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Ionospheric Perturbation[1]

(The Roles Played by the Ionosphere in Geomagnetic Pulsations)

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Possible roles played by the ionosphere in geomagnetic pulsations are reviewed in this report. First, relations between the quiet ionosphere and regular pulsations are discussed from the viewpoint of hydromagnetic wave propagation and ionospheric currents.

Ionospheric variations and correlated irregular pulsations during disturbances and storms are then discussed. These phenomena sometimes occur in correlated form during solar flares, sudden commencements and impulses, bays, DS variations, and polar elementary storms. The main causes seem to be solar electromagnetic radiations, hydromagnetic waves, incoming particles, and resultant ionospheric currents.

Ionospheric and micropulsation phenomena caused by nuclear explosions and meteors are very briefly reviewed. Emphasis is given to the type of work in this field which needs to be done in the future.

1. Introduction

Possible roles played by the ionosphere in geomagnetic micropulsations are briefly reviewed from the point of view of observed results, since there are no very satisfactory theories.

One of the roles the ionosphere plays in geomagnetic pulsations is the creation of earth-ionosphere cavity resonances. However, this topic is excluded in this report, because it is discussed by Wait [1965] in the present issue of this journal.

Relations between the quiet ionosphere and regular pulsations, ionospheric variations and correlated irregular pulsations during disturbances and storms, ionospheric and geomagnetic phenomena caused by nuclear explosions and meteors are discussed in the succeeding two sections.

2. Quiet Ionosphere and Regular Pulsations

2.1. Hydromagnetic Waves and the Ionosphere

There is no question that magnetospheric resonance and hydromagnetic (HM) waves are a cause of certain types of geomagnetic micropulsations. The damping of magnetospheric motions and HM wave propagations in the ionosphere are very important in the present study of ionospheric roles during both quiet and disturbed periods. However, since the theoretical details of magnetospheric resonance and HM propagation will be discussed by Dungey [1965, private communication] and by Sugiura [1965] in the present issue of this journal [also see Dungey, 1965], only a few studies are referred to briefly in the present section.

Cole [1963] concluded that the motion of the magnetosphere described by $\vec{E}_M + \vec{V}_M \times \vec{B}_M = 0$, in general, implies the dissipation of significant amounts of energy in the ionosphere. He showed that the time constant for the decay of such motion varies from < 0.1 sec at low latitudes to < 10 sec at middle latitudes. As is well known, the Alfvén velocity shows a sharp decrease below 1 to 2000 km and reaches a minimum at 300 to 400 km altitude [Dessler, 1958]. Hydromagnetic wave propagation in the ionosphere was studied by several workers [for example, Dungey, 1954; Piddington, 1959; Fejer, 1960; Watanabe, 1961a, b; Jacobs and Watanabe, 1962; Karplus et al., 1962]. In the ionosphere the Alfvén waves propagating along geomagnetic field lines toward the earth are transformed into electromagnetic waves such as those in an anisotropic metallic medium. After passing through the ionosphere they are propagated as electromagnetic waves in air and reflected at the earth's surface.

Figure 1 shows the modes of transverse waves in the ionosphere propagated along the geomagnetic field, where ω is the wave frequency and ω_i is the ion gyrofrequency. When ν_{en} and ν_{in} are the collision

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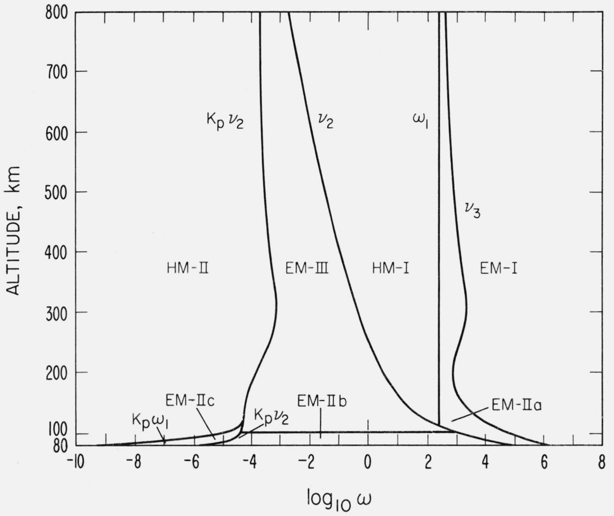


Figure 1. *Modes of transverse waves in the ionosphere propagated along the geomagnetic field lines* [*Watanabe, 1962*].

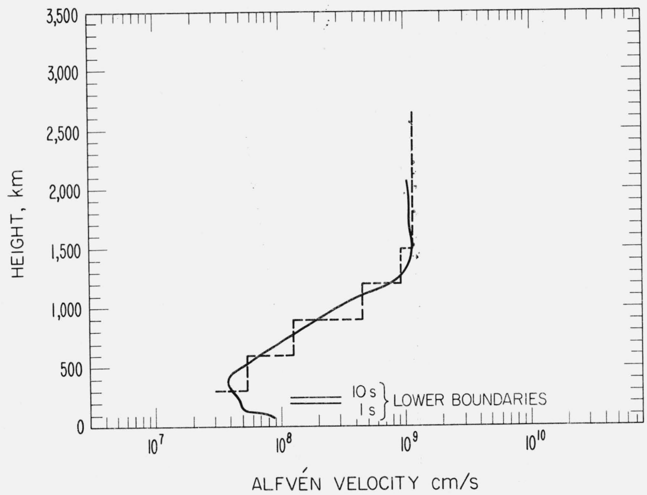


Figure 2. *Distribution of Alfven-wave speed with respect to height, in the daytime during the period of minimum sunspot activity* [*Jacobs and Watanabe, 1962*].

frequency of an electron and an ion with neutral particles, respectively, and ν_{ie} is the collision frequency of an ion with electrons, ν_2 and ν_3 in the diagram are

$$\nu_2 = \frac{1}{2}\nu_{in} + \left(\frac{m_e}{m_i}\right)\nu_{en}$$

$$\nu_3 = \nu_{ie} + \nu_{en} + \frac{1}{2}\left(\frac{m_e}{m_i}\right)\nu_{in}$$

where m_e and m_i are the electron and ion masses. In the figure, kp is approximately the ratio of the mass density of charged particles to that of neutral particles. The Alfvén waves responsible for pulsations can propagate in the zone between ν_2 and ω_i, which is named the HM–I zone in figure 1. The waves in the zones EM–II and EM–III behave as if they were electromagnetic waves in anisotropic metallic media. Incidentally, in the HM–II zone the propagation velocity becomes very slow, and only in the EM–I zone do the waves show a propagation mode such as predicted from magneto-ionic theory of electromagnetic-wave propagation in the ionosphere.

