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THE EARLY EFFECTS OF INCREASING SOLAR ACTIVITY UPON THE TEMPERATURE AND DENSITY OF THE 1000 KILOMETER IONOSPHERE

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ABSTRACT

Observations of electron temperature and concentration at 1000 km carried out continuously since October 1964 by electrostatic probes on Explorer XXII have permitted certain ionospheric effects of increasing solar activity to be detected. Midday and midnight measurements throughout the latitude range of approximately 60°N to 60°S for one month periods in January 1965, 1966 and 1967 are presented. Comparison of these latitude profiles shows that the daytime electron density at 1000 km increases with solar activity at all latitudes while the electron temperature increases initially (in the period from 1965 to 1966) but then decreases (1966 to 1967). The nighttime ionosphere is less affected by the increased solar activity, although N_e decreases somewhat and T_e increases slightly. This behavior of the 1000 km ionosphere can be understood qualitatively in terms of the changing composition and density of the neutral atmosphere, which in turn is caused by the increase in neutral temperature during this period of increasing solar activity. A factor of prime importance for the electron temperature is the early escape of neutral hydrogen which reduces the effective local cooling of electrons and permits T_e to rise

initially. The higher gas temperatures associated with further increases in solar activity cause enhancement of the heavier neutral constituents (O, He) which again increases the local electron cooling and results in a return to lower electron temperatures.

INTRODUCTION

The Explorer XXII satellite (known also as Beacon Explorer-B) was launched on October 10, 1964 into a nearly circular orbit at an altitude of 1000 kilometers having an orbital inclination of about 80°. In addition to the radio beacons employed for Doppler and Faraday rotation measurements, the spacecraft carried a pair of cylindrical electrostatic probes for the measurement of electron temperature T_e and density N_e. Brace and Reddy (1965) employed earlier measurements from this satellite to derive the latitudinal behavior of T_e and N_e at midday and midnight during solar minimum. Brace, Reddy and Mayr (1967) presented a much more extensive body of probe measurements which described the entire diurnal behavior of T_e and N_e for two consecutive seasons (Winter 1964 through Spring 1965) at solar minimum. In this paper we present more recent observations from the same experiment which describe the behavior of the 1000 kilometer level during the period of rising solar activity between January 1965 and January 1967.

THE EXPERIMENT

The theory of the cylindrical probe experiment and its implementation have been discussed extensively elsewhere (Spencer, et al., 1965) (Brace, Reddy, 1966) (Brace, Reddy, Findlay, 1967), therefore only a brief description is given here.

The experiment consists of two long, thin cylindrical collectors which protrude from opposite ends of the spacecraft. A sawtooth voltage is applied to one collector at a time and the resulting current collected from the plasma is measured and telemetered to earth, where it is recorded for later analysis in terms of the electron temperature (T_e) and concentration (N_e). Two collectors are employed to ensure that non-wake measurements will always be available.

The current sensitivities and applied voltages employed in the instrument are such that T_e can be determined when N_e lies in the range $1x10^3$-$1x10^5$/cc and N_e can be derived when it lies in the range $1x10^2$-$4x10^4$/cc. The accuracy of the measurement depends upon many factors such as telemetry noise level on the particular pass and the variation of current resolution with density; however the typical relative accuracy of T_e and of N_e is about 5%. The absolute accuracy of T_e is believed better than 10% and of N_e is about 20%. Comparison of N_e results with plasma resonance measurements by Alouette I (Nelms, private communication) indicates that our N_e values may be about 20% high at the relatively low values of N_e encountered in the Explorer XXII orbit. At higher densities the absolute accuracy is better than 10% (Spencer, et al., 1965). No correction for this effect is made in the density data presented here.

RESOLUTION OF SOLAR ACTIVITY

To appreciate why the data from this satellite are particularly valuable for the study of solar activity effects, one must consider the nature of the orbit and its long-term motions. The near circularity of the orbit (900 km perigee to 1090 km apogee) tends to suppress altitudinal effects in the data. This is especially true at higher altitudes in the ionosphere where T_e gradients are small and N_e scale heights are several times the total altitude excursion of the orbit. In spite of these advantages, altitude differences may be significant for some comparisons of data, and these will be considered in later discussion.

The orbital precession rate is particularly important to consider because it controls the phase between local time and seasonal effects in the observations. The orbital inclination of Explorer XXII (79.6°) provides a precession rate of 1° per day. When combined with the 1° per day mean motion of the earth in its orbit about the sun, this leads to an effective precession rate of 2° per day relative to the sun. Thus each leg of the orbit sweeps through all local times in six months. It is this accidental synchronism between local time sampling and the seasons which enhances the resolution of the very long-term ionospheric variations related to solar activity.

For example, the data taken from northbound passes in any particular month will correspond to the same local time year after year. The southbound half of the orbit will correspond to local times about 12 hours different, but these also will repeat year after year. It happens that the Explorer XXII orbit reaches the stable noon-midnight position in the months of January, April, July and October. The data from these months are particularly valuable as one can average over an entire month of data without significant distortion due to local time effects within these periods.

Because of the availability of data from January 1967 at the time of this writing, we have selected the January data from 1965, 1966 and 1967 to illustrate the solar cycle influence on the topside ionosphere. The solar activity effects at other seasons may be somewhat different, therefore these will be treated in a subsequent paper as later 1967 data become available. We, of course, hope that current and continuing operation of the experiment will provide this type of information for the entire range of solar activity.

