Whistler Observations of the Interchange of Ionization between the Ionosphere and the Protonosphere

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Whistlers recorded at Eights, Antarctica, in June 1965 were used to measure the electron content in magnetospheric tubes of force in the range $3.5 < L < 5$. Under quiet geomagnetic conditions, the observed rate of increase in daytime tube content gives an upward flux of $\sim 3 \times 10^8$ electrons/cm^2 sec across the 1000-km level, which is larger than the downward flux necessary to maintain the nocturnal ionosphere. The observed upward flux is primarily due to diffusion of protons through the diffusive barrier, rather than to an increase in the height of the barrier. The downward flux at night under quiet conditions is $\sim 1.5 \times 10^8$ electrons/cm^2 sec, an amount that is considered sufficient to maintain the nocturnal ionosphere. The protonosphere is depleted in less than a day during a magnetic storm or polar substorm activities, and subsequent recovery of tube content takes place at a rate of 3–5 $\times 10^{12}$ electrons/cm^2 per day. At this rate, an 'empty' tube requires about 5 days to reach the monthly median value, and even after 8 days of quiet conditions it continues to fill. The average spacing of geomagnetic disturbances is such that we expect that the protonosphere almost never reaches the saturation level it would attain if it were in equilibrium with the ionosphere.

INTRODUCTION

The coupling between the ionosphere and the protonosphere is complicated by the domination of the two regions by different ions and by the presence of the diffusive barrier that hinders free exchange of ionization between the regions. The existence of the diffusive barrier was first noted by *Hanson and Ortenburger* [1961]. The reason for its existence is that both the source and sink for protons in the protonosphere are located below the altitude at which protons become the major ion. Protons must therefore suffer frequent Coulomb collisions with O^+ in transit between the chemical equilibrium region and the protonosphere. This diffusive barrier effectively decouples the two regions, so that large diurnal changes are observed in the ionosphere, without corresponding changes in the protonosphere.

The effectiveness of the barrier must be evaluated quantitatively, to determine the extent to which one region affects the behavior of the other. For example, coupling with the protonosphere has been suggested as a possible explanation of various anomalies and disturbances in the ionosphere [*Piddington*, 1964]. In particular, the persistence of the nighttime ionosphere has been studied by many investigators [*Hanson and Patterson*, 1964; *Geisler and Bowhill*, 1965; *Yonezawa*, 1965*a*, *b*; *daRosa and Smith*, 1967; *Rishbeth*, 1968; *Kohl et al.*, 1968; *Titheridge*, 1968*b*], and it appears that the nocturnal F layer cannot be satisfactorily explained without invoking downward diffusion of ionization from the exosphere. The downward flux of ionization necessary to maintain the nocturnal layer depends on the peak density of the layer and the atmospheric model used in the calculations. For a layer with the peak density of 10^5 electrons/cm^3, *Hanson and Patterson* [1964] and *Geisler and Bowhill* [1965] agree on the figure of 2–3 $\times 10^8$ electrons/cm^2 sec, whereas *Yonezawa* [1965] gives 5×10^7 electrons/cm^2 sec. In midlatitudes, the protonosphere has a sufficient amount of ionization to supply the required flux throughout the night, but if such fluxes do exist, the amount of ionization that the protonosphere loses at night must be replenished by upward diffusion on the dayside. Theoretical studies showed, however, that a maximum of $\sim 1.5 \times 10^7$ protons/cm^2 sec can diffuse into the protonosphere from the daytime ionosphere [*Hanson and Patterson*, 1964; *Geisler and*

Bowhill, 1965; *Geisler*, 1967]. This flux is roughly an order of magnitude less than the downward flux that was mentioned above as necessary to maintain the nighttime ionosphere. From these results, it has frequently been inferred that the protonosphere does not function as a significant reservoir of ionization for the midlatitude nighttime ionosphere. The calculations of the maximum possible flux, however, involve several parameters that are not well known, and the above investigators have themselves stated that the actual flux might exceed their calculated values by as much as an order of magnitude (*Geisler and Bowhill* [1965]; Hanson, private communication). More recently, *Banks and Holzer* [1969] calculated polar wind fluxes of 2–7 $\times$ 10^8 protons/cm^2 sec, based on atmospheric models different from those used by the earlier investigators.

The present research involves the first detailed whistler study of the electron content of magnetospheric tubes of ionization. The accuracy and precision of the measurements permits determination of the net interchange of ionization between the *F* region and the protonosphere. The research shows that in midlatitudes the coupling fluxes are sufficient to maintain the ionosphere at night and to replenish the protonosphere on the dayside.

A brief description of the whistler method and the period of observation is given in the next section. The results are then presented and are followed by discussion and conclusions.