The exospheric region below about 2000 km has a screening effect and behaves like a filter; it amplifies the intensity of HM waves of certain *special* periods although it causes a decrease in their speed. Jacobs and Watanabe [1962] calculated the special periods and amplifying factor for several models of the atmosphere and tried to explain an origin of short period pulsations; figure 2 shows one of their models. The solid curve indicates the distribution of the Alfvén-wave speed with respect to height, calculated to represent the daytime conditions during the period of minimum sunspot activity. For simplicity of calculation this curve is approximated by a stepwise distribution shown by broken lines. The lower boundary of the region where HM waves may propagate is taken as the altitude at which the collision frequency of an ion with neutral particles is twice the angular frequency of the wave. In the figure the two lines indicating the lower boundaries correspond, respectively, to wave periods 10 sec and 1 sec. Jacobs and Watanabe found that the first characteristic period is about 3.5 sec and the maximum amplifying factor is about 40 for this model. This means that micropulsations with a period of about 3.5 sec should frequently be observed in the daytime during minimum sunspot activity; however, the period seems to be too short as compared with observed results.

There are a few theories stating that HM waves cause a dumping of trapped particles toward the ionospheric region [Wentzel, 1961 and 1962; Parker, 1961]. However, it may be difficult to prove that these particles dumped into the ionosphere cause geomagnetic pulsations during disturbances, and even more difficult during quiet periods. As is mentioned later, HM emissions may instead be produced by bunches of energetic particles oscillating along geomagnetic field lines, and these emissions may cause a certain type of pulsation during disturbances.

Figure 3 shows the equal-activity contours of regular pulsations at Fredericksburg, whose periods range from 5 to 40 sec (left), and contour lines of median *foF*2 values at Washington (right), with respect to local time and months of the year for 1958. Saito [1962] suggests that there is a correlation between the two diagrams and infers that as *foF*2 values become larger the density in the exosphere may become larger hence, the HM wave may be propagated more easily, and, thus, regular pulsations may occur more frequently. We probably need more studies before we can definitely draw this conclusion.

In any case we need to understand the different modes of HM-wave propagation and changes in these waves in the ionosphere.

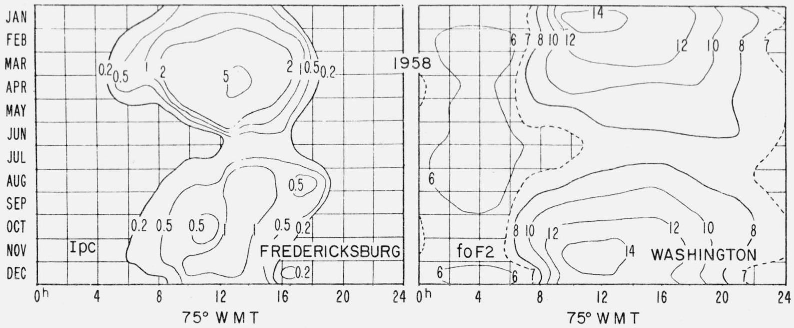


FIGURE 3. *Contour lines of equal activity of regular pulsations at Fredericksburg (left) and of median values of* foF2 *at Washington (right)* [*Saito, 1962*].

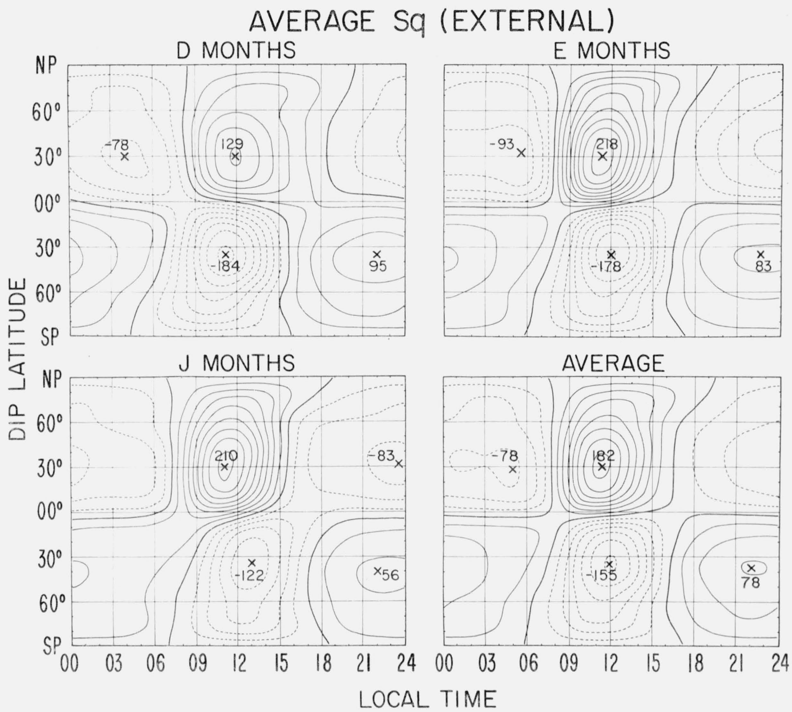


FIGURE 4. *Average* Sq *ionospheric current systems during December solsticial, equinoctial, and June solsticial months and their yearly average obtained from geomagnetic data at 69 IGY stations.*

The current intensity between the two adjacent lines is 25×10^3 A.

