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Some Features of Plasma Distribution in the Plasmasphere Deduced From Antarctic Whistlers

C. G. PARK

Radioscience Laboratory, Stanford University, Stanford, California 94305

Whistlers recorded in Antarctica were used to study the plasma distribution in the plasmasphere between $L \cong 2$ and 6. Certain features of the plasma distribution can be understood in terms of rapid (~1 day or less) depletion of the plasmasphere during geomagnetic disturbances, followed by slow refilling from the underlying ionosphere. At a given L value, the filling proceeds steadily until the plasmasphere reaches a well-defined density level where an equilibrium with the underlying ionosphere prevails. The time required to reach this equilibrium is related to plasmaspheric tube volume and varies from ~1 day at $L = 2.5$ to ~8 days at $L = 4$. Because of these long recovery times the plasmasphere usually consists of two distinct regions: an 'inner' plasmasphere, which is in equilibrium with the underlying ionosphere over a 24-hr period, and an 'outer' plasmasphere, which is still recovering from the previous disturbance. The monthly median data for June 1965 show that the transition from inner to outer plasmasphere occurred at $L \cong 4.5$. In November and December 1964 the transition occurred at $L \cong 4.0$, and the density levels were higher than they were in June by factors of 1.5–3. The latter result confirms the existence of large annual electron density variations in the plasmasphere, first discovered by the whistler technique more than a decade ago.

In recent years we have become increasingly aware of the dynamic nature of the plasmasphere (see, e.g., recent review papers by *Carpenter and Park* [1973] and by *Chappell* [1972]). Its outer boundary, the plasmapause, expands and contracts several earth radii in response to geomagnetic activity. Plasma densities within the plasmasphere exhibit complex spatial and temporal variations under the combined influence of geomagnetic activity and the conditions in the underlying ionosphere. An important pattern underlying this complex behavior of the plasmasphere is a cycle of rapid (~1 day or less) depletion during a magnetic disturbance and subsequent slow recovery, which may take many days.

During a magnetic disturbance we see reductions in the average plasmapause radius as well as in plasma densities inside the plasmapause. The latter is believed to be caused by the draining of flux tubes through the underlying ionosphere [*Park*, 1973]. Most dramatic depletions of the plasmasphere occur during periods of intense substorm activity such as the main phase of a magnetic storm, but moderate substorms involving $Kp = 4$ or less also produce significant effects.

Subsequent recovery of the plasmasphere takes place by filling from the underlying ionosphere. The recovery time depends strongly on invariant latitude. At low latitudes, where tube volumes are small, plasma flow from the ionosphere may fill the plasmasphere to an equilibrium level in a day or so. The time required for filling increases rapidly to ~10 days near $\Lambda = 60°$. This is longer than the average spacing between magnetic disturbances, so that the outer plasmasphere seldom, if ever, recovers fully from the previous disturbance. This means that the plasmasphere consists of two distinct parts: an 'inner' plasmasphere, which is, in a diurnal average sense, in equilibrium with the underlying ionosphere, and an 'outer' plasmasphere, which is still in a state of recovery. This is illustrated with an example of a poststorm recovery in the next section. In later sections we will see that the long-term average behavior of the plasmasphere also reflects the existence of these two distinct regions.

AN EXAMPLE OF STORM RECOVERY

Figure 1 shows plots of geomagnetic indices for the period June 14–26, 1965. A magnetic storm started with a sudden commencement near 1200 UT on June 15, reached peak activity late on June 16, and then began to fade rapidly. The main phase of the storm was over by June 17. There then followed an unusually long period of extreme quiet until it was interrupted by moderate substorm activity on June 25. During the main phase of the magnetic storm the plasmapause moved inward to $L \cong 2.4$ on June 16 [*Carpenter et al.*, 1971]. The depleted region beyond this contracted plasmapause started to refill late on June 17. Because of the unusually quiet magnetic conditions, the period between June 18 and 25 provided a unique opportunity to observe the recovery of the plasmasphere without complications arising from perturbing substorm activity. Observations during the same period in the range $L \cong 3.5$–5 have been reported earlier [*Park*, 1970]. In this paper, observations are extended to cover wider L ranges, and the results show important features not revealed by the earlier study.

