Characteristics of the Diurnally Varying Electron Flux Near the Polar Cap

by

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ABSTRACT

We report on the characteristics of the diurnally varying electron flux observed near the polar cap. The discussion is based upon balloon observations near Ft. Churchill, Manitoba in 1967 of both the electron flux vertically incident on the atmosphere and the electron splash albedo. We measured an electron splash albedo flux below 100 Mev equal to the flux of electrons below 100 Mev incident on the atmosphere during daytime. The observed diurnal variation of the flux of electrons with energies $\lesssim$ 100 Mev is consistent with geomagnetic cutoff variations calculated for models of the magnetosphere. We deduce a geomagnetic cutoff rigidity of $\lesssim$ 17 MV for the nighttime interval and between 70 and 110 MV for the daytime interval at an invariant latitude near 68° in 1967.

INTRODUCTION

Measurements of the energy spectrum of cosmic ray electrons are important to studies of the solar modulation and the origin of cosmic rays. At present, few direct measurements with satellite experiments outside the influence of the magnetosphere are available, and then only for energies below about 40 Mev [Cline *et al*, 1964], [Cline and McDonald, 1968], [Fan *et al*, 1968]. The majority of electron observations so far have been performed on balloon payloads, and were subject to atmospheric and geomagnetic influences. While the measurements of many investigators show reasonable agreement for electron fluxes at energies above several hundred Mev, the quoted results at lower energies are considerably more uncertain. Early measurements of electron fluxes below about 100 Mev by Meyer and Vogt [1961], L'Heureux [1967], Beedle and Webber [1968] contained a (then unknown) significant component of return albedo electrons. The study of the diurnal variation of low energy electron fluxes by Jokipii *et al* [1967] and the following work by Webber [1968] and Israel and Vogt [1968a] produced a more meaningful derivation of primary fluxes by identifying the daytime component of the diurnally varying electron flux at the top of the atmosphere as return albedo and the nighttime component as primaries. There still exists however, a concern about an apparent discrepancy between the low primary electron fluxes derived from balloon observations and the satellite results of Fan *et al* [1968], which are closer in magnitude to the higher albedo fluxes quoted by Israel and Vogt [1968b]. In this paper we shall present further evidence, based upon our 1967 observations of the diurnal variation of electron fluxes near the polar cap and direct measurements of the electron albedo, which supports the interpretation of the diurnal variation first proposed by Jokipii *et al* [1967].

INSTRUMENT

The detector system used in these observations was a scintillation counter telescope (T1, T2) including a gas Čerenkov counter (C), and a spark chamber with lead plates and a scintillation counter for energy determination. This detector system has been described in an accompanying paper [Israel 1969a], hereafter referred to as paper 1. Three of the balloon observations to be discussed (Flights C1, C2, C3) were performed with the "normal" detector configuration as described in paper 1. One other observation (Flight C4) was performed with a modified detector configuration. The first modification involved changing the coincidence requirement for analysis from a T1, T2, C triple coincidence to a double coincidence between T1 and T2, recording separately with each event whether a triple coincidence occurred. Secondly, we added four, 5.8 g/cm^2 thick lead plates to the spark chamber. They were placed in four spaces between chamber gaps where the normal configuration contained no lead. This modification allowed the measurement of low energy protons and alpha particles which stopped or interacted in the spark chamber. It also allowed a lower, although less clean, energy threshold for electron measurements. In this paper, all electron measurements are due to triple coincidence events except where otherwise noted.

BALLOON FLIGHTS

The data reported in this paper are derived from four balloon flights with our electron detector. The balloons were launched from Fort Churchill, Manitoba in June and July, 1967. Table 1 summarizes pertinent flight conditions. On flights C1, C2, and C4 the detector telescope pointed toward the zenith. During flight C3 the detector was inverted to look at the upward moving, splash albedo.

