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Vytenis M. Vasyliunas

CENTER FOR SPACE RESEARCH
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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Vytenis M. Vasyliunas

Department of Physics and Center for Space Research
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

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1. Introduction

Much observational work in space research within the past few years has been concerned with what are commonly called "low energy particles". That term is somewhat ambiguous: 100 Mev may be low energy to a cosmic-ray physicist, while 10 ev is probably a rather high energy to many ionospheric physicists. Hence I should begin by clarifying the meaning of "low energy" in the present context. Most of the early particle observations in the magnetosphere were obtained with instruments (such as Geiger tubes and scintillation counters) capable of observing electrons only above an energy of ~ 40 kev and protons above ~ 100 kev. Extensive data on particles above these energy limits had been accumulated by 1964 and the gross features, at least, of their distribution could be mapped out, while knowledge of lower energy particles within the magnetosphere was still rather meager by comparison. Since then, however, numerous observations with Faraday cups and curved-plate analyzers have extended our detailed knowledge of magnetospheric particles down to energies of some tens of ev; these are the so-called "low energy" observations - the energy is low compared to what was being measured some years ago.

However, these low energy observations represent more than a mere improvement in experimental technique. They are qualitatively different from the observations hitherto possible and provide a new way of looking at magnetospheric plasma. This can be illustrated with Figure 1, which shows schematically a typical electron energy spectrum in the magnetosphere. The older "high energy" observations were limited to the small fraction of particles whose energies greatly exceeded the average energy of the entire plasma, i.e. to the "high energy tail" of the particle distribution. The measured quantity usually was the total flux of particles with energies above some threshold set by the instrument and otherwise having no particular physical significance, plus a power-law exponent or some similar measure of the steepness of the spectrum; no information on the collective properties of the entire plasma could be obtained. By contrast, once the measurements were extended to energies of some hundred ev and below, a well-defined peak in the energy spectrum was found; below the peak the particle flux decreases rapidly with decreasing energy. Thus the magnetosphere contains a population of particles with an average energy in the ~100 ev to ~10 kev range, and the present "low energy" observations encompass a major fraction of this population. It is now possible to integrate the flux vs. energy curve (the rapid decrease of flux at energies below the peak allows one to extrapolate to zero energy, as sketched in Figure 1, with little effect on the value of the integral) and to compute quantities referring to the entire population, such as total density, total energy density, or total energy flux. The observational results can now be presented using terms of plasma physics, rather than terms borrowed from cosmic ray studies.

As indicated in Figure 1, there may also exist another population of (so-called "thermal") particles at still lower energies, below the range of present "low energy" observations. No reliable direct observations of such low energy particles in the outer magnetosphere and the magnetotail are presently available, to my knowledge; some indirect evidence will be discussed later.

This paper reviews certain aspects of low energy particle observations in the magnetosphere. First I will describe the over-all spatial distribution of the low energy particles. Then I will concentrate on the geomagnetic tail and discuss properties of the particle population within the plasma sheet, evidence bearing on the question of a "thermal" population, and present knowledge of particles outside the plasma sheet. Finally I will present some recent results on a topic of special interest to this meeting, namely, the connection between particle structures in the geomagnetic tail and auroral phenomena in the ionosphere. A major topic that will not be covered is time variations and their relation to geomagnetic substorm activity; the reader is referred to the work of Hones (1968a, b, 1969). The entire field of low energy observations has recently been reviewed by Gringauz (1969). Techniques of measurement and analysis will not be described; they are discussed in many of the original papers, and a recent review has been given by Vasyliunas (1969a).

2. Spatial distribution of low energy particles in the magnetosphere

Our present conception of the average distribution of low energy electrons in the equatorial region of the magnetosphere is sketched in Figure 2. Intense fluxes of electrons extend across the entire magnetotail, forming the plasma sheet, first detected by the Luna 2 space probe in 1959 (Gringauz et al., 1960a, b; Gringauz, 1961) and since 1964 extensively studied with instruments aboard the Vela and OGO satellites (Bame et al., 1966, 1967; Bame, 1968; Hones, 1968a, b, 1969; Vasyliunas, 1968a; Frank, 1967a, b, 1968a, b). On the evening side of the magnetosphere these electron fluxes terminate at a well-defined boundary, called the inner boundary (or inner edge) of the plasma sheet. This boundary lies at an equatorial radial distance of ~11 Re during magnetically quiet periods and 6-8 Re during times of magnetic bay activity, and has been traced from near the midnight meridian through dusk to a local time near noon, where it meets the magnetopause (Vasyliunas, 1968a, b). Earthward of the inner boundary, at local times between dusk and midnight the electron flux in the 100 ev to a few kev energy range is very weak in comparison with that within the plasma sheet (as will be discussed later, this is not a decrease in electron density but a decrease in their mean energy to values well below 100 ev). As one proceeds from dusk toward earlier local times, appreciable electron fluxes appear between the plasmapause and the inner edge of the plasma sheet, grow in intensity and acquire a marked outward radial gradient in the morning side, and become very intense (exceeding typical plasma sheet fluxes by an order of magnitude) at local times near and before dawn (Vasyliunas, 1968b). Electrons in the morning side of the magnetosphere were the first low energy particles to be detected in outer space, with an instrument aboard Luna 1 (February 1959) (Gringauz et al., 1960b; Gringauz, 1961, 1964). The very intense electron fluxes characteristic of the predawn hours were first observed with Explorer 12 by Freeman (1964); more recently they have been observed at a distance of 6.6 Re (only during times of magnetic bay activity) with ATS-1 by Freeman and Maguire (1967), who showed that these fluxes extend from dawn to midnight (although the ATS instrument is sensitive to both electrons and protons, it is most likely that these observations refer primarily to electrons [Vasyliunas, 1968b]). Other observations of low energy electrons in the equatorial region have been reported from IMP 1 (Serbu, 1964), IMP 2 (Binsack, 1966), Zond 2 (Gringauz and Khokhlov, 1965), and Pioneer 7 (Lazarus et al., 1968) on the morning side, and Pioneer 6 (Wolfe and McKibbin, 1968;

Howe, 1969) on the evening side; the first detailed mapping from dusk to dawn has only recently been obtained with OGO 3 (Vasyliunas, 1968b).

Observations of low energy protons have been far less numerous. (It should be noted that, for the same energy and number density, the proton flux is 43 times smaller than the electron flux and thus may require more sensitive instruments for detection.) The proton component of the magnetotail plasma sheet has been observed with the Vela satellites (Bame et al., 1967; Bame, 1968). On the evening side (as observed with OGO 3), the intense proton fluxes characteristic of the plasma sheet reach closer to the earth than the corresponding electron fluxes; at the "inner edge" of the plasma sheet, where the electron mean energy sharply decreases with decreasing distance, the proton energy instead increases (Frank, 1967b, 1968a, b). During magnetic storms low energy protons extend inward almost to the plasmasphere and form the ring current responsible for the storm main phase (Frank, 1967c, 1968a). Very recently Frank (1968c) has reported that the largest proton fluxes occur in the noon-to-dusk quadrant.

So far I have discussed particles in the equatorial region. Figure 3 illustrates schematically the distribution of low energy electrons in a meridian plane on the night side of the earth. (Also shown are typical orbits of some of the principal satellites that have provided data on low energy electrons.) In the geomagnetic tail, plasma sheet particles are confined in the north -

south direction to within a few Re of the magnetic neutral sheet, as first established by Vela measurements (Bame et al., 1966, 1967; Bame, 1968; Hones, 1968a, b, 1969) and confirmed by OGO 1 and 3 (Vasyliunas, 1968a). (This planar geometry was the reason for the term "plasma sheet", introduced by Bame et al., 1966.) A seasonal variation in the north-south position of the plasma sheet has been observed (Bame et al., 1967; Vasyliunas, 1968a) that reflects the north-south displacement of the neutral sheet as the earth's dipole - solar wind angle varies (Speiser and Ness, 1967; Russell and Brody, 1967). Thus the plasma sheet appears to be always at least roughly centered about the magnetic neutral sheet; however, its width of several earth radii greatly exceeds the ~10^3km width of the actual magnetic field reversal region (Ness, 1965; Speiser and Ness, 1967).

Even before the geometry of the tail plasma sheet had been observationally established, intense low energy electron fluxes were observed close to the earth at high latitudes by Mars 1 in 1962 (Gringauz et al., 1964) and Electron 2 in 1964 (Vernov et al., 1965, 1966). These fluxes occurred in a narrow band of latitudes, roughly at invariant latitudes 65-70°, i.e. in the neighborhood of the auroral zone. Gringauz et al. (1964) at once suggested that these electron fluxes were part of the same low energy particle region that had earlier been observed by Luna 2 near the equatorial plane and which we now know to be the plasma sheet. Vasyliunas

(1968a) traced the inner boundary of the plasma sheet from the equator up to latitudes of ~40° and concluded that the inner boundary coincides with a shell of magnetic field lines. All these observations suggest the picture sketched in Figure 3: plasma sheet electron fluxes extend from the magnetotail toward the earth in a pair of narrow "horns", reaching the ionosphere at or near the auroral zones. (Pictures of this kind were earlier presented and the connection with the aurora suggested by Dessler and Juday [1965], O'Brien [1967], Piddington [1967a], and possibly others.) Recently the secular change of the OGO 1 orbit has made it possible to investigate the precise connection between the plasma sheet and the auroral oval; I shall discuss this topic in section 4.

Outside the plasma sheet, particle fluxes in the magnetotail are very weak and have only recently been detected by Vela 4 (Bame, 1968); they were generally below the sensitivity and/or energy limits of earlier instruments (Bame et al., 1967; Vasyliunas, 1968a). This absence of strong fluxes at great heights above the neutral sheet persists right up to the magnetopause (Vasyliunas, 1968a; Bame, 1968); the early suggestion by Dessler and Juday (1965) of a Θ-shaped plasma sheet has not been borne out by the data.

3. Properties of low energy particle populations in the magnetotail

The early observations by Gringauz and co-workers indicated that within what we now call the plasma sheet the total flux of electrons with energies above ~200 ev is of the order of 2×10^8 cm^{-2} sec^{-1} and that most of these electrons have energies well below 50 kev; these observations did not provide any further information on the nature of the electron energy spectrum. The first direct observation that the electron energy spectrum peaks near 1 kev came from curved-plate analyzer measurements on Electron 2 (Vernov et al., 1965, 1966). In recent years detailed observations of the electron energy spectrum have been obtained with curved-plate analyzers on Vela (Bame et al., 1966, 1967; Bame, 1968) and OGO 3 (Frank, 1967a, b, 1968a, b; Schield and Frank, 1969). Less detailed observations that nonetheless are adequate to delineate the gross features of the electron energy spectrum have been obtained with Faraday cups on OGO 1 and 3 (Vasyliunas, 1968a), Pioneer 7 (Lazarus et al., 1968), and Pioneer 6 (Howe, 1969). The typical energy spectrum of electrons within the plasma sheet is found to be rather similar to the idealized sketch of Figure 1: there is a broad maximum at an energy that can range from ~100 ev to several kev, and a flux decrease at both low and high energies. Well above the peak the differential flux decreases roughly as an inverse power of the energy, with exponents typically in the range 3-5, and extrapolates more or less smoothly into the power law spectra observed at high (50-100 kev) energies (Montgomery et al., 1965; Montgomery, 1968). On the other hand, there is some evidence from occasional observation of a double-peaked energy spectrum (Frank, 1967a) and from detailed study of time variations of electron fluxes at different energies (Montgomery, 1968) that electrons above some 10 kev energy may not be merely the high energy tail of the main plasma sheet electron population but possibly a separate population. The angular distribution of electrons within the plasma sheet appears to be approximately isotropic at all energies up to hundreds of kev (Vernov et al., 1966; Bame et al., 1967; Hones et al., 1968; Retzler and Simpson, 1969).