2.2. Ionospheric Currents

Geomagnetic solar quiet daily variations (*Sq*) are mainly caused by ionospheric currents. Average *Sq* ionospheric current systems during three seasons and the yearly average using the IGY data are shown in figure 4. A fluctuation of a few percent in these currents may cause geomagnetic fluctuations whose amplitudes are similar to those of regular geomagnetic pulsations. However, it is difficult to explain long lasting regular behavior of pulsations as the fluctuation of these current systems which are caused by small ionospheric irregularities, such as those irregularities in ionospheric motions, electric conductivities, or electric field distributions. Plasma instabilities and their probable role in the ionosphere are discussed by Lepechinsky and Rolland [1964]. These phenomena may have an effect on pulsations during storms, but not during quiet periods.

Equivalent current systems for intense and long-period regular pulsations have been shown occasionally by several workers [for example, Jacobs and Sinno, 1960]. However, the quiet ionosphere by itself seems to be unable to create those current systems from internal changes alone, but needs to be acted upon by external factors, such as incoming HM waves.

The reader should be reminded here that the polar region is very frequently disturbed even when middle and low latitudes are quiet. Thus it is possible that on the so-called quiet days, ionospheric currents formed in disturbed polar regions flow toward lower latitudes and cause pulsations; in this case the amplitude depends on latitude but the period should be similar at different latitudes.

3. The Roles of the Disturbed Ionosphere in Pulsations

3.1. General Behavior

It can be easily supposed that during geomagnetic disturbances and storms both HM waves and charged particles actively come toward the ionosphere and cause active occurrences of pulsations. This increase of activity is demonstrated in figure 5, where the solid thin line is the geomagnetic *Ap* index, the thick vertical lines are the micropulsation index at Borrego, Calif., and the dotted line is the ionospheric index, I_f, at White Sands [Campbell, 1959a and b]. Here,

$$I_f=\frac{1}{3}\left(\frac{f_{\min}}{\overline{\overline{f_{\min}}}}+\frac{h'F}{\overline{\overline{h'F}}}+\frac{foF2}{\overline{\overline{foF2}}}\right).$$

When a geomagnetic disturbance occurs, the *Ap* value increases, and both micropulsation and ionospheric indices increase. During disturbances, at high and higher middle latitudes, $foF2$ usually decreases, but $f_{\min}$ and $h'F$ increase, hence I_f increases.

It is worthwhile to add here a short discussion of the general behavior of the so-called ionospheric storms, although Matsushita [1964a] has made a brief review of recent works in this field. During geomagnetic storms the electron density decreases greatly at high and middle latitudes but instead increases at low latitudes. It has been observed by satellites that the top half of the *F* region also shows the same behavior. Moreover, at middle latitudes, density variations show a seasonal change, namely the density decreases in summer and increases in winter [Matsushita, 1959a]. Concerning height variations of the maximum in electron density, an increase generally occurs during storms both in summer and in winter [Matsushita, 1963]. Thus, when we correlate an increase of pulsation activity with general ionospheric storm variations, we should take into consideration the latitudinal and seasonal dependencies in ionospheric storm variations. Also, we need a good theory of ionospheric storms. A simple increase of temperature caused by charged particles or HM waves or Joule heating is not a satisfactory explanation of ionospheric storm behavior.

3.2. Solar Flare Variations

Geomagnetic variations caused by solar flares are often recorded on normal-run magnetograms and occasionally on rapid-run magnetograms [Kato, Tamao, and Saito, 1959]. Figure 6 shows some examples of these flare variations obtained at Onagawa and Memambetsu.

We also know that f_0F2 values occasionally show a sudden increase at the time of the flare [Knecht and Davies, 1961; Winkelman and Dyce, 1964], in addition to the common increase of radio absorption in the low ionosphere. Figure 7.1 shows the $F2$ density increase obtained at Lindau, Okinawa, San Salvador, and Adak. Figure 7.2 shows a height variation of the ionosphere at Adak during a flare.

Using a Doppler frequency shift technique, Davies [1962, 1963] often observed frequency variations of reflected signals from the ionosphere during solar flares. By means of a similar radio technique, Kanellakos, Chan, and Villard [1962] estimated the altitude at which solar-flare induced ionization is created by soft x rays; it is initially somewhere just above the *E* region, very probably in the height region 120 to 200

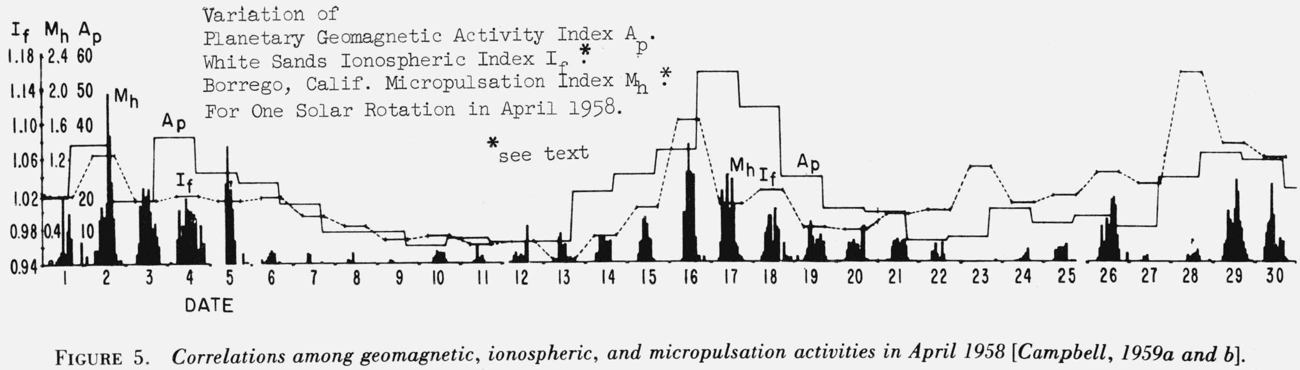


FIGURE 5. *Correlations among geomagnetic, ionospheric, and micropulsation activities in April 1958* [*Campbell, 1959a and b*].

