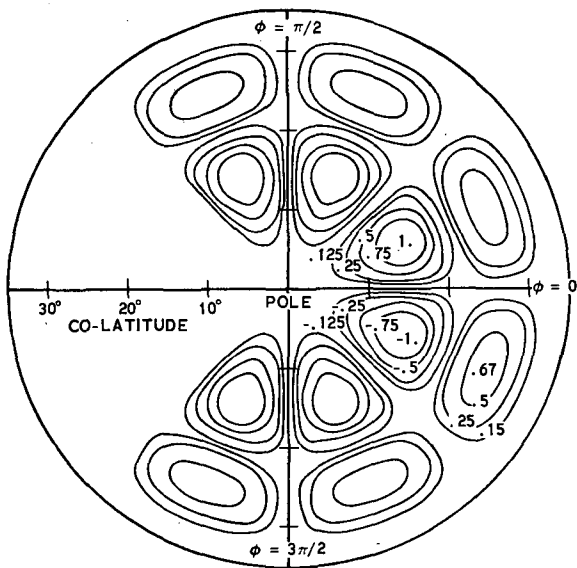


FIG. 3. Contour plot of the wave function factor $J_m(k\theta) \sin m\phi$ normalized to unity at the first maximum of the Bessel function. The values $m=4$ and $k=20$ are chosen to roughly model the zonal and meridional variations of Fig. 1.

1966), we shall not exhibit the derivations; we shall rather state the results appropriate for the high-latitude region. Indeed, the wave solutions for the high-latitude region are considerably simpler than the Hough functions of tidal theory, which are, of course, more general.

Under a coordinate scaling of time t and altitude z to the earth's angular speed Ω and the assumed isothermal scale height H , i.e., $(t, z) \rightarrow (\tau/\Omega, H\xi)$, where (τ, ξ) are dimensionless time and altitude respectively, the non-dimensionalized perturbation equations can be stated in terms of three dimensionless parameters. These are the Froude number $f_e \equiv gH/(\Omega^2 R_E^2)$, where g is the gravitational acceleration and R_E the radius of the earth, the aspect ratio $\alpha \equiv H/R_E$, and the heat capacity ratio $\gamma \equiv c_p/c_v$. An important feature of the upper atmospheric flow system defined by the above parameters is that f_e and γ are of order unity while the aspect ratio α is of order 10^{-2} or less. Consequently, the dispersion relations for adiabatic waves can be simplified considerably through the use of an expansion in α . In order to illustrate this, we define a dimensionless Brunt-Väisälä frequency $\omega_B^2 = f_e(\gamma - 1)/(\alpha^2 \gamma) \approx 10^4$. Since we are only interested in a spectrum of frequencies $\omega^2 \leq 10^2$, the approximation $\omega^2 \ll \omega_B^2$ is equivalent to truncation of the aspect ratio expansion at α^2 . Using the approximation $\alpha^2 \ll 1$, it is possible to obtain a slightly more general tidal equation which does not assume hydrostatic pressure balance in the vertical direction and which includes the vertical force equation for adiabatic waves. Since these differences from the standard tidal theory (Chapman and Lindzen, 1970, p. 108) are probably minor, it is only necessary to note

that the dimensionless pressure takes the form

$$P = Q(\theta) \Delta^{\frac{1}{2}} \exp[i(-\omega\tau + m\phi + K\xi)], \quad (1)$$

where ω is the dimensionless frequency in units of Ω , K the dimensionless vertical wavenumber, m the zonal wavenumber, and

$$\Delta = 4 \cos^2 \theta - \omega^2. \quad (2)$$

In (1), θ and ϕ are respectively the spherical coordinate co-latitude and azimuth; while K need not be purely real. The "tidal" equation for $Q(\theta)$ can be written

$$\frac{1}{\sin \theta} \frac{\partial}{\partial \theta} \left(\sin \theta \frac{\partial Q}{\partial \theta} \right) - \frac{m^2}{\sin^2 \theta} Q + F(\theta) Q = 0. \quad (3)$$

In (3), $F(\theta)$ is given by

$$F(\theta) = -\frac{3}{4} (d \ln \Delta / d\theta)^2 - M/\Delta - N\Delta, \quad (4)$$

where

$$\left. \begin{aligned} M &= 2m(\Delta + 2\omega^2) + 4(3 \cos^2 \theta - 1) \\ N &= iK\gamma(1 - iK) / [f_e(\gamma - 1)]. \end{aligned} \right\} \quad (5)$$

Although (3) is quite complicated, a number of approximations for $F(\theta)$ allow it to be solved in terms of spheroidal harmonics (Abramowitz and Stegun, 1964), which are different but reducible to the spheroidal harmonic solutions of Kuo (1959) and Longuet-Higgins (1964, 1965).