The observations of the plasmasphere were made using Antarctic whistlers, which allow continuous monitoring of equatorial electron concentration n_{eq} and electron tube content N_T in the range $L \sim 2$–6. Here N_T is defined as the total number of electrons in a tube of magnetic flux having 1-cm^2 cross-sectional area at 1000-km altitude and extending to the magnetic equator. Methods of calculating n_{eq} and N_T from whistlers have been described elsewhere [*Park*, 1972; *Bernard*, 1973]. The plasma density model adopted in this paper assumes a diffusive equilibrium along field lines at 1600°K and an ionic composition of 90% O$^+$, 8% H$^+$, and 2% He$^+$ at 1000-km altitude. Expected errors in N_T due to

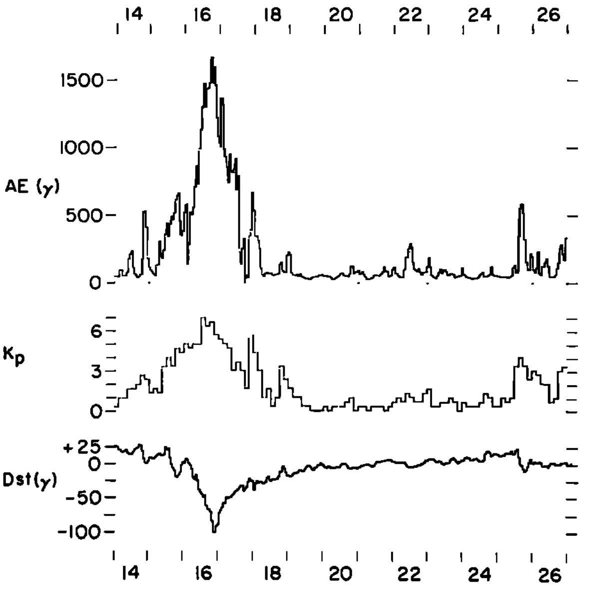

Fig. 1. Plots of auroral electrojet index, 3-hr *Kp*, and *Dst* for the period June 14–26, 1965.

an assumed field line distribution of plasma are ~10% or less [*Park*, 1972].

The results are summarized in Figure 2, in which N_T is plotted against L for each night from June 18 to 25. Most of the data points in the figure were obtained from whistlers recorded at Eights, Antarctica (77°W, geographic; 64°S, geomagnetic), within a few hours of local midnight. Whistlers recorded at Argentine Islands, Antarctica (74°W, geographic; 54°S, geomagnetic), provided a few data points near $L = 2$. This figure shows only net changes in N_T from night to night. The actual temporal behavior includes diurnal oscillations due to daytime filling and nighttime draining [*Park*, 1970].

At $L \gtrsim 4$, N_T increases steadily at the rate of $\sim 5 \times 10^{12}$ el/cm^2 d throughout the period of observation. This net increase is the result of a daytime filling flux of $\sim 3 \times 10^8$ el/cm^2 s and a nighttime draining flux of $\sim 1.5 \times 10^8$ el/cm^2 s [*Park*, 1970]. Apparently the filling was still incomplete on June 25, and the tube content probably would have increased further if the magnetic conditions had remained quiet. This filling process, however, was interrupted when moderate substorm activity on June 25 (see Figure 1) caused a rapid depletion of the plasmasphere. This depletion event has been described in an earlier paper [*Park*, 1973]. Below $L \sim 4$, N_T increases at a rate similar to that for $L > 4$, but it reaches a well-defined saturation level where the plasmasphere is in equilibrium with the underlying ionosphere over a 24-hr period. This saturation level increases with increasing L value, primarily owing to increasing tube volume.

Smooth curves have been drawn through the data points in Figure 2, and the results are shown in Figure 3*a*. The demarcation between the inner and the outer plasmasphere moved from $L \sim 2.5$ on June 19 to $L \sim 4$ on June 25. The outer plasmasphere continued to fill at a fairly uniform rate except on June 21 when a much larger net increase was observed. This was a day with a slightly higher level of geomagnetic activity than the other days (see Figure 1). It is not clear, however, if there is any causal relationship between the two. If we recall that the refilling started on June 17, then the recovery time of the plasmasphere may be said to vary from ~1 day at $L = 2.5$ to ~8 days at $L = 4$. Figure 3*b* shows equatorial electron concentration profiles corresponding to the tube content profiles shown in Figure 3*a*.