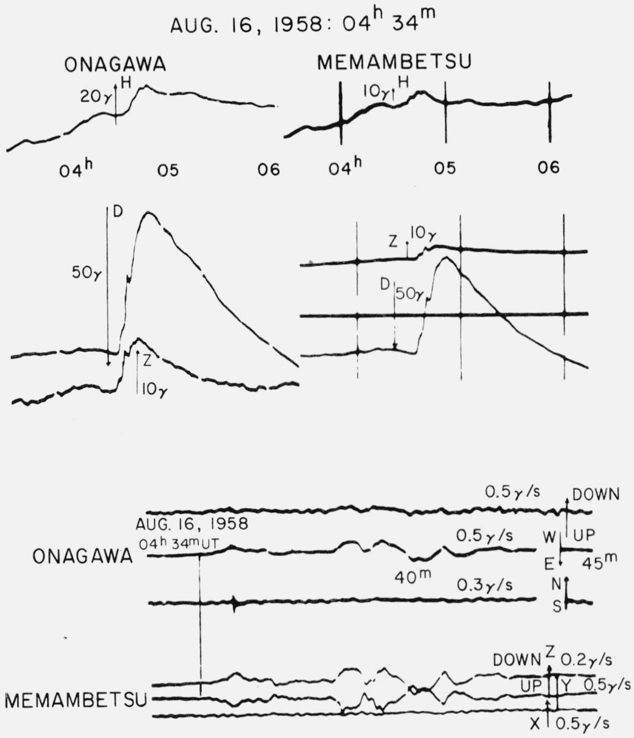


FIGURE 6. *Geomagnetic variations caused by the solar flare beginning at 04:34 UT August 16, 1958, as recorded on normal-run magnetograms (top four) and on rapid-run induction magnetograms (bottom two) [Kato, Tamao, and Saito, 1959].*

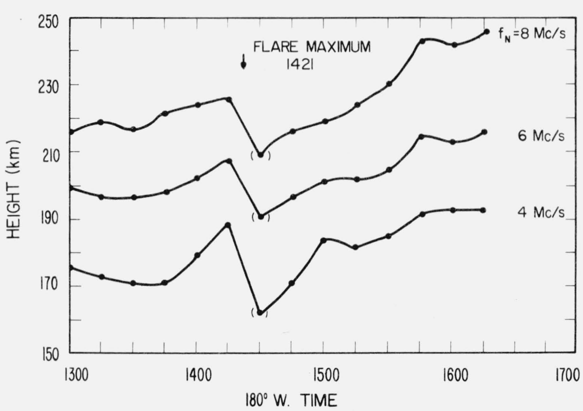


FIGURE 7.2. *Height variations of fixed radio frequencies (8, 6, and 4 Mc/s) at Adak, Alaska, during the solar flare of November 15, 1960 [Knecht and Davies, 1961].*

km. Figure 7.3 is one example of the frequency variation of WWV 10 Mc/s. A solar flare started at 14:25 and reached its maximum at 14:35. The solid line under the frequency variation curve indicates geomagnetic variations of the horizontal component obtained at Fredericksburg; about a 4 gamma decrease occurred soon after the ionospheric variation.

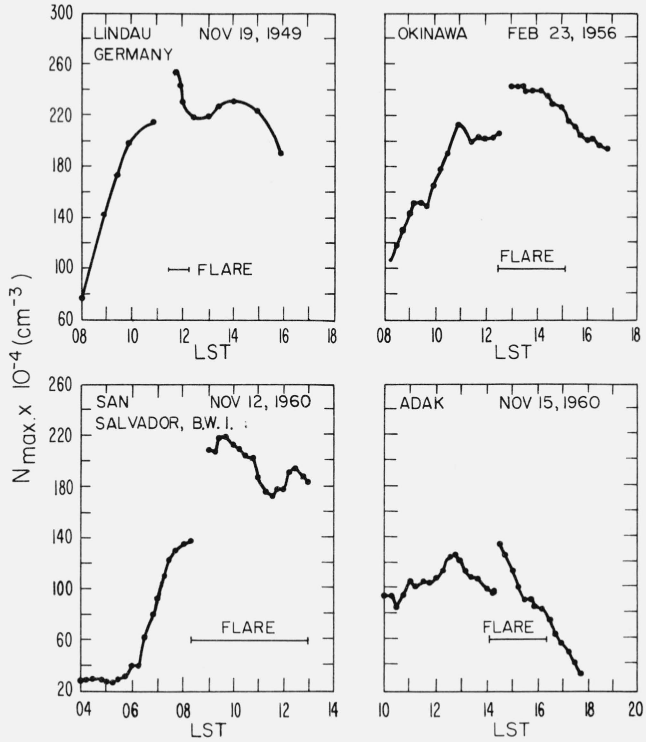


FIGURE 7.1 *Variations in F layer maximum electron density during four cosmic ray associated flares [Knecht and Davies, 1961].*

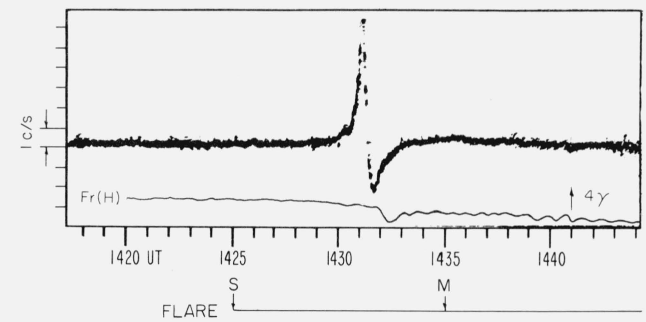


FIGURE 7.3. *Frequency changes of WWV-10 Mc/s signals as recorded at Boulder [Zacharisen, 1962] and correlated geomagnetic variations of the horizontal component at Fredericksburg, on September 4, 1961.*

The solar ultraviolet radiation and x rays emitted during solar flares may cause an exospheric temperature increase and ionospheric density and height variations, hence creating certain electric currents in the ionosphere. These ionospheric currents may easily cause geomagnetic pulsations. Thus we have no particular theoretical difficulty in explaining the correlation, but we need more observations in order to prove a one-to-one correspondence between ionospheric and geomagnetic fluctuations at the same observing station.

