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THE DAYSIDE MIDLATITUDE PLASMA TROUGH

NATHAN J. MILLER

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Thermosphere and Exosphere Branch

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ABSTRACT

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The electrostatic probe experiment aboard the ISIS-1 satellite detects a quasi-stable dayside plasma trough in the protonosphere with a characteristic time of at least 2 weeks. This behavior contrasts with measurements at 1000 km from Explorer-22, which indicate a trough of a characteristic time less than a satellite orbit period. Associated with the protonospheric trough is an electron temperature maximum ~6000°K that is sharp at midnight and broad at noon. In spring and summer, a second noontime temperature maximum often appears poleward of 70° invariant latitude, accompanied by an enhancement in the ionization. Considering the protonospheric trough as part of the low-altitude plasmaspheric boundary, it is noted that the spatial and temporal characteristics of the trough differ from those at the equatorial plasmaspheric boundary. In particular, the time dependence of the protonospheric trough does not suggest an expansion of the plasmasphere in the dusk time sector. Assuming that the geophysical process producing a plasmasphere acts most directly upon the light ions, one factor causing the distinction between the plasma trough and the equatorial plasmapause is the increasing influence of O^+ on total plasma behavior at lower altitudes. The ISIS-1 data indicates that local processes such as dayside F-region photoionization and ionization by energetic cusp particles produce enhancements in plasma density and electron temperature. These enhancements modify the plasmaspheric boundary to varying degrees along a magnetic field tube, thus leading to a plasmaspheric boundary with distinctive features at various positions along a field tube.

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THE DAYSIDE MIDLATITUDE PLASMA TROUGH

INTRODUCTION

There is a general feeling among atmospheric scientists that both the equatorial plasmapause (Carpenter, 1963) and the midlatitude plasma trough (Muldrew, 1965) result from the effects of a common geophysical mechanism acting on the thermal plasma. In this context, each phenomenon is viewed as a feature associated with the outer limits of the plasmasphere. Despite the possible phenomenological link between the equatorward edge of the trough and the equatorial plasmapause, ionization processes and plasma transport sufficiently modify the density distribution at differing altitudes within a magnetic flux tube to produce low and high altitude plasmaspheric boundaries with configurations that are often dissimilar and display divergent local time patterns (Jelly and Petrie, 1969).

Researchers find that on the macroscopic scale, what is referred to as the plasma trough can appear as either a broad polar depression (Miller and Brace, 1969) or as a U-shaped trough (Tulunay and Sayers, 1971), whereas the region beyond the equatorial plasmapause appears as a general depression in the basic plasma density even though clouds of enhanced ionization have been measured. (Taylor et al., 1970; Chappell et al., 1970; Chappell et al., 1971; Chappell, 1972). The equatorial plasmapause is observed at a wide range of local times (Carpenter, 1963). The plasma trough has been most distinctly seen on the nightside. The trough has been detected in electron density distributions at the F_2 peak (Muldrew, 1965) and below (Bowman, 1969); it has been detected in total ion density in the F-region (Sharp, 1966) and in individual ion species at altitudes below 1000 km (Taylor et al., 1968); it has been detected in total electron content below 1000 km (Liszka, 1967) and in electron density measurements at 1000 km (Miller and Brace, 1970).

A dayside plasma trough is not as readily observable as the nightside trough. However, among individual ion species, a persistent dayside H^+ density trough is observed (Taylor, 1972). The accumulated evidence implies that the mechanism responsible for a plasmapause phenomenon is one which primarily affects the light ions, H^+ and $H_e{}^+$ (Taylor and Walsh, 1972). By combining ion mass spectrometer measurements with simultaneous VLF detection of the plasmapause, researchers find that both the low altitude light ion trough and the high altitude plasmapause fall on the same L-shell during specific local times (Carpenter et al., 1969; Taylor et al., 1969). One expects, then that above some altitude the light ion trough evolves into a total plasma density trough that is stable on the dayside to the same extent as on the nightside. This report presents quiet-time data ($A_p \leq 12$) that display a dayside-plasma density distribution that is quasi-stable over at least a 2 week period.

The purpose in reporting these plasma trough observations is to suggest that the altitude regime between 2500 and 3500 km is one in which a quasi-stable dayside plasma trough is detectable. However, the evidence does not suggest a 1:1 correlation between the time dependance of the plasma trough and that of the equatorial plasmapause. Electron density (N_e) and electron temperature (T_e) distributions are displayed in invariant latitude. The measurements come from the electrostatic probe experiment aboard the ISIS-1 satellite with emphasis on data taken in the noon-midnight and dawn-dusk meridians during the years 1969 and 1970. Samples of Explorer-22 data taken at 1000 km are also included as specific examples of the structural difference in the plasma trough configuration at altitudes where O^+ has a strong influence on the plasma behavior.

THE EXPERIMENT

ISIS-1, launched in January 1969, has an 88° orbital inclination and perigee and apogee altitudes of 600 km and 3500 km, respectively. On ISIS-1, two probes measure N_e and T_e at the mounting positions shown in Figure 1. The use of satellite and rocket-borne electrostatic probes to determine N_e and T_e is discussed by Brace and Spencer (1964), Spencer et al. (1965), and Brace and Reddy (1965).

The satellite probes operate in alternate 2-minute intervals. A sawtooth voltage, swept from -2 volts to +10 volts in 2 seconds, is applied to a probe. The sweep period is sufficient to allow for the generation of 10-volt-ampere curves during a satellite rotation. The probe sensitivity is sequenced through four levels with a single level selected for the N_e determinations and a separate level selected for the T_e determinations. The final values of N_e and T_e determined for the 2-minute interval when a probe is active are averages of the values deduced from each unwaked volt-ampere curve. Each value of N_e and T_e is taken as a representative parameter for a 240 km segment along the satellite orbit. The time-averaged parameters are spatially separated by about 9° in invariant latitude, making them best suited to the study of time-averaged macroscopic plasma properties rather than to the study of rapid time variations or of microstructure. The boom probe is less susceptible than the axial probe to satellite induced perturbations because of its mounting position. Therefore, only values of N_e and T_e taken from measurements made with the unwaked boom probe are used in this study. Details on the expressions used to calculate N_e and T_e from volt·ampere curves, plus a detailed discussion of the electrostatic probe experiment on ISIS-1, can be fround in Brace et al. (1973).