We have just seen an example of how the plasmasphere recovers under exceptionally quiet geomagnetic conditions. Under ordinary circumstances, such orderly recovery is frequently interrupted by substorms, which have a tendency to produce irregular structures by mixing tubes with different content [*Park and Carpenter*, 1970; *Carpenter and Park*, 1973] or by localized draining through the ionosphere [*Park*, 1973].

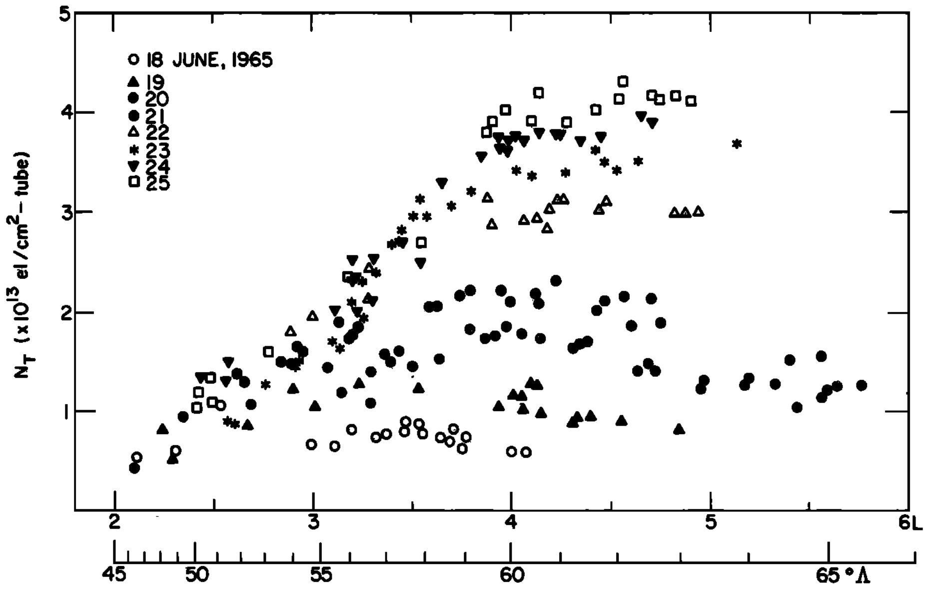

Fig. 2. Plots of electron tube content versus dipole *L* showing the recovery behavior of the plasmasphere following a magnetic storm. The data were taken within a few hours of local midnight at whistler receiving stations.

Comparison With the Ionospheric Behavior

We will now compare the results of the previous section with the recovery behavior of the ionosphere. Figure 4 shows the storm effect on the F_2 layer critical frequency f_oF_2 over Winnipeg, Ottawa, Washington, and Mexico City during the period June 15–20, 1965. These stations are located near the meridian of whistler observations and range from $\sim$30° to 60° in geomagnetic latitude. The solid curves show the monthly median behavior at each station. The data shown in Figure 4 are typical of ionospheric storms at these stations during local summer. On the first day of the storm (also on the second day in some cases) there is a sharp increase in f_oF_2 above the monthly median level, followed by a depression in the daytime f_oF_2 values for several days.

Two important differences are evident between the ionosphere and the plasmasphere in the recovery behavior. First, the ionosphere appears to have completely recovered by June 19, whereas the plasmasphere still has many more days of filling before the recovery is complete. (In the topside ionosphere, where a mixture of O^+ and H^+ exists, the recovery time may be intermediate between the recovery times of the F_2 layer peak and the equatorial plasmasphere.) Second, the recovery time of the ionosphere shows no latitude dependence, in sharp contrast with the behavior of the plasmasphere. These facts are interpreted as evidence that the depression in f_oF_2 is not caused directly by upward fluxes of ionization into the plasmasphere. The depression is probably associated with heating and composition changes of the neutral atmosphere [e.g., *Obayashi and Matuura*, 1972]. This does not imply, however, that the ionosphere and the plasmasphere are decoupled during storms. On the contrary, there is evidence for enhanced coupling between the two regions during the main phase of a magnetic storm [*Park*, 1973; *Obayashi*, 1972]. The present results show only that the poststorm recovery of the two regions proceeds at different rates, governed by different physical processes in each region.