Method and Period of Observation

Method of observation. Nose whistlers recorded at Eights, Antarctica, ($L \sim 4$) were used to measure electron concentrations in the protonosphere and electron tube content, which is defined as the total number of electrons in a tube of force that has cross-sectional area 1 cm^2 at 1000 km and extends from 1000 km altitude to the geomagnetic equator. The effects of production and loss of ionization and of diffusion across field lines above 1000 km are assumed to be small compared with effects of diffusion along the field lines, and hence the time rate of change of tube content is interpreted in terms of flux along the field lines across the 1000-km level.

The methods of computing electron concentration and tube content from nose whistlers are well documented in the literature and will not be repeated here (see, for example, *Angerami* [1966] or *Park* [1970]). The parameters of the magnetospheric ionization-density model used in this study are: $T_e = T_i = 1600°K =$ constant, and ionic composition of 90% O^+, 8% H^+, and 2% He^+ at 1000 km. Ionization was assumed to be in diffusive equilibrium along field lines above 1000 km. (A 'collisionless' model [*Angerami*, 1966] was used to calculate equatorial electron density for June 16 and 17 in Figure 1, when density was extremely low, but those two data points do not enter into the measurement of flux.) Calculated tube content does not depend sensitively on assumed models, as shown in the appendix. A dipole geomagnetic field was used, because the observations of the coupling flux were made during a relatively quiet period.

Electron columnar content in the ionosphere was estimated from simultaneous records of vertical incidence sounders in the vicinity of the ends of whistler ducts. By using these estimates, the small ionospheric contribution to the whistler dispersion was taken into account, as described elsewhere [*Park*, 1970].

Period of observations. The observations of coupling flux reported in this paper were made during the period June 18–25, 1965. At the top of Figure 1 are 3-hour values of *Kp* from June 14 to 26, with *Kp* increasing downward. A major storm of -102-γ maximum D_{st} developed, following a sudden commencement near 1100 UT on June 15 (marked by an arrow in Figure 1). The recovery phase started on June 17, and, by June 18, D_{st} was less than 30 γ. June 19 through midday on June 25 was a period of extreme quiet, with maximum *Kp* of 2_-.

During the main phase of the storm, the plasmapause as detected by whistlers recorded at Eights, Antarctica, moved inward to $L \cong 2.4$. The protonosphere beyond this L value was depleted of ionization, and then began to fill steadily as the storm receded. Representative nighttime values of electron concentration at the equator at $L = 4$, for June 14–26, are shown in the middle of Figure 1. The values were obtained from Eights whistlers recorded within a few hours of local midnight. Diurnal variations are of order 20%, except on June 16 and 17, when the densities are less than 5

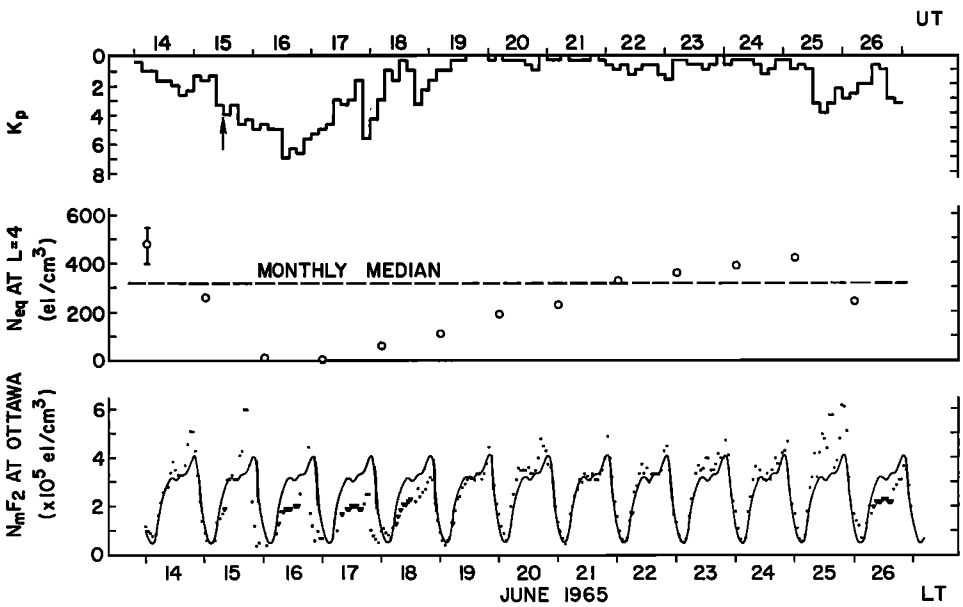

Fig. 1. Time history of geomagnetic conditions and electron density in the protonosphere and the ionosphere during the period of measurement of the coupling flux reported in this paper. At the top are 3-hour values of *Kp*, increasing downward. The sudden storm commencement on June 15 is marked by an arrow. In the middle are shown nighttime values of equatorial electron concentration at $L = 4$ deduced from whistlers recorded at Eights, Antarctica. The vertical bar on June 14 shows the range of uncertainty due to scatter of data points for that night. At the bottom, the dots are hourly values of N_mF_2, and the triangles are hourly upper limits of N_mF_2 at Ottawa. The monthly median behavior is shown as a solid line. The horizontal scales are UT days at top and Ottawa-Eights LT days at bottom.

electrons/cm^3. The monthly median value of 320 electrons/cm^3 was obtained from nighttime electron density profiles for 29 days in June. Beginning on June 17, the density recovered steadily for 8 days to a value of 420 electrons/cm^3, or about 30% above the monthly median value. A moderate disturbance involving $Kp = 4$ during the second half of June 25 was accompanied by a decrease in density to 240 electrons/cm^3. The plasmapause was at $L \cong 2.4$ on June 16 and $L \cong 3.5$ on June 17 [*Carpenter et al.*, 1969], but on all other days, including June 26, it was beyond $L = 4$.