EXPERIMENTAL RESULTS

Plotted in Figure 2 are N_e and T_e values determined at 1000 km with the Explorer-22 probe experiment. Data points associated with the same satellite pass are connected by straight lines so that individual latitude profiles can be seen. Though it is clear that a trough is present, the location is not certain, and the density gradients associated with the individual passes are not steep. The most that can be determined is that sometimes there is an apparent density minimum. The data are separated into longitude bands in order to make it clear that any variability among the observed trough configurations is a temporal characteristic rather than a longitude effect. Figure 3 demonstrates that even on the nightside of the noon-midnight meridian the trough configuration at 1000 km contains a high degree of variability.

Measurements made in the 2500- to 3500-km altitude range during the spring equinox contrast with those made at 1000 km during a similar equinox period. In Figure 4, high-altitude data from the dayside of the noon-midnight meridian display a quasi-stable plasma trough. In addition, the electron temperatures suggest a latitude structure consisting of a temperature minimum between two maxima, one associated with the equatorward edge of the trough and the other associated with the density increase poleward of the 70° invariant latitude.

The winter trough structure in Figure 5 shows some contrasts with the spring structure. High temperatures persist in the trough as in the spring, but the extra enhancement in density poleward of 70° invariant latitude is mostly nonexistent, resulting in a configuration that is more akin to an equatorial plasmapause than to a U-shaped trough.

Finally, summer trough structure for day and night are shown in Figures 6 and 7. The dayside trough in Figure 6 implies a density minimum near 70° invariant latitude, which is poleward of the locations in spring and winter for similar local times. However, the temperature structure follows the same trend as that for the spring data with the position of the temperature minimum unaltered. The nightside trough shows a broad polar depression in the plasma density that is barely affected by the fact that photoionization is occurring at the base of those field lines passing through the sunlit F-region. The temperature structure contains the T_e maximum that has been associated with the nightside trough.

When studying plasma trough characteristics, a natural question to pursue is whether this trough shows promise of following the kind of local time dependence generally ascribed to the equatorial plasmapause. The equatorial plasmapause contains a bulge in the dusk sector; thus if a similar bulge is not obvious in the time dependence of the trough location there is little chance of a time correlation between the trough and the plasmapause. Directly comparing quiet-time trough locations in the dawn and dusk time segments should give an indication of the existence of a plasmaspheric bulge at 3000 km. Probe data from the dawn-dusk meridian in the Southern Hemisphere are directly compared in Figure 8. If the time averaged trough configuration is studied on the time scale of a single orbit pass, individual dawn-dusk comparisons from the same pass can be made as in Figure 9. The data displays no evidence of a bulge in the dusk sector.

DISCUSSION

The inner ionized atmosphere, extending to roughly 1000 km, is referred to as the regular ionosphere (Carpenter and Park, 1973). This atmospheric region is one in which O^+ exerts a heavy influence upon the plasma properties of the atmosphere. Beyond the regular ionosphere, H^+ eventually becomes the major ion and exerts the dominant ion influence upon the plasma distribution. The significance of ion composition in determining the distribution of thermal plasma about the earth is demonstrated by the variations in the form of the plasmaspheric boundary at different altitudes, e.g., the contrast between the density structure of the equatorial plasmapause produced in H^+ and that of the midlatitude plasma trough produced in a mixed O^+, H^+ environment.

When comparing pass to pass observations of the dayside plasma trough at 1000 km, one can see within the Explorer-22 probe results an indication that the characteristic time is on the order of the satellite orbiting period. Even the nightside trough at 1000 km does not appear as stable as the dayside trough at 3000 km. Those field tubes that pass through the sunlit F-region exhibit the effects of photoionization through a general increase in trough densities poleward of the 65° geomagnetic latitude. The probe data implies that the Explorer-22 experiment is operating at the edge of the regular ionosphere in a region where the plasma distribution is highly sensitive to the level of photoionization activity within the F-layer and to the interaction of O^+ with the geomagnetic and geoelectric fields.

The outer ionized atmosphere extends from the top of the regular ionosphere to the magnetopause. This altitude region, containing both thermal ions and trapped energetic particles, is referred to as the magnetosphere or protonosphere. The ISIS-1 data, which serves as the basis for this report, is representative of the probe measurements in the altitude range 2500 to 3500 km. Figures 4 to 7 illustrate that the superposition of 2 or more weeks of satellite data within a 2-hour local time frame shows general agreement on the configuration and location of the density trough, even though there may have been fluctuations in the K_p. The quasi-stable latitude profiles of N_e suggest that the plasma trough configuration in the protonosphere has a characteristic time of at least 2 weeks. This stability apparently continues through all seasons.

Seasonal differences in the dayside trough minimum indicate a density level on the order of 0.5×10^3/cc in the winter increasing to 1.5×10^3/cc in the summer. An indication of ionization by energetic cusp particles is most obvious in spring and summer through the high latitude enhancements in the latitude profiles of N_e and T_e. The spring and summer profiles display a U-shaped trough and a second T_e maximum above 70° invariant latitude. The T_e maximum that is ordinarily associated with the trough structure appears in a latitude range of monotonic change in N_e; the T_e maximum associated with ionization by cusp particles appears to coincide with an enhancement in N_e. The difference in the N_e trends associated with the two T_e maxima is consistent with the contention that two separate processes are involved.

Analysis of the magnitude of T_e in the plasma trough reveals a protonospheric T_e maximum on the order of 6000° K as compared to 3000° K in the regular ionosphere. Allowing for a degree per kilometer increase in T_e at increasing altitudes would project a slightly lower T_e in the protonosphere; but, the additional amount of heating can be linked to evolution of the solar cycle between the time of the Explorer-22 measurements and the ISIS-1 measurements. The Explorer-22 probe results apply to solar minimum whereas the ISIS-1 measurements apply to solar maximum. The extra heating needed to make the protonospheric T_e consistent with both the Explorer-22 measurements and prevailing ideas about the magnitude of the gradient in T_e can come from the increased solar activity at the time of the ISIS-1 measurements.

