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ELECTRON DENSITY IN THE PLASMASPHERE: WHISTLER DATA ON SOLAR CYCLE, ANNUAL, AND DIURNAL VARIATIONS

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Abstract. Whistler data are used to present a statistical view of equatorial plasmaspheric electron density n_{eq} and associated tube electron content N_T (defined as the number of electrons in a geomagnetic flux tube of 1cm^2 cross-sectional area at 1000km altitude and extending to the magnetic equator). The data were acquired between 1959 and 1973 at Byrd ($L \simeq 7$), Eights ($L \simeq 4$), and Siple ($L \simeq 4$), Antarctica, which are within 1 hour of the same geomagnetic meridian, and from Stanford, California ($L \simeq 2$). The plasmaspheric n_{eq} profile beyond $L \simeq 3$ is dominated by variations associated with magnetic disturbances and subsequent recovery. In the aftermath of disturbances the plasmasphere tends to be divided into an inner 'saturated' region, which is in equilibrium with the underlying ionosphere in a diurnal average sense, and an outer 'unsaturated' region, which is still filling with plasma from below. In the outer plasmasphere byond ~3.5 R_E, diurnal variations appear as relatively small effects superimposed on larger storm-associated variations. Large numbers of whistler traces (as many as 3000 in some cases) were scaled for each of several months. These data sets form the basis for approximations to n_{eq} profiles to form $\log_{10}(n_{eq}) = aL + b$. These profiles are offered for reference use in estimating plasmasphere density levels. The previously reported annual and solar cycle variations are further documented by new evidence that these effects diminish with increasing L beyond $L \simeq 3$.

1. Introduction

The whistler method of determining electron density in the magnetosphere has been applied with success to many problems in magnetospheric plasma structure and dynamics, and to problems of protonosphere-ionosphere coupling. However, a description of the main features of plasmaspheric electron density based on large quantities of whistler data has been slow to emerge. This is partly due to the demanding nature of the data analysis and to the fact that routine analysis of magnetospheric electron density features has not, as in the case of the ionosphere, been undertaken by organizations dedicated to this task. There is an increasing need for information on plasma density as part of wave-particle interaction studies, studies of ionosphere-protonosphere coupling, and studies of the magnetosphere as a propagation medium at various radio frequencies. The whistler method is particularly well suited to providing estimates of average properties. The method may be applied over extended periods of time at a single longitude and is free of many of the complications that best in situ probes [e.g., Whipple et al., 1974].

The present paper brings together results from measurements taken over a period of nearly 20 years. The emphasis is on a compact presentation of salient features within the plasmasphere. At the plasmasphere boundary, or the plasmapause, equatorial electron density usually drops abruptly by a factor of ~10 to 100 within a fraction of an earth radius. The plasmapause location may vary from $L \simeq 2$ to $L \simeq 8$, depending upon magnetic conditions and local time. Although some limited information is available on the plasmapause location and on the density profile through and beyond the plasmapause [e.g., Carpenter and Park, 1973; Chappell, 1972], it is not sufficient at present to provide a basis for an accurate model. Continuing work using whistlers and other techniques will hopefully improve this situation. In this paper we present density models that we believe can be used with a fair degree of confidence out to a known or assumed plasmapause location.

2. Sources of Data and Methods of Analysis

The sources of data are whistlers recorded between 1959 and 1973 at Byrd (80°S, 120°W; $L \simeq 7$), Eights (75°S, 77°W; $L \simeq 4$), and Siple (76°S, 84°W; $L \simeq 4$) in Antarctica, which are within 1 hour of the same geomagnetic meridian, and from 1957 through 1964 at Stanford, California (37°N, 122°W; $L \simeq 2$).

The whistler technique of measuring electron densities in the magnetosphere is well documented in the literature (see, for example, Helliwell [1965], Carpenter and Smith [1964], Brice and Smith [1971], Park [1972], and Y. Corcuff [1975]). Its special advantages include (1) highly repeatable propagation of successive whistlers on discrete geomagnetic-field-aligned paths distributed in equatorial radius and (2) sensitivity to plasma density and geomagnetic field strength near the equatorial portion of the path.