THE OBSERVATIONS

The procedure for evolving the T_e and N_e behavior is the same as adopted earlier by Brace and Reddy (1965) and Brace, Reddy and Mayr (1967). The point measurements from individual passes of the satellite near ground stations are plotted versus geomagnetic latitude as shown in Figures 1 and 2 for the daytime January 1967 data. The individual measurements are made at latitude intervals of about 10°, and a typical pass covers about 50° of latitude. Those points derived from a single pass are joined by straight lines to illustrate how the instantaneous latitudinal structure differs from day to day. The origins of these day to day variations have not been identified fully, but they exceed the 5% scatter which may arise from the measurement accuracy. We have limited the display of data to magnetically quiet periods ($Ap < 15$) since it has been demonstrated that T_e and N_e vary significantly during storms (Reddy, et al., 1967). To minimize the already small longitudinal effects (Brace, et al., 1967) we have restricted our attention to the data from stations more or less along the 75th west meridian. An exception to this is our inclusion of the data from the Australian stations, the only source of data from high southern magnetic latitudes. To obtain the mean quiet behavior which is required for evaluating solar activity effects, the data from each January have been averaged. The resulting latitude profiles for the three Januaries are shown in Figure 3. The corresponding levels of solar activity are indicated by the sunspot number and the 10.7 cm flux shown in Figure 4. The range of local times of the observations in these three Januaries is indicated in Figure 5.

DISCUSSION

The primary objective of this paper is to present the experimental evidence from the Explorer XXII probe experiment which bears upon solar activity effects in the topside ionosphere. With this task completed we will now go on to consider qualitatively the origin of the structural changes which are observed.

A number of the gross features of the 1000 kilometer ionosphere appear consistently in the averaged latitudinal profiles of T_e and N_e in all three years discussed here. All of these features have been identified in the solar minimum data and were discussed in earlier papers (Brace and Reddy, 1965) (Brace, et al., 1967) and (Mayr, et al., 1967). They are the following:

1. The pronounced equatorial maximum of N_e in the daytime, and the two middle latitude maxima which form at night.

2. The equatorial minimum of T_e in the daytime, and the broad equatorial trough of very low temperature which forms at night.

Although the absolute values of temperature and density vary somewhat from year to year (Figure 3), these features persist at least through this initial period of rising solar activity.

These features of the topside ionosphere are beginning to be understood in terms of the conservation of energy and density along geomagnetic field lines. Employing the 1965 equinox data from Explorer XXII, Mayr, et al. (1967) showed that the latitudinal structure of T_e is coupled to the latitudinal distribution of ion composition. Furthermore, both the electron temperature and the ion composition were found to be sensitive to the composition of the neutral atmosphere in the upper F-region, especially to the concentrations of atomic hydrogen and oxygen which are important in the charge exchange process as the main source for protons. The interaction of composition and electron temperature arises primarily from the dependence of the electron cooling rates upon the kinds of ions and neutrals present. A quantitative understanding of this interaction was attained by Mayr et al. by performing simultaneous solutions of the energy and particle continuity equations along several appropriately chosen field lines. It was found that the latitudinal variation of electron temperature and ion composition are a natural result of the different particle and energy balance along the various field lines and that this arises from the configuration of the geomagnetic field itself. For example, electrons distributed along the shorted field lines that lie entirely within the dense neutral atmosphere are subjected to significantly different local cooling effects than those which populate the longer field lines. Therefore, the equilibrium temperature and ion composition profiles along different field lines vary strongly with latitude. A satellite like Explorer XXII which crosses the various field lines at a fixed altitude encounters significant latitudinal variation in temperature, density and ion composition.

Although these considerations of particle and energy balance provide valuable insight into the relationship between ion composition, neutral composition and electron and ion temperature in the topside ionosphere, they cannot provide a truly quantitative explanation of the observed 1000 kilometer behavior. The topside ionosphere is strongly a product of the processes occurring at lower altitudes in the F-region. Most of the thermal energy at 1000 kilometer is released in the lower and much denser regions of the atmosphere where ultraviolet radiation produces the photoelectrons which eventually heat the topside electrons. The topside electrons themselves are produced primarily in the region of the F_2 maximum. This region was not considered by Mayr, et al. (1967) and must be included before a definitive explanation of the topside ionosphere is possible. In this paper we will not attempt to interpret the effects of solar activity in terms of this more complete and more complex problem. We will instead present a more qualitative interpretation in terms of the processes which occur entirely within the topside region itself following Mayr, et al. (1967).

Description of Solar Activity Effects

The electron temperature is the first parameter to show the effects of increasing solar activity (Figure 3). The daytime temperature increased by more than 1000°K over the entire latitude range between January 1965 (dots) and January 1966 (dashes), an increase which appears far out of proportion to the small change in solar flux shown in Figure 4. This initial increase was followed in January 1967 by a general decrease of about 400°K, in spite of the continued increase in solar flux.

The nighttime temperatures also increased between 1965 and 1966, but changed little between 1966 and 1967. The increase was more pronounced at middle and high latitudes, a factor which tended to narrow the broad nighttime trough that was characteristic of solar minimum.

The daytime electron densities (Figure 3) behaved quite differently from the temperature over this period. N_e decreased slightly between 1965 and 1966 in apparent conflict with the large increase observed in T_e. A large increase in daytime N_e occurred between 1966 and 1967, again in spite of the moderate decrease in T_e over this period.