The bottom of Figure 1 is a plot (in local time) of ionospheric data for Ottawa, which is in the vicinity of the terminal points of the protonospheric tubes of interest. Hourly values of N_mF_2 are plotted together with the monthly median values (solid line). The triangles pointing downward represent upper limits. The main effects of the storm on the ionosphere are: (*a*) sharp increases in N_mF_2 in the late afternoon on June 15 and 16; (*b*) apparent sunset earlier by 2–3 hours on June 15, 16, and 17; and (*c*) decreases in daytime N_mF_2 by about 30% below the monthly median values on June 16, 17, and 18. On June 25, the first day of disturbance after a long quiet period, N_mF_2 reached values up to 50% larger than the monthly median, but on the following day the ionosphere was depleted. We note that, after the sudden commencement storm of June 15, the ionosphere returned to normal by June 19, whereas the protonospheric density did not reach the monthly median value until June 22. The differences in storm recovery behavior between the ionosphere and the protonosphere will be discussed further in the following section.

Results

Continuous observation of selected whistler ducts. Several whistler ducts were identified and monitored continuously for about two hours during daytime on June 18, 1965. Whistler

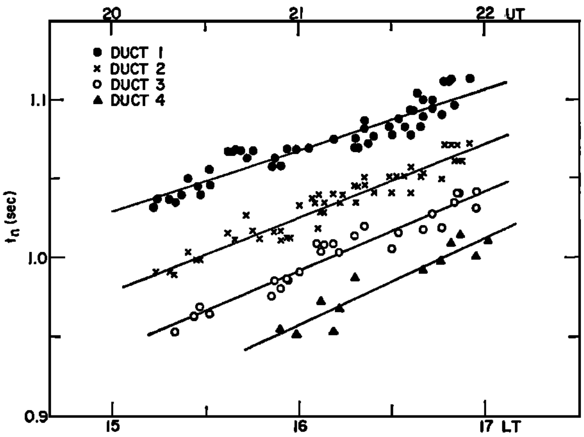

Fig. 2*a*. Plot showing increases with time in whistler travel time at the nose frequency (t_n) for four different ducts on June 18, 1965. (UT at the top and Eights LT at the bottom). Straight lines represent a least squares fit to the data points for each duct.

traces propagating in four of the ducts were well defined for a period long enough to permit measurements of the upward flux of electrons into the protonosphere. Figure 2*a* shows how the minimum time delay of nose whistlers propagating through the four different ducts increased progressively during the period of observation. The horizontal scale is given both in universal time (top) and local time for the whistler receiver at Eights (bottom). The longitudinal 'viewing' range of the receiver is about ±15° [*Carpenter*, 1966], so that there is a ±1-hour ambiguity in the local time of the ducts. The straight lines in the figure represent a least squares fit to each set of data points. The small scatter of order 1% in the data points about the straight lines can be explained by random measurement errors due to the widths of whistler and lightning traces on the spectrogram, location of the lightning source (see appendix), and tape flutter of the recording instrument.

Figure 2*b* shows nose frequencies for the same four ducts. Straight lines again represent a least squares fit to each set of data. The lines show only a slight slope, thus indicating that the ducts remained on approximately the same magnetic shells during the period of observation. There are fewer data points for nose frequency than for time delay at the nose (Figure 2*a*), because the definition of the whistler trace is often sufficient for the measurement of the

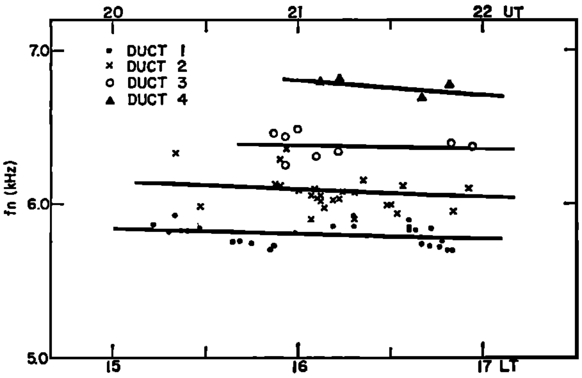

Fig. 2*b*. Plot showing nearly constant behavior with time of nose frequencies of whistlers propagating in the four ducts of Figure 2*a*. Not all of the whistler traces scaled for travel time were scaled for nose frequency.