A smooth, broad, single-peaked, isotropic particle distribution can be quantitatively characterized by two parameters, which may be chosen as the number density n and the energy density U; in terms of the particle velocity distribution function $f(\underset{\sim}{v})$ these are

$$n = \int d\underset{\sim}{v}\; f(\underset{\sim}{v})$$
$$U = \int d\underset{\sim}{v}\; 1/2\, mv^2\; f(\underset{\sim}{v})$$

One may then define the mean particle energy $E \equiv U/n$ (if the distribution function is Maxwellian with a temperature T, then $E = 3/2\, kT$). (Other sometimes useful quantities such as total omnidirectional particle or energy flux may be defined in a similar manner.) These quantities may be deduced from the measurements either by approximating the integrals by sums and estimating the required values of $f(\underset{\sim}{v})$ from the measured fluxes, or by assuming a specific functional form for $f(\underset{\sim}{v})$ and varying parameters to obtain a best fit to the measurements; these methods have been reviewed by Vasyliunas (1969a).

Two major surveys of the quantitative properties of the plasma sheet electron population have been published, as of the time of this writing. Vasyliunas (1968a) used OGO 1 Faraday cup measurements at local times from ~17 to ~22 hours and distances up to 24 Re. Figure 4 shows the distribution of electron parameters obtained from a sample of these measurements; the electron properties were found to be more or less uniform over the entire surveyed region of the plasma sheet. Hones (1968a, 1969) used curved-plate analyzer measurements from the Vela satellites to construct maps showing the average values of electron density, energy density, and mean energy as function of latitude and local time at a constant distance of 17 Re. The maps indicate that the electron mean energy is ~1 kev near the center of the plasma sheet, decreases with increasing latitude to ~0.3 - 0.5 kev near the boundaries of the plasma sheet, and shows no significant dependence on local time. The density and energy density show a minimum near midnight; in the center of the plasma sheet the density is ~0.1 - 0.3 cm^{-3} near midnight and ~0.3 - 0.4 cm^{-3} near the flanks of the magnetotail, while the energy density in the same regions is ~0.1 - 0.2 and ~0.3 - 0.4 kev cm^{-3}, respectively. The local time dependence of all quantities is roughly symmetric about midnight; the striking dawn-dusk asymmetry observed in high energy (E>45 kev) electrons (Montgomery et al., 1965; Bame et al., 1967; Hones, 1968b; Montgomery, 1968) apparently does not persist at lower energies.

Comparing the numbers given by Hones with those in Figure 4, it is apparent that both sets of measurements agree on the electron mean energy but there may be some discrepancy on density and energy density: the "most probable" values given by Vasyliunas are a factor of ~3 higher than the "average" values of Hones for the same local time range. Whether the discrepancy is significant is difficult to say at present; the difference is no larger than the spread of individual values in Figure 4, and may perhaps be due in part to sampling statistics. Of the other electron measurements that have been reported, the curved-plate analyzer results from OGO 3 (Frank, 1967a, b; Schield and Frank, 1969) give density values in agreement with those of Vasyliunas, while the Faraday cup measurements on Pioneer 7 (Lazarus et al., 1968) are somewhat closer to the values of Hones (thus the discrepancy appears to be, at any rate, not related to the type of instrument used).

Although one may discuss "typical" or "average" values, it is also clear from Figure 4 that observed individual values of electron density and mean energy vary over a range of several decades. High densities, however, tend to be accompanied by low mean energies and vice versa, so that the electron energy density shows relatively little variation (Vasyliunas, 1968a). This is illustrated in Figure 5, in which mean energy is plotted against density (from the same data as Figure 4); lines of constant energy density have been drawn and labeled by the magnetic field strength corresponding to twice the energy density. The individual points in Figure 5 come from a wide range of spatial locations and conditions of geomagnetic activity (note that very high densities and low energies usually occur during magnetic storms). Figure 5 thus primarily represents gross, large-scale spatial and temporal variations in plasma sheet properties; it shows that the electron energy density is little affected by such variations and on the average is of the same order of magnitude as the magnetic field energy density.

The relation between the instantaneous values of magnetic and plasma energy density (as opposed to the over-all average behavior just discussed) was investigated by Lazarus et al. (1968), using magnetic field and electron measurements during the single magnetotail traversal of Pioneer 7. Figure 6, taken from their paper, shows the magnetic field pressure and the sum of it and twice the electron pressure. (Magnetic field pressure is equal to the energy density; particle pressure is 2/3 of the energy density.)

As can be seen, major decreases in magnetic pressure are generally compensated by increases in electron pressure, so that the total pressure remains approximately constant; this is especially apparent in Figure 6 during the intervals 22-23h, 1-2h (which contains a magnetic neutral sheet crossing), and 5-9h.

It appears, then, that plasma sheet electrons undergo at least two types of variations. First, their energy density may change, but at the same time the magnetic field also changes so that the total (particle plus field) pressure remains constant; thus these variations preserve, at least approximately, a condition of hydrostatic balance. Second, the electron density and mean energy may both change by as much as an order of magnitude, but the energy density remains approximately constant; these variations preserve what may loosely be called equipartition of energy between electrons and magnetic field.

The proton component of the plasma sheet has been detected with curved-plate analyzers (Bame et al., 1967; Frank, 1967b, 1968a, b; Bame, 1968; Hones, 1968a), but our knowledge of it is as yet far less detailed than that of electrons. The proton energy spectrum has a smooth, broad, single-peaked shape, qualitatively similar to the electron spectrum. The proton angular distribution is approximately isotropic, but slight (~10%) anisotropies possibly indicative of a bulk flow (with speeds $\lesssim 50$ km sec^{-1})

have been observed (Hones, 1968a). The number density of protons equals that of the electrons, to within the observational uncertainties. The proton mean energy appears to exceed the electron mean energy, but by how much is not yet entirely clear: the ratio of proton to electron mean energy is ~5 according to Hones (1969) and $\gtrsim$10 according to Bame (1968), while Frank (1967b) reports examples of proton and electron spectra in which the mean energies of the two are approximately the same (although the proton spectrum has a much broader shape), and Lazarus et al. (1968) infer by an indirect argument based on pressure balance that the ratio is ~1 to 3.

We now come to the question whether a significant population of very low energy ($\lesssim$ few ev) particles exists within the plasma sheet. Observing such particles directly by means of instruments of the Langmuir probe type does not appear to be possible; when such probes have been used outside of the ionosphere (Serbu and Maier, 1966), several features of the results cast grave doubts as to their validity. First, the probes fail to detect the density change at the plasmapause, whose existence has been firmly established by a great variety of observations (see, e.g. the summary by Binsack, 1967, and also Carpenter et al., 1968, 1969). Second, within the magnetosheath and the solar wind the probes yield electron densities exceeding by more than an order of magnitude the proton densities obtained by solar wind detectors (see, e.g., Axford, 1968). (It should be kept in mind that even if a so-called "thermal" component existed in the solar wind, it would have to move with the solar wind velocity, at least as far as motion across magnetic field lines is concerned; thus the "thermal" protons would have energies of hundreds of ev and would be readily observable with the usual solar wind detectors.) Since Langmuir probes apparently do not work properly either near the plasmapause or beyond the magnetopause, there is little reason to suppose that they work in the outer magnetosphere and the magnetotail. The difficulty appears to lie in the large fluxes of ~1 ev electrons that can be produced at the surface of the satellite by photoemission and secondary emission; Whipple and Parker (1969a, b) have recently demonstrated that these secondary fluxes can account for the anomalous probe results in the solar wind.

Very low energy particles thus must be studied by indirect techniques, the most important of which is observing the effect of the particles on electromagnetic wave propagation. Dispersive effects in radar signals reflected from the moon were used by Howard et al. (1965), Yoh et al. (1966), and Howard (1967) to infer the total electron content per unit area in a column between the earth and the moon. After removing the contribution of the ionosphere, values of the order of 10^{17} electrons m^{-2} were obtained in the direction of the magnetotail. If spread uniformly between the earth and the moon, as was done by Howard et al. and Yoh et al., this columnar content would correspond to a density of ~200-300 cm^{-3}. However, the electron distribution along the column is certainly not uniform, and it was shown by Howard (1967) that the entire observed content can within experimental uncertainties be accounted for by electrons within the plasmasphere; for the average electron density between the plasmapause and the moon, these observations yield only an upper limit of approximately 30 cm^{-3}.

Electron densities within the plasmasphere and out to several earth radii beyond it have been extensively studied by the well-known whistler technique (see, e.g., Carpenter and Smith, 1964; Helliwell, 1965; Carpenter, 1966; Angerami and Carpenter, 1966; and many other papers). These measurements do not extend far enough out to provide data on densities within the plasma sheet. Nevertheless, a comparison between the electron density values as measured beyond the plasmapause by the whistler technique and within the plasma sheet by low energy particle detectors may have some significance, since the low energy electron density appears not to change appreciably across the inner boundary of the plasma sheet (Vasyliunas, 1968a). Figure 7, for example, shows an inner boundary crossing observed by OGO 1; the electron energy is observed to drop precipituously as the satellite moves earthward, but the density shows little variation. This result has recently been confirmed by Schield and Frank (1969), using curved-plate analyzer measurements with high spectral resolution from OGO 3. The inner boundary of the plasma sheet thus appears to be a discontinuity in electron energy but not density.

With this in mind, Figure 8 shows, as a function of radial distance, the electron density in the equatorial region, measured by the two techniques. The whistler measurements, taken from Angerami and Carpenter (1966), represent the total plasma density, including electrons of all energies. The OGO 1 measurements represent the density of the observed plasma sheet electron population (the points at distances less than 10 Re come from periods of bay activity, when the inner boundary of the plasma sheet is displaced earthward). Near 4 Re the densities obtained from whistler measurements show the familiar drop, from several hundred to $\sim 10\ cm^{-3}$, that constitutes the plasmapause; then they decrease gradually and near 6-7 Re join more or less smoothly onto the $\lesssim 1\ cm^{-3}$ densities measured in the plasma sheet. This is consistent with the supposition that a very low energy ("thermal") electron population either does not exist within the plasma sheet or, if it does exist, its total density is at most comparable to the density of the electron population that has already been observed. The argument, however, is not conclusive since it is based on comparison of two sets of data taken in different years, at different local times, and under a variety of geomagnetic activity conditions.) The observation mentioned earlier that within the plasma sheet the measured electron and proton number densities are equal is also consistent with this supposition.