The spatial distribution of plasma at the plasmaspheric boundary apparently differs along a field tube since the plasma trough is often U-shaped, whereas the equatorial plasmapause does not appear as a trough-like phenomenon. What may be less obvious is that the temporal characteristics of the plasmaspheric boundary also differ along a field tube. At the equator the plasmapause, as detected by whistler studies, expands in the dusk time sector relative to the dawn time sector causing the dusk plasmapause to appear at the higher L-values. However, satellite measurements do not reveal any significant asymmetry in the spatial locations of the trough when the dawn and dusk time sectors are directly compared, whether the data is viewed collectively as in Figure 8 or over individual satellite passes as in Figure 9.

Among mechanisms that contribute to the spatial and temporal differences between the equatorial and midlatitude boundaries of the plasmasphere are F-region photoionization and ionization by energetic cusp particles. Photoionization raises the general density level in the trough and can change the apparent location of the trough minimum. The protonospheric response to F-region photoionization is exemplified by the summer dayside and nightside trough data of Figures 6 and 7. The dayside densities are slightly higher at most latitudes. More significantly, the dayside trough minimum seems to fall at higher latitudes than on the nightside. The nightside latitude profiles of N_e indicate a negligible increase as the satellite moves poleward from 60° and passes through field tubes in which F-region photoionization is taking place. The protonospheric plasma density associated with these field tubes doubles in the time required to reach the noon local time sector. Under similar circumstances in the regular ionosphere, the plasma density doubles in value almost as soon as the satellite begins to cross field tubes passing through a sunlit F-region. The total T_e, N_e latitude structure suggests that F-region photoionization within the plasmasphere has a direct impact on the protonosphere through an increase in the T_e and N_e over their nightside values. Beyond the plasmaspheric boundary, F-region photoionization has a delayed effect in increasing the protonospheric plasma density.

Ionization by energetic cusp particles is the likely source of the dayside density enhancements and accompanying T_e maxima that are often observed poleward of the trough. The process is one whose effects show best in the spring data of Figure 4. Heikkila and Winningham (1971) have measured noontime soft electron fluxes in the latitude range of the protonospheric ionization enhancements. The energy spectrum of the particles matches that of magnetosheath electrons, thus strengthening the postulate that energetic solar wind particles have direct access to the ionosphere through the dayside geomagnetic field in the region between field lines that are swept back into the magnetotail and those that remain closed on the dayside.

A suggested mechanism to produce the T_e maximum associated with the trough is heat conduction along the plasmaspheric boundary from the equator. High-temperature thermal electrons have been observed at the equator (Serbu and Maier, 1967). In addition, mechanisms for energy exchange between ring current particles and the thermalplasma at the plasmaspheric boundary have been proposed. During disturbed periods, interaction between the ring current particles and thermal plasmaspheric electrons has been modeled as a heat source to produce sub-aurora red (SAR) arcs at the plasmapause (Cornwall et al., 1971). During quiet times there could still be enough of an energy interchange to contribute to the T_e maximum in the plasma trough. On the nightside, where downward heat conduction along field lines at the plasmaspheric boundary is the most likely source of heat input to the thermal electrons, the T_e maximum is sharp. On the dayside, photoelectrons are produced in the sunlit F-region that are capable of providing heat input to the thermal electrons. Thermal-electron heating by photoelectrons occurs over a broad range of latitudes and can mask the effect of any localized heating effect at the plasmaspheric boundary by producing a broader T_e maximum.

CONCLUSION

Measurements from the ISIS-1 probe experiment at the altitudes 2500 to 3500 km add to greater understanding of the plasma trough in particular and the protonosphere in general. A quasi-stable dayside plasma trough can be detected in the protonosphere, but the spatial and temporal characteristics do not match those of the equatorial plasmapause. Specifically, the plasma trough configuration often differs from that of the equatorial plasmapause, and the data does not suggest a plasmaspheric bulge in the dusk sector.

The T_e maximum generally associated with the nightside trough is present. Heat conduction along the plasmaspheric boundary from a heat source at the equator can be invoked as the mechanism producing the T_e maximum with both hot thermal electrons and an interchange of energy between ring current particles and the plasmaspheric boundary serving as possible heat sources. On the basis of 1° per km temperature gradient, trough temperatures require an extra heating source. This source is most probably the increased solar activity associated with solar maximum.

Within the plasmasphere, the protonosphere is seen to respond directly to F-region photoionization by the observation of increased N_e and T_e. It can be inferred from the data that though the protonospheric plasma external to the plasmasphere is affected by photoionization processes occurring in the F-region, the plasma response is not dramatic and requires a longer time period relative to the response time of the regular ionosphere. Evidence of ionization produced by energetic cusp particles appears in the protonosphere as simultaneous enhancements in N_e and T_e poleward of 70° invariant latitude.

If the underlying mechanism producing a plasmasphere is postulated to primarily affect the light ions, the difference in the characteristics of the plasmaspheric boundary within various segments of a magnetic field tube can be attributed to a combination of changing ion composition and the F-region processes of ionization by solar radiation and by energetic cusp particles.