In the present work we use the empirical formulas developed by Park [1972] to calculate the L value (or corresponding equatorial radius R_{eq}), equatorial electron density n_{eq}, and electron tube content N_T from the whistler frequency of minimum travel time, or nose frequency f_n, and the time delay at the nose t_n. The electron tube content is defined as the total number of electrons in a geomagnetic flux tube extending from 1000km altitude to the geomagnetic equator and having a cross-sectional area of 1cm^2 at the base. We assume a centered dipole geomagnetic field and a diffusive equilibrium plasma distribution along field lines. Inside the plasmapause, uncertainties in L, n_{eq}, and N_T due to use of an assumed field line plasma distribution model are estimated to be ~0.3%, ~10%, and ~4%,

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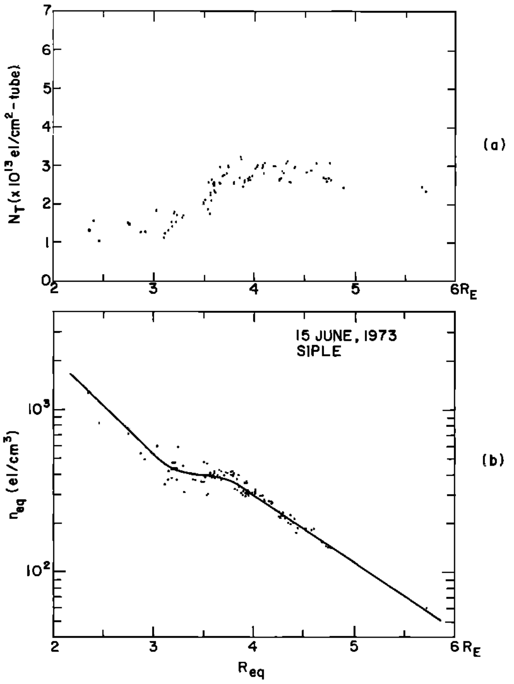

Fig. 1. (a) Electron tube content versus equatorial crossing radius deduced from whistlers recorded at Siple, Antarctica, between 0015 and 2155 UT on June 25, 1973. (b) Corresponding equatorial electron density profile.

respectively [Park, 1972]. Under quiet geomagnetic conditions (k_p = 0-1) the use of a centered dipole model results in ~3%, ~10%, and ~6% errors in the above parameters near L = 4 [Seely, 1977]. These errors increase with increasing magnetic activity; during periods of moderate activity ($k_p \simeq$ 2-4) they are estimated to be about twice the values quoted above. Geomagnetic-field-associated errors tend to be of a fixed sign; when it is necessary, their effects can be reduced through calculations employing a model that approximates the effects of both internal and external sources of the geomagnetic field [Seely, 1977].

The present study focuses on the plasmasphere under conditions of quiet or moderate disturbance, i.e., k_p = 0-4. Data from periods of severe disturbance are included in some of the presentations, but their effect on the plasmasphere profile analyses is small because of the reduced radius of the plasmasphere and the reduced number of scalable whistlers during such periods. In the present research, f_n and t_n were estimated by Bernard's [1973] curve-fitting method when they could not be measured directly on the spectrograms. Curve fitting was applied mostly to whistlers propagating below L = 2.5; these have nose frequencies close to or above 20 kHz. Care was taken to ensure that the expected errors in estimating f_n and t_n [Bernard, 1973] were less than 8% and 4%, respectively. This in turn ensures that the corresponding errors in L, n_{eq}, and N_T are less than ~3%, ~30%, and ~15%, respectively.

It should be pointed out that an underestimate of n_{eq} tends to be accompanied by an overestimate of L and vice versa, regardless of whether the error stems from the process of measuring f_n and t_n or from the inaccuracies in magnetospheric models used. (In a loose sense, t_n may be thought of as being proportional to the product $Ln_{eq}^{1/2}$. If the time of origin of a whistler is known, t_n may be relatively accurately measured by either direct or extrapolation techniques. Then an uncertainty of one sign in L due either to an error in measuring f_n or to inaccuracy of the magnetospheric model leads to an error of opposite sign in inferred n_{eq}.) Since n_{eq} generally decreases with increasing L, the two errors tend to cancel one another when the data are used to estimate the n_{eq} versus L profile. Thus, while the boundaries in L of large-scale density features such as the plasmapause may be in slight error, uncertainties in the density levels within each major feature (n_{eq} at a given L) are actually about one third of the errors quoted above for n_{eq} derived from an individual whistler trace.

The next section briefly reviews important physical processes that control the plasmasphere, thus providing a framework within which a number of the results of the present survey can be understood.