In high-latitude regions appropriate for the present discussion, the solutions become especially simple since $\sin \theta$ and $\cos \theta$ in $F(\theta)$ can be expanded as power series of θ . If the expansion for $F(\theta)$ is truncated at terms of order θ^2 , the solution wave functions become Bessel functions

$$Q \sim J_m(k\theta), \quad (6)$$

where k is a sort of meridional wavenumber. [In terms of the usual sinusoidal wave definition, k is, strictly speaking, a meridional wavenumber only in the asymptotic limit of $k\theta \ll 1$. Nearer the origin, the wave function (6) is considerably different from sinusoidal; therefore, k is not exactly the meridional wavenumber.] For a given m , the Bessel function $J_m(k\theta)$ maximizes in the

TABLE 1. Polar region wave solutions.

Case	Solution	Comment
(a) $\omega^2 \ll 4$	$J_m(k\theta)$	Retrograde Rossby modes
$\theta^2 \ll \left 1 - \frac{\omega^2}{4} \right $		
(b) $\omega^2 = 4$	$J_{m-1}(i\theta/\sqrt{2})$	Semi-diurnal mode, no meridional phase propagation
$\theta^2 \ll 1$		
(c) $\omega_B^2 \gg \omega^2 \gg 4$	$J_m(k\theta)$	Intermediate frequency planetary mode
$\theta^2 \ll \left 1 - \frac{\omega^2}{4} \right $		

region for which $k\theta$ is less than, but in the vicinity of the first zero of J_m . Therefore, if planetary waves are generated by auroral heating of the form shown in Fig. 1, i.e., restricted to a band of values of θ and m , then the wave energy would also be concentrated in a narrow band of values of k . Now, by virtue of the dispersion relation, this implies a definite band of meridional phase propagation speeds once the spectrum of waves in m and ω is established. To illustrate this, Fig. 3 shows the wave function factor $J_m(k\theta) \sin m\phi$ normalized to unity at the first maximum of the Bessel function. The values $m=4$ and $k=20$ are chosen to roughly model the zonal and meridional variations of Fig. 1.

Next, we undertake to discuss the properties of the various modes appropriate for the high-latitude regions. The most convenient way to do this is to classify them by frequency, since there are only three relevant regions in (θ, ω) space for which the spheroidal harmonic solutions of (3) reduce to simple Bessel functions. Table 1 gives a short summary of these regions.

The waves of interest to the present study are the cases (a) and (c) since case (b) does not have meridional phase propagation. Both of these cases are governed by the dispersion relation,

$$-(k^2 + \frac{1}{2}) = (1 + 2m/\omega) \left(\frac{4 + \omega^2}{4 - \omega^2} \right) + N(m, \omega, K). \quad (7)$$

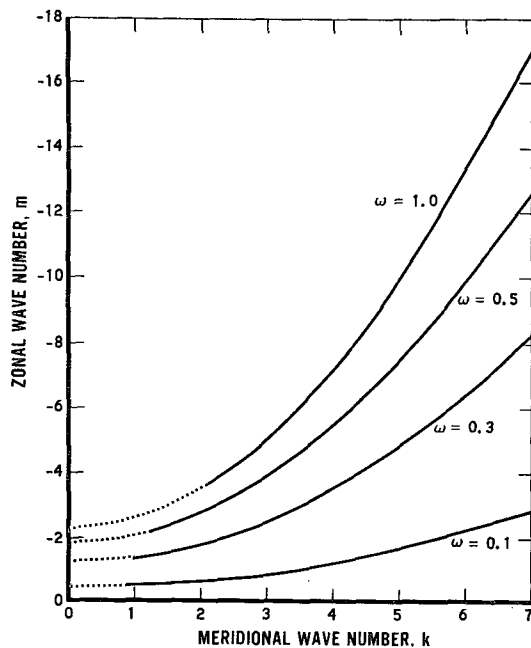


FIG. 4. Solutions of the dispersion relation for Rossby mode planetary waves ($\omega < 2$) for the case of no zonal mean flow and no vertical propagation ($l=0$). The dotted portions indicate regions of (m, k) space for which a slightly better but much more cumbersome relation than (18) may be required. It is seen that real solutions exist for $m < 0$ only; thus, these modes propagate in the retrograde zonal direction.