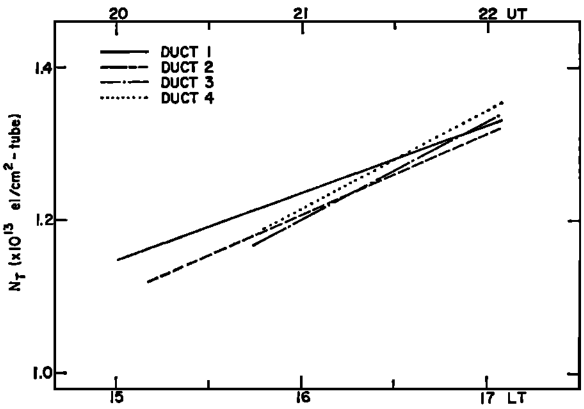

Fig. 3*a*. Plot of electron tube content versus time for the four ducts of Figure 2. The curves for tube content are computed from the least squares fit curves of Figures 2*a* and *b*. Electron tube content is defined as the total number of electrons in a tube of force with cross-sectional area 1 cm² at 1000 km and extending from 1000 km altitude to the geomagnetic equator.

time delay, but not the nose frequency. Some ducts involve better defined whistlers than others, and the relatively large scatter of data points for all ducts is of order 2%, which is within the expected precision of the present method.

The least squares fit curves of Figures 2*a* and *b* were used to compute the whistler path equatorial radii and electron tube content during the 2-hour interval. Figure 3*a* shows how tube content in all four ducts increased at nearly the same rate. The values of upward flux of electrons computed from the slope of these curves are listed in Table 1. The spread in the values could be attributed to local time differences between the ducts or variations in local ionospheric conditions at the feet of the ducts. Because the electron distribution in the protonosphere was assumed to be symmetric about the geomagnetic equator, the fluxes given here represent an average over both hemispheres. The flux for each duct was weighted according to the total number of data points for the ducts in Figures 2*a* and *b*, and a weighted average of 2.9×10^8 electrons/cm² sec was thereby obtained.

The feet of the ducts are near 48°N and 71°S geographic latitude. The northern ends of the

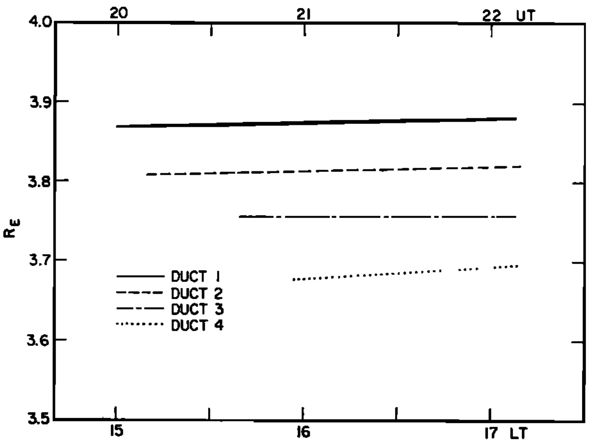

Fig. 3*b*. Plot of path equatorial radii versus time for the four ducts of Figure 2. The radii remain constant within measurement error between 1500 and 1700 LT at Eights. The curves were obtained in a manner similar to that used in Figure 3*a*.

TABLE 1. Daytime Upward Flux of Electrons across the 1000-km Level Inferred from the Slopes of Figure 3*a*

Duct	Flux, electrons/cm² sec	Number of Data Points
1	2.43×10^8	77
2	2.95×10^8	76
3	3.5×10^8	35
4	3.5×10^8	16
Weighted average	2.91×10^8	

tubes are certain to be in sunlight during the period of observation, but, in the southern hemisphere, sunset at 200 km altitude occurs near 1600 LT [*Colin and Myers*, 1966]. It is possible that the southern ends of the ducts were in darkness during the period of observation, and that the tubes were being filled only from the northern hemisphere. Even before local sunset, ionospheric densities in the southern hemisphere were lower than corresponding northern hemisphere densities, so that upward fluxes in the northern hemisphere were likely to be larger than the average fluxes given in Table 1.

In Figure 3, it was assumed that the ionosphere remained unchanged between 1500 and 1700 LT. Vertical ionosonde data from Ottawa and the Argentine Islands indicates that the combined ionospheric electron columnar content in the northern and the southern hemisphere may have decreased by about 30% during that interval. If this were taken into account, the fluxes computed above would be increased by about 15%.

Figure 3*b* shows that the path equatorial radii of the four ducts remained constant within ~0.02 earth radius during the 2-hour period. The small apparent displacement reported here could be the result of actual cross-*L* drift, but it can also be explained in terms of the effects of the above-mentioned changes in the ionosphere on whistler nose frequency.