3.3. Sudden Commencements and Impulses

As reported by Matsushita [1962 and 1964b] commencements of geomagnetic micropulsations, sudden increases of riometer cosmic noise absorption, bursts of bremsstrahlung x rays at balloon altitudes, and Doppler frequency changes of reflected signals from the ionosphere are occasionally associated with sudden commencements (SC) and sudden impulses (SI). The apparent shape of SC and SI also shows local-time and longitudinal dependencies, and the amplitude of SC and SI is enhanced in the magnetic equatorial zone during daylight hours. All these phenomena indicate that, during SC and SI events, charged particles as well as HM waves penetrate to the region of the ionosphere and cause some variations, such as oscillations, as well as a density increase of charged particles with resulting additional electric current systems which may cause a part of SC and SI geomagnetic variations. For example, Tamao [1964] has described HM wave effects on ionospheric currents which are responsible for "preceding reverse type" SC.

Nishida and Jacobs [1962] have suggested that since there are frequent worldwide changes in the geomagnetic field which have similar behavior to SC and SI, there is a permanent interaction between the solar corpuscular stream and the geomagnetic field. Patel and Cahill [1964] made a comparison of geomagnetic vector diagrams obtained by Explorer XII and at College, Alaska, for variations with about 200 sec period and suggested the resemblance as evidence of HM-wave propagation.

In addition to an interesting study of the correspondence between radio-frequency changes of reflected signals from the ionosphere and the event of SI [Chan and Villard, 1962; Kanellakos, Chan, and Villard, 1962], Chan, Kanellakos and Villard [1962] studied correlations between the radio-frequency changes and SC, particularly the phase between the two phenomena. They also showed a remarkable correlation between the frequency change of oblique waves and geomagnetic pulsations (for example, see fig. 8). Rishbeth and Garriott [1964] discussed these correlated phenomena in terms of dynamo currents and HM waves. However, improved theoretical work and further observations with vertical incidence phase sounders and rapid-run magnetometers at the same location are required.

3.4. Geomagnetic Bay, DS, and Polar Elementary Storms

During bay, DS, and polar elementary storms, a phenomenon called pulsation storms and an increase of radio absorption in the ionosphere often occur, as is shown by figure 9.1 [see also Campbell and Leinbach, 1961]. A blanketing $F2$, an increase of Es, and the occurrence of a radio blackout along with a disturbance development are commonly observed in the ionosphere [Matsushita, 1958]. A burst of bremsstrahlung x rays at balloon altitudes and an increase of cosmic noise absorption are also often associated with bays and bay-type disturbances (see fig. 9.2). Tepley and Wentworth [1962] studied regular oscillatory micropulsations in the frequency range 0.4 to 7 c/s (called by them HM emissions), associated x-ray bursts, and increased riometer absorption. Anderson and Milton [1964] are observing x-ray bursts with

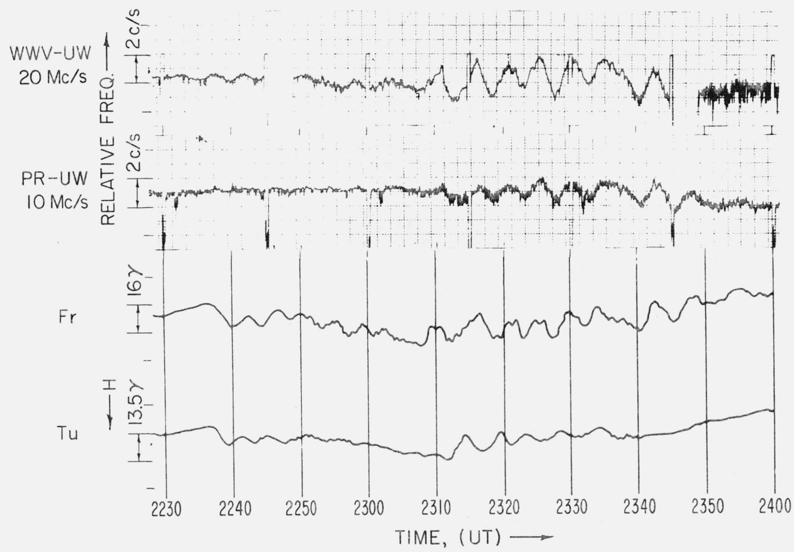


FIGURE 8. *Variations in the radio frequencies of WWV 20 Mc/s and Puerto Rico 18 Mc/s received at the University of Washington, Seattle (top two), and correlated geomagnetic horizontal-field variations observed at Fredericksburg and Tucson (bottom two), on November 16, 1960* [*Chan, Kanellakos, and Villard, 1962*].