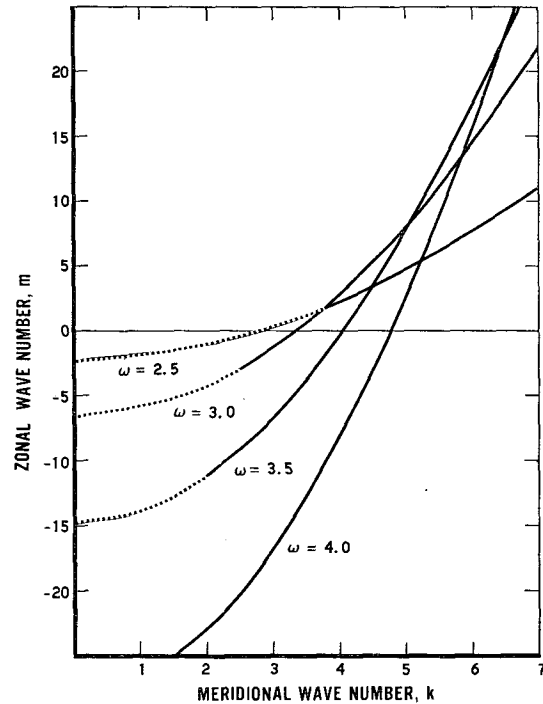


FIG. 5. Solutions of the dispersion relation for intermediate-frequency planetary waves ($\omega < 2$) for the case of no zonal mean flow and no vertical propagation ($l=0$). The dotted portions indicate regions of (m, k) space for which a slightly better but much more cumbersome relation than (18) may be required. The first feature to be noted is that, for fixed ω , a wave propagates eastward or westward depending on k . The second feature to be noted is that, for increasing ω , k becomes less and less dependent on m .

The solution to (7) consistent with no energy dissipation is

$$K = l - i/2$$

$$-(k^2 + \frac{1}{2}) = (1 + 2m/\omega) \left(\frac{4 + \omega^2}{4 - \omega^2} \right) + \left. \frac{\gamma(4 - \omega^2)}{f_e(\gamma - 1)} (l^2 + \frac{1}{4}) \right\}, \quad (8)$$

where l , purely real, is the proper dimensionless vertical wavenumber. For $\omega < 2$, it is easily seen from (8) that m must be negative for all values of l ; therefore, these waves can be identified as Rossby waves which have westward phase propagation in the zonal direction only. For $\omega > 2$, both eastward and westward phase propagation are allowed; however, as ω approaches the Brunt-Väisälä frequency, which is of order 10^2 in our dimensionless units, wave dispersion begins to become independent of zonal wavenumber m since $2m/\omega$ becomes insignificant when compared to unity. In order to give a complete illustration of the dispersion relation (8) one would have to resort to a four-dimensional (ω, k, m, l) space. However, since (8) is sufficiently simple we shall only illustrate the dispersion relation for the case of no vertical phase propagation ($l=0$). This is shown in Figs. 4 and 5. For reference purposes, the relationship