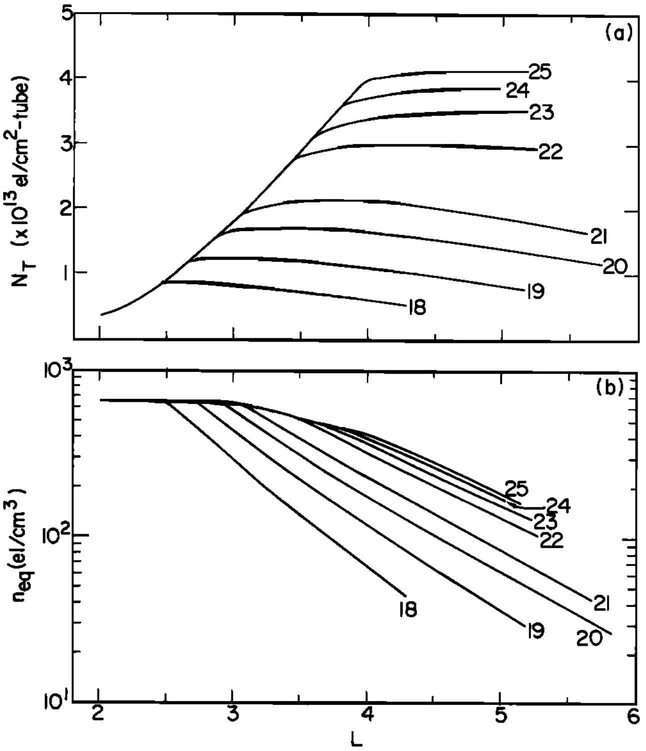

Fig. 3. (*a*) Tube content profiles obtained by drawing smooth curves through the data points in Figure 2. The numbers indicate universal time days in June 1965. (*b*) Equatorial electron concentration profiles corresponding to tube content profiles in Figure 3*a*.

These results also suggest that the normal daytime ionosphere can supply the observed upward fluxes of the order of 10^8 el/cm^2 s without suffering significant depression in O^+ concentration near the F_2 layer peak. This is consistent with Alouette 2 satellite observations of the topside ionosphere by *Banks and Doupnik* [1973]. This is also con-