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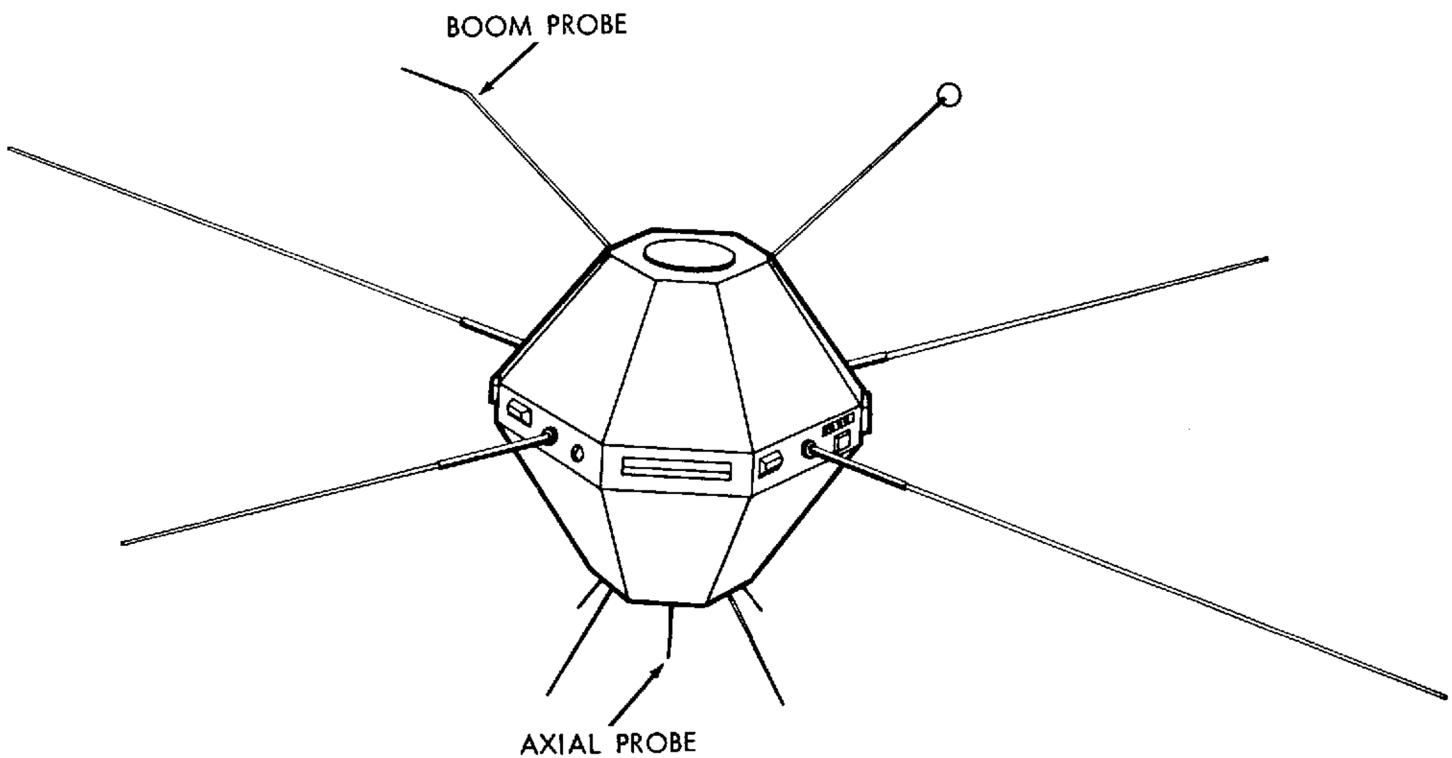

Figure 1. The ISIS-1 spacecraft and probe locations. The boom probe is 1.2 meters from the spacecraft and perpendicular to the spin axis. The axis probe is on the spin axis.

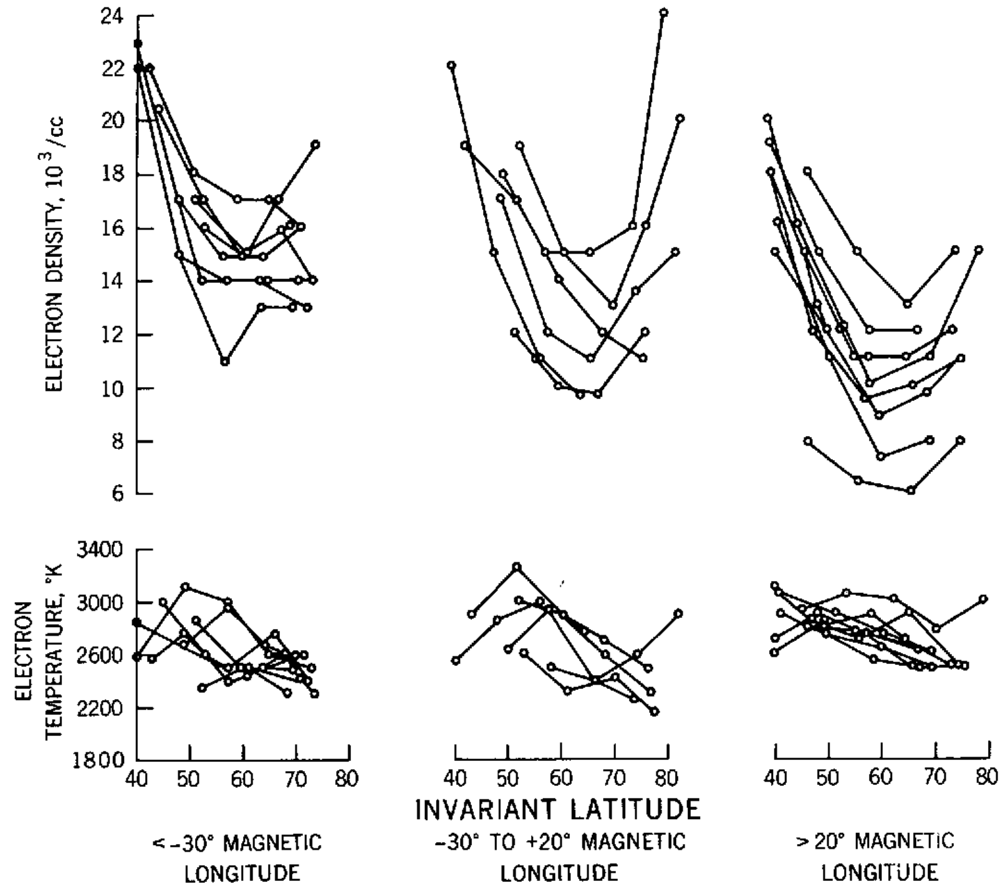

Figure 2. Explorer-22 quiet-time dayside electrostatic probe measurements at 1000 km for local times 11 to 13 hours, May 13, 1965, through May 23, 1965.