The nighttime density decreased markedly at all latitudes between January 1965 and January 1966 but then apparently increased again in 1967. It will be noted later that most if not all of this increase in 1967 can be attributed to the lower altitude of the satellite in those particular observations. The greatest changes between 1966 and 1967 occurred at middle latitudes where the nighttime

N_e maxima are formed. These peaks of density were near 35° geomagnetic latitude during solar minimum and appeared to move toward the equator through this entire period. The maxima are near 26° in January 1967.

The Diurnal Variation

Very significant changes in the total diurnal variation are evident through this period of increasing solar activity. In 1965 the nighttime N_e at middle latitudes exceeded the daytime values; in 1966, there was little diurnal variation at middle latitudes; and in 1967, the daytime N_e greatly exceeded the nighttime N_e. This was the major change in the diurnal variation at the 1000 kilometer level and was mostly the result of the ever-increasing daytime density through this period.

Figure 6 summarizes these results for the three latitudes of 45°N, 0°, and 45°S geomagnetic. The altitudes of observation corresponding to these latitudes are shown in Figure 7. The hatched area represents the ranges of altitude corresponding to the actual data employed from each January. It will be seen later that the year to year variation shown in Figure 3, and summarized in Figure 6, are too great or in the wrong sense to be primarily altitudinal in origin. The single exception to this is the nighttime 1967 data noted earlier.

INTERPRETATION

The latitudinal and diurnal behavior indicated by these observations is believed to be consistent with the following response of the atmosphere to increasing solar activity.

At solar minimum (January 1965 in this set of data), the daytime gas temperature is about 800°K (Jacchia, 1964). Neutral hydrogen is abundant in the atmosphere, owing to its low escape rate at low temperature. The heavier neutrals, H_e and O, are present at 1000 kilometers in concentrations similar to that of H. Protons, which are created at lower altitudes by charge exchange with O^+ and by photo ionization of H, are also abundant. As a result of this, and the relatively low temperature and scale height of the F region, the lower boundary of the protonosphere remains well below the altitude of these observations over a wide range of geomagnetic latitude (40°N to 40°S in the daytime and 50°N to 50°S at night). The resulting low mean ion mass and the corresponding large scale heights in the region below cause the electron density at the altitude of this satellite to be moderately high in 1965, despite the low electron temperature. The presence of H^+ as the major ion contributes to the low T_e by providing the electrons with an effective local cooling path to the neutral atmosphere (Mayr, et al. 1967).

In January 1966 the sunspot number and decimeter flux index have begun to rise (Figure 4) and the neutral gas temperature is about 900°K in the daytime. This increase in gas temperature produces a greater escape of hydrogen from the exosphere and results in a reduction of the proton content, an upward movement of the O^+-H^+ boundary and therefore an increase in the mean ion mass at all levels. The less efficient local cooling of electrons to O^+ and O permits a great increase in T_e in the daytime and some increase at night. However, the increased mean ion mass is sufficient to more than compensate for the rise in T_e and the topside scale height decreases in 1966. As a result, the electron density at 1000 kilometers actually decreases slightly in 1966, both day and night.

By January 1967, the rise in solar activity is well underway and the gas temperature is about 1000°K in the daytime. Further escape of hydrogen and expansion of the neutral atmosphere has moved the protonosphere boundary to altitudes well above that of the orbit, at least in the daytime. Increased ionization in the F region contributes to the lifting of the protonosphere and increases the daytime electron density. In spite of the less effective cooling rates provided by the heavier ions and neutrals, and the possible increase in local heating by escaping photoelectrons, the greater abundance of O^+ and O provides sufficient additional local cooling to lower the electron temperature in 1967.

The Nighttime

There are a number of aspects of the nighttime behavior which require separate discussion. It appears that the slightly increased temperature at all latitudes at night is greater than the expected increase in gas temperature through this period. This is not particularly surprising since the electrons are not in thermal equilibrium with the neutral gas, even at solar minimum. The source of the higher electron temperatures, especially evident at higher latitudes, is still a matter of conjecture. Brace and Reddy (1965) and Brace, et al. (1967) have suggested that the nighttime temperature peaks at 55° geomagnetic latitude might be due to conduction downward from the protonosphere. The heat may also reflect particle precipitation near the inner edge of the outer radiation belt. In any case, a nocturnal source exists which is latitudinally dependent. It would not be surprising to find that it also varied with solar activity.

The flat-bottomed equatorial trough of T_e observed during solar minimum offered some encouragement to the belief that thermal equilibrium existed at night over a wide range of low latitudes. Two factors seem to preclude this possibility; (1) the nighttime temperatures at southern latitudes tended to be significantly lower than those observed at similar northern latitudes, and (2) the night-to-night variation at each location, although greater than the experimental error, was several hundred degrees. Neither of these is likely to be characteristic of the temperature of the neutral atmosphere. Therefore we conclude that the general increase in nighttime temperature observed through this period primarily reflects changes in the nocturnal heat source during this period.

As noted earlier, the nighttime behavior of electron density with changing solar activity is not reflected accurately in Figure 3, especially with respect to the 1967 data. This arises from the small altitude differences in these three Januaries, and is enhanced by the much lower scale heights which are characteristic of the nighttime in 1967. The 1967 observations were taken at an average altitude of about 940 kilometers. This is about 30 kilometers below the 1965 data and 100 kilometers below the 1966 data. Assuming a nighttime scale height of 400 kilometers at the satellite, the entire 1967 profile of nighttime N_e should be displaced downward by about 20% to make a more realistic comparison with 1966 data. With this correction, one finds that there was little change in nighttime N_e between 1966 and 1967. This is a bit surprising in view of the decreasing scale height associated with the heavier ions present in 1967 as the lower boundary of the protonosphere continued to move upward. We assume that enhanced F region ionization through this period was sufficient to balance the reduced scale heights, although no detailed study of ionosonde data has been attempted to verify this.

