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A LARGE DIURNAL VARIATION
OF THE GEOMAGNETICALLY-TRAPPED
RADIATION*

by

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ABSTRACT

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The satellite Injun I was used to find the high latitude termination of trapping of electrons with energy $E \gtrsim 40$ keV at 1000 km altitude over North America. On the average, this termination is at $L \sim 16$ or $\Lambda \sim 75°$ in the local day and at $L \sim 8$ or $\Lambda \sim 69°$ in the local night. As a consequence, in the range $8 \lesssim L \lesssim 16$ or $69° \lesssim \Lambda \lesssim 75°$, the average intensity of trapped electrons is some one hundred times greater in the local day than it is at local night. Several explanations are suggested but none is proven. The results show that McIlwain's L parameter loses its simple applicability for $L \gtrsim 6$ or $\Lambda \gtrsim 66°$.

INTRODUCTION

The time averaged intensity of electrons with energy $E \gtrsim 40$ keV which are trapped at 1000 km altitude over North America is essentially constant from mid-latitudes up to some high northern latitude, and then it decreases by several orders of magnitude within a few more degrees of latitude [see Fig. 8 of O'Brien, 1962a]. In this note we examine the quiescent variations in the magnetic latitude at which this abrupt change of intensity occurs. Briefly, we find that this latitude is on the average some five to ten degrees higher during the local day than it is during the local night. In the following paper [Maehlum and O'Brien, 1962] the variation of this latitude during magnetic storms is discussed.

It has been known for some time that several geophysical phenomena move in magnetic latitude as a function of local time. For example, Axford and Hines [1961] have summarized such a movement of several types of geomagnetic disturbance [see also Hope, 1961], of visible auroras, spread F, sporadic E and auroral zone radio absorption. Also, Reid and Rees [1961] find a similar movement in the latitude of peak emission of Balmer (hydrogen) lines in auroras.

Attempts have been made to attribute several of these effects to similar diurnal movement of geomagnetically trapped particles. In this note we show directly for the first time, that the geomagnetically trapped radiation does indeed have a comparable diurnal variation of the requisite qualitative form. But we also find that the cause of this variation is not apparent, and neither is its relation to the variations of the above phenomena.

EXPERIMENTAL DETAILS

All data discussed here were obtained with the State University of Iowa radiation research satellite Injun I over North America. Injun I was launched on June 29, 1961, and is still operating at this time, sixteen months later. It is in an orbit with apogee altitude 1010 kilometers, perigee 890 kilometers, period 104 minutes and inclination 67°. Over North America Injun therefore passes over and north of the auroral zone (magnetic latitude $\lambda \sim 67°$) and it reaches up to about 80° N magnetic latitude. It has an array of thirteen particle detectors and other apparatus, and with several of these directional intensity j of electrons with energy $E \gtrsim 40$ keV can be measured as a function of the pitch angle α between a particle trajectory and the local magnetic field vector $\vec{B}$, which is of magnitude B gauss. In this note we discuss mainly the directional intensity at $\alpha = 90°$, which is the intensity $j_\perp$ of those particles which "mirror" and are reflected at Injun altitudes and are trapped to form the outer radiation zone. Details of detector characteristics, data reception and decoding, etc. are given in a general study of outer-zone electrons [O'Brien, Laughlin, Van Allen, and Frank, 1962].

At launch Injun was spinning rapidly, but the spin rate damped out in the first few days. During those days $j_\perp$ was measured several times in each pass as the particle detectors spun through the angle $\alpha = 90°$. In this way, the variation of $j_\perp$ with magnetic latitude (i.e., the latitude profile of particle intensity) could be determined for both northbound and southbound passes of the satellite.

Now, soon after launch the orientation of the satellite orbit in space with respect to the sun was such that the northbound passes over North America were at local times between about 1200 and 1600 hours ("local day"), while the southbound passes were at local times between about 1900 and 2300 hours ("local night"). So comparison of the latitude profiles obtained on northbound passes with those obtained on southbound passes as in Fig. 1 gives a measure of the local time dependence of this profile.