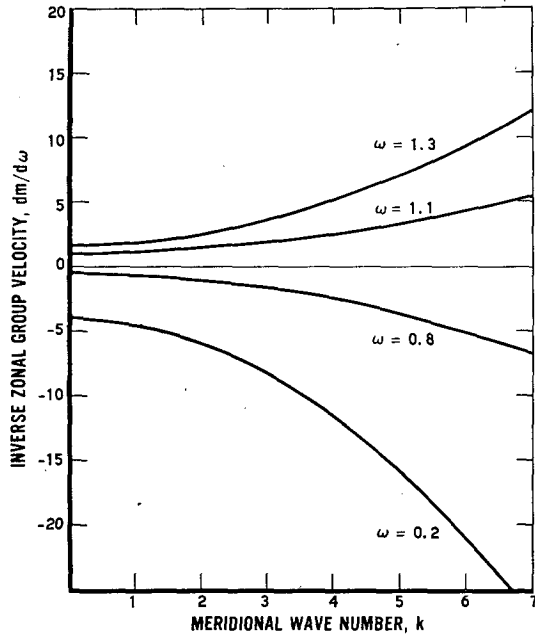


FIG. 6. The inverse group velocity $dm/d\omega$ of intermediate-frequency planetary waves ($\omega > 2$) corresponding to the solutions shown in Fig. 5. It is seen that group propagation in the zonal direction depends not only on k but also on ω .

for the inverse of the zonal group velocity, $d\omega/dm$, is shown in Figs. 6 and 7 as functions of ω and k .

While the exploitation of the dispersion relation for such low-frequency planetary waves for observation purposes will be considered in the next section, we summarize this section by noting some outstanding characteristics of these waves in the 100-km region of the upper atmosphere.

1) For wave frequencies much smaller than the Brunt-Väisälä frequency, solutions to the basic adiabatic perturbation equations in the spherical, stratified, and rotating upper atmosphere can be constructed in terms of spheroidal harmonics of the co-latitude θ and in terms of the usual sinusoidal functions of longitude ϕ , altitude ξ and time τ . In the polar regions, the harmonic wave functions in θ approach the form of Bessel functions.

2) Because of the action of a latitude-dependent Coriolis force, the low-frequency planetary waves so obtained exhibit asymmetries in their zonal and meridional propagation characteristics. This is to be contrasted with acoustic-gravity modes in a plane-stratified atmosphere for which the two horizontal directions are indistinguishable.

3) As has been noted by many authors, the spectrum of waves consists of a purely westward propagating Rossby regime with frequency below the semi-diurnal oscillation and a zonally dispersive planetary wave regime with frequency intermediate between the semi-

diurnal oscillation and the Brunt-Väisälä frequency which marks the classical acoustic-gravity regime.

4) Waves in the Rossby regime propagate westward in phase; however, their group propagation shows a splitting at about $\omega=1$ —the lower frequency group propagates westward while the higher frequency group propagates eastward. Group propagation in zonal directions is independent of meridional wavenumber.

5) For planetary waves with frequency $\omega > 2$, the phase propagation for fixed ω is westward for low meridional wavenumber and is eastward for high meridional wavenumber. A similar relation holds for group propagation, which would result in the splitting of a disturbance.

3. Possible observational consequences

By associating features observed in the visual aurora, in the ionosphere and in the polar neutral atmosphere, we have conjectured in Section 1 that these planetary-scale phenomena are probably different manifestations of propagating planetary waves caused by auroral heating of the neutral atmosphere in the 100-km altitude region. In Section 2, we discussed the dispersion characteristics of such planetary waves in order to identify some features which may help to test the above conjecture. In this section, we shall discuss some *in-situ*, as well as statistical, studies which may help in this identification, although it must be recognized at the

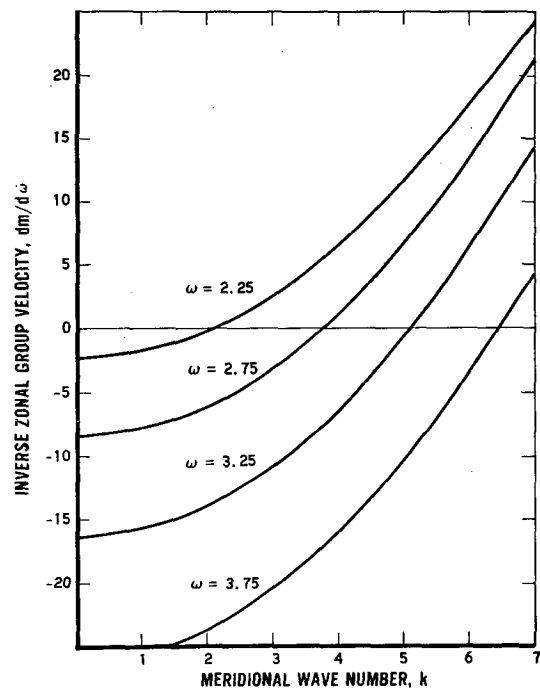


FIG. 7. The inverse group velocity $dm/d\omega$ of Rossby mode planetary waves ($\omega < 2$) corresponding to the solutions shown in Fig. 4. It is seen that group propagation eastward or westward depends on ω only, and not on k .