In summary, (1) lunar radar observations impose an upper limit of some tens cm^{-3} on the total density of very low energy particles, below the energy range of present detectors, in the magnetotail; (2) comparison of whistler and plasma sheet observations, as well as the observed equality of proton and electron densities suggest (although do not necessarily prove) that within the plasma sheet the density of such particles does not significantly exceed the density already measured; (3) there is at present, to my knowledge, no observational evidence that a distinct population of such very low energy particles actually exists within the plasma sheet.

In regions of the magnetotail outside of the plasma sheet, i.e. more than a few earth radii above or below the magnetic neutral sheet, particle fluxes were until recently undetectable with available instruments, as already mentioned in section 2. Vasyliunas (1968a) considered the upper limits on the electron population that could be deduced from the absence of a measurable flux in the OGO 3 Faraday cup. He concluded that (1) if the electron mean energy was $E \sim 1$ kev, their density was $n \lesssim 1 \times 10^{-2}$ cm^{-3}; (2) if $E \sim 50$ ev, then $n \lesssim 5 \times 10^{-2}$ cm^{-3}; (3) if one insisted that the density be high, $n \sim 1$ cm^{-3}, the mean energy had to be very low (to place most of the electron distribution at energies below the range of the detector), E < 10 ev. With curved-plate analyzers on Vela 4, Bame (1968) has actually detected electrons outside of the plasma sheet and found that they have an average energy near or under 100 ev and a density that is rather close to the upper limit of Vasyliunas; an example published by Bame shows an electron density $\lesssim 4 \times 10^{-2}$ cm^{-3} and an energy density of $\lesssim 2$ ev cm^{-3}, hence a mean energy of ~ 50 ev.

4. Relation of the plasma sheet to the auroral oval

That the auroral oval and the plasma sheet are in some way connected is strongly suggested by the meridian plane configuration of the plasma sheet sketched in Figure 3, as already discussed in section 2. Hitherto available observations, however, have not been adequate to establish the nature of the connection (due largely to uncertainties in attempting to trace field lines from the position of the observations to the ionosphere) and a number of theoretical suggestions have been made that can be classified into three major groups:

(1) Aurora occurs on all magnetic field lines threading the plasma sheet. This is essentially the concept argued by O'Brien (1967). The equatorward edge of the auroral oval corresponds, in this interpretation, to the inner boundary of the plasma sheet which, as discussed by Vasyliunas (1968a), lies on field lines

that are definitely closed and in fact still of a roughly dipolar (although distorted) shape; the poleward edge of the oval corresponds to the outer boundary of the plasma sheet and thus lies on (so-called "open") field lines extending far into the magnetotail.

(2) Aurora occurs on field lines that come from the immediate vicinity of the magnetic neutral sheet (and thus are "open"). This suggestion has been made by a number of authors, among them Dessler and Juday (1965), Coppi et al. (1966), Speiser (1967a, b), Piddington (1967a, b), and has often been coupled with a theory of particle acceleration at the neutral sheet. Since the inner edge of the plasma sheet, as just discussed, coincides with closed field lines that must lie well earthward of the magnetic neutral sheet, this suggestion implies that the equatorward edge of the auroral oval occurs poleward of the field lines passing through the inner edge of the plasma sheet.

(3) It has recently been proposed by Schield (1968; see also Schield et al., 1969) that aurora occurs at the inner boundary of the plasma sheet and that the auroral oval corresponds to the layer (~1 Re thick at the equator) within which the change in the electron energy spectrum associated with the inner boundary occurs (Vasyliunas, 1968a). If the precise location of the inner boundary is taken to be the point at which the electron spectrum just begins to change from its plasma sheet character, as done consistently

by Vasyliunas, then Schield's model implies that the poleward edge of the auroral oval coincides with field lines through the inner boundary of the plasma sheet.

Recently I have obtained some observational evidence directly bearing on this problem from electron measurements on the OGO 1 satellite. What follows is a brief description of the results; a more detailed account has been given by Vasyliunas (1969b).

The change of the OGO 1 orbital plane inclination from 31° at launch in September 1964 to 45° a year later allowed the satellite, during certain orbits in 1965 which were favorably phased relative to the daily wobble of the earth's dipole, to approach the earth at relatively high geomagnetic latitudes. A typical nearly equatorial orbit of 1964 and a "high latitude" orbit of 1965 have already been sketched in Figure 3. Data from six such "high latitude" orbits are available, and in each of them the narrow "horns" of the plasma sheet as indicated in Figure 3 were clearly observed. In particular, at these high latitudes the plasma sheet still has a clearly discernible inner boundary, which was crossed by the satellite at geocentric distances ranging between 2.5 and 3 Re. From such close distances, magnetic field lines can be traced to the earth's surface fairly accurately using the earth's main field alone (inclusion of fields due to magnetopause and tail currents changes the latitude and longitude of the field line intersection with the earth by ~ 1°). Thus the observed position of the inner edge of the plasma sheet can be mapped to ionospheric heights and compared with data on the auroral oval. Simultaneous ground observations of the aurora are not available, but according to Feldstein and Starkov (1968) the actual location of the aurora at a particular time is closely approximated by the statistical auroral belt for the corresponding degree of geomagnetic activity (Feldstein and Starkov, 1967).

In Figure 9 the observed positions of the inner edge of the plasma sheet, mapped to the ionosphere as described above, are shown together with the equatorward boundary of the auroral oval as determined from radar backscatter observations (Bates, 1966), for quiet geomagnetic conditions. It has been shown by Bates et al. (1969) that radar and visual oval aurora are closely associated; these particular radar observations are shown here because they were obtained in the same year as the OGO 1 data. In Figure 10 the same observations of the inner edge of the plasma sheet are compared with the auroral oval for quiet geomagnetic conditions as given by Feldstein and Starkov (1967); also included in Figure 10 are the positions of the inner edge observed by OGO 1 in the equatorial plane and mapped to the ionosphere using the field line mapping determined by Fairfield (1968). As can be seen in both figures, the inner edge of the plasma sheet lies on or close to the equatorward boundary of the auroral oval and (in Figure 10) is well removed from its poleward boundary. The same result is even more apparent in Figure 11, which shows observations during periods of magnetic bay activity. The earthward displacement of the inner edge of the plasma sheet during magnetic bays to distances $\lesssim$ 6 Re, observed in the equatorial plane (Vasyliunas, 1968a), here is seen to correspond precisely to the well-known equatorward expansion of the auroral oval during magnetically disturbed periods.

The observations thus strongly suggest that the inner edge of the plasma sheet and the equatorward boundary of the auroral oval coincide. This supports suggestion (1) of the three theoretical suggestions described earlier and is in definite disagreement with (2) and especially with (3). The position of the poleward boundary of the oval in relation to the plasma sheet is not so clear (the OGO 1 observations of the outer boundary of the plasma sheet occur at larger radial distances where reliable mapping does not appear to be possible). The observation by McDiarmid and Burrows (1968) that the poleward boundary of the auroral oval marks the limit of observable high energy (E>40 kev) electron fluxes, together with the fact that high energy electron fluxes observed within the magnetotail are confined to a region (Murayama, 1966; Anderson and Ness, 1966; Montgomery, 1968) that appears to coincide with the plasma sheet, may be taken as (admittedly inconclusive) evidence that the poleward boundary of the auroral oval and the outer boundary of the plasma sheet also coincide. The general configuration of plasma and magnetic fields on the night side suggested by all these observations is sketched in Figure 12: the auroral oval is simply the plasma sheet mapped down to the ionosphere. (The connection between the poleward boundaries of the oval and the plasma sheet, however, is far from being well established, and the relation of either of them to the soft precipitation zone recently observed at low altitudes by Burch [1968] and Hoffman [1969] is not clear.)

It is now of interest to compare the electron energy fluxes observed within the plasma sheet with the energy fluxes precipitated into the auroral oval. Figure 13 shows individual values of the omnidirectional electron energy flux measured by OGO 1 within the plasma sheet (from the same set of data as Figures 4 and 5), as a function of the Kp index. Also shown is the average precipitated electron energy flux into the night side auroral oval, obtained from results published by Sharp and Johnson (1968); this is the total precipitated energy flux averaged over the latitudinal width of the oval and has been multiplied by 4 to make it directly comparable with the equatorial omnidirectional flux (it is readily shown that, if the particle distribution in the equatorial region is isotropic over all directions including the loss cone, then the total precipitated flux observed at the ionosphere is one quarter of the omnidirectional flux observed near the equator). Except possibly at very low Kp values, the equatorial and the precipitated energy fluxes are of the same order of magnitude; averaging all the measurements gives a precipitated flux (times 4) of 5 ± 1 ergs cm^{-2} sec^{-1} and a flux within the plasma sheet of 4 ± 2 ergs cm^{-2} sec^{-1}. This means that if the precipitated particles come from the plasma sheet, the energy flux per steradian within the loss cone is of the same order of magnitude as the energy flux per steradian averaged over all directions. This result is in agreement with the hypothesis of Kennel (1969) and Vasyliunas (1969c), that strong pitch angle diffusion maintains the plasma sheet electron distribution approximately isotropic over the loss cone, and further indicates that the electron precipitation implied by this hypothesis is just adequate to supply the *average* energy flux observed in the auroral oval. (It should be emphasized that we are here discussing only values averaged over the width of the auroral oval; the present results shed no light on the origin of the individual auroral forms.) Independently of theoretical speculation, the observations indicate that the source of auroral particles, whatever it may be, maintains an average energy input to the ionosphere of the same order of magnitude as the maximum energy flux that can be drawn out of the plasma sheet electron population by pitch angle scattering processes.

The present results are consistent with the observation by Chase (1969) that the electron energy spectrum in post-breakup aurora closely resembles, in both shape and intensity, the spectrum within the plasma sheet.

5. Summary

Intense fluxes of low energy particles exist within the geomagnetic tail. They are confined to the equatorial region of the tail and form a plasma sheet several earth radii thick and centered about the magnetic neutral sheet. The mean energy of electrons within the plasma sheet typically ranges from a few hundred ev to a few kev; the mean energy of protons is appreciably higher. The electron and proton number densities are equal. Typical values of the number density ranging from 0.1 to 1 cm^{-3} have been reported; the lowest values occur near midnight. The plasma energy density is comparable to the magnetic field energy density; correlated plasma and magnetic field variations have been observed in which the sum of plasma and magnetic field pressures remains constant. Large correlated changes in electron density and energy, which maintain the energy density constant, have also been observed. There is no direct evidence for a very low energy ("thermal" or "background") particle population within the plasma sheet; if such a population exists at all, its electron density must be less than some tens of particles cm^{-3}, and there are indirect arguments that the density is less than ~ 1 cm^{-3}.

In the high latitude regions of the magnetotail, above and below the plasma sheet, the observed electron density is $\lesssim 4 \times 10^{-2}$ cm^{-3} and the electron mean energy is $\lesssim$ 100 ev; thus the energy density is very low in comparison with that within the plasma sheet.