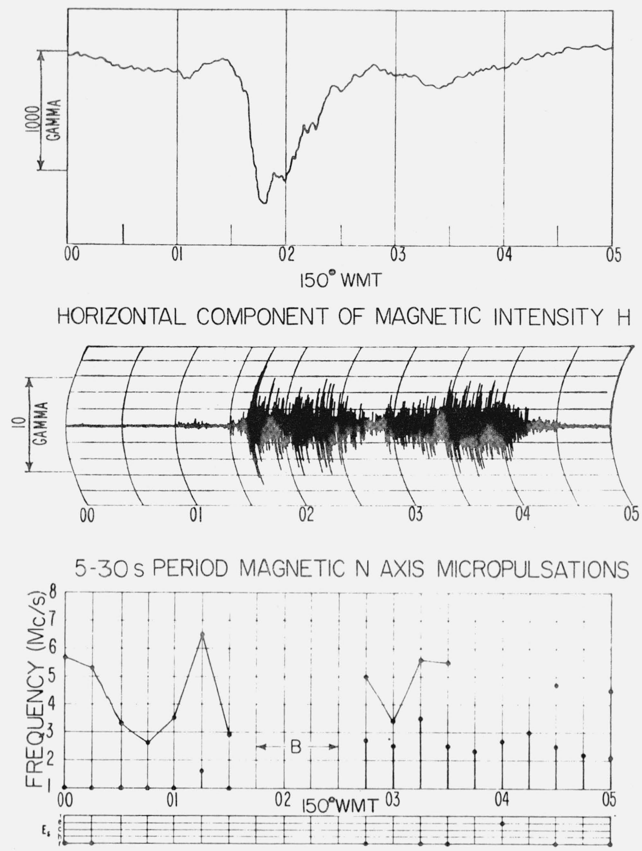


FIGURE 9.1. *Magnetograms (top), micropulsation record (middle), and ionospheric* f *plot (bottom) recorded at College, Alaska, on July 30, 1960* [*Campbell and Matsushita, 1962*].

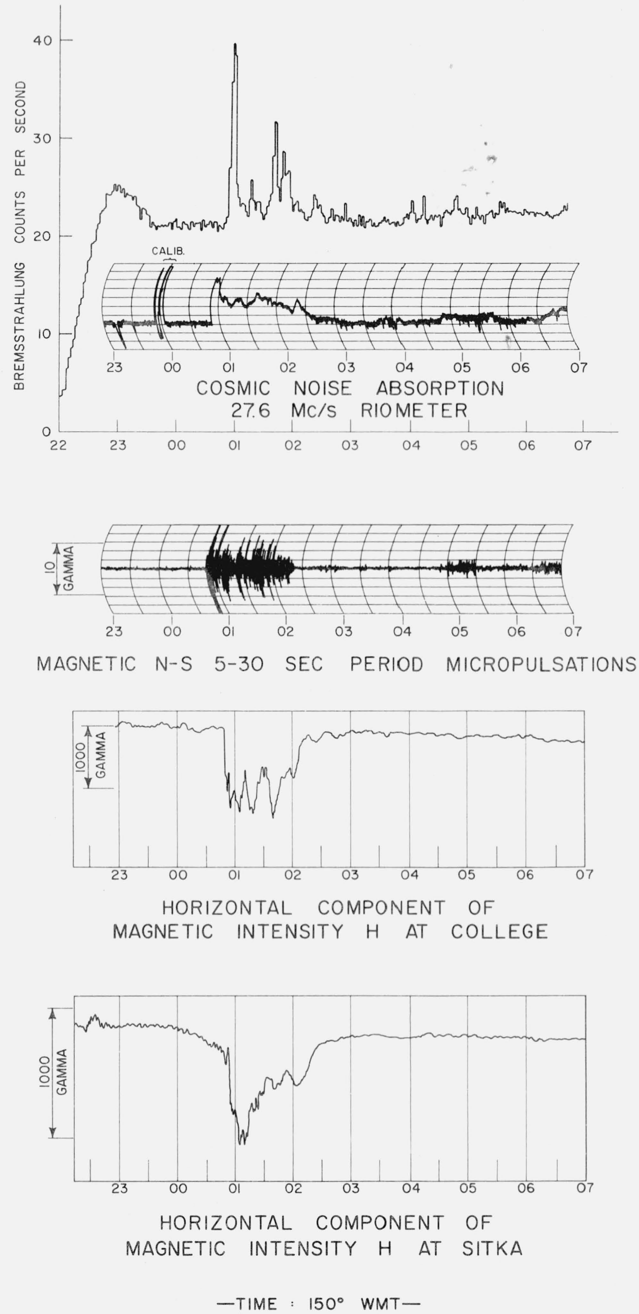


FIGURE 9.2. *Correlation among bremsstrahlung x-ray bursts, cosmic noise absorption, and a micropulsation storm during a bay disturbance, June 28, 1960* [*Campbell and Matsushita, 1962*].

high time resolution; it will be very desirable to establish a one-to-one correspondence between these bursts and micropulsations. Campbell [1960a] and Campbell and Rees [1961] showed a correlation between geomagnetic micropulsations and auroral coruscations, and Campbell and Young [1963] examined infrasonic pressure waves from the auroral zone related to ionospheric disturbances and geomagnetic activity. Maeda and Watanabe [1964] theoretically discussed these infrasonic waves from the auroral zone.

As is shown in figure 10, Jacobs and Sinno [1960] inferred an electric current system responsible for pulsations associated with a negative bay and showed a latitudinal distribution of the average amplitude of pulsations mainly associated with positive bays. A small increase of the amplitude in the equatorial zone which is shown in the bottom diagram may indicate an ionospheric current effect, although more studies are needed. One study in this field was made by Hutton [1962] who examined correlations between micropulsations and ionospheric disturbance currents in Ghana.