outset that there does not appear to have been a single experiment which would give a complete identification of these waves. The major reason for the difficulty is the restriction that direct identification must be made on the neutral component of the atmosphere.

a. Determination of scale sizes

The scale sizes of traveling ionospheric disturbances are determined by correlational studies of columnar electron content observations taken simultaneously at several stations separated by distances of the order of 1000 km (Davis and DaRosa, 1969). Since traveling ionospheric disturbances have long been thought to be caused by the ionic drag force exerted by neutral wave disturbances, the spectrum of scale sizes measured for traveling ionospheric disturbances probably reflects that of neutral waves. However, since ionospheric disturbances occur at high altitudes, it would be desirable to measure the neutral wave scale size directly in the 100-km region and below.

Insofar as scale size measurement in the 100-km region is concerned, the most elegant experiment seems to be the measurement of cross-track wind forces exerted on a low-altitude polar-orbiting satellite (Fig. 2). Accurate measurements of wind magnitude and pattern of directional change along a satellite orbit can be obtained with accelerometers mounted on atmospheric satellites with large cross-sectional area normal to the orbital direction. However, such an experimental arrangement is limited by the probability of encounter with geomagnetic disturbances during the short lifetime of such low-altitude satellites. The density variations associated with the planetary waves can also be used to determine the scale size. Such measurements would determine density variations by means of in-track accelerometers or ion gauges. Indeed, high-latitude density disturbances with scale sizes of 1000 km have been detected by ion gauges on board the satellite 1972-32A in the 200–300 km altitude region during magnetically disturbed periods (B. K. Ching, private communication). Unlike measurement of cross-track wind patterns, the scale size derived from density measurements is subject to uncertainty of interpretation in terms of density variation in the vertical or in the horizontal directions.

For the middle atmosphere, satellite measurements are not feasible, although the existence of magnetic-activity-related planetary waves becomes more significant for consideration of coupling processes between the upper and lower atmospheres. Simultaneous rocket launches from high-latitude stations spaced hundreds of kilometers apart seems to be the only available means of scale size determination in the upper regions of the mesosphere. In the stratosphere, spatial correlation from a network of balloon measurements in the auroral region would be the most promising method. In this regard, the very significant correlation between stratospheric temperature and D region ion density

(Bossolasco and Elena, 1963), which was discovered in temporal correlation studies, prompts us to ask, in connection with the present conjecture, whether there is a spatial limit to the above correlation.

b. Determination of phase propagation

Determination of the scale size does not establish the wave character of the disturbances. Therefore, it would be necessary to show that the wave phase propagates anisotropically in the horizontal directions as prescribed by the dispersion relation discussed previously. Unlike measurement of scale sizes, the direct determination of phase propagation for neutral waves is rather difficult. It is unfortunate that the excellent methods for scale size measurements are not applicable to measurements of phase propagation unless somewhat ad hoc assumptions are made. First, all satellite measurements suffer from the drawback that particular features of a wave can be tracked only once every orbital period, if at all. Since the orbital period of polar atmospheric satellites is about $1\frac{1}{2}$ hr, such a sampling frequency does not yield any information on the phase propagation of waves of similar frequency. Second, measurements based on disturbances in total electron content, while excellent for tracking ionospheric disturbances of the F region, yield little information on the phase propagation of the driving neutral waves because the ionospheric wave, once generated, travels under magnetic constraints which are absent for the neutral wave. The dynamics of ion-neutral interactions in the presence of electric fields in the F region (Reid, 1965; Farley, 1969; Haerendel, 1970; Chiu, 1974) requires too many parameters to be measured before the neutral motion can be deduced. Besides, the main objective of our study is to test the existence of planetary modes in the 100-km region, not the 200–400 km region.