Contours of constant geomagnetic cutoff rigidity in the Churchill vicinity are shown in Figure 1. Also shown are the trajectories of the four flights [Raven, 1967]. The cutoffs in this figure were calculated using a spherical harmonic expansion of the earth's internal magnetic field [Shea et al, 1968]. The true cutoffs are lower than these values and vary with local time as shown in this paper.

All flights occurred during quiet geomagnetic conditions. Figure 2 shows the planetary magnetic index, Kp, during the period of our observations [Lincoln, 1968]. The daily averages of the Mt. Washington neutron monitor count rate during all flights differed by less than 2 percent from that of flight C1 [Lockwood, J. A., private communication]. Further evidence that these flights occurred during quiet times comes from the solar proton monitor on the Explorer 34 satellite [ESSA, 1968]. No solar protons with energy above 30 Mev were detected outside the magnetosphere from 9 June, a week before flight C1, through the end of July. A barely detectable flux of 10 Mev protons, less than 0.2 particles/cm^2 sec sr, was present during flight C1, but none was detected at the dates of our other flights.

OBSERVATIONS

Figure 3 shows the event rate of low-energy electrons observed at float altitude as a function of local time. The clearest evidence of a diurnal flux variation occurs in these events of type 1, which represent electrons of approximately 12 to 50 Mev at the detector. (The discussion of energy determination and event types is given in paper 1.) The first three curves of Figure 3 represent the rate of type 1 events during the float periods of flights C1, C2, and C4, in which the detector was oriented toward the zenith. The dashed curves indicate the atmospheric secondary contribution as discussed in an accompanying paper [Israel, 1969b], hereafter referred to as paper 3. Variations in the secondary flux reflect changes in the balloon altitude.

The first two intervals plotted for flight C1 represent data gathered during the last seventy minutes of ascent. They are included in this plot to indicate the morning transition, which fortuitously occurred just as the balloon reached float altitude. This time is the latest recorded occurrence of the morning step, and this flight is the first to record both a morning flux increase and an evening decrease. In the data of flights C2 and C4 the morning step is also apparent, occurring earlier and less sharply than in C1. Flights C2 and C4 were terminated before the evening transition.

For comparison, the bottom curve in Figure 3 gives the rate of type 1 events observed during flight C3, when the detector was oriented toward the nadir to observe splash albedo. This plot displays no transition comparable to the steps during the other flights. We expect no transition because the primary cosmic rays responsible for the albedo electrons have rigidity above 0.8 GV, substantially higher than the internal field geomagnetic cutoff along our flight trajectories.

In Figures 4, 5, and 6 we present the time dependence of the event rate for each of the four types of electron events for flights C1, C2, and C4, respectively. The counting statistics for type 2 events are not as good as for type 1 and the flux variation is not as large, but an evening transition is apparent during flight C1 and a morning transition in C2. There may be a similar transition in C4, but it is not as obvious.

The event rates for types 3 and 4 display no significant diurnal flux variation. This fact, as well as the lack of a flux transition in flight C3, indicates that the transitions in the flux of low energy electrons observed on flights C1, C2, and C4 are not instrumental effects. Additional evidence that the detector response did not vary during the flights comes from the observed flux of very high energy protons. The bottom plot, labeled P, in Figures 4, 5, and 6 displays the rate of events satisfying the following criteria:

a) Čerenkov counter signal accompanies the event.

b) Both energy loss counters register a pulse height corresponding to energy loss between 0.5 and 1.7 times "minimum".

c) No guard counter signal accompanies the event.

d) The spark chamber contains a single straight track.

These events record protons above 16 Gev which do not interact in the detector. Because of their very high rigidity, we expect the flux of these protons to display no temporal variation.