Low energy proton fluxes extend from the magnetotail earthward to well within the outer radiation belt, where during magnetic storms they become very intense and form the ring current responsible for the storm main phase. Low energy electron fluxes extend from the magnetotail along the flanks of the magnetosphere and merge with the complicated (and as yet only partly explored) low energy electron structures on the day side of the magnetosphere. In the evening sector, however, these intense electron fluxes do not extend far into the radiation belts but terminate at the so-called inner boundary of the plasma sheet, which lies at an equatorial distance of 10 Re during magnetically quiet periods and moves inward to distances ~ 6 Re during magnetic bays. At this inner boundary the electron density appears not to change but the electron mean energy decreases very rapidly with decreasing distance.

The inner boundary of the plasma sheet has now been traced in latitude to ~ 55° (geocentric distance of ~ 2.5-3 Re) and shown to coincide with magnetic field lines through the equatorward boundary of the auroral oval. It has been suggested that the entire auroral oval is simply the plasma sheet mapped down to the ionosphere, but further study of the poleward boundaries especially is needed. The average precipitated energy flux into the auroral oval appears to be of the same order of magnitude as the electron flux within the plasma sheet.

Acknowledgments

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Figure captions

Figure 1. —— Solid line: Sketch of a typical electron energy spectrum (differential flux per unit energy) observed in the outer magnetosphere and the magnetotail. Dashed line: Spectrum of a hypothetical unobserved "thermal" electron population (here drawn with a total density 10 times that of the observed low energy electron population).

Figure 2. —— The average low energy electron distribution in the equatorial region of the magnetosphere, viewed from the north pole. The density of dots indicates qualitatively the flux of electrons with energies from 100 ev to several kev. The shaded region in the predawn sector has not yet been studied in detail; it is, however, known that strong electron fluxes are present within it.

Figure 3. —— The average low energy electron distribution in a meridian plane on the night side of the magnetosphere. The sun is to the left, the magnetotail to the right. The satellite orbits are shown rotated into a common meridian plane,

without regard to local time (the Vela observations cover all local times, the OGO-1, OGO-3, and Mars 1 observations are mostly between dusk and midnight, and the Electron 2 observations are near midnight and near dawn).

Figure 4. —— Frequency of occurrence of various electron parameters within the plasma sheet at local times from dusk to midnight from observations with OGO-1 (plus a few observations with Vela). The histograms are constructed at intervals of 1/2 decade in (a), (b), and (c), at 1/4 decade in (d) and (e). The Vela observations were taken from sample values published by Bame et al. (1967) and may not be representative of the entire set of Vela observations.

Figure 5. —— Plot of electron mean energy vs. density, for the same set of data as Figure 4. Points enclosed in circles refer to measurements during the October 3, 1964, magnetic storm; those enclosed in squares refer to the November 15, 1964, storm.

Figure 6. —— Magnetic field pressure (solid line) and total pressure (data points), assuming equal proton and electron pressures, measured during the

magnetosphere passage of Pioneer 7. The spacecraft crossed the magnetotail at a nearly constant local time of ~2 hours; its distance was 11 Re at the beginning of the figure (the high field values reflect the proximity to the earth) and 32 Re at 10 hours on August 18. (After Lazarus et al., 1968.)

Figure 7. —— Typical variation of electron properties across the inner boundary of the plasma sheet. E_o is the energy corresponding to the most probable speed and in the present case is approximately 1/2 of the electron mean energy; N is the electron number density and U the energy density. The local time is approximately 19 hours.

Figure 8. —— Equatorial electron density measured by the whistler technique (taken from Figures 4 and 8 of Angerami and Carpenter, 1966) and electron density within the plasma sheet measured with a Faraday cup on OGO-1 (excluding measurements during magnetic storms).

Figure 9. —— Observed positions of the inner edge of the plasma sheet, mapped to the ionosphere, and the average equatorward boundary of radar aurora as given by Bates (1966).

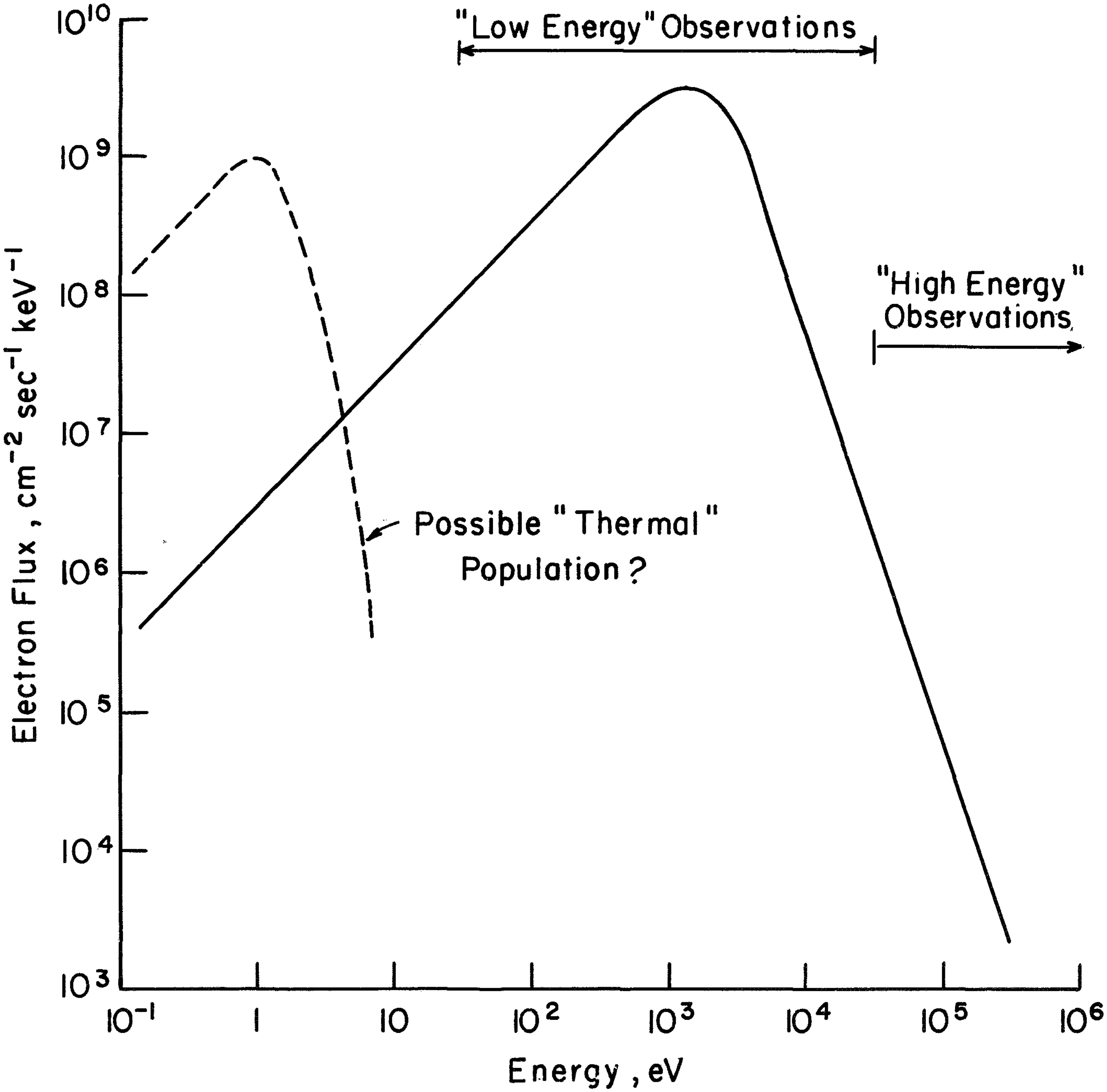
Figure 10. —— Observed positions of the inner edge of the plasma sheet, mapped to the ionosphere, and the auroral oval as given in Figure 5 of Feldstein and Starkov (1967) for different values of the geomagnetic activity index Q. The observation at K_p=0o was preceded by an interval of 12 hours with K_p not exceeding 0+, and 42 hours with K_p not exceeding 1o.

Figure 11. —— Same as Figure 10 but during disturbed geomagnetic conditions.

Figure 12. —— Configuration of the magnetic field lines and the plasma in a meridian plane on the night side of the magnetosphere. The 45° hatching indicates the plasma sheet, which corresponds to the auroral oval according to theoretical suggestion (1) and the present observations; the horizontal hatching indicates the "boundary layer" at the inner edge of the plasma sheet within which the change of electron properties occurs, which would be associated with the auroral oval according to suggestion (3).

Figure 13. —— The omnidirectional electron energy flux within the plasma sheet and the precipitated

flux into the auroral oval. The latter was obtained from Table 2a of Sharp and Johnson (1968), dividing their parameter PRECP (which represents the energy flux integrated over the latitudinal width of the oval) by the average width of the oval near midnight for the appropriate value of K_p, as given by Feldstein and Starkov (1967).



"Low Energy" Observations
"High Energy" Observations
Possible "Thermal" Population ?
Electron Flux , cm⁻² sec⁻¹ keV⁻¹
10¹⁰
10⁹
10⁸
10⁷
10⁶
10⁵
10⁴
10³
10⁻¹
1
10
10²
10³
10⁴
10⁵
10⁶
Energy , eV

Figure 1.