For the 100-km region, the most promising method for measuring phase propagation of neutral waves seems to be a correlation study of ion drift motion obtained from *three* incoherent backscatter stations triangulated with base lines of several hundred kilometers. In the D and E regions of the ionosphere, the neutral-ion collision frequency is sufficiently large that ion motion reflects neutral motion with little magnetic constraint. Given such circumstances, the method of phase propagation measurement parallels that for the case of traveling ionospheric disturbances (Davis and DaRosa, 1969) although the parameter to be measured is ion velocity rather than electron content. Even though such an observational arrangement is not available at present, we believe that it would yield valuable information on the motions of a region where coupling processes between the upper and lower atmospheres, if any, take place.

4. Conclusions

From recent satellite observations of substorm-related events bearing on the horizontal scale of atmo-

spheric disturbances in the lower thermosphere, we conjecture that there may exist planetary waves of several hour period and of ~ 2000 km horizontal scale in the 100-km altitude region. While the possible existence of such atmospheric disturbances during auroral substorms is interesting in itself, a related area of significance may be that such waves would be of the proper size scale to interact with upper stratospheric or mesospheric circulation systems in ways analogous to the interaction of tropospheric planetary waves with circulation in the stratosphere (Dickinson, 1968). Clearly such possibilities are in the realm of conjecture; however, such a hypothesis should be examined if correlations between geomagnetic activity and stratospheric trough activity (Roberts and Olson, 1973; Wilcox *et al.*, 1973) are confirmed.

These conjectured mesospheric waves seem to be intermediate in frequency and scale size between the Rossby and acoustic-gravity modes. Because of the action of a latitude-dependent Coriolis force, propagation of these waves in the zonal and meridional directions is strongly asymmetric; in contrast, acoustic-gravity modes propagate isotropically with respect to the two directions. In particular, the planetary modes in question disperse in such a way that an impulse may split into eastward and westward propagating groups depending on the meridional wavenumber. Since such substorm-related waves may interact with upper atmospheric circulation, we propose that their existence be tested by coordinated satellite and ground-based observations. It is known that ionospheric disturbances of ~ 2 hr period have been observed to propagate to mid-latitudes; however, according to the perturbation analysis, the horizontal asymmetry of the wave with respect to zonal and meridional propagation is the crucial feature which distinguishes waves of such large horizontal scale from small-scale acoustic-gravity modes. Moreover, it seems that the vertical structure of such conjectured waves must be very extensive indeed if auroral heating (~ 100 km) and traveling ionospheric disturbances (200–800 km) are closely related phenomena. In any case, it is probable that a coordinated observation of the same substorm event by satellite (auroral form and wind field in the ~ 100 -km region) and by ground-based ionospheric stations (triangulated with a base-line of ~ 1000 km) may reveal interesting properties of these disturbances in the upper atmosphere.

We realize that our conjecture is based upon a few observations of phenomena which may not be related and that our theoretical analysis is at best crude and oversimplified; however, our purpose is to call attention to the lack of information on the horizontal scale of the substorm-related waves in the neutral atmosphere. Therefore, our analysis was performed in the spirit of determining the basic structure of such waves and of determining what to look for in observations. To determine the realistic structure of such waves one would

have to take into account ducting effects in a diurnally varying atmosphere with zonal circulation. Further, the thermal driving of such disturbances may also interfere with the normal dynamical systems of the 100-km region of the upper atmosphere. We hope to consider such questions in a later communication.

Acknowledgments. We are indebted to Mr. D. F. Nelson and Dr. E. H. Rogers who kindly provided us with photographs and data on auroral forms.