3. A Qualitative Description of the Plasmasphere

Thermal plasma in the plasmasphere originates in the ionosphere, where the photo-ionization of O produces copious amounts of electrons and O^+ ions. The resulting photoelectrons with energies of tens of electron volts can easily escape into the plasmasphere, thereby increasing the energy density levels in that region. However, photoelectrons, unaccompanied by ions, do not result in net density increases in the plasmasphere, because an equal number of cold electrons must flow downward in order to maintain charge neutrality. An increase in plasmaspheric number density requires upward fluxes of both electrons and ions. Ionospheric O^+ ions are too heavy to accompany the electrons to great heights; O^+ ions in the topside ionosphere first undergo a charge exchange reaction

$$O^+ + H \rightarrow O + H^+$$

and the resulting H^+ ions diffuse upward to populate the plasmasphere. The changeover from O^+ to H^+ ions occurs typically at 1000-2000km, the so-called 'transition altitude.'

There are two important mechanisms for loss of plasma from the plasmasphere. If plasma pressure in the underlying ionosphere decreases below an equilibrium level at night, or during magnetic storms, downward flow from the plasmasphere results. O^+ ions are produced by downcoming protons through charge exchange with O (a reversal of the reaction cited in the foregoing paragraph) and help maintain and O^+-dominated F layer. The other loss mechanism involves large-scale convection electric fields that carry tubes of plasma into high-latitude 'open field' regions, permitting the plasma to escape into the geomagnetic tail or interplanetary space. The second process has been widely accepted as an explanation of the large density jump at the plasmapause [i.e., Nishida, 1966; Brice, 1967]. The

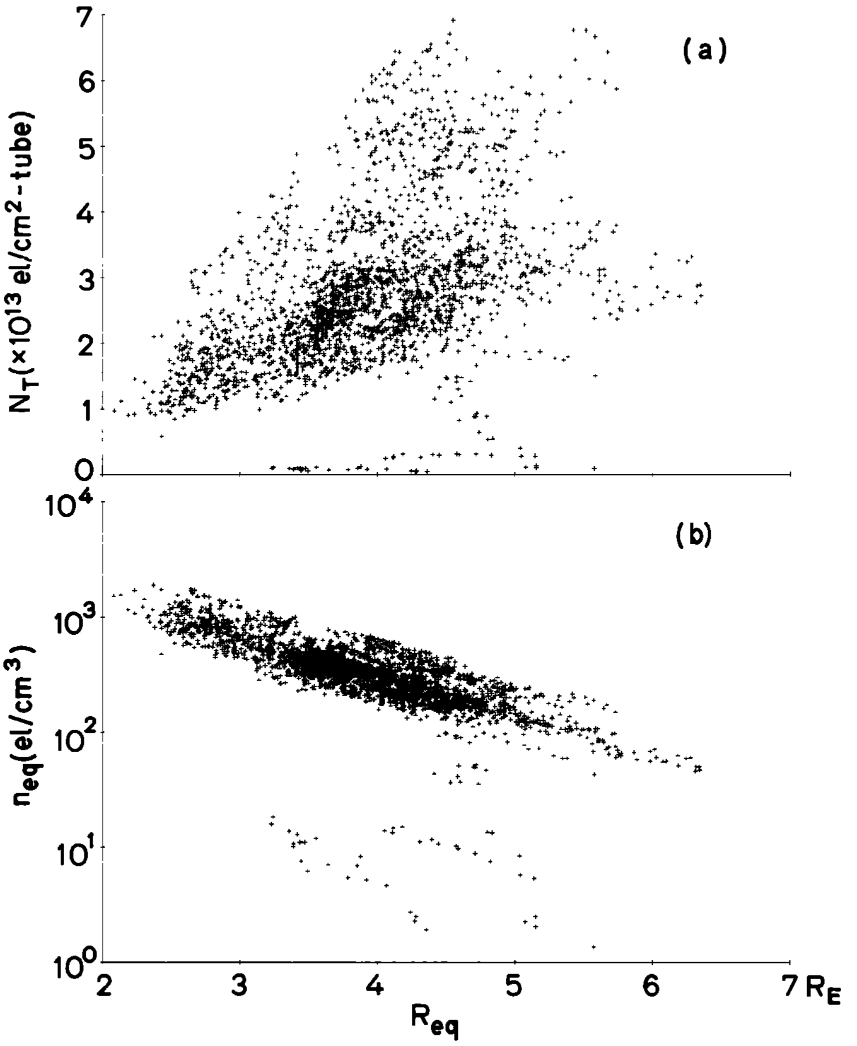

Fig. 2. (a) Mass plot of electron tube content versus equatorial crossing radius deduced from whistlers recorded at Siple, Antarctica, during the month of June 1973. Approximately 3000 whistler traces have been used. (b) Corresponding equatorial electron density plot.

plasmapause position may range from L = 2 during severe magnetic storms to L = 8 during very quiet times. For references on the plasmapause, including its diurnal and storm time behavior, and problems of definition and identification during recovery periods, see Carpenter [1966, 1968], Chappell [1972], Carpenter and Park [1973], and Maynard and Grebowsky [1977].