In Fig. 1 the particle intensities are plotted against the coordinate L introduced by McIlwain /1961/ rather than against magnetic latitude. By taking account of several invariants of the motion of geomagnetically trapped radiation McIlwain defined a parameter L which uniquely labels a magnetic shell on which a trapped particle bounces in latitude and drifts in longitude. Numerically, L is such that, if the earth's magnetic field was that of a perfect dipole, then the equatorial radial distance to a given magnetic shell would be L in units of earth radii. The earth's field is <u>not</u> that of a perfect dipole, but in evaluating L for a given point in space, McIlwain [1961] used the best expressions then available for the real magnetic field. He showed that the two coordinates L and B can be used in studies of the radiation zones in the time-stationary state up to $L \sim 5$. We will show in this note that L does not retain its simple applicability for $L \gtrsim 6$.

A coordinate (Λ) analogous to magnetic latitude (λ) can then be derived from L from the relation $L \cos^2 \Lambda = 1$. We have called Λ the invariant latitude so as to indicate its derivation from L, and we include it in Fig. 1. Actually, over North America where these Injun observations were made, λ and Λ do not differ by more than about 2°, and in this note they can be regarded as essentially the same.

The results of Fig. 1 show that the zone of trapped electrons at 1000 km altitude extends to higher latitudes on the daytime side of the earth than it does on the nighttime side. Although the high latitude "edge" of the zone is not at all sharp at this altitude and at these times, we will refer to that latitude where the intensity has dropped to about 1% of its low latitude value as the northern "boundary" latitude Λ_n. From Fig. 1, the boundary latitude is $\Lambda_n \sim 75°$ (or $L_n \sim 16$) in the local day, and about $\Lambda_n \sim 69°$ (or $L_n \sim 8$) in the local night. The spread in Λ_n at a given local time is large and real, as discussed below, and also in Maehlum and O'Brien, [1962].

Although there are many parameters such as magnetic-storm activity, longitude or altitude which can affect the intensity of trapped electrons at a given value of L, none of these parameters was sufficient to explain the effect in Fig. 1. For example, the legend of Fig. 1 shows how the planetary magnetic disturbance index K_p varied between 0 and 6 (its total range possible is only 0 to 9) while the difference in the northbound and southbound profiles persisted. Any longitude effect is also negligible, since the passes criss-crossed over the same range of longitude (~ 230° E to 340° E) again and again as the earth rotated inside the satellite orbit. Also, since the altitude of the northbound passes was about 980 kilometers and that of the southbound passes about 1000 kilometers, any altitude effect is negligible here.

The only remaining parameter we can find is then local time. Ideally, we should find latitude profiles for many months as the plane of the orbit rotated with respect to the sun-earth vector, and then plot the boundary latitude (Λ_n) as a function of local time over the full range of twenty four hours. However, the launch malfunction which failed to separate another satellite (Greb) from Injun frustrated our aim to measure $j_\perp$ continuously after the spin damped out [see O'Brien et al., 1962]. On one pass in which Injun *was* oriented continuously, at a local time of 0300 hours L_n was ~ 10, so that $\Lambda_n \sim 71.5°$ [see Fig. 3 of O'Brien et al., 1962]. But generally the satellite spins so much yet so sluggishly that only a very few measures of $j_\perp$ are obtained during a single pass, far too few in general to define Λ_n accurately.

So instead, from all available measurements of $j_\perp$ in a given narrow range of L, $j_\perp$ was plotted as a function of local time. One such plot is shown in Fig. 2, and this shows clearly that for the range $8 \leq L < 10$ [$69.3° \leq \Lambda < 71.5°$] the intensity of trapped electrons in the local day was more than one hundred times the intensity of the local night. As one would predict from Fig. 1, a similar effect persisted for $10 \leq L < 12$, $12 \leq L < 14$, etc., with the peak (i.e., daytime) intensity becoming less as L increases.