Various sources of error in computing tube content from nose whistlers are discussed in the appendix. A conservative estimate of the over-all uncertainty in the observed flux would be ±30%. The upward flux averaged over the two hemispheres is then 2–4 × 10^8 electrons/cm² sec, which is larger than the downward flux necessary to maintain the nocturnal ionosphere (see Introduction).

Comparison of profiles near sunrise and sunset. In the absence of significant spatial gradient in tube content and perturbing magnetospheric convection activity, tube content profiles near sunrise and sunset can be compared as a means of estimating the flux of ionization. (Complex structures in tube content profiles and related magnetospheric convection activity can be detected by the whistler technique [*Park and Carpenter*, 1970], but there was no evidence of such effects during the period of observation reported in this subsection.)

Figure 4 shows tube content for $3.5 < L <$

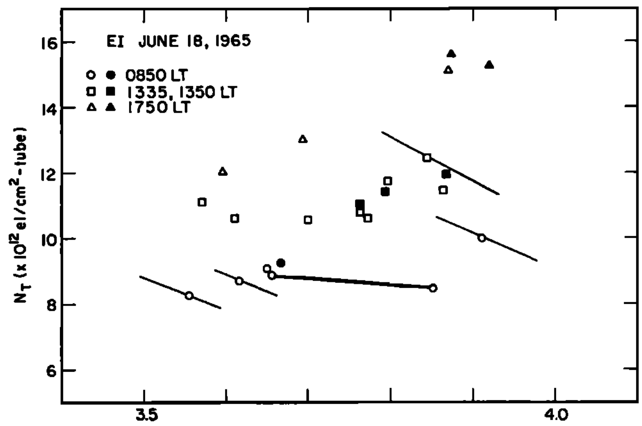

Fig. 4. Plot of tube electron content as a function of tube equatorial radius at three different local times at Eights on June 18, 1965. Filled symbols represent higher quality data, and the bars represent the range of measurement error.

4.0 at 0850, 1335–1350, and 1750 LT (at Eights) on June 18, 1965. Various symbols represent the three observing times. Filled symbols represent whistler traces of superior quality, and the bars connected to some of the data points represent the range of measurement error for those points. As noted earlier, individual whistler ducts may be up to ±15° away from the Eights meridian. In the L range of the data, the 200-km level is sunlit in both hemispheres between ~0800 and ~1600 LT. By assuming symmetry of the two hemispheres, an upward flux of 1–3 $\times$ 10^8 electrons/cm^2 sec is inferred from the increases in tube content shown in Figure 4. This value is in good agreement with the results presented in the first part of this section.

In Figure 4, the flux appears to be larger during later hours and at higher L. It is not possible to assess the significance of these effects, since continuous records were not available for the entire period, and it is not known whether the same tubes of ionization were observed at the different times of measurement (the tubes of ionization may drift in radial direction or may not strictly corotate with the earth and also may have limited lifetimes as 'ducts').

Day-to-day change of tube content. The best nose whistlers were selected from recordings at Eights within 2 hours of local midnight, and electron tube content was computed as a function of equatorial radius for each night from June 18 to 25, 1965. Figure 5 shows nightly tube-content profiles for $3.5 < L < 5$. The straight lines represent a least squares fit to the data points for each night, and the numbers are UT days. Tube content is a well-behaved function of L, and it increases smoothly and steadily for 7 days. The profiles initially show a slightly negative slope, but as the protonosphere recovers the slope becomes slightly positive. It is only a small effect in the L range shown, but it may be interpreted as a tendency for the daily net flux to be larger at higher L values. This tendency is consistent with the previous findings that tube content frequently increases with L in this region under quiet conditions [*Angerami and Carpenter,* 1966; *Park and Carpenter,* 1970]. The approximate uniformity of the recovery as a function of L suggests that the tubes are filled primarily from the ionosphere, and not by a cross-L diffusion process.

Electron tube content at $L = 4$ is taken from the least squares fit curves of Figure 5 and is plotted against UT day in Figure 6. Tube content increases at a nearly constant rate of 5.2 $\times$ 10^{12} electrons per day for about 5 days (this rate is represented by a dashed line in the figure), after which the rate of filling slows to about 3 $\times$ 10^{12} electrons per day.

Using the daytime upward flux of 3 $\times$ 10^8 electrons/cm^2 sec from the first part of this section, and 5.2 $\times$ 10^{12} electrons/day for the net daily increase in tube content, an average downward flux of 1.8 $\times$ 10^8 electrons/cm^2 sec is obtained for 12 hours at night. This is just the amount of flux necessary to maintain the nocturnal ionosphere [*Hanson and Patterson,*