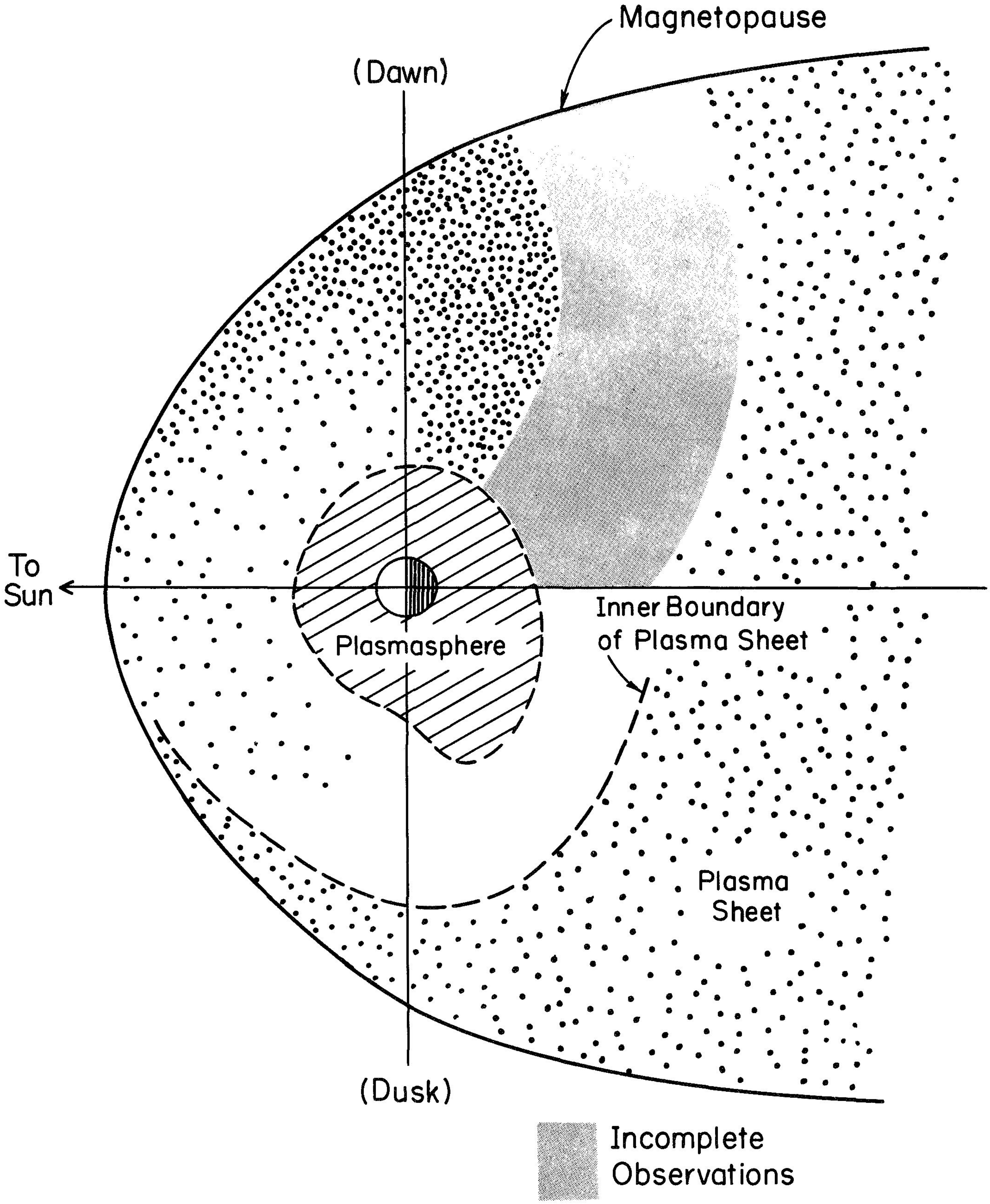

Magnetopause
(Dawn)
To Sun
Inner Boundary of Plasma Sheet
Plasmasphere
Plasma Sheet
(Dusk)
Incomplete Observations

Figure 2.

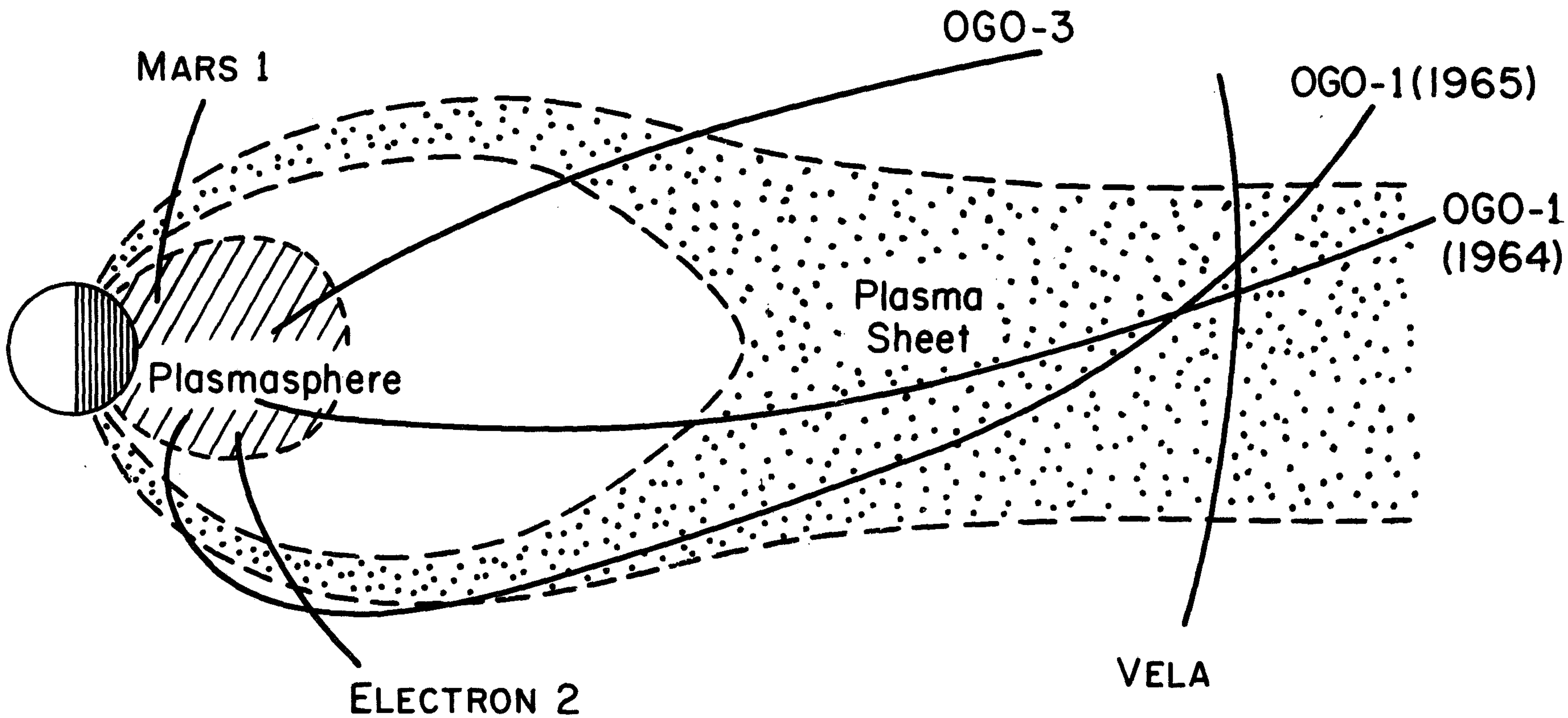
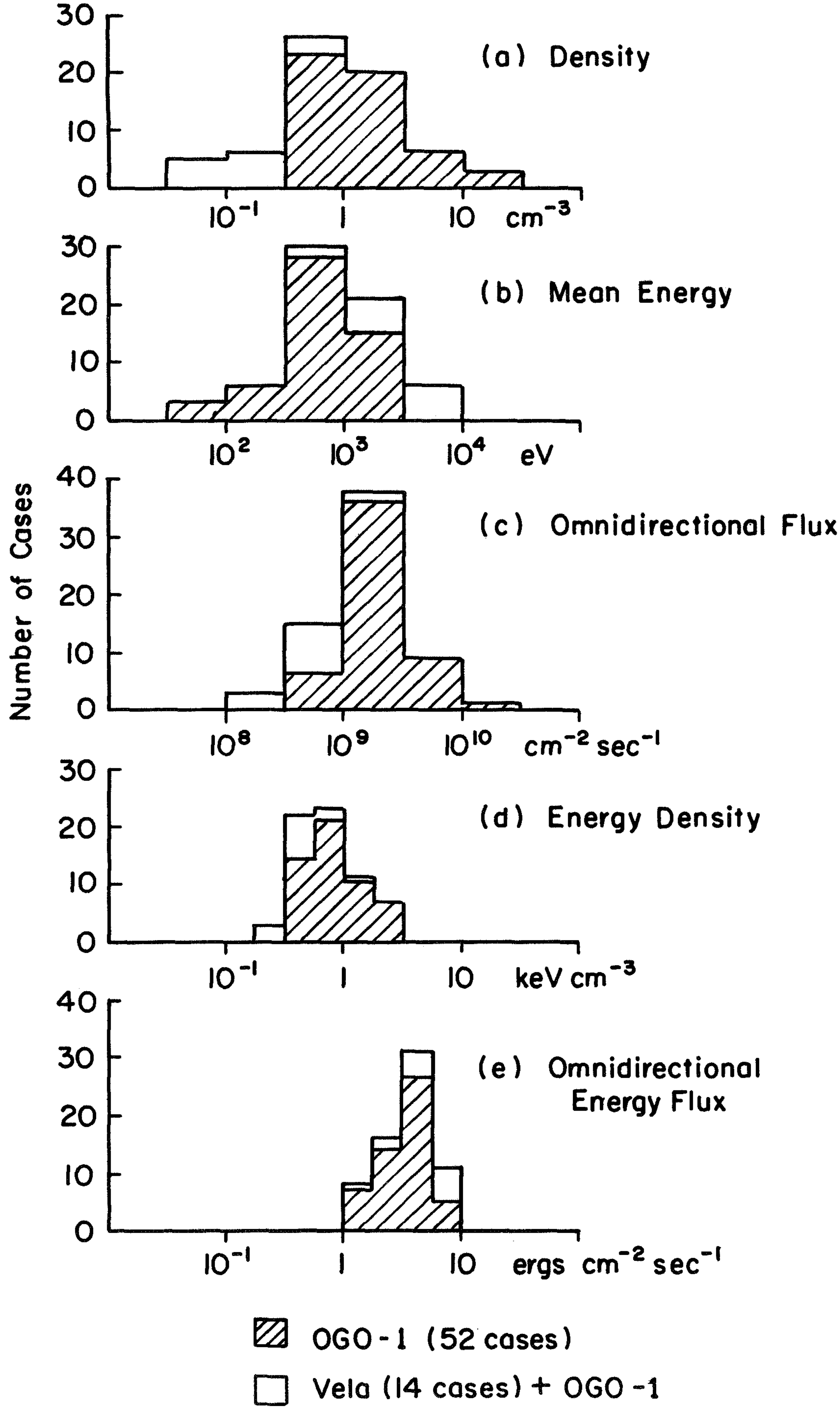

OGO-3
MARS 1
OGO-1(1965)
OGO-1
(1964)
Plasma
Sheet
Plasmasphere
VELA
ELECTRON 2

Figure 3.



Number of Cases
(a) Density
30
20
10
0
10⁻¹
1
10
cm⁻³
(b) Mean Energy
10²
10³
10⁴
eV
(c) Omnidirectional Flux
40
10⁸
10⁹
10¹⁰
cm⁻² sec⁻¹
(d) Energy Density
keV cm⁻³
(e) Omnidirectional
Energy Flux
ergs cm⁻² sec⁻¹
OGO-1 (52 cases)
Vela (14 cases) + OGO-1

Figure 4.