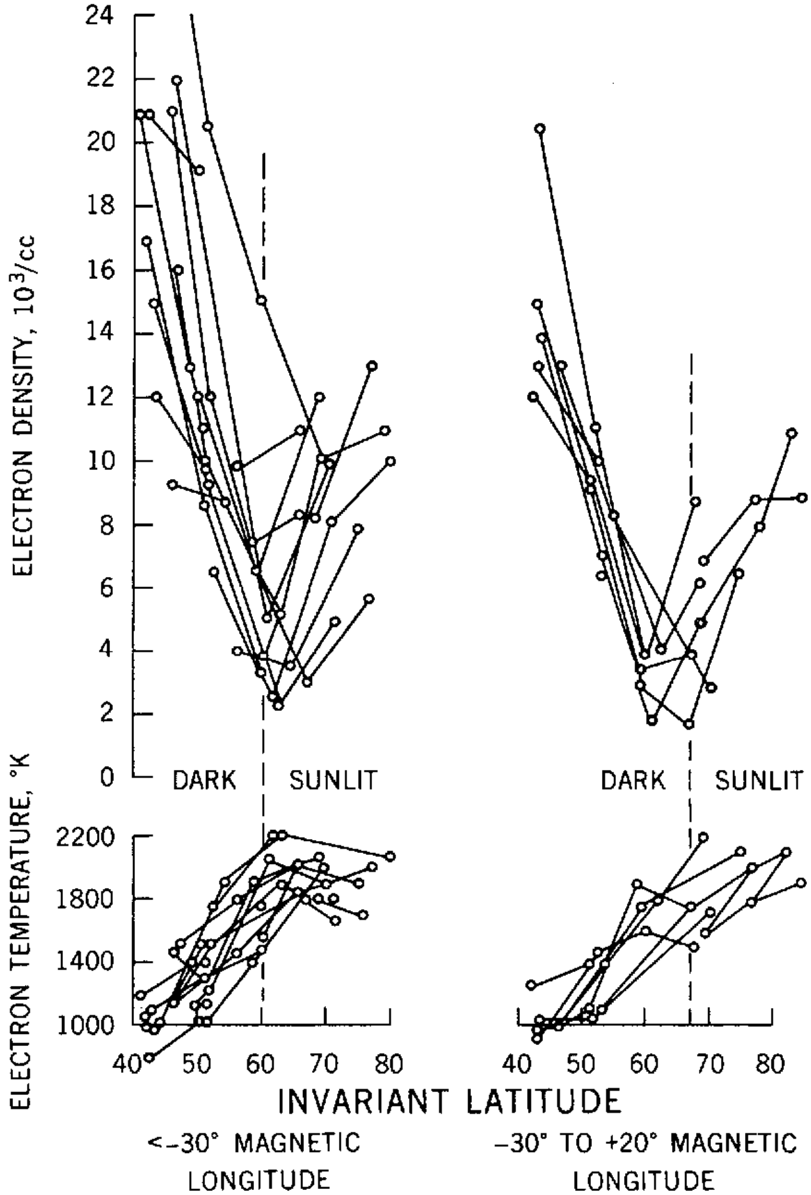

Figure 3. Explorer-22 quiet-time nightside electrostatic probe measurements at 1000 km for local times 23 to 01 hours, May 29, 1965, through June 7, 1965. Invariant latitudes at which the field lines are passing through a sunlit F-region are those latitudes in the area labeled as sunlit.

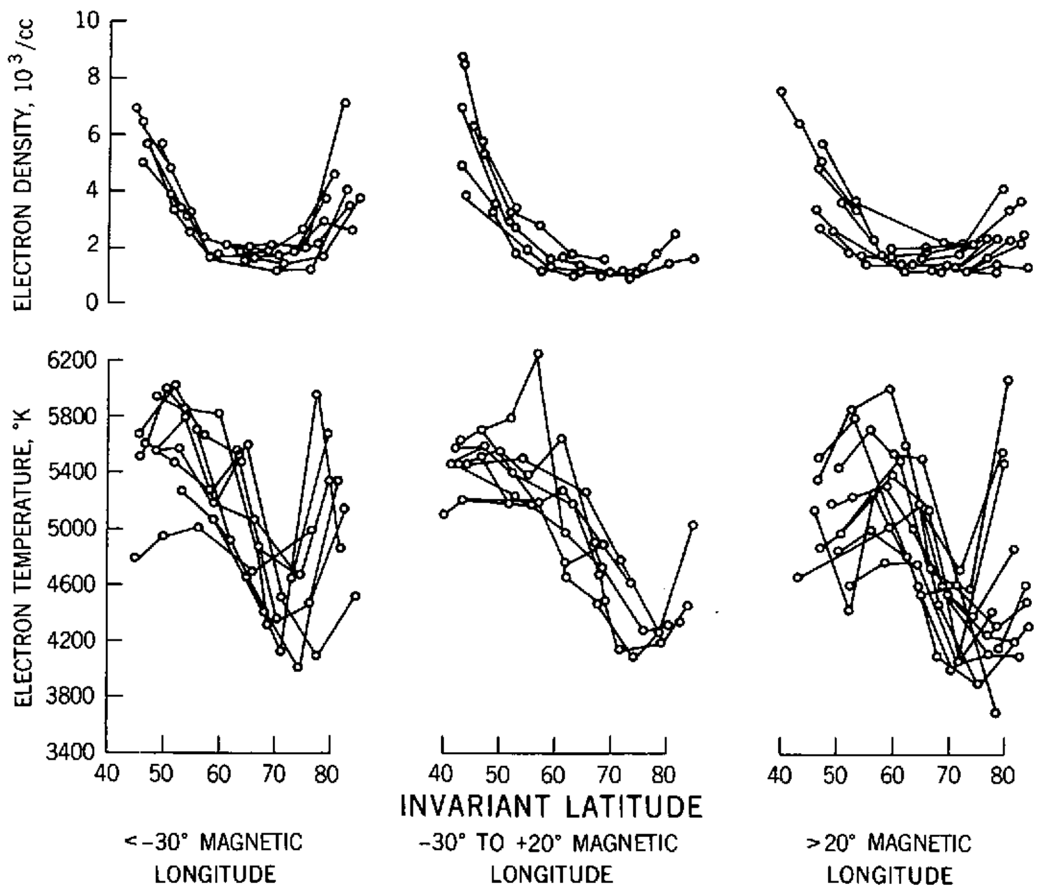

Figure 4. ISIS-1 quiet-time dayside electrostatic probe measurements at altitudes from 2500 to 3500 km for local times 11 to 13 hours, May 5, 1970, through May 11, 1970.