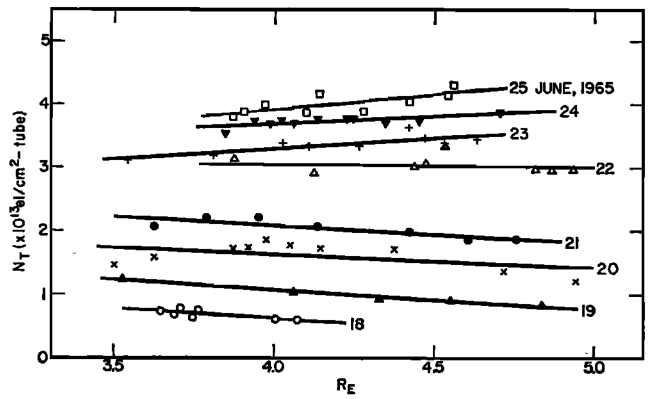

Fig. 5. Plot of nighttime tube electron content as a function of tube equatorial radius for June 18–25, 1965. Data were obtained from whistlers recorded at Eights within 2 hours of local midnight. The straight lines represent a least squares fit to the data points, and the numbers inside the figure are UT days.

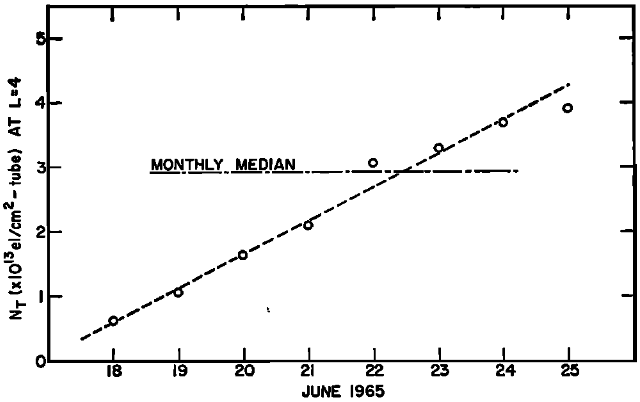

Fig. 6. Nighttime tube electron content at $L = 4$ obtained from the straight lines in Figure 5 and plotted against UT day in June, 1965.

1964; *Geisler and Bowhill*, 1965; *Yonezawa*, 1965*a*, *b*].

Figure 7 shows the tube content at $L = 4$ as a function of local time at Eights for June 18 through 22, 1965. The dashed curve is a theoretical curve that represents the expected behavior of tube content, assuming an upward flux of 3×10^8 electrons/cm^2 sec when the 100-km level is in sunlight, and a downward flux of 1.8×10^8 electrons/cm^2 sec when in darkness. The actual data are consistent with such a pattern. The average gain in tube content from dawn to dusk (excluding June 20 when the dusk data are not available) is 9.1×10^{12} electrons. From this and the net day-to-day increase of 5.2×10^{12} electrons, lower limits on upward and downward fluxes can be placed at 2×10^8 and 1×10^8 electrons/cm^2 sec, respectively. Figure 7 clearly shows decreases in tube content when both ends of the tube are in darkness on June 18, 21, and 22 (data are not available on June 20, and it is hard to interpret the data on June 19). Downward fluxes deduced directly from these nighttime data are close to the values quoted above. It should be mentioned, however, that the fluxes deduced simply by comparing tube content measured at two different times are not always reliable. Magnetospheric convection acting within the finite 'viewing' area of a station may cause tubes of ionization with different content 'histories' to be observed at different times.

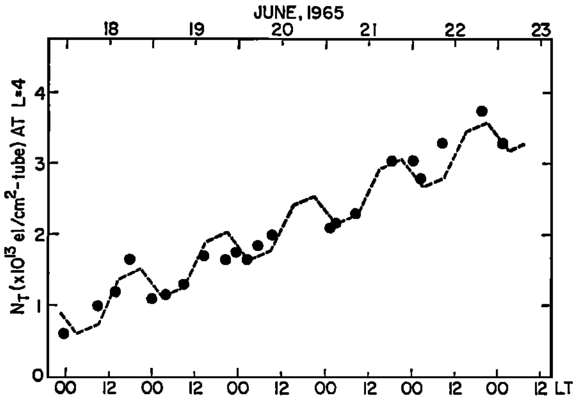

Fig. 7. Plot of tube electron content at $L = 4$ as a function of local time at Eights, showing the diurnal variation and the net day-to-day increase. The dashed curve is a theoretical curve assuming an upward flux of 3×10^8 electrons/cm^2 sec across the 1000-km level when the tube is in sunlight at 100 km altitude, and a downward flux of 1.8×10^8 electrons/cm^2 sec when in darkness.

The broken horizontal line in Figure 6 shows the monthly median tube content of 3×10^{13} electrons/cm^2 tube at $L = 4$. This value was determined from nighttime tube content profiles for 29 days in June. We recall that, from Figure 1, the ionosphere as observed by the vertical sounding method returned to normal by June 19, but the tube content in the protonosphere did not reach the monthly median value until June 22. Furthermore, as magnetic conditions continue to be quiet, the protonosphere continues to fill past the median value, although at a somewhat reduced rate. The filling rate does not appear to be strongly influenced by the tube electron content itself. The inferred rate varies only slightly, by ~40%, whereas tube content increases by an order of magnitude between June 18 and 25. Similarly, the filling rate does not appear to be strongly controlled by N_mF_2 in the ionosphere. From this evidence, it can be inferred that protonospheric tube content is rarely in an equilibrium state, and that even when tube content is 30% above the monthly median, the tubes will continue to fill if quiet conditions persist.