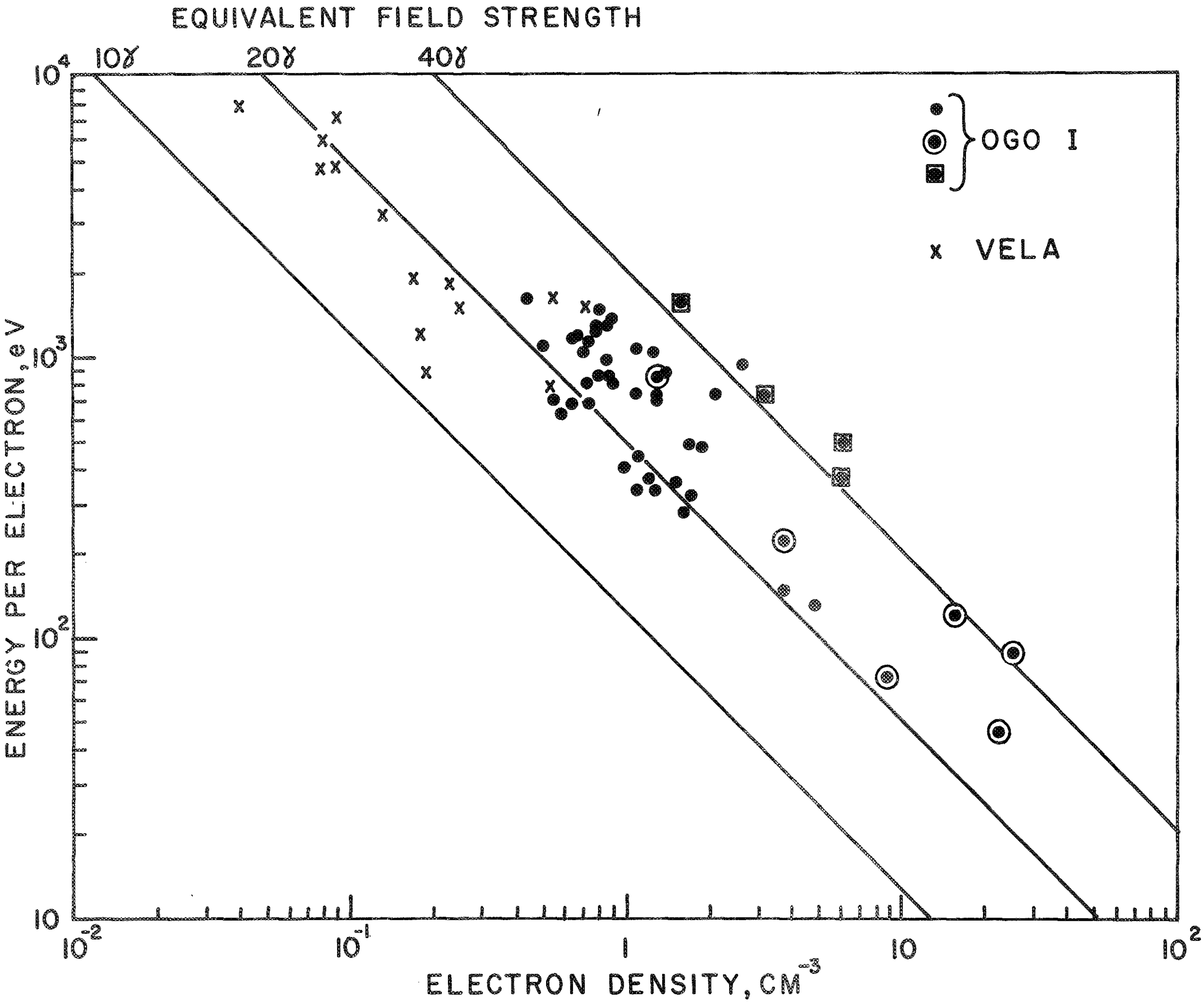
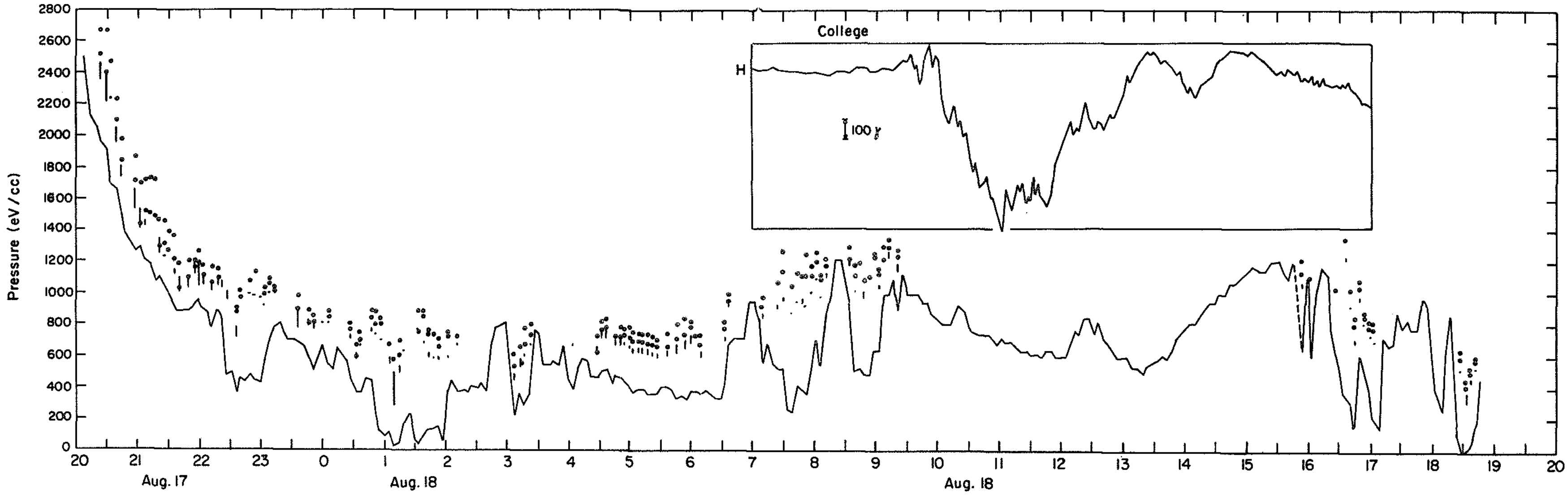
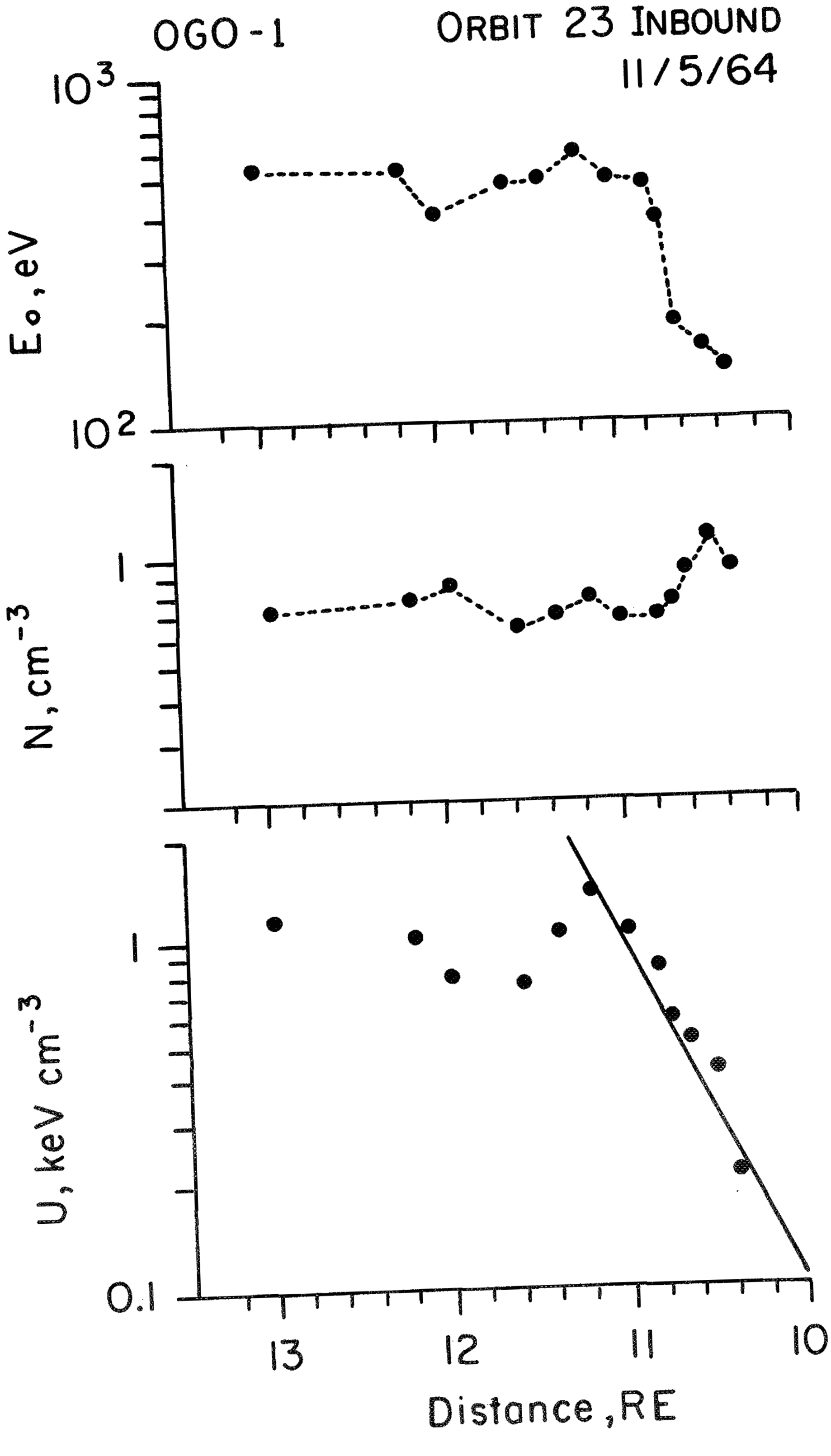

EQUIVALENT FIELD STRENGTH
10γ
20γ
40γ
OGO I
VELA
ENERGY PER ELECTRON, eV
ELECTRON DENSITY, CM⁻³
10^4
10^3
10^2
10
10^{-2}
10^{-1}
1
10
10^2

Figure 5.