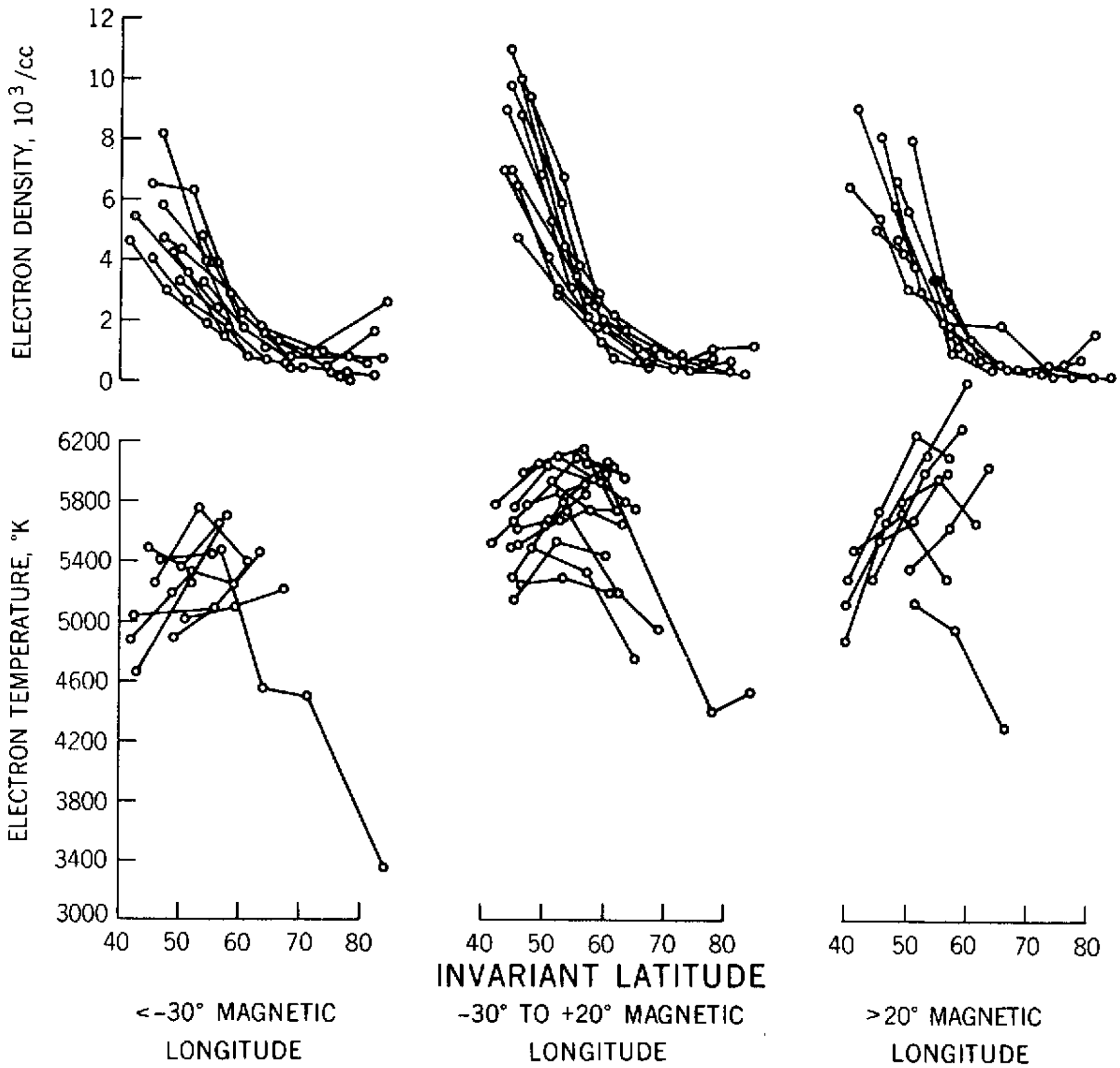

Figure 5. ISIS-1 quiet-time dayside electrostatic probe measurements at altitudes 2500 to 3500 km for local times 11 to 13 hours, December 1, 1969, through December 23, 1969.