REFERENCES

- Abramowitz, M., and I. A. Stegun, 1964: *Handbook of Mathematical Functions*. National Bureau of Standards Applied Mathematics Series, p. 752.
- Bossolasco, M., and A. Elena, 1963: Absorption de la couche D et temperature de la mesosphere. *C. R. Acad. Sci.*, **256**, 4491–4493.
- Chapman, S., and R. S. Lindzen, 1970: *Atmospheric Tides*. New York, Gordon and Breach, 106–121.
- Charney, J. G., and P. G. Drazin, 1961: Propagation of planetary scale disturbances from the lower into the upper atmosphere. *J. Geophys. Res.*, **66**, 83–109.
- Chiu, Y. T., 1970: Traveling waves of arbitrary amplitude in compressible hydrodynamics under gravity: An exact solution. *Phys. Fluids*, **13**, 2950–2957.
- , 1972: Thermospheric convective instability. *Space Research XII*, Akademie-Verlag, Berlin, 1025–1028.
- , 1974: Self-consistent electrostatic field mapping in the high-latitude ionosphere. *J. Geophys. Res.* (in press).
- Davis, M. J., and A. V. DaRosa, 1969: Traveling ionosphere disturbances in the auroral oval during polar substorms. *J. Geophys. Res.*, **74**, 5721–5735.
- Dickinson, R. E., 1968: Planetary Rossby waves propagating vertically through weak westerly wind waveguides. *J. Atmos. Sci.*, **25**, 984–1002.
- Eckart, C., 1960: *Hydrodynamics of Oceans and Atmospheres*. New York, Pergamon Press.
- Einaudi, F., 1969: Singular perturbation analysis of acoustic-gravity waves. *Phys. Fluids*, **12**, 752–756.
- Evans, J. V., 1972: Ionospheric movements measured by incoherent scatter: A review. *J. Atmos. Terr. Phys.*, **34**, 175–209.
- Farley, D. T., Jr., 1969: A theory of electrostatic fields in a horizontally stratified ionosphere subject to constant, vertical magnetic field. *J. Geophys. Res.*, **64**, 1225–1231.
- Feess, W. A., 1968: LOGACS wind analysis. TOR-0200(9990)-1, The Aerospace Corporation, El Segundo, Calif.; also paper presented at the COSPAR Fourteenth Plenary Meeting at Seattle, 1971.
- Finger, F. G., H. M. Woolf and C. E. Anderson, 1966: Synoptic analyses of the 5, 2 and 0.4 millibar surfaces for the IQSY period. *Mon. Wea. Rev.*, **94**, 651–661.
- Haerendel, G., 1970: Electric fields and their effects in the ionosphere. *Solar-Terrestrial Physics*, Dyer, Ed., Riedel, Holland, 87–116.
- Hasegawa, A., 1970: Theory of aurora bands. *Phys. Rev. Lett.*, **24**, 1162–1165.
- Kuo, H. L., 1959: Finite-amplitude three-dimensional harmonic waves on the spherical earth. *J. Meteor.*, **16**, 524–534.
- Lindzen, R. S., 1966: On the theory of the diurnal tide. *Mon. Wea. Rev.*, **94**, 295–301.
- , 1967: Planetary waves on β -planes. *Mon. Wea. Rev.*, **95**, 441–451.
- Longuet-Higgins, M. S., 1964: Planetary waves on a rotating sphere. *Proc. Roy. Soc. London*, **A279**, 446–473.
- , 1965: Planetary waves on a rotating sphere II. *Proc. Roy. Soc. London*, **A284**, 40–68.
- Matsuno, T., 1970: Vertical propagation of stationary planetary

- waves in the winter Northern Hemisphere. *J. Atmos. Sci.*, **27**, 871-883.
- Morse, F. A., D. F. Nelson, E. H. Rogers and R. C. Savage, 1973: Low energy electrons and auroral forms. Paper presented at the COSPAR Sixteenth Plenary Meeting, Konstanz, FRG.
- Newell, R. E., and R. E. Dickinson, 1967: On the application of a proposed global system for measuring meteor winds. *Pure Appl. Geophys.*, **68**, 162-172.
- Phillips, N. A., 1965: Elementary Rossby waves. *Tellus*, **18**, 295-301.
- Reid, G. C., 1965: Ionospheric effects of electrostatic fields generated in the outer magnetosphere. *Radio Sci.*, **69D**, 827-834.
- Roberts, W. O., and R. H. Olson, 1973: Geomagnetic storms and wintertime 300-mb trough development in the North Pacific-North America area. *J. Atmos. Sci.*, **30**, 135-140.
- Thome, G., 1968: Long-period waves generated in the polar ionosphere during onset of magnetic storms. *J. Geophys. Res.*, **73**, 6319-6336.
- Wilcox, J. M., P. H. Scherrer, L. Svalgaard, W. O. Roberts and R. H. Olson, 1973: Solar magnetic sector-structure: Relation to circulation of the earth's atmosphere. *Science*, **180**, 185-186