SUMMARY AND CONCLUSIONS

The Explorer XXII probe measurements of electron temperature and density in these three Januaries following solar minimum reflect significant changes in the structure of the ionosphere at the 1000 kilometer level. A monotonic increase in daytime density through these years was accompanied by an initial rise and a later fall in electron temperature. A general decrease in nighttime electron density accompanied an increase in temperature. These effects are qualitatively consistent with the expected changes in the temperature and composition of the neutral atmosphere through this period. The higher neutral gas temperatures lead to escape of neutral hydrogen, an upward expansion of the heavier constituents and corresponding changes in ion composition. The heavier ions and neutrals provide less effective electron cooling, and this in turn causes a change in the energy balance and particle distributions along the various field lines.

A more quantitative treatment of these solar activity effects awaits the availability of more extensive and more precise experimental definition of both the neutral and charged particle structure and behavior throughout the F-region. Detailed study of the neutral atmosphere has been severely limited by the scarcity of satellite measurements of neutral composition and density. In the absence of direct simultaneous measurements of the neutral atmosphere, one can little more than speculate about the control it exerts upon the ionosphere. If further investigations show that the topside ionosphere is as sensitive to the neutral atmosphere as our interpretation of Explorer XXII data suggests, the extensive body of ionosphere measurements now being accumulated by satellites will become an invaluable source of information about the behavior of the high neutral atmosphere itself. As an example of this, Brace, et al. (1967) were able to conclude from Explorer XXII probe measurements that the concentration of neutral hydrogen in the atmosphere at solar minimum is much higher than had been expected. This conclusion was later confirmed by satellite-borne neutral mass-spectrometer measurements from the Explorer XXXII satellite (Reber, et al., 1967).