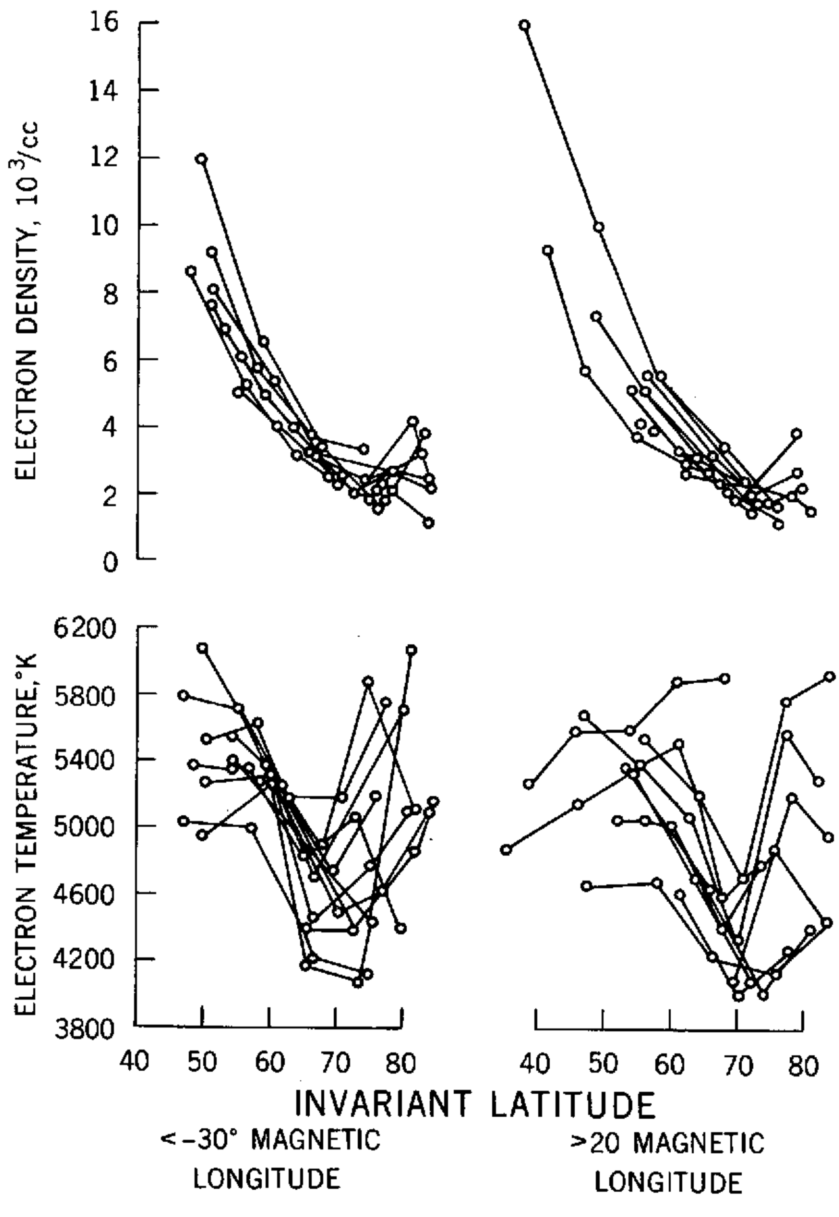

Figure 6. ISIS-1 quiet-time dayside electrostatic probe measurements at altitudes 2500 to 3500 km for local times 11 to 13 hours, June 11, 1969, through July 6, 1969.

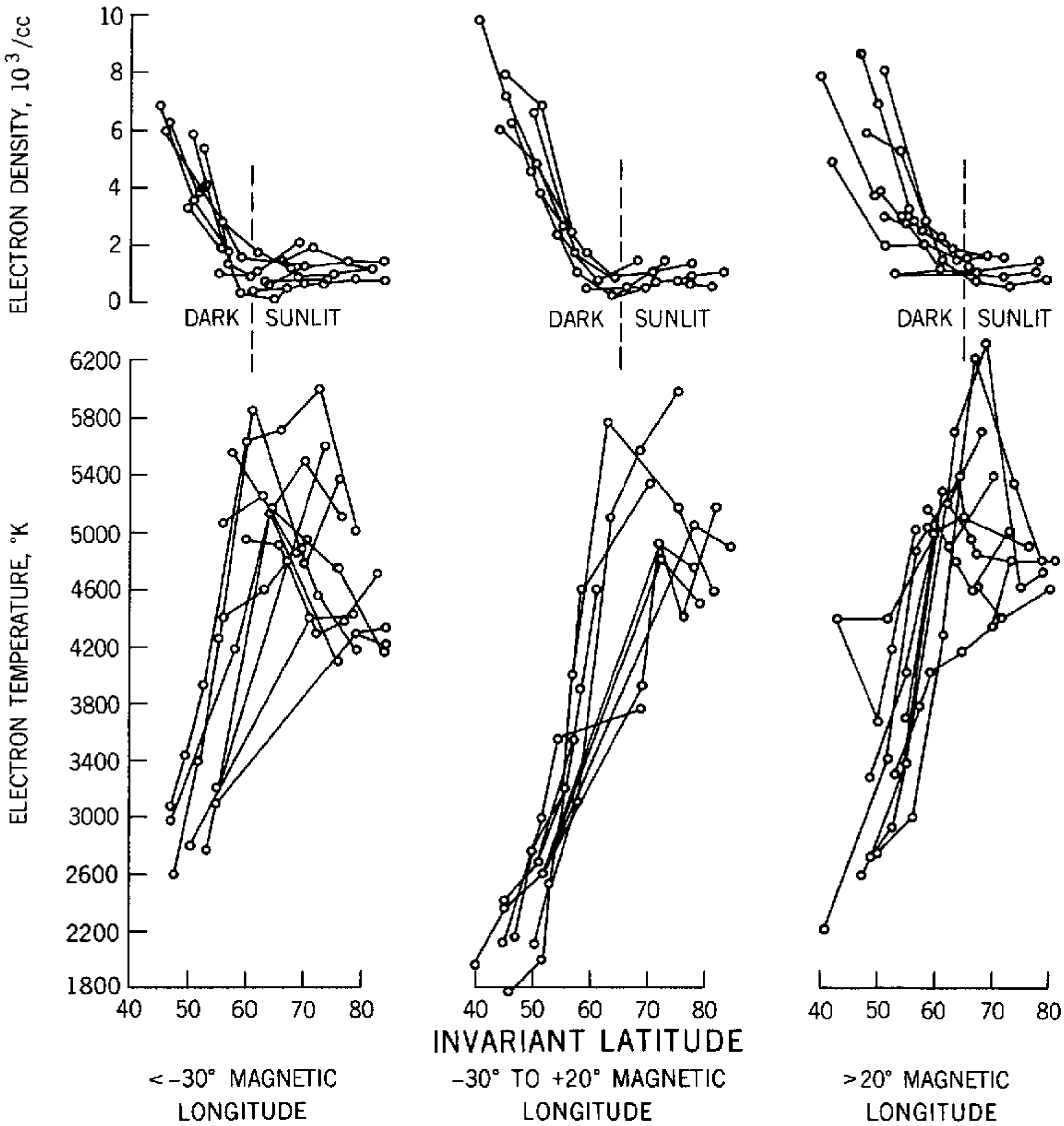

Figure 7. ISIS-1 quiet-time nightside electrostatic probe measurements at altitudes 2500 to 3500 km for local times 23.4 to 1.4 hours, June 11, 1969, through July 6, 1969. Invariant latitudes at which the field lines are passing through a sunlit F-region are those latitudes in the area labeled as sunlit.