The spread in the points of Fig. 2 at a given local time arises from

i) magnetic storms changing Λ_n [see the following paper by Maehlum and O'Brien, 1962] and

ii) spatial variations due to the plotted value of $j_\perp$ being measured wherever the satellite happened to orient in the range $8 \leq L < 10$. (Fig. 1 shows clearly how $j_\perp$ at $L \sim 8$ can be very much greater than $j_\perp$ at $L \sim 10$).

As a result of this spread, we cannot resolve the exact shape of the diurnal variation, and shall refer to it merely as a day-night effect.

As can be seen from Fig. 1, there is little, if any, diurnal variation in the intensity of electrons trapped at 1000 km altitude at $L \sim 5$. The average intensity in local day is the same as that in local night to within a factor of two, and reliable delineation of any diurnal effect by a method such as sketched in Fig. 2 is not possible with our data because magnetic activity causes variations in intensity by at least an order of magnitude. In other words, if a diurnal variation is the "signal" and magnetically controlled variations are the "noise", then at $L \sim 8$ the signal-to-noise ratio is more than ten, and the signal is readily detectable. But at $L \sim 5$, the signal-to-noise ratio is less than ~ 0.2, and we have not measured the signal accurately.

DISCUSSION

The mere observation of a high latitude termination of trapping at the low (Injun) altitude of 1000 kilometers does not necessarily imply that there is really any termination in the equatorial plane. However, data from Explorer XII which reached a radial distance of about 83,000 kilometers, show that trapping of electrons with $E \gtrsim 40$ keV does indeed cease or become very small in the equatorial plane at a radial distance which varies from about 8 to 11 earth radii as geomagnetic storm activity varies /Rosser, O'Brien, Van Allen, Laughlin, and Frank, to be published/ but which is the same location as the interface between the geomagnetic field and interplanetary space /Cahill and Amazeen, 1962/. The Explorer XII data are insufficient to determine any diurnal variation in this distance of termination.

The Explorer XII data provide sufficient evidence to suggest (but not prove) that Λ_n does represent a magnetic latitude at which trapping ceases, and that it represents a magnetic field line which, in an idealized simplification, is the terminal field line at the interface of the geomagnetic field with interplanetary space. Then, from Fig. 1 and the Explorer XII data, a sketch of the geomagnetic field configuration can be drawn as in Fig. 3.

These Injun observations may be summarized by the statement that the termination of trapping is found at an invariant (or magnetic) latitude of about 75° at local noon and at about 69° at local midnight. These are very approximate values only (see Fig. 1).

Several other geophysical phenomena show a similar movement in magnetic latitude as a function of local time. For example, in Fig. 11 of Axford and Hines [1961] similar effects are plotted for several types of geomagnetic disturbance [see also Hope, 1961], visible auroras, spread F, sporadic E, and auroral zone radio absorption. Also Reid and Rees [1961] find a similar effect in the latitude of peak emission of hydrogen lines in auroras.

There has been theoretical study of the cause of the effects listed in the previous paragraph, and several authors [Vestine, 1960; Reid and Rees, 1961] have associated the diurnal variation in the latitude of these phenomena with a variation in the latitude to which geomagnetically trapped particles move as they drift in longitude in the geomagnetic field distorted by a solar wind as in Fig. 3. As they drift in longitude, the several adiabatic invariants of their motion are conserved, and thus they must move (so state the theories) to lower magnetic latitudes on the night side than on the day side. So we may state as a suggested explanation of this effect:

Hypotheses 1: that the geomagnetic field is distorted by the solar wind as in Fig. 3, and that geomagnetically-trapped particles obeying one or more adiabatic invariants of their motion must therefore move from high latitudes at local noon to lower latitudes at local midnight.