ACKNOWLEDGMENTS

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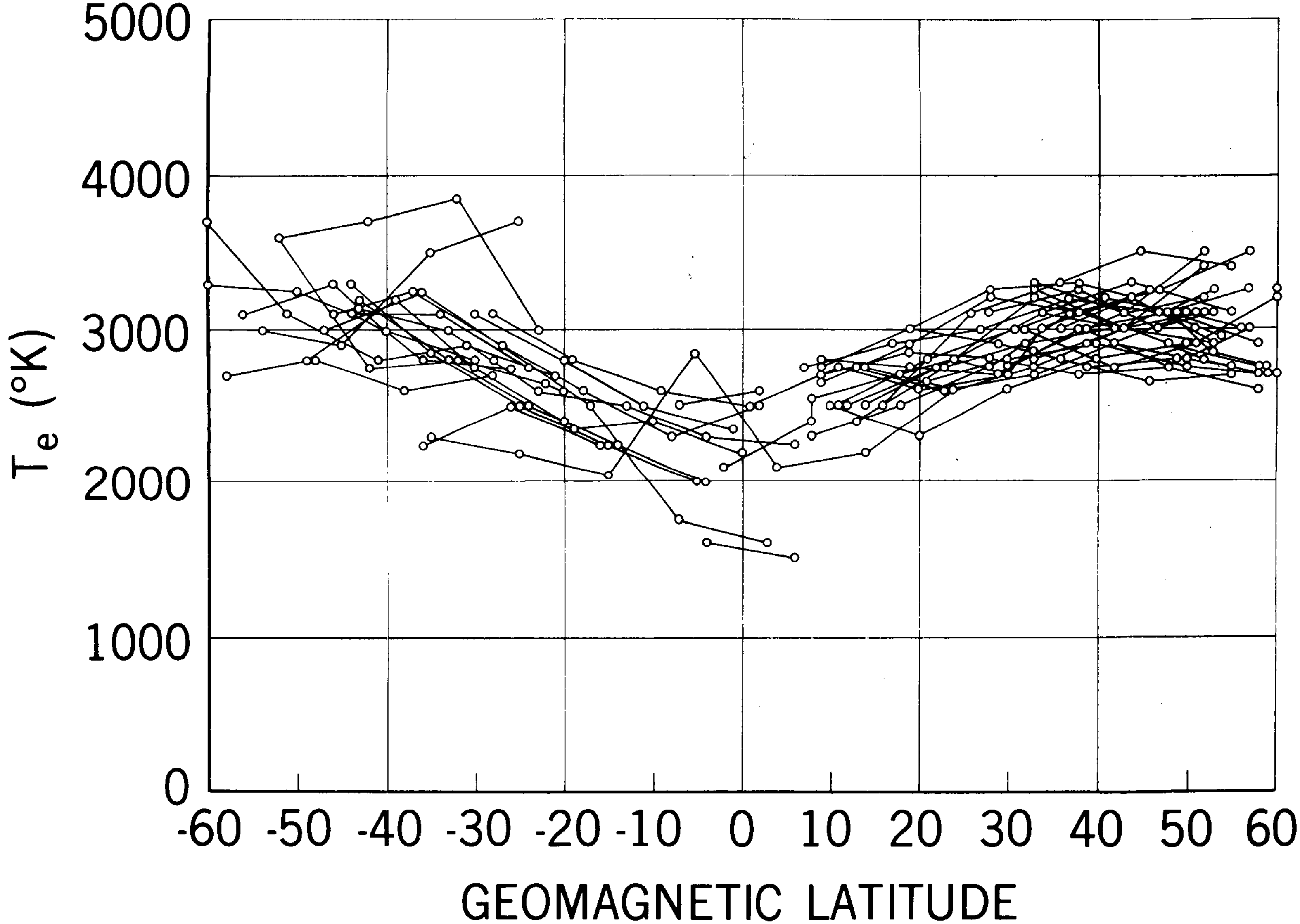
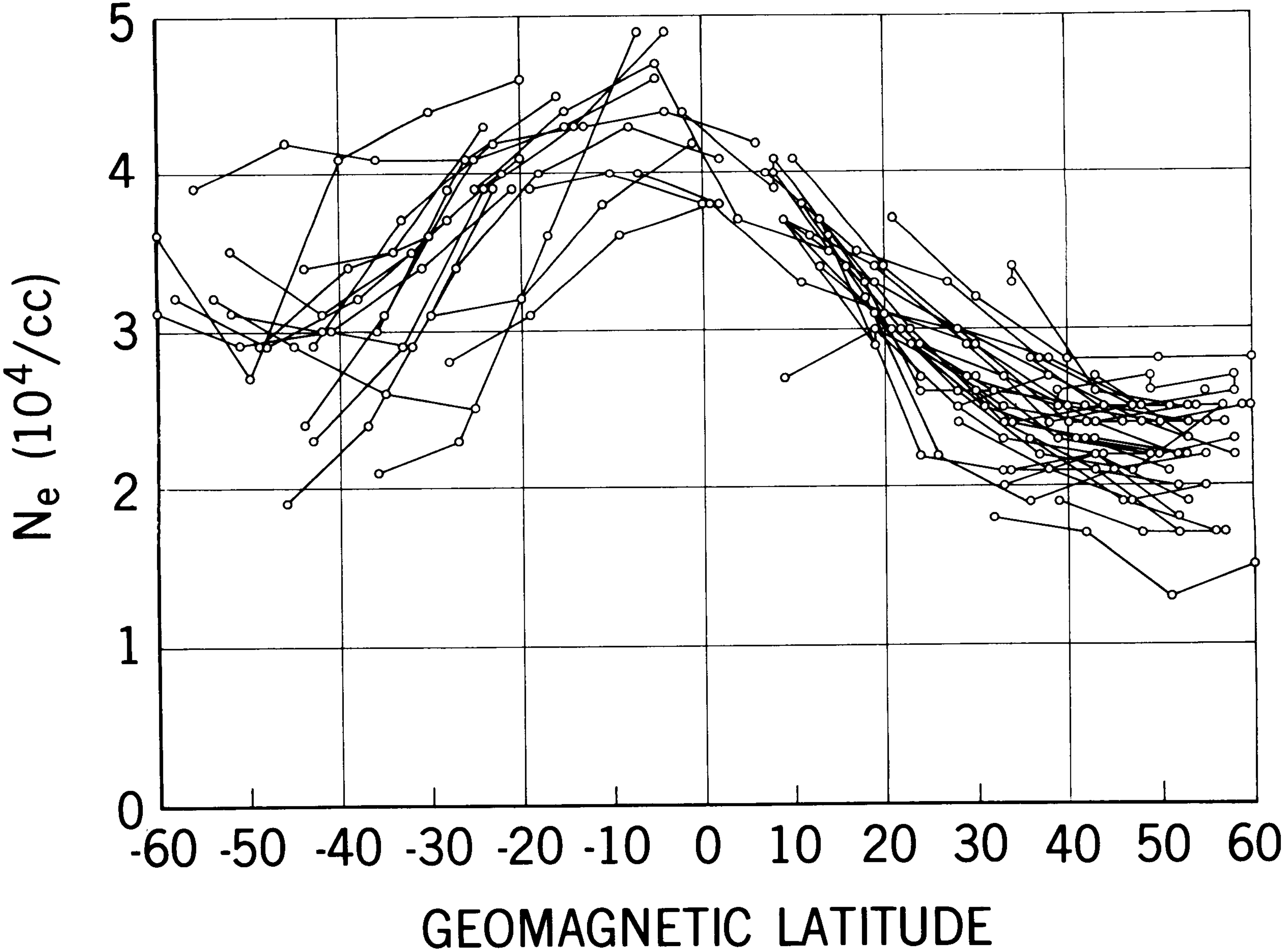
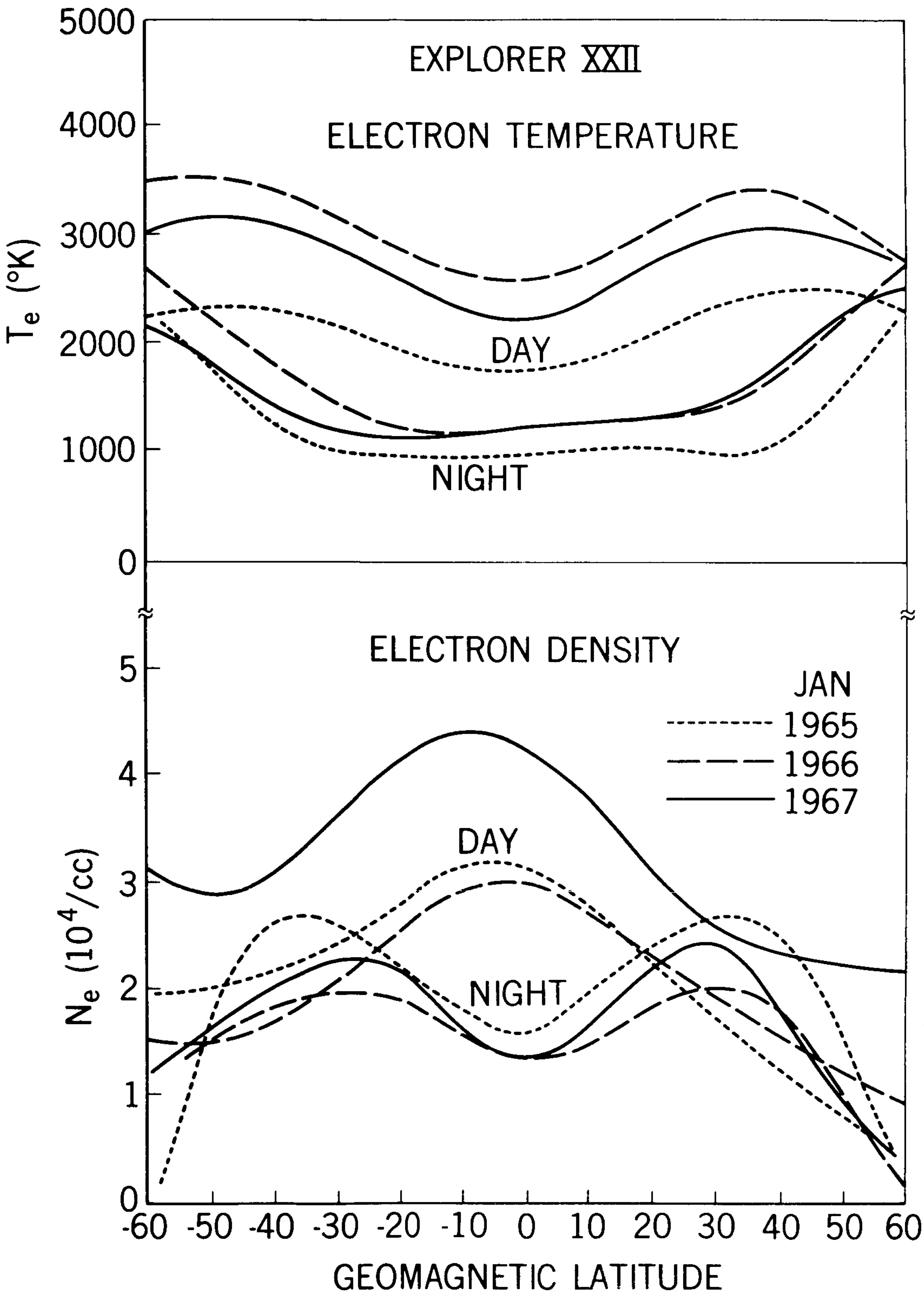
FIGURE CAPTIONS