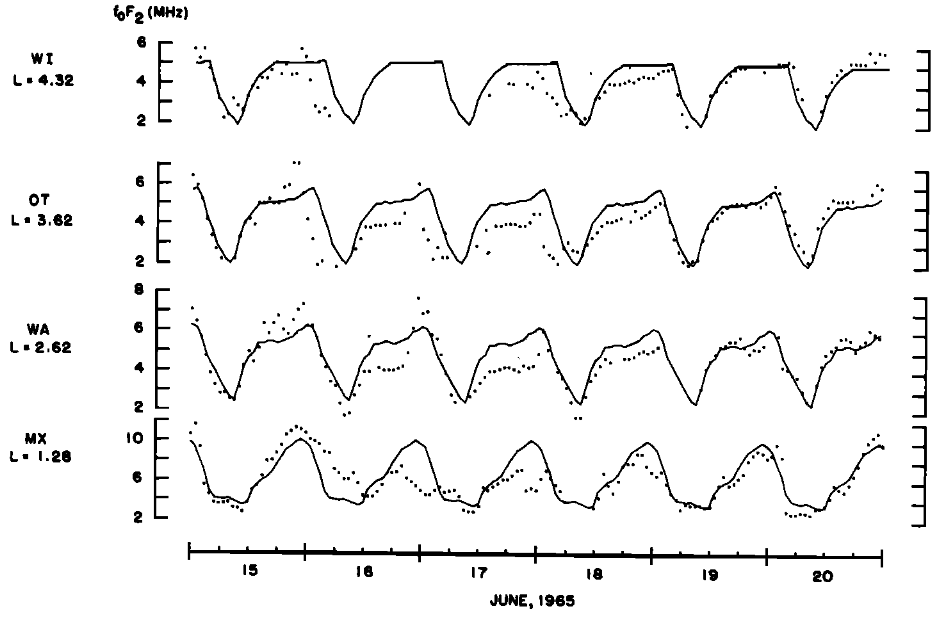

Fig. 4. Hourly values of the F_2 layer critical frequency over Winnipeg (WI), Ottawa (OT), Washington (WA), and Mexico City (MX) from June 15 through June 20, 1965. The horizontal scale is universal time. The local standard time is 5 hr behind universal time at Ottawa and Washington and 6 hr behind at Winnipeg and Mexico City. The solid curves show the monthly median behavior at each station.

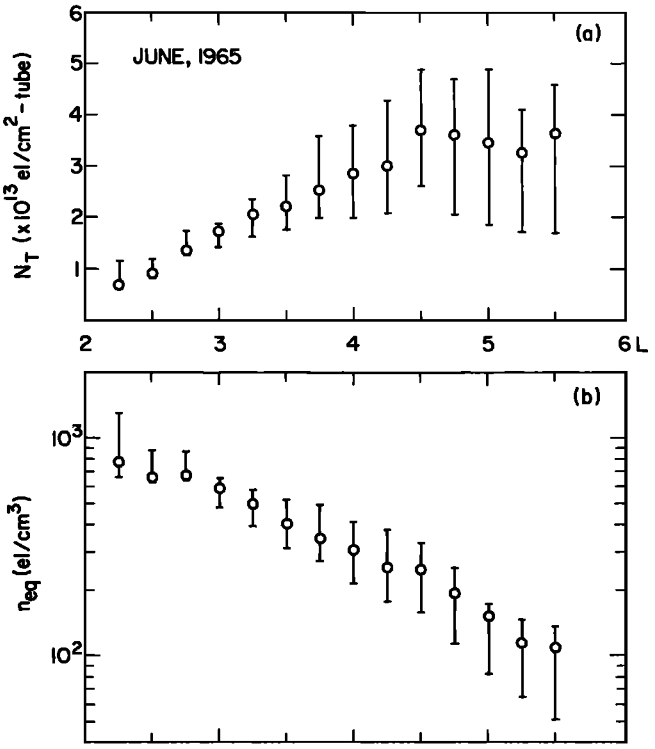

Fig. 5. (*a*) Monthly median values of nighttime electron tube content in June 1965 plotted against L. The bars indicate the upper- and lower-quartile values. (*b*) Equatorial electron concentrations corresponding to the tube content data in Figure 5*a*.

sistent with the diurnal behavior of the ionospheric trough region. The plasmapause near the equatorial plane exhibits sharp radial gradients in electron concentration at all local times. On the nightside this gradient extends along field lines and frequently appears as a sharp latitudinal gradient at ionospheric heights. The corresponding feature is normally absent on the dayside ionosphere; this indicates that the O^+ concentration in the sunlit ionosphere is not strongly influenced by the H^+ concentration at much higher altitudes [e.g., *Taylor and Walsh*, 1972].

AVERAGE BEHAVIOR OF THE PLASMASPHERE

In this section we describe the 'average' electron concentration profile in the plasmasphere for the month of June 1965. Whistlers recorded at Eights within a few hours of local midnight were used to construct nightly profiles of equatorial concentration and tube content in the range $L \sim$ 2–6. Smooth curves were drawn through the data points of each night, as in Figures 2 and 3. Figure 5 shows the monthly median values of tube content and equatorial electron concentration at intervals of $0.25L$. The bars represent upper- and lower-quartile values. Thus the length of the bar represents the range of values within which 50% of the nightly profiles fall. A comparison between Figures 5*a* and 3*a* reveals several similarities. The N_T values show larger excursions with increasing L value. Both the median and the upper-quartile values increase with increasing L at first but then level off at $L \sim 4.5$. Interpreted in the context of Figure 3, this means that, in a long-term average sense, the transition from inner to outer plasmasphere occurred near $L = 4.5$ in June 1965.