During magnetic disturbances the above two processes act so as to diminish the size of the plasmasphere and generally to reduce density levels within the reduced plasmasphere volume [Carpenter and Park, 1973; Park, 1973]. Subsequent recovery takes place by filling from the underlying ionosphere, but this refilling is a slow process requiring many days [Park, 1974; Murphy et al., 1975]. We may say that the plasmasphere at a particular L value is fully recovered when the equatorial density reaches a level at which upward flow during the day is just balanced by downward flow at night. At this 'saturation' level the plasmasphere is in equilibrium with the underlying ionosphere in a diurnal average sense. The time required to reach saturation depends strongly on the L value and ranges from ~2 days at L = 2 to ~8 days at L = 4 [Park, 1974]. Since the average interval between magnetic disturbances that affect the plasmasphere is less than 8 days, the plasmasphere beyond L = 4 rarely, if ever, reaches saturation. Thus in recovery periods the plasmasphere usually consists of two distinct regimes: an inner, or 'saturated,' part that is in equilibrium with the underlying ionosphere in a diurnal average sense and an outer, or 'unsaturated,' part that is still filling from below. The transition between the two regimes is usually quite sharp and typically lies between L = 3 and L = 4 [Park, 1974]. Large-scale density irregularities can exist in the unsaturated plasmasphere [Park and Carpenter, 1970], but they tend to be smoothed out as densities approach the saturation level.

From the foregoing discussion we expect plasmaspheric densities to show small diurnal variations due to more or less regular plasma flow up and down the field lines. The small diurnal effects should be superimposed on large but ir-

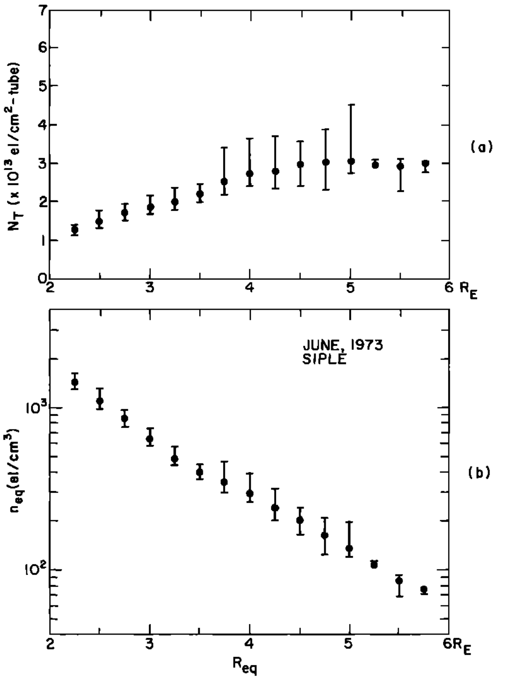

Fig. 3. (a) Monthly median values of electron tube content as a function of equatorial crossing radius deduced from whistlers recorded at Siple, Antarctica, during the month of June 1973. The vertical bars indicate upper and lower quartile values. (b) Corresponding equatorial electron density data.

regular storm time variations with cycles of rapid (~1 day) depletion and slow (up to ~10 days or more) recovery. A statistical view of these and other variations will be presented in the following section.

4. Results

Illustrative single-day profiles. Broadband whistler recordings were made at the field stations on a synoptic schedule of 1 min every 5 or 15 min. For several 1-month periods, well-defined whistlers were selected from each day's data to provide electron density profiles. In the selection process, attempts were made to obtain a profile every few hours and thus avoid giving too much weight to periods of high whistler activity. Figure 1 shows plots of (a) tube content and (b) equatorial density as a function of L for June 15, 1973, deduced from whistlers recorded at Siple throughout most of the UT day. A smooth curve is drawn through the data points in Figure 1b to obtain a representative equatorial density profile for the day. The period was one of moderate agitation during recovery from a weak magnetic storm on June 11-12. A plasmapause was not identified within the L ~ 2.3-5.7 limits of the data on this day.