Qualitatively, this hypothesis yields the observed diurnal effect. Quantitatively, it does not. Consider the longitudinal integral invariant of particle motion

$$I = \int_{M}^{M^*} \sqrt{1 - B/B_m}\, ds$$

where the integral is evaluated along the guiding center ($\sim$ a line of magnetic force) between the mirror points M and M* at which the magnetic field intensity is B_m. Vestine /1960/ suggested that the solar wind distorts the geomagnetic field lines by compressing them on the sunlit side and extending them on the night side. To conserve I and to mirror at the same B_m, a particle must then drift to lower latitudes on the dark side. However, Malville /1961/ calculated the magnitude of the resultant movement in latitude and found that even for a severe magnetic storm causing distortion of the geomagnetic field, (i.e., for a very strong solar wind), conservation of I alone would lead to a latitude displacement of less than 2°, far less than that reported here and in other geophysical studies. It would appear that the small magnitude of the effect is due to the fact that the field lines on the night side are not extended, but indeed are slightly compressed [Dessler, private communication]. We do not discuss this further here.

On the other hand, Reid and Rees [1961] invoked the concept that particles trapped in the equatorial plane would drift in longitude in a region of constant field strength B. Using the Chapman-Ferraro [1931, 1932] model of an image dipole of the same moment as the earth's dipole, situated at local noon at twice the radial distance of the interface, Reid and Rees [1961] calculated the radial distances on the noon side at which B was the same magnitude as at chosen radial distances on the midnight meridian. In order to make this calculation, and correlate it with ground-level observations, they had to assume that the magnetic field lines which are orthogonal to the stream front at local noon are those of the undistorted dipole field. This is an over-simplification, and the fact that they then predict diurnal latitude drifts of up to ten degrees for solar winds of moderate strength cannot be used immediately here. In fact Malville [1961] claims that his calculation of only a small latitude change by conservation of I refutes the estimate of Reid and Rees [1961].

Malville /1961/ does suggest that an expansion of the field lines due to trapped particles could be invoked to explain the observed latitude effect as following directly from conservation of I if the field lines were extended in length by a factor of four or so. This appears to us to be an unreasonably large elongation, at least for steady-state or quiescent times such as we have included here.

In summary, Hypotheses I gives qualitatively the observed diurnal variation, but in the presently developed theories of distortion of the geomagnetic field by the steady solar wind the magnitude of the predicted effect is much less than the observed one.

We might also advance

Hypothesis II: that there is a steady-state "source" of electrons accelerating them within a cone of a few degrees about $\overline{B}$ in the equatorial plane on the sunlit side of the earth.

This hypothesis will satisfy the Injun observations, since the particles follow the invariant relation

$$\frac{\sin^2 \alpha}{B} = \text{constant} = \frac{\sin^2 \alpha_o}{B_o} = \frac{1}{B_m}$$

where the subscript o refers to values in the equatorial plane. Then,

$$\sin^2 \alpha_o = \frac{B_o}{B_m} \sim \frac{1}{L^3}$$

Hence a particle with a given equatorial pitch angle $\alpha_0 = 2°$ (say), will be precipitated into the atmosphere for $L \lesssim 6$ but will be trapped at Injun altitudes for $L \gtrsim 10$.

On the basis of this hypothesis, we would expect to see electrons with $E \gtrsim 40$ keV

(a) being precipitated into the atmosphere over a wide range of L during the day, and

(b) trapped at ~ 1000 km altitude at large L values during the day but not necessarily during the night.

There is evidence of relatively poor statistical weight that effect (a) does occur. Specifically, in eight out of eight early Injun passes when the angular distribution of the electrons could be measured, there was precipitation from L ~ 2 to L ~ 10 during local day. In only one out of eight nighttime passes over the same period was there precipitation /O'Brien, 1962b/.

The evidence presented in this paper shows that effect (b) does occur. Hypothesis II may be tentatively accepted, but it is by no means established firmly.

Indeed, Hypothesis II does not indicate why the quasi-trapped electrons at high L values on the daytime side are not there at night. Nor does it explain the diurnal variation in latitude of the other geophysical phenomena mentioned above.