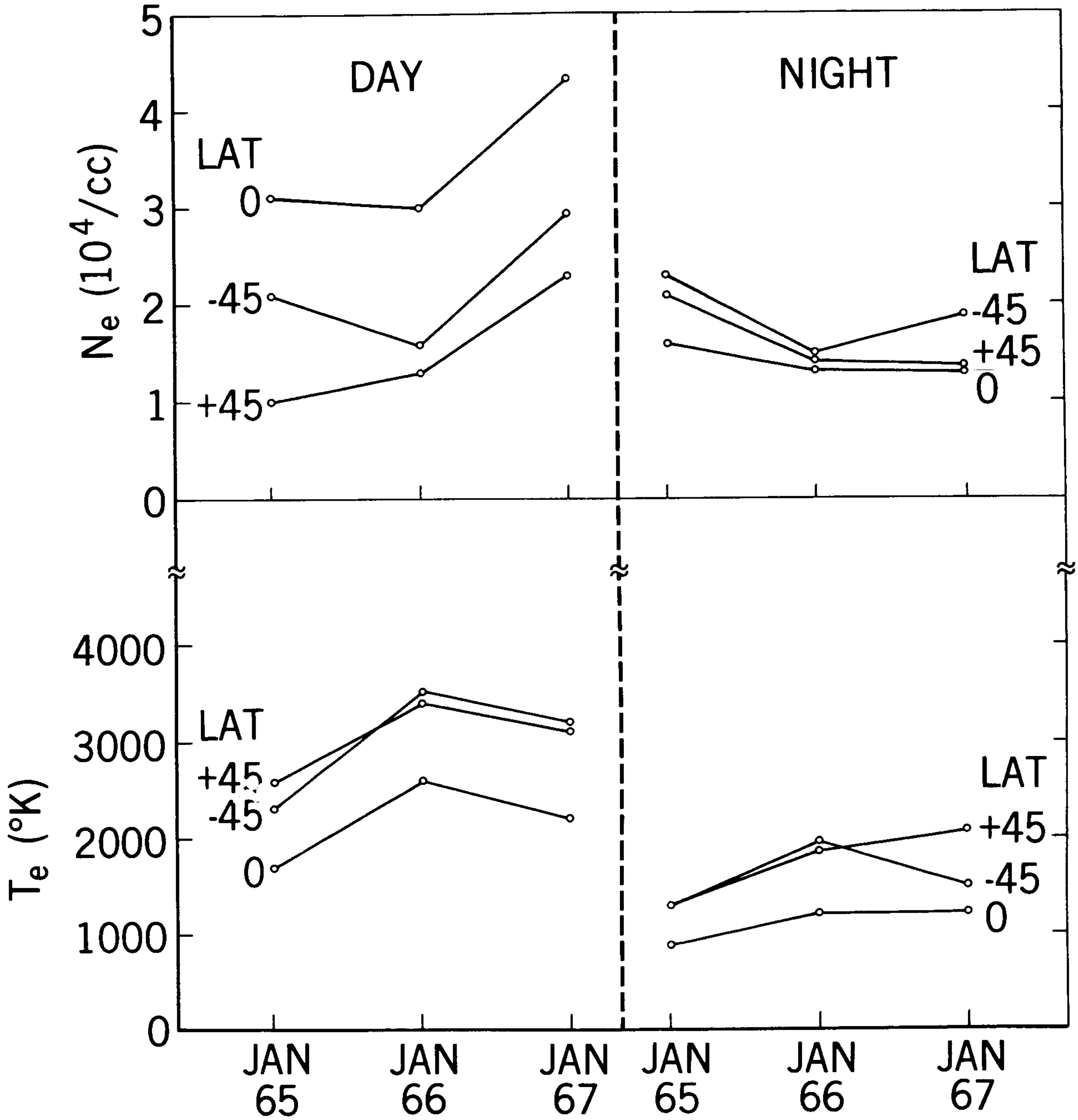
1. Daytime electron temperature measurements from January 1967. The points which are joined by lines represent measurements from the same pass of the satellite.
2. Daytime electron density measurements corresponding to the same January 1967 passes as employed in Figure 1.
3. Average behavior of T_e and N_e in January 1965, 1966 and 1967.
4. Levels of solar activity as indicated by the sunspot number (R) and the decimeter flux (Flux $\bar{S}$) for the three Januaries of the measurements.
5. Local time range of the observations in January 1965, 1966 and 1967, shown in Figure 3.
6. Summary of T_e and N_e behavior at the three geomagnetic latitudes, 45°N, 0° and 45°S.
7. The altitudes of the observations at 45°N, 0° and 45°S geomagnetic latitude.