Profile statistics from a month of data. Figure 2 shows mass plots of N_T and n_{eq} obtained from whistlers recorded at Siple during the month of June 1973. Over 3000 whistler traces were used. Three important features can be identified in the figure: (1) well-defined upper limits of N_T and n_{eq}, (2) general clustering of data points somewhat below the upper limits, particularly at $L \gtrsim 3.5$, and (3) presence of some data points at relatively low levels, well separated from the majority. The low-content and low-density points come from whistlers propagating outside the plasmapause and are not included in the following statistical description of plasmaspheric densities.

The first two features mentioned are consistent with the concept of a saturation level that is rarely reached in the outer plasmasphere. The well-defined saturation level can provide a useful upper limit to electron density estimates used in modeling magnetospheric processes.

Monthly median profiles. Daily equatorial density profiles, illustrated by the curve in Figure 1b, were scaled at intervals of 0.25L, and the resulting daily values were used to obtain monthly median profiles. Figure 3b shows the median equatorial density profile for the month of June 1973, while Figure 3a shows the corresponding tube content profile. The vertical bars represent upper and lower quartile values, or the ranges within which 50% of the daily values lie. All whistlers used in Figure 3 were recorded at Siple, Antarctica.

Similar procedures were used to obtain the profiles shown in Figures 4, 5, and 6 using whistlers recorded at Eights and Byrd, Antarctica. Figure 4 shows the monthly median behavior for June 1965 based on whistlers recorded at Eights. These data were discussed earlier by Park [1974]. Figure 5 shows the median behavior for November and December 1964, also based on Eights data. Because of relatively low whistler occurrence rates in austral summer compared with winter, 2 months' data were combined in order to increase the data base. In Figure 6 the monthly median behavior for June 1959 is based on whis-

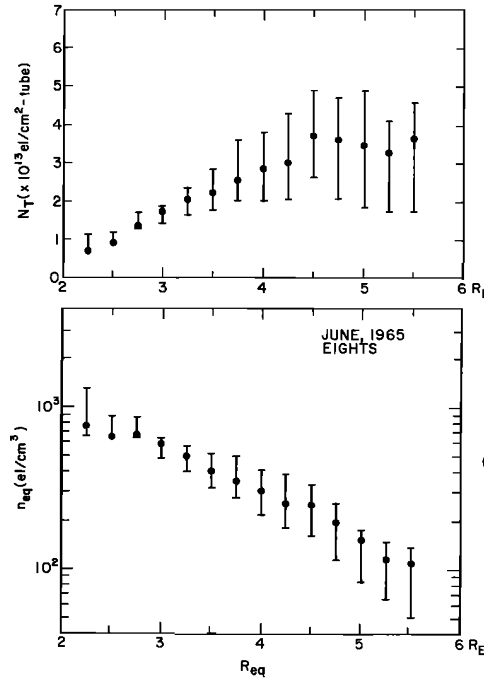

Fig. 4. Same as Figure 3 but deduced from whistlers recorded at Eights, Antarctica, during the month of June 1965.

tlers received at Byrd. Data coverage in this case was not very good for $L < 3.25$ because of the high latitude ($L \simeq 7$) of the receiving station.

Equatorial density profiles in Figures 3-6 may be approximated by straight lines to yield empirical formulas in the form $\log_{10} (n_{eq}) = aL + b$. Table 1 summarizes the results of least-square approximations of the data.

The formulas of Table 1 should be used with caution. They are considered to be good estimates of density levels near the geomagnetic longitude sector of these stations, for the conditions specified, but should not be used for estimating density gradients. Gradient features such as those of Figure 1b are often present in an individual day's profiles, but such features tend to disappear in the averaging process associated with Figures 3-6.

Tube content profiles in Figures 3-6 show a tendency to increase with L, at low L, but level off between $L \simeq 3.5$ and $L \simeq 4.5$. The amount of scatter in the data, as indicated by the upper and lower quartile values, increases with L. These features are consistent with the earlier qualitative description of the 'recovering' plasmasphere in terms of a well-behavied saturated inner region and a more dynamic unsaturated outer part. In Figure 6a, tube content shows a trend toward decreasing values beyond $L = 4$. This could be due to more frequent depletions of the outer plasmasphere near sunspot maximum.

Diurnal variations. The Siple data from June 1973 were divided into 3-hour intervals, and a smooth equatorial density profile was drawn for each time interval in the manner of Figure 1b. Figure 7 shows monthly mean values of n_{eq} for these time intervals and for four L values. The vertical bars for $L = 3$ and $L = 4$ show the magnitude of one standard deviation. At $L = 3$ there is evidence of a significant variation, with minimum values in the postmidnight period. Beyond $L = 3$, however, diurnal effects are obscured by relatively large day-to-day variations due to storm and substorm effects.