The similarity in the diurnal variation of the trapped radiation and of these other phenomena suggests that the first is the cause of the others /as Vestine, 1960, and others would suggest/ or else that they have a common cause. We have established elsewhere that the trapped particles cannot be the primary cause of auroras, and suggested they may be secondary effects resulting from trapping of some of the splashed electrons produced in the violent auroral acceleration mechanisms /O'Brien, 1962a/. On the other hand, in the following paper /Maehlum and O'Brien, 1962/ it is shown that there is a correlation between electrons detected at 1000 km altitude and auroral radio absorption. Hence, it is attractive to visualize all these diurnal effects as following from a single primary cause viz.

Hypothesis III: that auroral and similar acceleration mechanisms can occur only on closed field lines.

Since this hypothesis cannot be tested at present except by precise conjugate point studies, it is not examined here. It hardly solves these problems however, since it gives no indication of why the latitude deviation is of the observed magnitude, or of the nature of the "acceleration mechanisms".

CONCLUSION

In conclusion then, we have observed the diurnal variation in the high latitude termination of the outer radiation zone, which many authors speculated might exist in order that it could cause the observed diurnal variations of other phenomena. However, we claim on the basis of other evidence /O'Brien, 1962a/, that if the several diurnal phenomena are related at all, it is only in the sense that they are effects of a common and as yet unknown cause. A few hypotheses to explain the observations have been listed but none is completely satisfactory. Doubtless many other hypotheses can be suggested also. These observations were made over a period of about six months, and showed that the diurnal effect persists even during magnetically quiet periods. This may be taken as additional evidence for the continual existence of a solar wind.

These results point up the great scientific value of instrumenting and orbiting as soon as possible a satellite into the so-called geostationary orbit at $L \sim 6.6$ earth radii, where diurnal effects may be studied so readily.

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FIGURE CAPTIONS

Figure 1. Latitude profiles of the intensity of trapped electrons obtained in ten passes with local time between 1200 and 1600 hours (local day) and in eleven passes with local time between 1900 and 2300 hours (local night) soon after launch when the satellite was spinning rapidly.

Figure 2. Intensity of trapped electrons as a function of local time for $8 \leq L < 10$ or $69.3^\circ \leq \Lambda < 71.5^\circ$. Each point is the average intensity over that part of the latitude range for which the detector was oriented on a given pass. The vertical error bars give the range of intensities observed when the detector was oriented for an appreciable part of the above latitude range. The horizontal lines are average intensities, excluding the great September 25, 1961 event.

Figure 3. Sketch, not to scale, suggesting the extent of the trapping regions which might be inferred for magnetically-quiet times from Injun I and Explorer XII observations.