5000
4000
3000
2000
1000
0
T_e (°K)
-60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60
GEOMAGNETIC LATITUDE

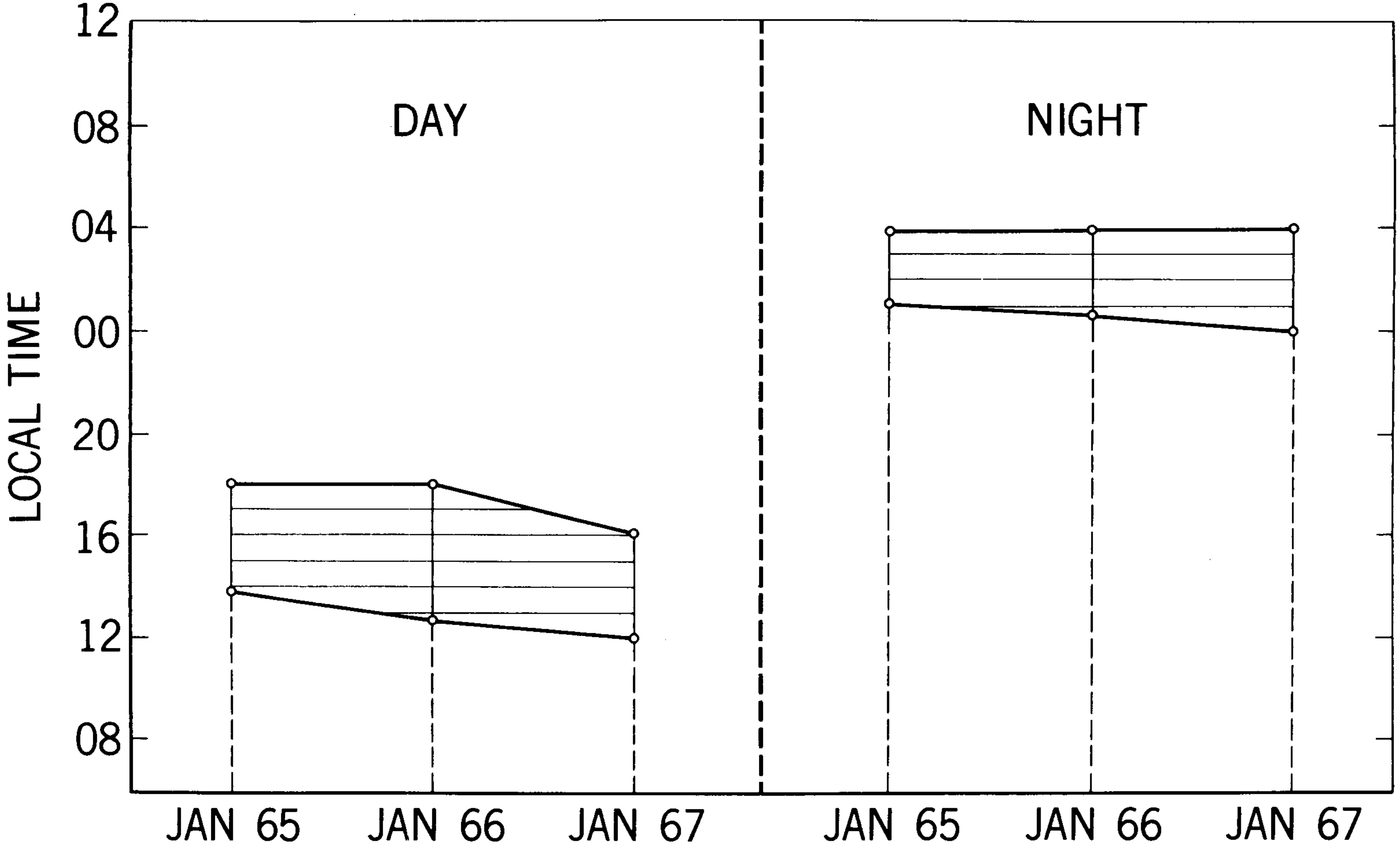


5
4
3
2
1
0
N_e (10^4/cc)
-60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60
GEOMAGNETIC LATITUDE