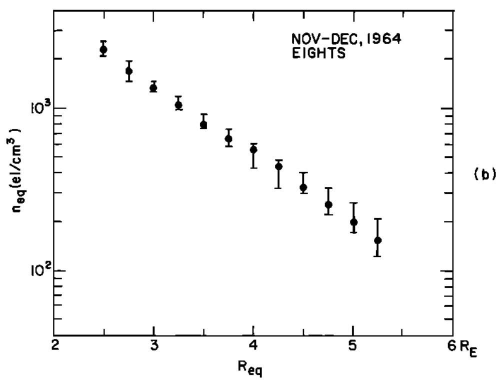

Fig. 5. Same as Figure 3 but deduced from whistlers recorded at Eights, Antarctica, during the 2-month period, November to December 1964.

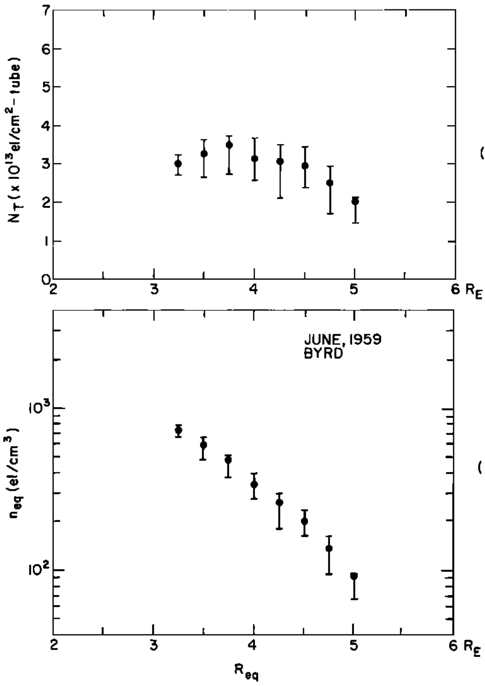

Fig. 6. Same as Figure 3 but deduced from whistlers recorded at Byrd, Antarctica, during June 1959.

Daytime upward fluxes from the ionosphere are limited to $\lesssim 3 \times 10^8$ el cm^{-2} s^{-1} by the action of the diffusive barrier to H^+ [Park, 1970; Evans, 1971; Banks and Holzer, 1969]. Fluxes of this magnitude are not sufficient to produce clear diurnal variations in the outer plasmasphere, where the average tube content is high. Larger percentage variations are expected outside the plasmapause, where the average tube content is usually lower than nearby plasmasphere values by a factor of ~10.

Annual variations. Figure 8 compares monthly median values of N_T and n_{eq} at Eights for June 1965 with the median values at the same station for the 2-month period November and December 1964. The November and December densities are 1.5-3 times larger than the June values, the ratio increasing with decreasing L values.

Figure 9 shows the annual variation by means of data on travel time t or dispersion 'D' of whistlers recorded at Stanford ($L \simeq 2$) during the period 1957-1964. The travel times were measured at 5 kHz and are plotted in units of $tf^{1/2} = D = t(5000)^{1/2}$. Each data point represents an intensity-weighted average of travel time over the traces of a multicomponent whistler. The quantity D is then roughly proportional to $(n_{eq})^{1/2}$ along the 'effective' L value of propagation. (This L value is that of a fictitious whistler trace with the average travel time.) Its annual average was found in an earlier study to be ~2.5 [Carpenter, 1962]. Day-

TABLE 1. Plasmaspheric Equatorial Density Model

Month and Year	Station	Formula	Applicable Range
June 1959	Byrd	$\log_{10}(n_{eq}) = -0.511L + 4.57$	$3.25 \leq L \leq 5.0$
Nov. to Dec. 1964	Eights	$\log_{10}(n_{eq}) = -0.423L + 4.40$	$2.5 \leq L \leq 5.25$
June 1965	Eights	$\log_{10}(n_{eq}) = -0.269L + 3.54$	$2.25 \leq L \leq 5.5$
June 1973	Siple	$\log_{10}(n_{eq}) = -0.359L + 3.91$	$2.25 \leq L \leq 5.75$

to-day variations in the n_{eq} level as well as in the 'effective' L value of the multipath whistler propagation contribute to the scatter in the data.