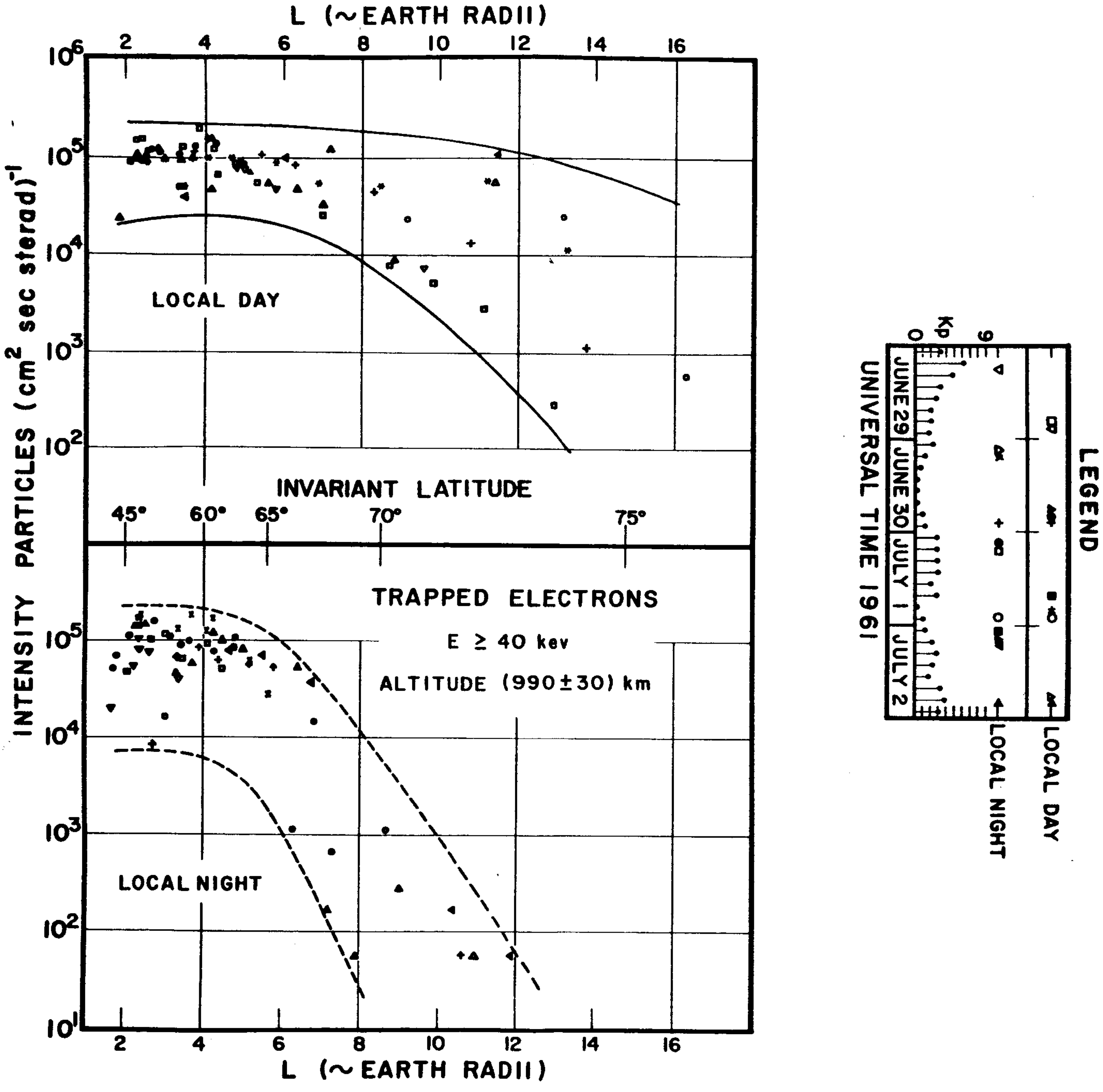
L (~EARTH RADII)
2
4
6
8
10
12
14
16
10⁶
10⁵
10⁴
10³
10²
10¹
INTENSITY PARTICLES (cm² sec sterad)⁻¹
LOCAL DAY
INVARIANT LATITUDE
45°
60°
65°
70°
75°
TRAPPED ELECTRONS
E ≥ 40 kev
ALTITUDE (990±30) km
LOCAL NIGHT
LEGEND
LOCAL DAY
LOCAL NIGHT
Kp
0
9
JUNE 29
JUNE 30
JULY 1
JULY 2
UNIVERSAL TIME 1961