In Figure 6, we also plot, as type 0, events satisfying all criteria for type 1 except for the lack of a Čerenkov signal. These represent electrons of approximately 4 to 12 Mev; i.e., they have sufficient energy to penetrate the telescope counters, but their energy is below the Čerenkov counter's effective threshold. We expect a large fraction of these events to be due to atmospheric secondary gammas which pair-produce or Compton-scatter in the first lead plate and produce an upward-moving electron that triggers the telescope. Because of the large background, it is difficult to derive a meaningful absolute electron flux from these events. However, we expect the background to be constant, so the change in count rate observed between 0600 and 0800 local time indicates that the diurnal variation does occur for electrons whose energy at the detector is below 12 Mev.

Table 2 summarizes the observed rates for each type of event. We tabulate rates for night and day intervals, as well as for the entire float periods. The arrows at the top of Figures 4, 5, and 6 indicate the data used for the night and day parts of this tabulation. These data were selected to include only time intervals when both type 1 and type 2 event rates were within one standard deviation of their mean night or day values. The rates shown in Table 2 verify our previous qualitative statements, that events of types 0, 1 and 2 have a clear diurnal variation, while events of types 3, 4, and P have no statistically significant variation.

DISCUSSION

Our results clearly show the presence of the diurnal variation of low energy electron fluxes near Fort Churchill in 1967, which was seen by Jokipii et al [1967] in 1965 and 1966, and by Webber [1968] in 1966. Our data from flight C1 (see Fig. 3) also represent the first observation of the morning and evening transition on the same flight, lending support to the model of Jokipii et al [1967] and Webber [1968] that their observations of individual morning or evening transitions fit into the pattern of a diurnal variation, i.e., that the higher fluxes exist during the whole daytime interval, and the lower fluxes during the whole nighttime interval, and are not restricted to a few hours. As proposed by Jokipii et al [1967], the diurnal variation of low energy electron fluxes can be related to a diurnal change in the geomagnetic cutoff, with lower cutoffs prevailing during the nighttime interval. If the nighttime cutoff value lies below the detector threshold, the observed nighttime electron flux at the top of the atmosphere consists of primary particles. During the day interval, when a higher cutoff prevails, primaries below cutoff are excluded, and return albedo particles with rigidities below cutoff are observed.

The lowered nighttime cutoff due to the tail structure of the magnetosphere was first calculated by Reid and Sauer [1967]. Subsequently, Taylor [1967] and Gall et al [1968] computed cutoffs at various latitudes and local times by numerical integration of charged particle orbits in the Williams and Mead [1965] model magnetosphere, or a similar model. We shall compare their results with our observations below.

Experimental evidence for the diurnal variation of geomagnetic cutoffs at rigidities $\geq$50 MV has also been derived from satellite observations of low energy protons [Stone, 1964], [Paulikas et al, 1968]. The electron measurements allow us to extend these studies to lower rigidities, below 20 MV.

Our analysis benefits from the important fact that we made measurements of both the diurnally varying, downward moving flux and of the splash albedo. These data were gathered with the same detector, near the same location, within one month on magnetically quiet days, and so permit a direct comparison between the diurnally varying flux of downward moving electrons and the splash albedo electrons near the same location. The mean daytime type 1 rate in flights C1, C2, and C4 is 35 $\pm$ 1.5 events/hour. Subtracting our best estimate of the atmospheric secondary contribution (see paper 3) leaves 26.8 $\pm$ 1.5 events/hour as the rate due to electrons incident at the top of the atmosphere. This value is in good agreement with the corresponding splash albedo rate of 25.6 $\pm$ 1.8 events/hour. The agreement supports the model in which the high daytime flux of electrons is return albedo.

Further support for the model comes from the observation that the nighttime flux is significantly lower than the splash albedo. As shown in paper 3, the nighttime type 1 event rate is consistent with the rate expected from atmospheric secondaries alone; an upper limit to the contribution from electrons incident at the top of the atmosphere is 3.9 events/hour. By assuming there are no primary electrons, 3.9 events/hour represent an upper limit to the return albedo. Thus, the return albedo at night is less than 15 percent of the splash albedo, and in fact may be zero. This lack of return albedo at night over a wide range of local times provides strong support for the model in which the measured nighttime flux (after subtracting atmospheric secondaries) is the full primary flux. We know of no mechanism by which both return albedo and primaries can be excluded from the observations. The lack of return albedo indicates that the splash albedo escapes from the earth; primary particles must be able to travel similar trajectories in the opposite direction and reach the earth.