Late on June 25, the *Kp* index reached 4_o, and by the following night the tube content at $L = 4$ had decreased to about 2×10^{13} electrons/cm^2 tube. This behavior was shown in Figure 1 in terms of equatorial electron density. Stormtime behavior of the protonosphere is extremely complex, and the mechanism for depletion of the protonosphere both inside and outside the plasmapause is presently under investigation.

A preliminary study indicates that the data for $L < 3.5$ were not as well behaved as the corresponding data presented here for $3.5 < L < 5$, and the coupling fluxes at $L < 3.5$ may have been significantly different from those reported here. Care should therefore be exercised in extrapolating the results and conclusions of this paper to $L < 3.5$.

Discussion

In studying ionosphere-protonosphere coupling, the base of the protonosphere should be defined as the O^+-to-H^+ transition level. Because information on the location of the transition level is not readily available, however, the base of the protonosphere was defined at a fixed altitude of 1000 km in this study.

A flux of ionization across the 1000-km level may consist of two components: (1) a flux of protons diffusing through the diffusive barrier; and (2) a flux of protons and O^+ due to changes in the height of the diffusive barrier. In the first case, the altitude of the diffusive barrier is unchanged and a diffusion flux of protons and electrons increases concentrations in the protonosphere without significantly changing the shape of the profile along the field lines. In the second case, no protons diffuse through the barrier, but the height of the barrier changes, due to changes in temperature or ion composition in the topside ionosphere. A flux of the second kind is accompanied by changes in the profile along the field line and affects concentrations at lower altitudes more than near the top of the field line. It is only the first kind of flux mentioned above that is relevant to the problem of interchange of ionization between the ionosphere and the protonosphere. As will be discussed in the following paragraphs, whistlers are more sensitive to this flux, so that the results presented here should be identified with true ionosphere-protonosphere coupling flux.

The travel time of ducted whistlers is given by

$$t(f) = \frac{1}{2c} \int \frac{f_p}{f^{1/2} f_H^{1/2} \left(1 - \frac{f}{f_H}\right)^{3/2}} ds$$

where c is the speed of light, f_p is the plasma frequency, f_H is the electron gyrofrequency, f is the wave frequency, and ds is an element of path length along the field line (see *Helliwell* [1965]). Because of the gyrofrequency terms in the integral, the travel time depends much more sensitively on conditions near the top of the path than near the base of the protonosphere. For example, a given number of electrons placed near the top of the path will increase the travel time more than the same number of electrons at low altitudes. Large changes in the assumed temperature and ion composition at 1000 km result in only a few per cent change in computed tube content, as shown in the appendix. The whistler method, therefore, discriminates in favor of the proton diffusion flux.

Another argument is that, if diffusive equilibrium is assumed along a field line above 1000 km to the magnetic equator, then approximately 80% of the whistler time delay occurs within about 30° of the equator, where protons are the only ions present (except, of course, traces of heavier ions). Therefore, if the time delay for a given path changes by more than 10%, it cannot be explained by any reasonable changes at latitudes above 30°. The results presented in Figures 2, 4, and 6 show increases in time delay by ~10%, ~25%, and a factor of 3, respectively. These must be interpreted in terms of changes in proton content.

The second kind of flux mentioned above was investigated by *Titheridge* [1968*a*], who assumed that the diffusive barrier was completely effective and computed the flux of ionization across the 1000-km level due to diurnal changes in the height of the barrier. His results showed that the flux depends on geomagnetic latitude, and significant flux exists only in the latitude range 20°–45°. In this range, the total flow of ionization across the 1000-km level between noon and midnight, corresponding to a change in the transition level from 1000 to 500 km, is 10^{12} electrons/cm². At 60° geomagnetic latitude, the flow drops to less than 4×10^{11} electrons/cm². These numbers should be compared with the flux of $\sim 9 \times 10^{12}$ electrons/cm² from dawn to dusk near 60° ($L = 4$) reported in the previous section. The assumption of a completely effective diffusive barrier is clearly not valid, at least for latitudes above 50°. The flux computed by Titheridge could, however, contribute significantly to the maintenance of the nighttime ionosphere at geomagnetic latitudes of 25°–45°, as he suggested [*Titheridge*, 1968*a*, *b*]. Simultaneous observations of tube content by whistler methods and the local parameters near the base of the protonosphere by some other methods, such as incoherent backscatter, mass spectrometer, or probe method, will be useful in separating the two different kinds of fluxes.