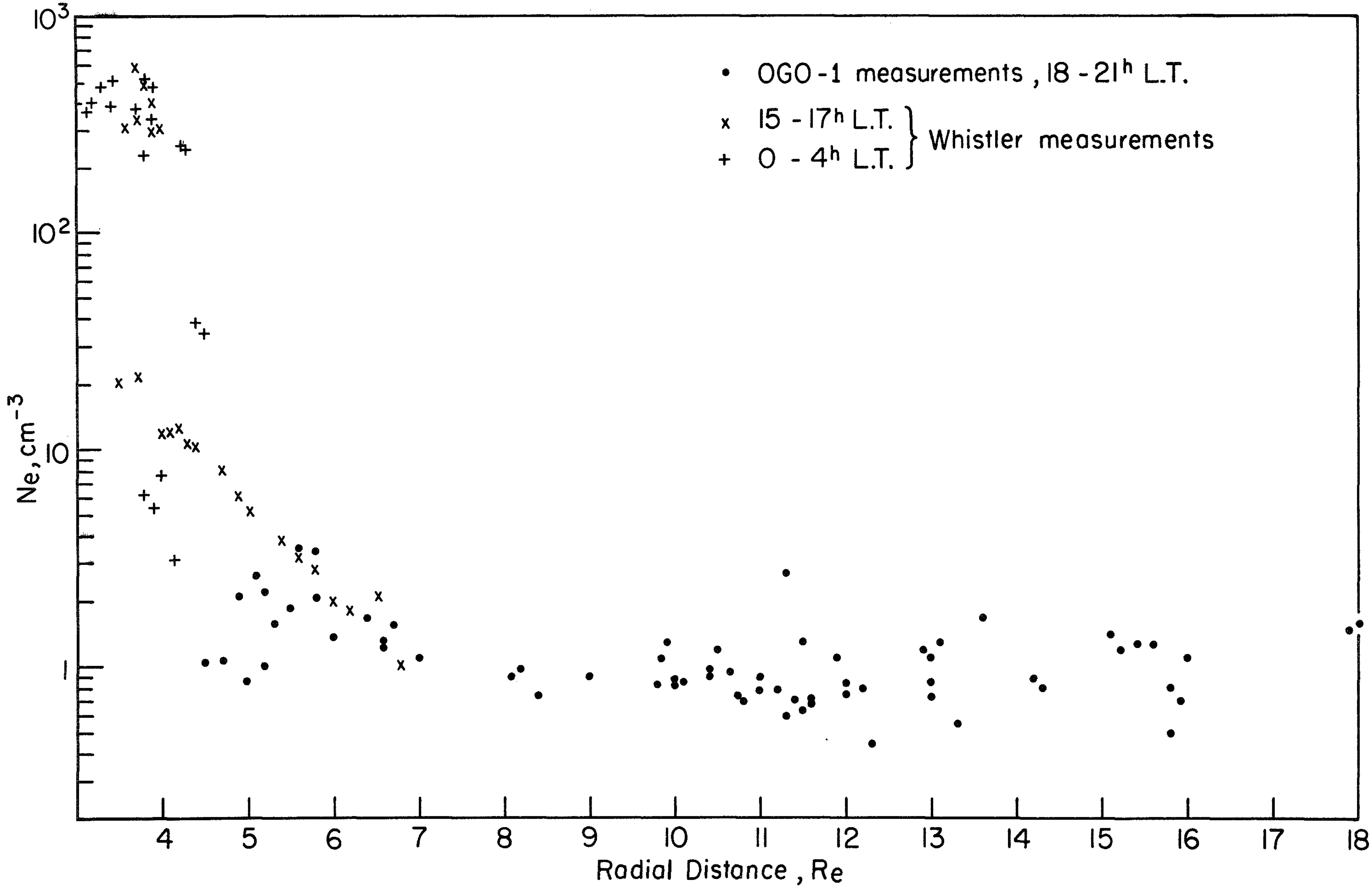
College
H
100 γ
Pressure (eV/cc)
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
20
21
22
23
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Aug. 17
Aug. 18
Aug. 18

Figure 6.



OGO-1
ORBIT 23 INBOUND
11/5/64
10^3
E_o, eV
10^2
1
N, cm^{-3}
1
U, keV cm^{-3}
0.1
13
12
11
10
Distance, RE

Figure 7.



10³
10²
10
1
Ne, cm⁻³
• OGO-1 measurements, 18-21h L.T.
x 15-17h L.T.
+ 0-4h L.T.
Whistler measurements
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
Radial Distance, Re

Figure 8.

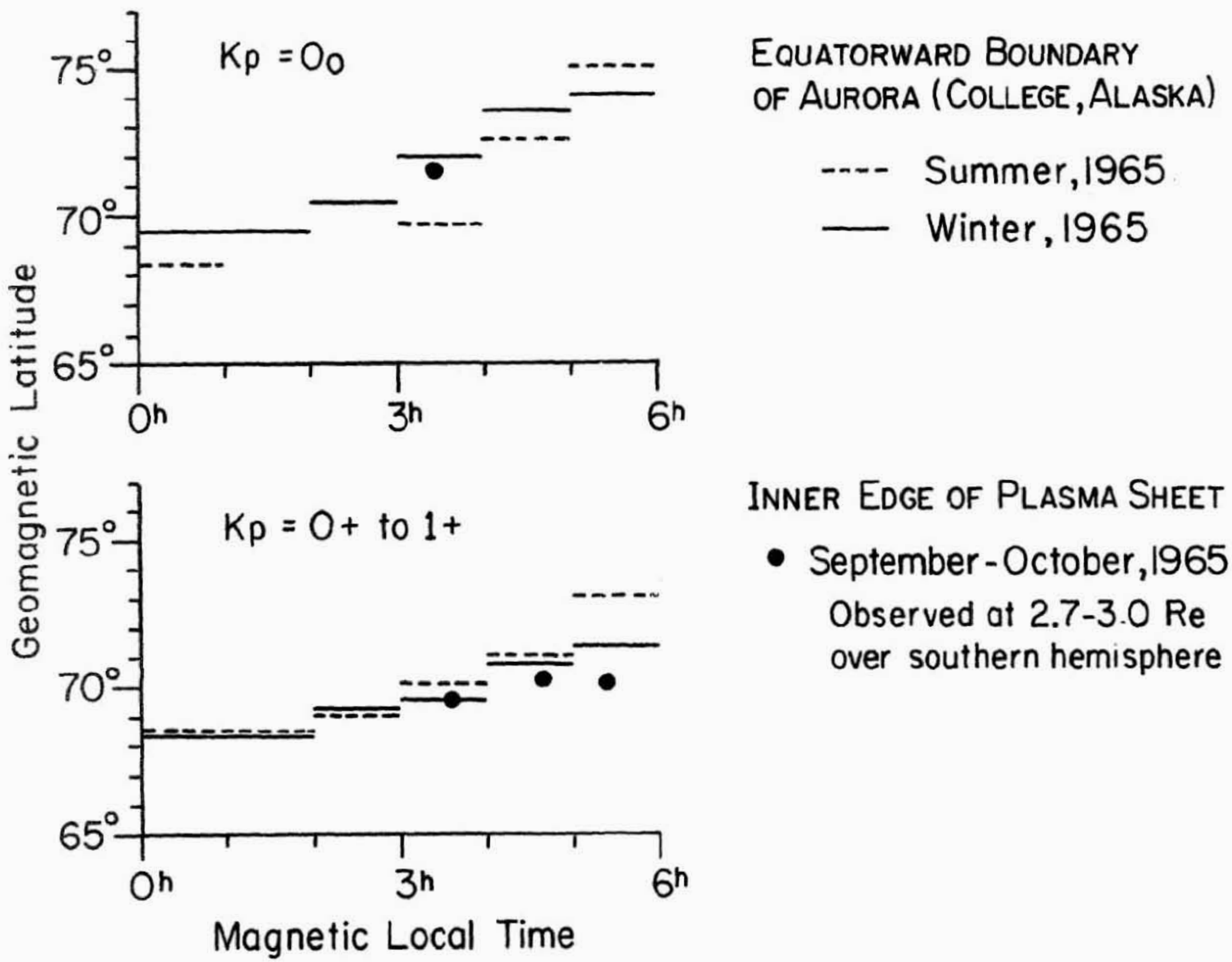

Kp = 0o
Kp = 0+ to 1+
75°
70°
65°
0h
3h
6h
Geomagnetic Latitude
Magnetic Local Time
EQUATORWARD BOUNDARY OF AURORA (COLLEGE, ALASKA)
Summer, 1965
Winter, 1965
INNER EDGE OF PLASMA SHEET
September-October, 1965
Observed at 2.7-3.0 Re
over southern hemisphere

Figure 9.

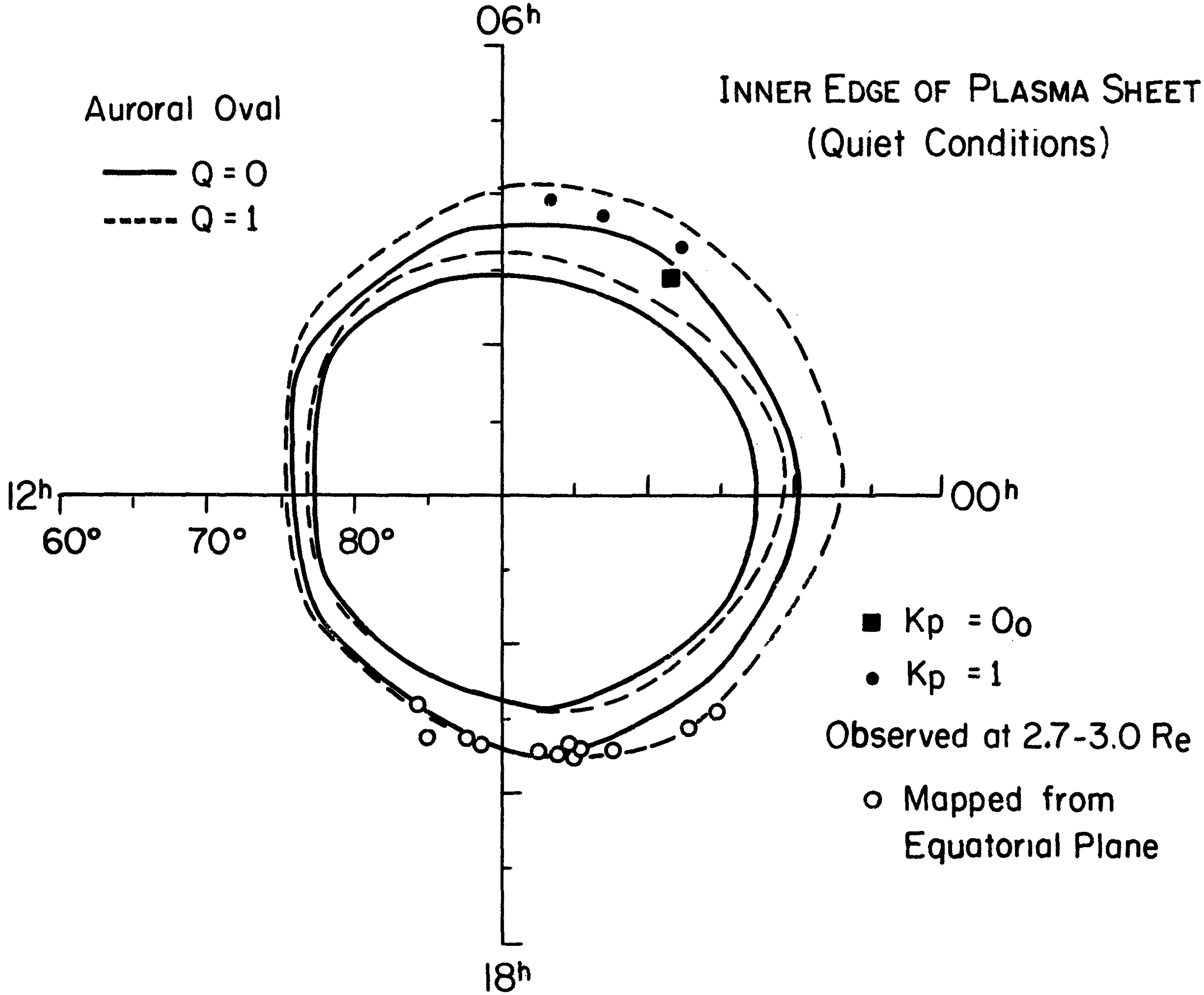
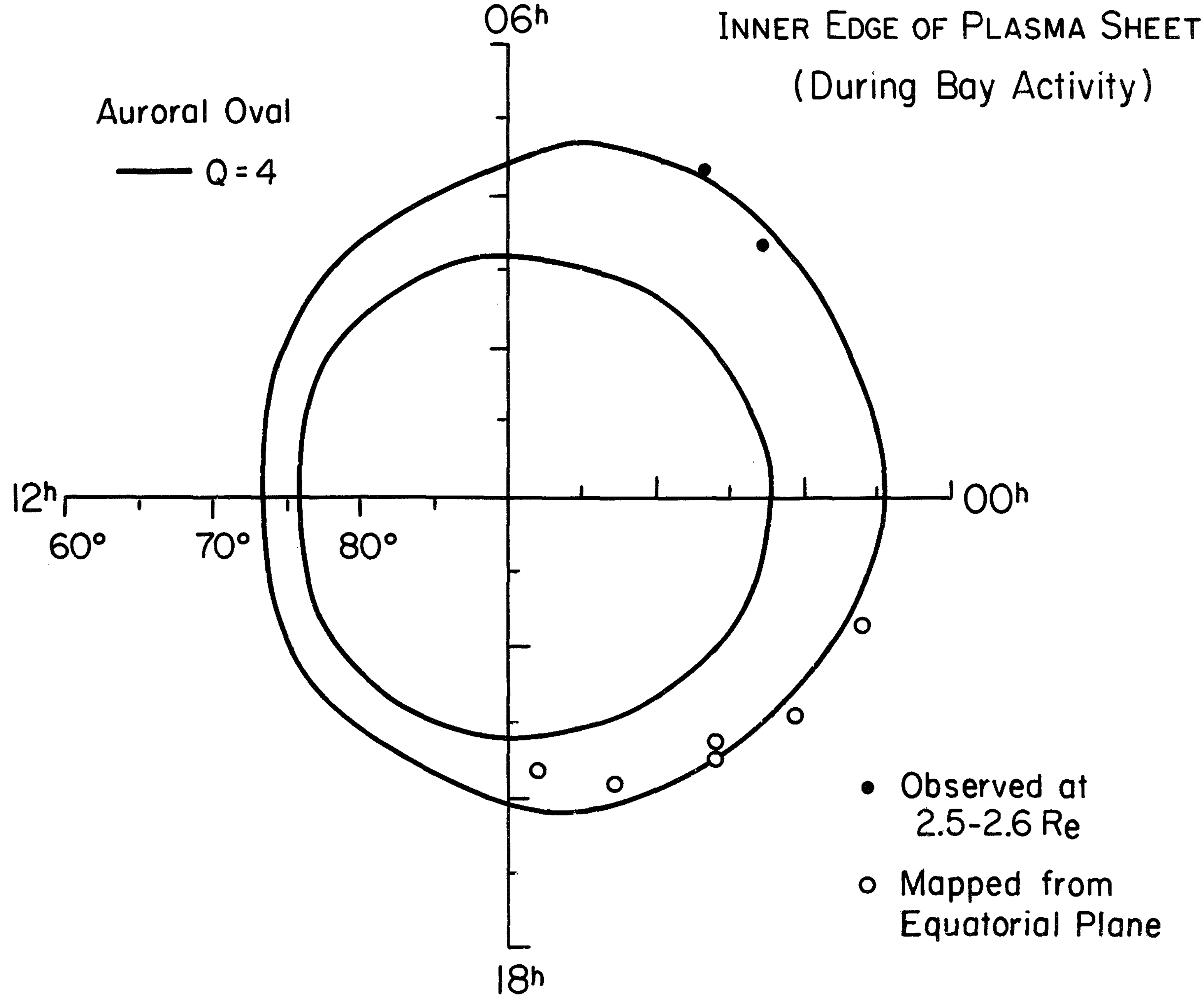