We derive an upper limit to the nighttime cutoff rigidity (averaged over the nighttime period of observation) in the following manner: We treat the events of type 1 as being electrons with energy between 12 and 50 Mev at the detector. This interval corresponds to 17 to 57 Mev at the top of the atmosphere. We assume that the daytime count rate, after subtracting atmospheric secondaries, represents the flux of return albedo between 17 and 57 Mev, while the corresponding nighttime count rate represents return albedo between 17 Mev and E_n, the electron energy corresponding to the nighttime cutoff. Let j(E) be the differential energy spectrum of return albedo; r_d and r_n are the daytime and nighttime count rates for events of type 1 (after subtracting secondaries). Then

$$\frac{\int_{17}^{E_n} j(E)dE}{\int_{17}^{57} j(E)dE} = \frac{r_n}{r_d} \qquad (5)$$

We take $j(E) = KE^{-1}$ in accordance with the measured splash albedo spectrum below 100 Mev (see paper 1). This gives

$$E_n = (17\ \text{Mev}) \exp \frac{r_n}{r_d} \ \ell n \frac{57}{17} \tag{6}$$

Taking r_d = 26.8 events/hour and $r_n \leq 3.9$ events/hour, we derive $E_n \leq 20$ Mev.

For flight C4 we may further lower this estimate for the average nighttime cutoff by considering the type 0 events (Fig. 6). The change in count rate indicates that the nighttime cutoff lies somewhere in or below the interval 4 to 12 Mev. Since 12 Mev at the detector corresponds to 17 Mev at the top of the atmosphere, we conclude that the average nighttime cutoff rigidity during flight C4 is below 17 MV.

To estimate the daytime cutoff energy, E_d, we assume that the daytime energy spectrum has a discontinuity at E_d', the electron energy at the detector corresponding to E_d at the top of the atmosphere. Electrons with energy above E_d' are above the cutoff at all times, day and night, so we take the total daytime spectrum (primaries plus atmospheric secondaries) above E_d' to be the same as the locally measured nighttime spectrum at the same energies (see paper 3). Below E_d' the daytime spectrum is the sum of return albedo and atmospheric secondaries. We estimate the return albedo spectrum as equal to our measured splash albedo spectrum (see paper 1), and the daytime atmospheric secondary spectrum as equal to the nighttime one.

We then calculate, for various values of E_d, the ratio of daytime to nighttime count rates for each type of electron event. We find that the observed day/night ratio for type 3 events, 1.05 ± 0.28, is inconsistent ($> 1.5\sigma$) with the calculated ratio if $E_d > 110$ Mev. On the other hand, the observed day/night ratio of type 2 events in flights C2 and C4, 3.25 ± 0.95, is inconsistent with the calculated ratio if $E_d < 70$ Mev. We thus estimate that the geomagnetic cutoff rigidity averaged over the daytime interval lies between 70 and 110 MV.

In Figure 7 we compare the cutoff rigidities, derived above under the assumptions of a sharp cutoff and the equality of the splash and return albedo spectra with those of other experiments and calculations. The daytime cutoffs observed in this experiment and by Stone [1964] and Webber [1968] are in qualitative agreement with the calculations of Gall et al [1968] showing a sharp decrease in the daytime cutoff near 70° latitude. However, the experimental data show that this decrease occurs near 68° rather than 70° as calculated by Gall et al [1968]. Our nighttime cutoff upper limit which is valid at latitudes as low as 67°, is in qualitative agreement with Gall et al [1968] but extends about 2° lower in latitude than their calculations predict. Our nighttime result is consistent with those of other experimenters, and is also consistent with the calculation of Reid and Sauer [1967] and that of Taylor [1967].