All these phenomena clearly indicate that HM waves and charged particles actively come toward the ionospheric region. A few theories have proposed that HM emissions are produced by bunches of energetic charged particles oscillating along the geomagnetic field lines. A model of fast electron bunches was suggested by Wentworth and Tepley [1962], a model of fast proton bunches was made by Gendrin [1963] and

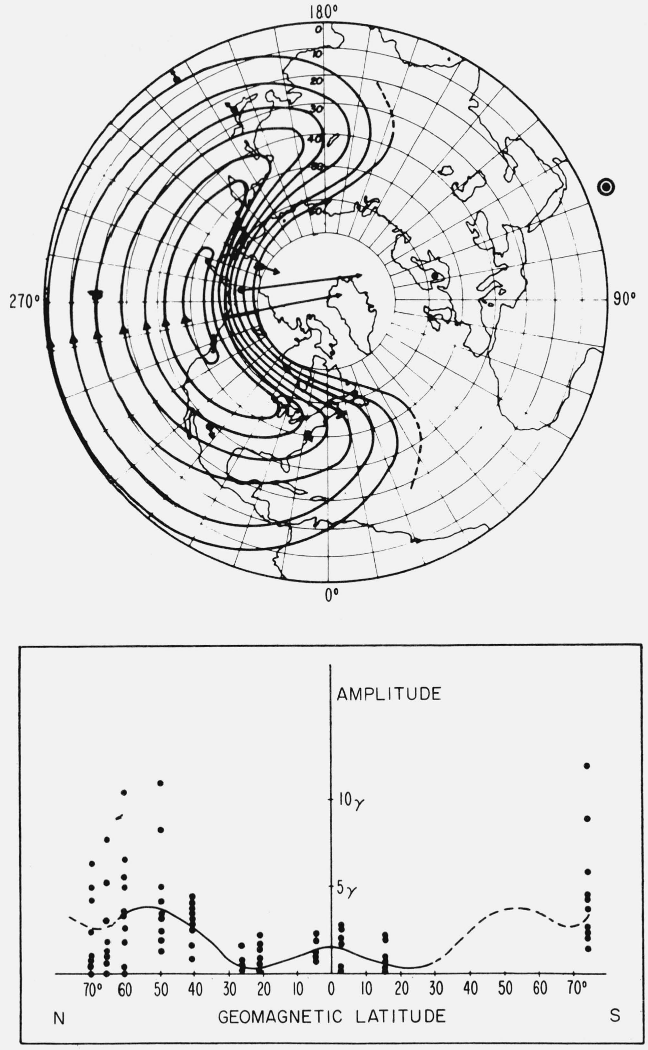
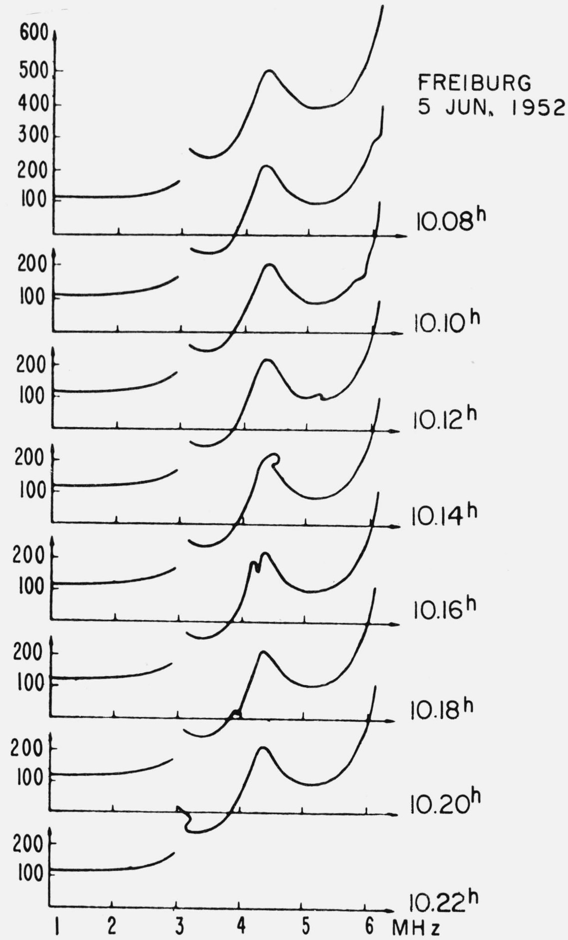
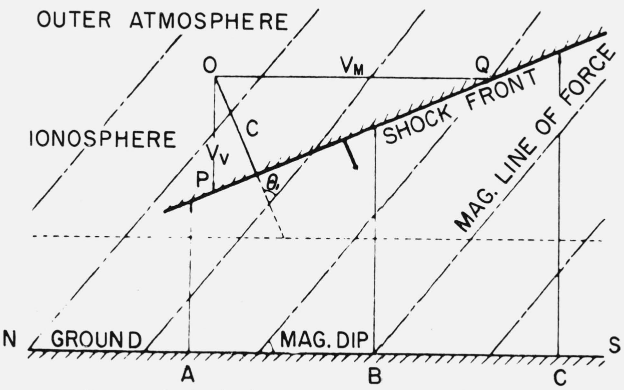


FIGURE 10. *Top: Equivalent overhead current system for pulsations associated with a negative bay at 09:36 UT, December 26, 1957 (the current intensity between two adjacent lines is 5×10^3 A); Bottom: Latitudinal distribution of average amplitudes of pulsations mainly associated with positive bays [both from Jacobs and Sinno, 1960].*



Transitional phenomenon in the F layer.
(*after* BIBL (29), *Z. für Geophysik* (1953) p. 138)



Geometrical relations of a shock wave in the ionosphere.

FIGURE 11. *A quick transitional phenomenon in the F layer over Freiburg (top) and geometrical properties of a shock wave in the ionosphere (bottom) [Akasofu, 1956].*

a model of slow proton bunches was proposed by Jacobs and Watanabe [1963]. An alternative theory that HM emissions are produced in a manner similar to atmospheric whistler trains has recently been suggested by Watanabe [1965, private comminication] and by Obayashi [1965, private communication].

Basic theories of plasma and HM waves are well discussed in books by Spitzer [1956] and by Stix [1962]. Using basic equations described in these books, Nishida [1964] attempted to explain irregular micropulsations associated with bays by a dispersion equation of HM waves derived in a three-component plasma composed of magnetospheric ions and electrons containing a beam of high-speed electrons (about 10 keV). He also discussed oblique propagation of these growing HM waves to lower latitudes, about which we need more detailed theories in the future.