Figure 1

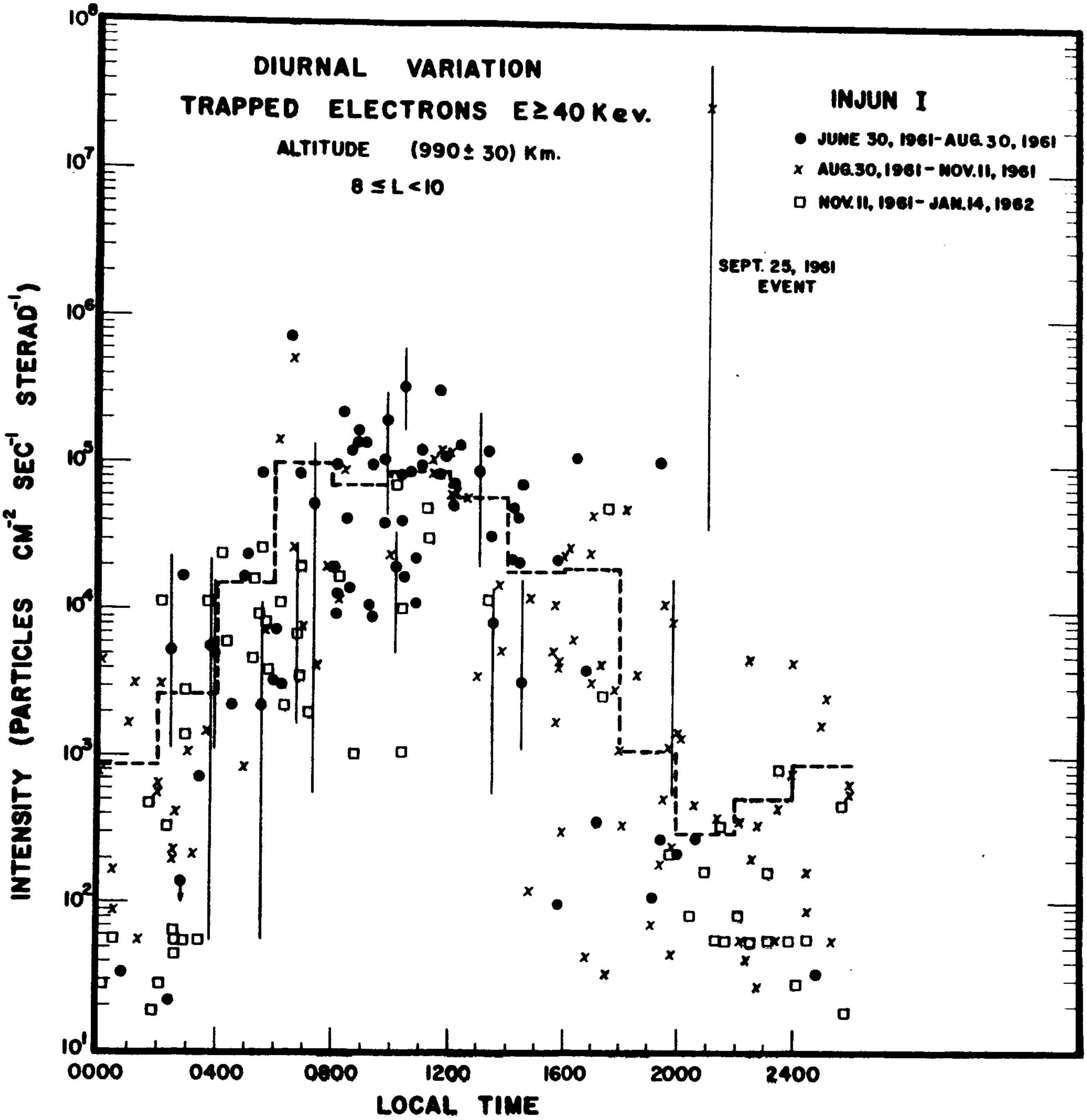
DIURNAL VARIATION
TRAPPED ELECTRONS E≥40 Kev.
ALTITUDE (990± 30) Km.
8 ≤ L < 10
INJUN I
● JUNE 30, 1961 - AUG. 30, 1961
x AUG. 30, 1961 - NOV. 11, 1961
□ NOV. 11, 1961 - JAN. 14, 1962
SEPT. 25, 1961 EVENT
INTENSITY (PARTICLES CM⁻² SEC⁻¹ STERAD⁻¹)
10⁸
10⁷
10⁶
10⁵
10⁴
10³
10²
10¹
0000
0400
0800
1200
1600
2000
2400
LOCAL TIME