We do not consider the discrepancy between the observed cutoffs and those calculated by Gall et al [1968] as serious. Similarly, the discrepancies among the various calculations are not serious. Each of these calculations uses a highly idealized model of the magnetosphere in which the earth's internal field is taken as a simple dipole; the dipole axis and the geographic axis are both assumed to be perpendicular to the ecliptic plane. Different values of the position and field strength of the neutral sheet are used in each calculation, and the true values of these parameters are not yet accurately known. We must conclude that the qualitative agreement between the measured and calculated cutoff behavior supports the basic properties of the model.

While the observations of Jokipii et al [1967] and Webber [1968] place the morning and evening transitions of low-energy electron fluxes approximately at 0600 and 1800 hours local time respectively, we have investigated the dependence of the transition time on geomagnetic latitude. In Figure 8 we represent the trajectories of flights C1, C2, and C4 in a coordinate system of geomagnetic latitude vs. local time. Along each trajectory we indicate when the type 1 event rate was within one standard deviation of its day or night value (from Fig. 3). It appears that the geomagnetic cutoff remains below 20 MV later in the morning at higher latitudes. This is qualitatively reasonable because at sufficiently high latitudes ($> 70^{\circ}$ in the model of Gall et al [1968]) the cutoff would remain below 20 MV at all times. It would not be appropriate to make any detailed, quantitative conclusions from the results in Figure 8. In most cases the counting statistics introduce at least a half hour uncertainty in the time of a flux change. Furthermore, the three flights occurred over a period of a month, and changes in the detailed configuration of the magnetosphere during that time, although unlikely (see Fig. 2), could produce some of the differences which we observe between flights.

Referring to Figures 4, 5, and 6 we note an additional feature of the transition time. The rate of type 2 events drops to its nighttime value earlier in the evening and returns to the daytime value later in the morning than does the rate of type 1 events. This feature indicates that the change in cutoff from below 20 MV to near 90 MV occurs over a period of from one to three hours. Gall <u>et al</u> [1968], have calculated the variation of geomagnetic cutoff with time at 67.8° latitude. As previously noted, their noon and midnight cutoff rigidities do not agree quantitatively with our observations; however, we again have qualitative agreement, because their calculations show that the change in cutoff rigidity occurs gradually over a period of several hours.

The consistency of essential features of the observed diurnal variation of low energy electron fluxes with predictions based on models of the magnetosphere, together with direct measurements of the electron albedo, strongly supports the conclusion that primary electron flux measurements below about 100 Mev can be performed only during the nighttime interval.

ACKNOWLEDGEMENTS

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TABLE 1

BALLOON FLIGHTS

Flight number	C1	C2	C3	C4
Launch date (1967)	17 June	2 July	9 July	21 July
Launch time (a)	10:27	03:58	03:23	03:20
Begin float (a)	13:40	09:00	09:00	09:30
Terminate float (a)	03:30	17:45	19:25	21:15
Floating depth (g/cm^2)	2.1-3.4	2.0	2.3	2.1
Sensitive time at float (min)	791	504	496	530
Orientation	zenith	zenith	nadir	zenith
Configuration (b)	normal	normal	normal	modified
Kp (c)	3-	0+	1-	1+
Mt. Washington neutron monitor (d)	2274	2244	2285	2317

(a) Universal Time

(b) See "INSTRUMENT"

(c) Mean of three hour K_p indices during float [Lincoln, 1968]

(d) Mean of hourly count rate during float [Lockwood, J. A., private communication]

TABLE 2

ELECTRON-EVENT RATES

(Rates are expressed as events/hour. Only statistical uncertainty is indicated)