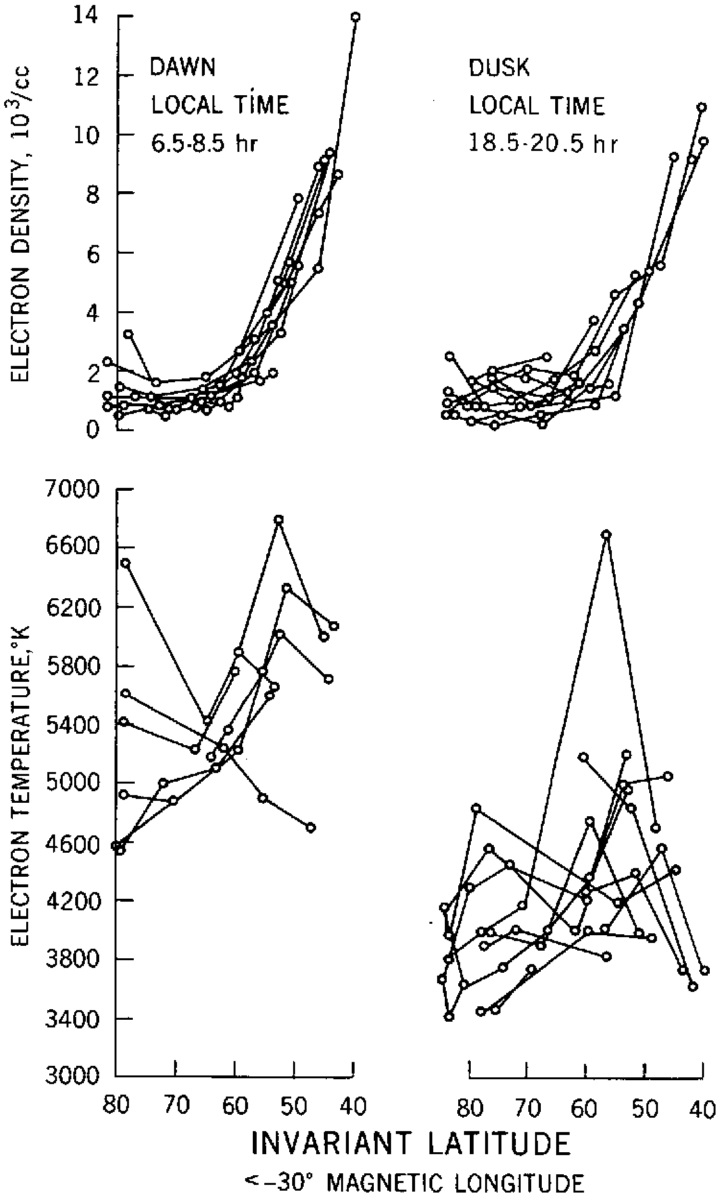

Figure 8. ISIS-1 quiet-time electrostatic probe measurements in the dawn-dusk meridian at altitudes 2500 to 3500 km for local times 6.5 to 8.5 hours and 18.5 through 20.5 hours, February 28, 1969, through March 23, 1969.

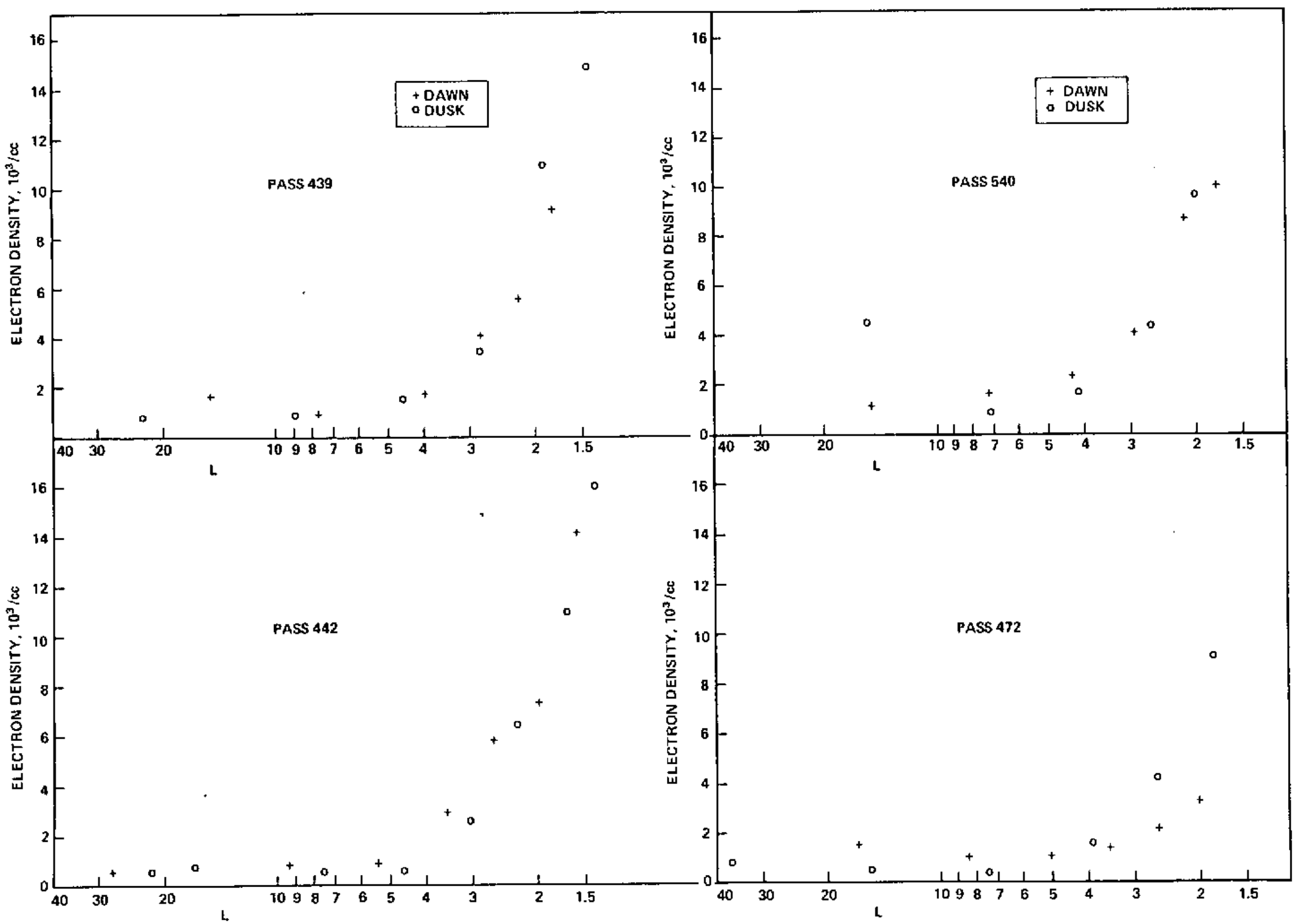

Figure 9. Measurements from representative passes included in Figure 8 for cases where both dawn and dusk data are available over the complete orbit segment crossing the boundary between dusk and dawn.