The December maxima and June minima are clear, particularly in the years 1958-1959 near solar maximum. There were exceptionally high electron densities in November 1958 when magnetic activity was temporarily low. The June minima are relatively narrow, suggesting the influence of the semiannual variation, with peaks at the equinoxes, reported by Y. Corcuff [1962]. The December-June variation of n_{eq} inferred from the data of Figure 9 is a factor of ~1.5 at $L \simeq 2.5$. Bouriot et al. [1967] reported a December-June n_{eq} difference by a factor of ~1.5 for the period 1958-1965, based on analysis of whistlers propagating at $L \simeq 2.3$ to Poitiers, France.

The data from Eights (Figure 8) appear to show a larger December-June variation at $L \simeq 2$ than do those from Stanford and Poitiers. Additional analyses are needed in order to confirm such an effect.

Annual density variations in the plasmasphere have been known since the early days of whistler research [Helliwell, 1961; Smith, 1961; Carpenter, 1962; Y. Corcuff, 1962] but still remain unexplained. A recent discussion of this problem can be found in the work by Park [1974].

Solar cycle variations. Figure 10 shows the median values of N_T and n_{eq} for the month of June 1959, 1965, and 1973. The year 1959 was near sunspot maximum (annual mean sunspot number R = 159), whereas both 1965 (R = 15) and 1973 (R = 38) were near sunspot minimum. The whistler data for the three years come from Byrd, Eights, and Siple. Evidently, plasmaspheric densities do not depend strongly on sunspot cycle beyond $L \simeq 3$. (Further conclusions are difficult to draw from Figure 10, since the 1-month periods sampled are relatively short.) At sunspot maximum, reduced H densities in the thermosphere tend to decrease upward fluxes of H^+ into the plasmasphere. In addition, the plasmasphere is depleted more frequently by magnetic disturbances at sunspot maximum. Apparently, these two effects are counterbalanced by higher ionospheric densities that tend to increase upward fluxes.

At $L < 3$ a significant solar cycle variation in the plasmasphere has been observed. The effect is shown in Figure 9; a visual 12-month running average of the D values reveals a decrease from ~80 to ~60 between 1957 and 1964. This is a mixed measure of changes in $n_{eq}^{1/2}$ at $L \simeq 2.5$ and in average whistler path location. The decrease in n_{eq} is estimated to be by a factor of ~1.5 [Carpenter, 1962], which agrees relatively well with results for $L \simeq 2.3$ of Bouriot et al. [1967] for the longitude of Poitiers. From this, and the results of Figure 10, we estimate that during the years in question the solar cycle variation was by a factor of 1.5 at $L \simeq 2$ but fell

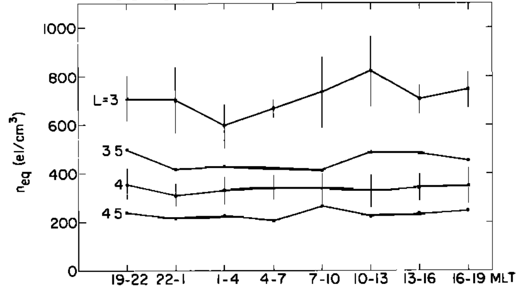

Fig. 7. Magnetic local time variations of equatorial electron density observed at Siple, Antarctica, during June 1973. Vertical bars indicate the magnitude of one standard deviation.

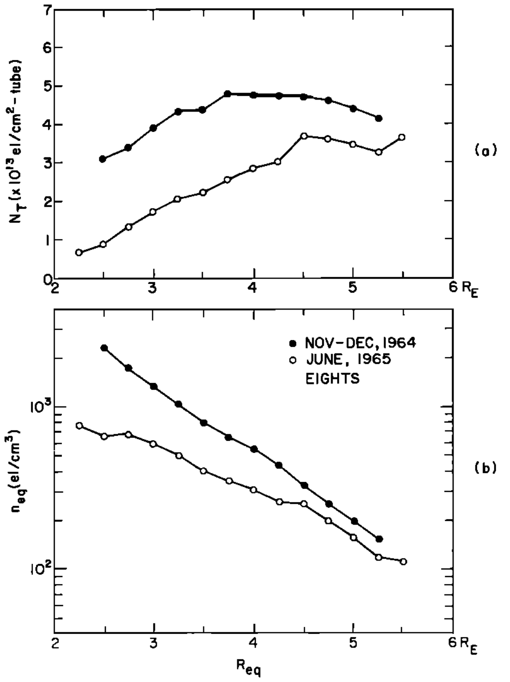

Fig. 8. A comparison at Eights of (a) median tube content and (b) equatorial electron density profiles for June 1965 and for November to December 1964.