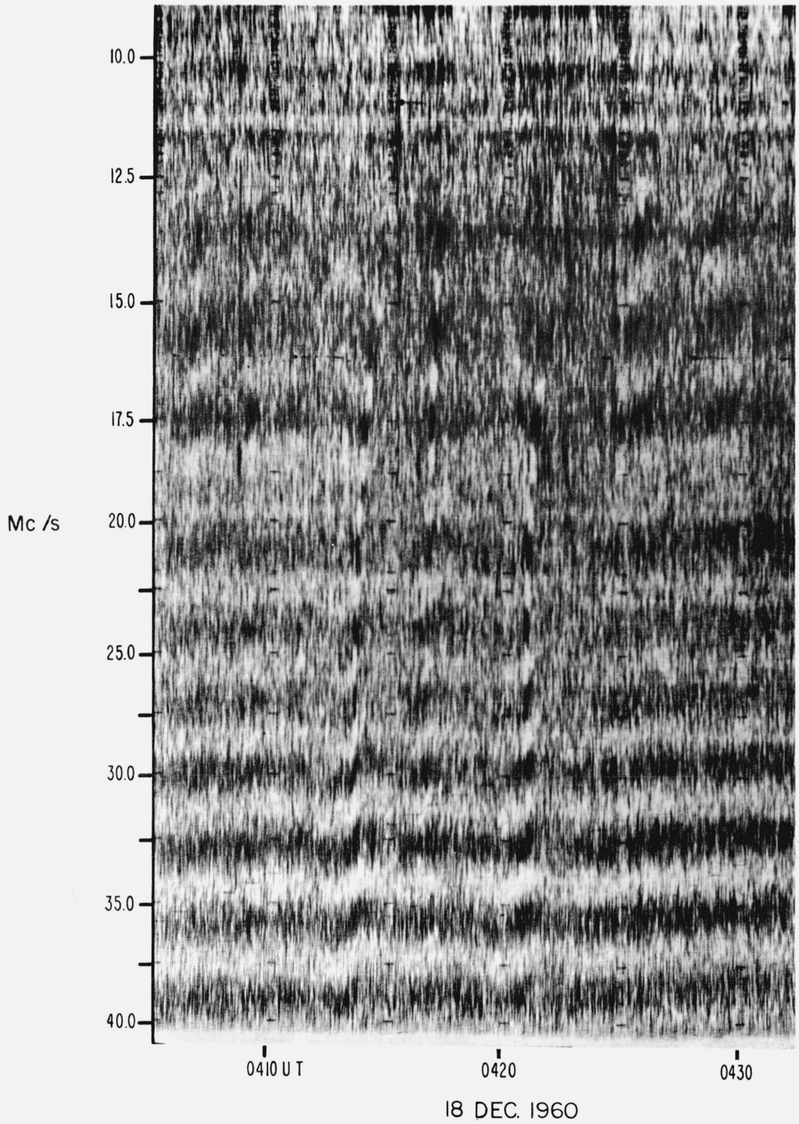


FIGURE 12. *Dynamic spectrum of a large focused scintillation which appeared on a swept-frequency interferometer record of Cassiopeia A in the frequency range from 7.6 to 41 Mc/s observed at Boulder* [*Warwick, 1964*].

Based on this type of records Warwick estimated the wavelike irregularities at about 200 km altitude with a wavelength of 17 km and a phase velocity of about 60 m/sec.

3.5. Irregularities

Additional irregular disturbances are discussed in this section. As shown in figure 11, a quick transitional phenomenon in the *F* layer is occasionally observed, which is inferred by Akasofu [1956] to be a result of HM wave propagation. We should investigate whether or not we have micropulsations when we observe this type of phenomenon on ionograms.

It may also be worthwhile to compare other rapid motions in the ionosphere which can be measured by radio waves, and ionospheric perturbations and waves which can be estimated from observations of radio-star scintillations, such as discussed by Warwick [1964] (see fig. 12), with the occurrence of some localized geomagnetic fluctuations.

Geomagnetic micropulsations arising from nuclear explosions were mentioned by Karzas, Selzer, and others at the Symposium on Ultra Low Frequency Electromagnetic Fields, in Boulder, Colo. Geomagnetic and ionospheric variations of longer periods associated with nuclear explosions also have been discussed by various workers. Local dynamo effects, an augmentation of *Sq* currents, diamagnetic plasma effects, and artificial ring currents seem to be the main causes of these variations [see for example, Matsushita, 1959a and b; Maeda et al., 1964].

Campbell [1960b] has presented a fine review of meteor effects, and has shown increased micropulsation activity associated with the η Aquarid, δ Aquarid, and Perseid meteor showers in 1958. S. Chapman and A. A. Ashour (private communication) have recently discussed the possibility that meteors may be the cause of some small magnetic variations. Since we know that meteors sometimes cause the so-called *Y*-type sporadic *E* on ionograms, we need to study the correlation between certain magnetic variations and the appearance of Y-type sporadic E.

4. Conclusion

In this report all of the roles conceivable at the present time for the ionosphere in geomagnetic pulsations are briefly reviewed. Reference is made to certain theories in order to provide readers with a broad, general survey of the field.

We certainly need further observations and detailed statistical studies of each aspect, particularly theoretical studies. We have some theories of plasma and of HM waves which can be applied to the fully ionized magnetosphere. However, we have difficulty applying these theories to partially ionized gases, such as the ionosphere. Simple Alfvén waves propagating along magnetic field lines often have been discussed by many theorists. But other types of HM wave propagation in the lower exosphere and ionosphere have not been sufficiently studied. Unless we have basic theories for these waves we cannot fully understand the present field; we need to do extensive work in this field in the future [see Akasofu, 1965].

I thank D. E. Billings and J. W. Warwick for their valuable comments and Mrs. K. McKean for her assistance in preparing the present review paper.

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