ANNUAL VARIATIONS

From the foregoing discussion, it is expected that the saturation level of plasmaspheric densities and the location marking the transition between inner and outer plasmasphere would depend on the magnitude of upward fluxes from the ionosphere and the frequency with which geomagnetic disturbances deplete the plasmasphere. These in turn would depend on the season and sunspot cycle. A detailed survey of seasonal, annual, and solar cycle variations in the plasmasphere is underway. Here we will show an example of annual variations only.

Figure 6 compares median values of N_T and n_{eq} for November and December 1964 with those for June 1965. The June data are reproduced from Figure 5, and the November–December data represent the median behavior obtained from nightly profiles in a manner similar to that used in Figure 5. All the whistlers used in Figure 6 were recorded at Eights. The November and December densities are 1.5–3 times larger than the June values, the ratio increasing with decreasing L value. We can see in Figure 6*a* that, on the average, the demarcation between inner and outer plasmasphere during the November–December period is at $L \sim 4$, approximately $0.5L$ less in comparison with the June period.

Annual density variations in the plasmasphere have been well known since the early days of whistler research [*Helliwell*, 1961; *Carpenter*, 1962; *Corcuff*, 1962], but they still remain unexplained. The problem is compounded by the tilt of the earth's magnetic axis, which may make annual variations longitude dependent. The data presented here come from a longitude sector where the magnetic equator

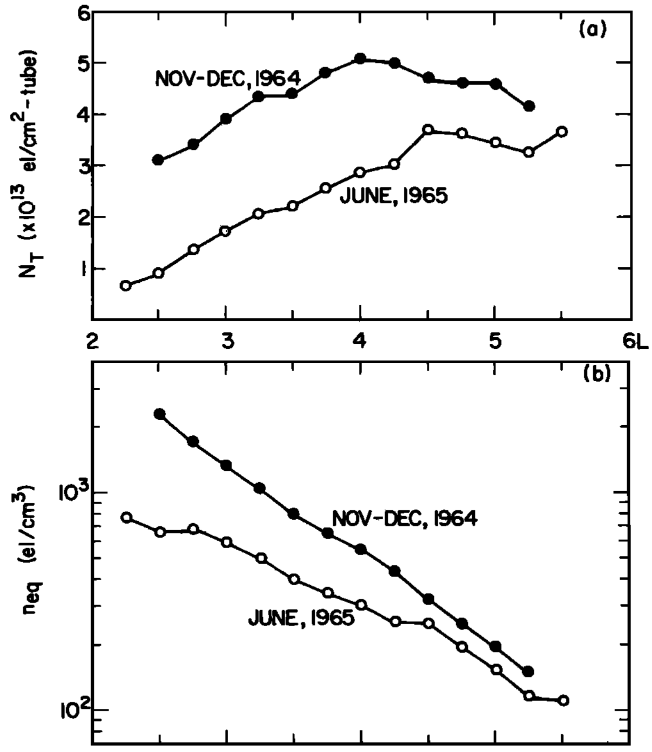

Fig. 6. (*a*) Plots of median nighttime tube content values for June 1965 and for November and December 1964, showing large annual variations. (*b*) Plots of equatorial electron concentrations corresponding to the tube content data in Figure 6*a*.

has the maximum southerly displacement with respect to the geographic equator. At these longitudes, the ionospheric ends of a flux tube corotating with the earth are exposed to sunlight each day for a longer period in December than they are in June. Another complication arises from the fact that at these longitudes the mid-latitude ionosphere in the southern hemisphere has a peculiar diurnal behavior in local summer. Ionospheric densities there show a midnight maximum and a noon minimum [e.g., *Chan and Colin*, 1969]. These two factors may have contributed to the annual variation shown in Figure 6. However, earlier work based on whistlers from stations widely separated in longitude suggests that the annual variation is global in scale and that it is in phase everywhere. More data are needed, particularly from the eastern hemisphere, in order to clearly identify any longitudinal effects in the annual variation.

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