06h
Inner Edge of Plasma Sheet
(Quiet Conditions)
Auroral Oval
Q = 0
Q = 1
12h
60°
70°
80°
00h
18h
Kp = 0o
Kp = 1
Observed at 2.7-3.0 Re
Mapped from
Equatorial Plane

Figure 10.



Inner Edge of Plasma Sheet
(During Bay Activity)
Auroral Oval
Q = 4
06h
12h
00h
18h
60°
70°
80°
Observed at 2.5-2.6 Re
Mapped from Equatorial Plane

Figure 11.

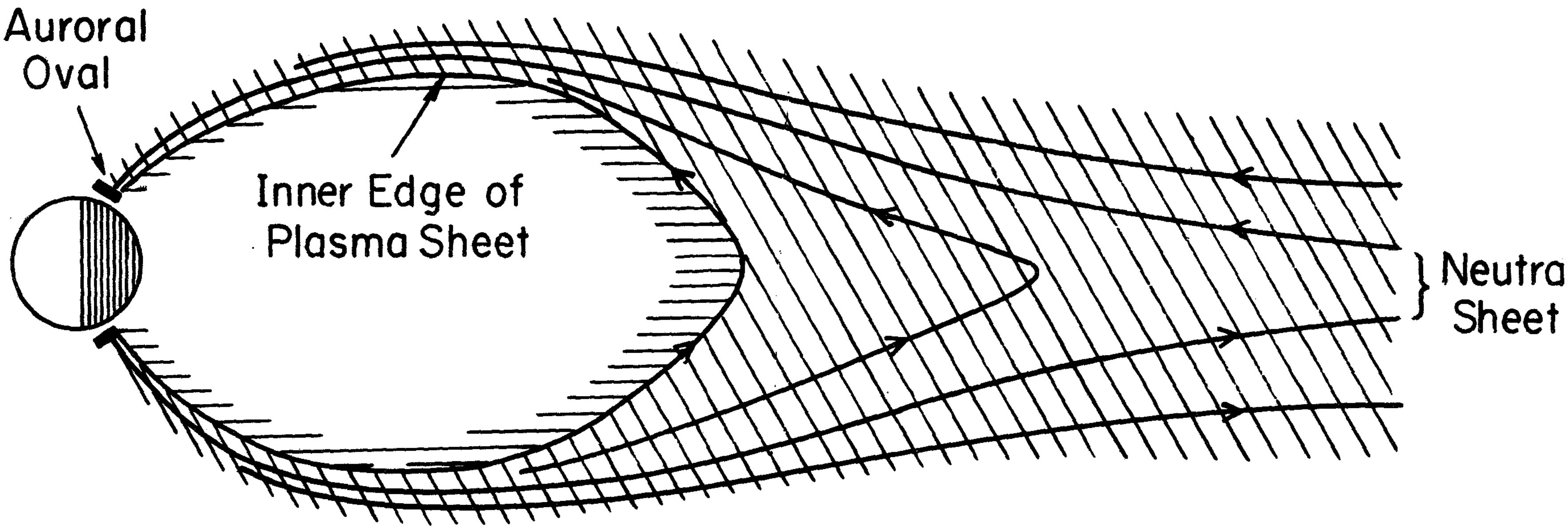


Figure 12.

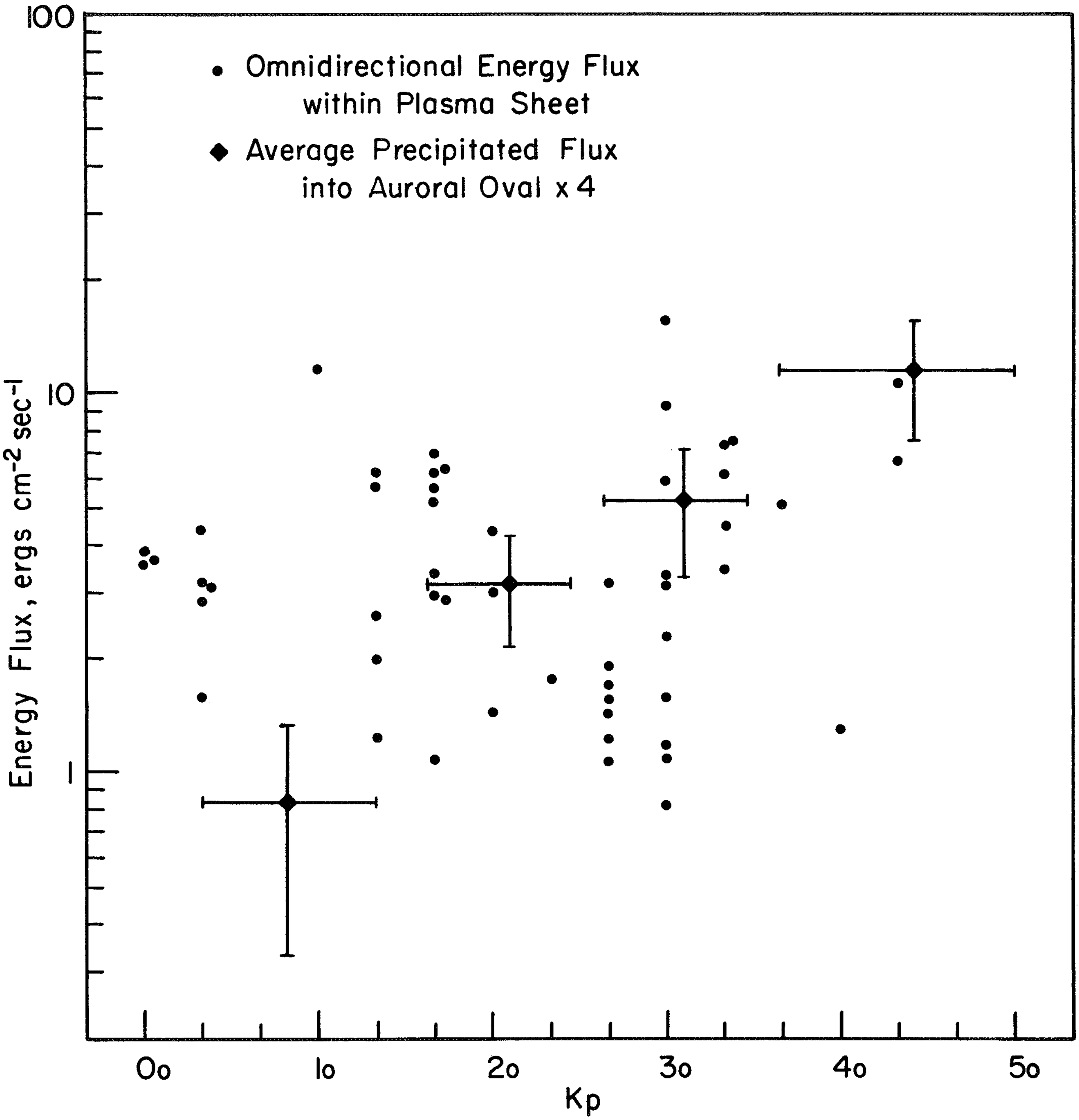

Omnidirectional Energy Flux
within Plasma Sheet
Average Precipitated Flux
into Auroral Oval x 4
100
10
1
Energy Flux, ergs cm-2 sec-1
0o
1o
2o
3o
4o
5o
Kp

Figure 13.