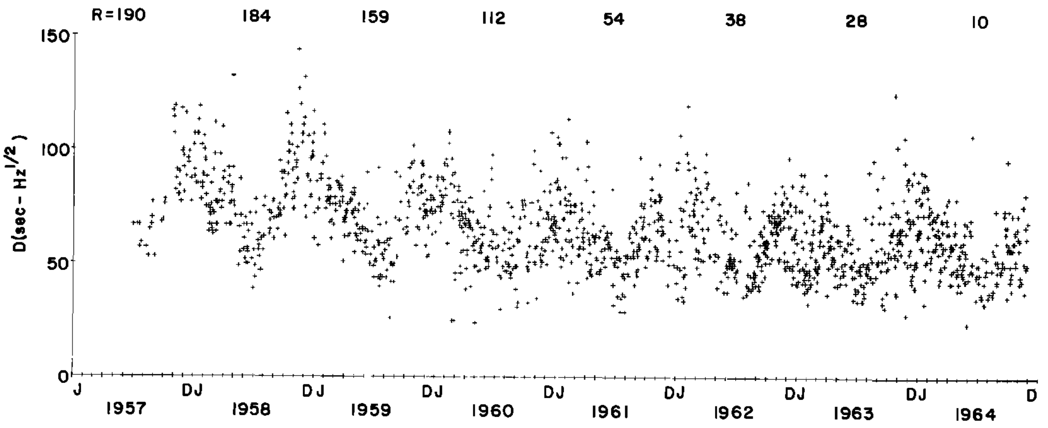

Fig. 9. Daily average values of whistler dispersion $tf^{1/2}$ measured at 5 kHz from mid-1957 through 1964. The whistlers were recorded at Stanford, California. Yearly average sunspot numbers are shown at top.

essentially to unity, that is, to no variation, at L ≃ 4.

5. Discussion and Concluding Remarks

The foregoing results are presented as a general reference on plasmaspheric density and tube content. We believe that the results can be used with confidence in studies requiring estimates of plasmasphere electron density levels. The mass plot of data from one month (Figure 2) is consistent with studies in which data were sorted according to local time and magnetic disturbance activity and is consistent with current models of protonosphere-ionosphere interchange of ionization. In cases in which the whistler method could be compared directly with simultaneous or near-simultaneous results from a satellite-borne ion mass spectrometer [P. Corcuff et al., 1972; Carpenter and Chappell, 1973] and with ULF techniques [Webb et al., 1977], the results have been in good agreement.

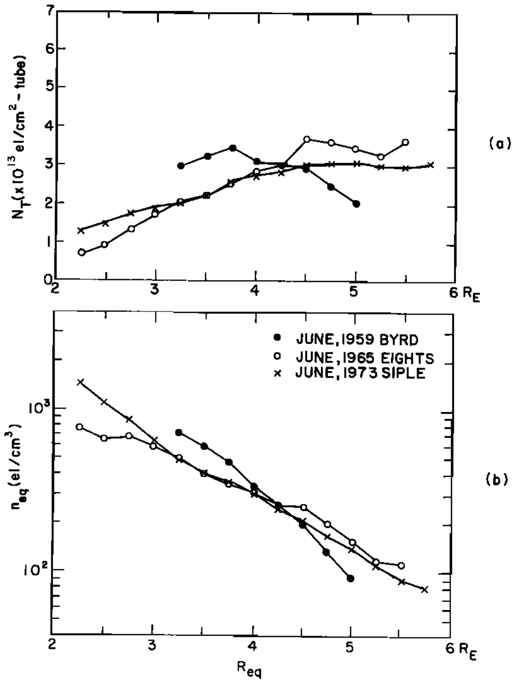

Fig. 10. (a) Monthly median tube content and (b) equatorial electron density profiles for the month of June in 1959, 1965, and 1973.

Electron density at any given time could, of course, be significantly different from the average values given in this paper. However, if there is a need to assume electron density values, it is important to bear in mind that the whistler data show well-defined upper limits, as illustrated in Figure 2. These upper limits are also useful in comparing electron density measurements obtained by various techniques.

Little is known of plasmasphere density variations with longitude. Current VLF probing campaigns at spaced longitudes (that are being conducted as a part of the International Magnetospheric Study) should lead to important new knowledge in this area. For present modeling purposes we speculate that worldwide variations in mean plasmasphere density levels are not large. We note that the quiet day density levels near L = 4 published for Alaska meridians (~160°W geographic) by Morgan [1976] and for the vicinity of Kerguelen Island (≃70°E geographic) by P. Corcuff et al. [1972] agree well with the numbers reported here.

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