It was noted in a previous section that the protonosphere was not in equilibrium with the ionosphere, even when the tube content was ~30% above the monthly median. Geomagnetic disturbances deplete the protonosphere in less than a day, but subsequent recovery to the saturation level takes longer than the average spacing of disturbances, so that the protonosphere appears to be always recovering from previous disturbances. It is not known at what density level the protonosphere becomes saturated and the net upward flux of ionization ceases. Examination of more data (not yet published) shows that the saw-toothlike behavior of electron density (see Figure 1) and its anticorrelation with Kp are characteristic of the protonosphere at $L \gtrsim 3$ during sunspot cycle minimum.

The above statement does not imply that the ionization in the topside ionosphere and protonosphere departs significantly from a diffusive-equilibrium distribution. If diffusion is fast, large fluxes can exist with only slight departures from an equilibrium distribution. In the region considered here, the only slow diffusion is that of protons in the diffusive barrier; thus, significant departure from an equilibrium distribution is expected only for protons inside the barrier region, where they are minority ions. The majority ions and electrons are expected to have a nearly equilibrium distribution throughout the topside and the protonosphere.

Conclusions

The conclusions of this study for $3.5 \lesssim L \lesssim 5$ near sunspot minimum are summarized as follows: (1) The observed daytime electron flux from the ionosphere into the protonosphere under quiet geomagnetic conditions is $2\text{–}4 \times 10^8$ electrons/cm² sec. This flux is larger than the downward flux necessary to maintain the nocturnal ionosphere. (2) The observed downward electron flux at night under quiet geomagnetic conditions is $\sim 1.5 \times 10^8$ electrons/cm² sec, an amount considered sufficient to maintain the nocturnal ionosphere. (3) Under quiet geomagnetic conditions, the coupling flux does not depend sensitively on electron concentration either in the protonosphere or in the ionosphere. (4) In the case studied, the ionosphere recovered from a storm in about 3 days, whereas the protonosphere required about 5 days to reach the monthly median level, and it did not reach any saturation level during the 8 days that elapsed between successive storms. (5) The post-storm recovery of the plasmasphere takes place primarily by filling from the ionosphere. (6) Electron concentration in the protonosphere is strongly affected during geomagnetic disturbances, and the protonosphere is most of the time recovering from previous disturbances. (7) The coupling flux is large enough for the protonosphere to have significant influence on the behavior of the ionosphere, but the diffusive barrier is sufficiently effective to prevent the protonosphere from coming to equilibrium with the ionosphere.

Appendix

The sources of error in determining tube content from nose whistlers is reviewed, and the magnitude of probable error from each source is given.

Measurement error. The spectrograms from which the nose frequency and time delay were scaled have a long-term stability of better than 2% in frequency and time. This corresponds to ~4% uncertainty in computed tube content. When whistlers are recorded continuously, however, as was the case described in the first part of the Results section, small systematic drifts in frequency and time scale can be corrected for by means of standard frequency time marks on the spectrogram. Uncertainty in computed tube content in such a case is less than 1%. Small measurement errors of random nature are smoothed out and do not affect the results presented in this paper.

Uncertainties due to assumed magnetospheric parameters. If the ionic composition at 1000 km is changed from 90% O^+, 8% H^+, and 2% He^+ to 50% O^+, 40% H^+, and 10% He^+, with the temperature of 1600°K in both cases, the computed tube content increases by about 0.1% at $L = 4$. If the ionic composition is fixed at 90% O^+, 8% H^+, and 2% He^+, and the temperature is changed from 1600°K to 3200°K, then the computed tube content increases by ~2% at $L = 4$.

Uncertainties due to the ionosphere. The ionospheric contribution to whistler dispersion is accounted for by a constant dispersion, $D = tf^{1/2}$, where f is the whistler wave frequency and t is the travel time (see *Helliwell* [1965]). The value of D can be estimated from ionosonde or Faraday rotation data near the feet of the tube within ± 1 $sec^{1/2}$ (D is typically 4 at night and 9 near noon during sunspot minimum). For a given error in D, per cent error in tube content depends on the content itself; the error is less for larger content. For a tube content of 10^{13} near $L = 4$, which is representative of the situation of June 18, the error is 4% per unit of D. After June 18, the per cent error is less.

Uncertainties due to sub-ionospheric propagation time. Whistler time delay is measured on the spectrogram with respect to the arrival time of the lightning signal at the whistler receiver. A correction must be made for the travel time of the signal in the earth-ionosphere waveguide from the lightning source to the whistler receiver and to the entrance of the whistler duct. For a duct located at $L = 4$ (60° geomagnetic latitude), if the lightning source is above 60° latitude, the necessary correction is ~45 msec. If the source is at the equator, no correction is necessary. By examining relative intensities of the lightning at conjugate receivers, it is possible to decide whether the lightning source was near the equator or near one of the receivers. In this way, the uncertainty in sub-ionospheric propagation time can be reduced to ± 15 msec. On June 18, 1965, this causes an error of ~3% in computed tube content. At later times, when tube contents are larger, the per cent error is correspondingly smaller.

For a more detailed discussion of error in whistler methods, see *Park* [1970].

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