Figure 2

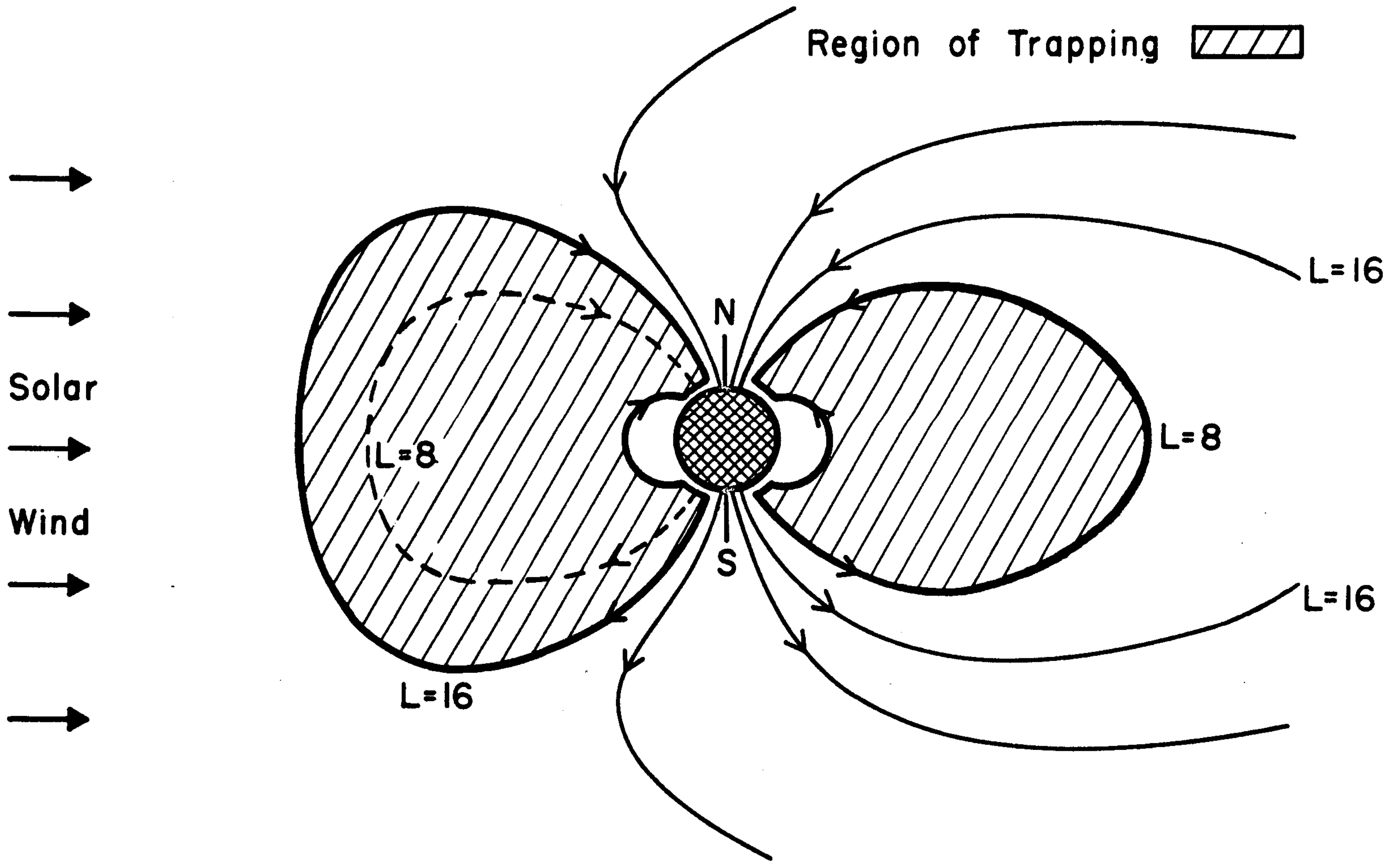

Figure 3