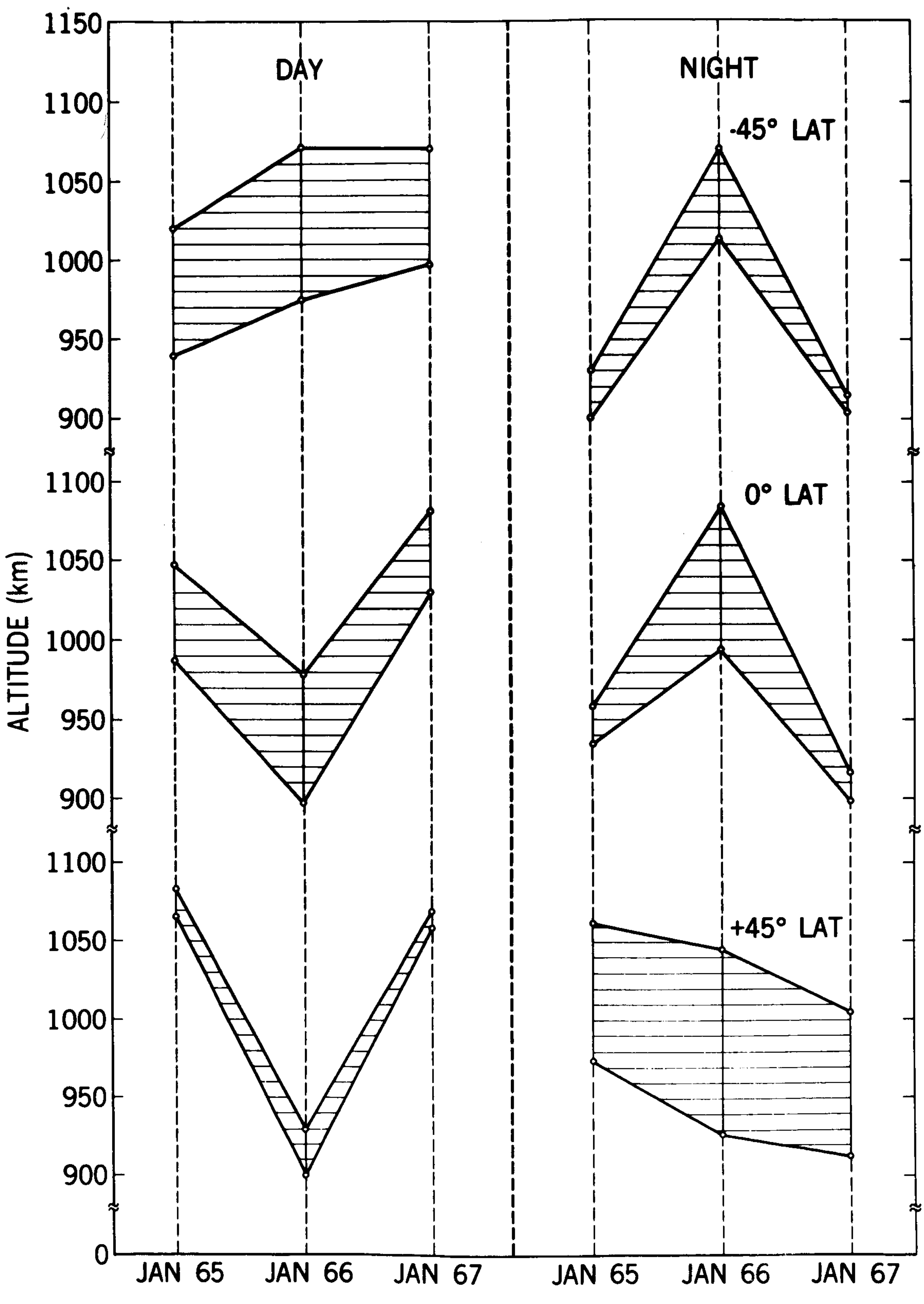

EXPLORER XXII
ELECTRON TEMPERATURE
T_e (°K)
5000
4000
3000
2000
1000
0
DAY
NIGHT
ELECTRON DENSITY
N_e (10^4/cc)
5
4
3
2
1
0
JAN
1965
1966
1967
DAY
NIGHT
-60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60
GEOMAGNETIC LATITUDE



DAY
NIGHT
LAT
0
-45
+45
LAT
-45
+45
0
N_e (10^4/cc)
5
4
3
2
1
0
LAT
+45
-45
0
LAT
+45
-45
0
T_e (°K)
4000
3000
2000
1000
0
JAN 65
JAN 66
JAN 67
JAN 65
JAN 66
JAN 67



Pub. 0838-8 Fig. 5



DAY
NIGHT
-45° LAT
0° LAT
+45° LAT
ALTITUDE (km)
1150
1100
1050
1000
950
900
0
JAN 65
JAN 66
JAN 67