Event Type	Interval (a)	Flight C1	C2	C4	C3
0	N			45.1 ± 4.4	
	D			59.4 ± 3.6	
1	N	10.7 ± 1.9	8.1 ± 2.0	8.7 ± 1.9	-
	D	33.0 ± 1.9	39.0 ± 3.6	36.4 ± 2.9	-
	F	-	-	-	25.6 ± 1.8
2	N	6.9 ± 1.5	3.1 ± 1.2	3.5 ± 1.2	-
	D	11.4 ± 1.1	9.6 ± 1.8	10.2 ± 1.4	-
	F	-	-	-	10.4 ± 1.1
3[b]	N	3.1 ± 1.0	2.0 ± 1.0	3.0 ± 1.1	-
	D	2.7 ± 0.6	2.0 ± 0.8	3.9 ± 1.0	-
	F	3.0 ± 0.5	1.7 ± 0.4	3.1 ± 0.6	2.5 ± 0.6
4[b]	N	3.1 ± 1.0	1.0 ± 0.7	1.3 ± 0.7	-
	D	2.7 ± 0.6	3.3 ± 1.0	1.2 ± 0.5	-
	F	2.7 ± 0.5	2.7 ± 0.6	1.4 ± 0.4	0.36± 0.21
P	N	9.6 ± 1.8	9.2 ± 2.2	11.3 ± 2.2	-
	D	9.8 ± 1.1	10.6 ± 1.9	9.2 ± 1.5	-
	F	9.5 ± 0.8	9.3 ± 1.1	9.8 ± 1.1	-

(a) N - night interval
D - day interval
F - entire float period, including night, day, and intermediate intervals.

(b) In flight C4 (modified configuration) the calibration for events of type 3 and 4 is different from corresponding calibrations for other flights. See paper 1 and "INSTRUMENT" in this paper.

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FIGURE CAPTIONS

Fig. 1 Trajectories of the balloon flights and contours of constant geomagnetic cutoff rigidity. Cutoffs are derived from the internal geomagnetic field only.

Fig. 2 Planetary magnetic index, K_p, during summer 1967. Numbered bars indicate balloon flights.

Fig. 3 Type 1 event rate vs. local time at the detector, during flights C1, C2, C4, and C3.

Solid line - observed event rate. Error bars indicate typical statistical errors.

Dashed line - calculated rate due to atmospheric secondary electrons.

Fig. 4 Flight C1. Rate of electron events of type 1, 2, 3, 4 and proton events (type P) vs. local time at the detector. The four types correspond approximately to electron energies at the top of the detector of 12 to 50, 50 to 100, 100 to 350, and 350 to 1000 Mev respectively (see paper 1). Typical statistical errors are shown.

Fig. 5 Flight C2. (See caption of Fig. 5)

Fig. 6 Flight C4. (See caption of Fig. 5). In addition, events of Type 0 are included.

Fig. 7 Geomagnetic cutoff rigidity vs. geomagnetic dipole latitude. The curves represent calculated vertical cutoff rigidities (R_c).

Curve 1 - internal field, $R_c = 14.9 \text{ GV} \cos^4 \lambda$.

Curve 2 - noon cutoff [Gall <u>et</u> <u>al</u>, 1968]

Curve 3 - midnight cutoff [Gall <u>et</u> <u>al</u>, 1968]

Curve 4 - midnight cutoff [Reid and Sauer 1967]

The crosses indicate the noon and midnight cutoffs calculated for particles incident parallel to the local field lines [Taylor 1967]. Experimental results (Open symbols represent daytime cutoffs; solid symbols, nighttime cutoffs.)

Circles - this work

Triangles - Stone [1964] The horizontal bar indicates the range of latitudes over which the "polar foot" was observed during the day.

Diamonds - Paulikas _et al_. [1968]

Squares - Webber [1968]

The calculations assume that the internal field of the earth is a simple dipole; the latitude shown is the dipole latitude. Our experimental points are plotted at a latitude, λ, defined by $R_c = 14.9$ GV $\cos^4 \lambda$ where R_c is the cutoff calculated on the basis of the real internal field [Shea _et al_. 1968]. For the latitudes considered in this paper, the latitude so derived agrees within $\pm 0.2^o$ with invariant latitude.

Fig. 8 Latitude and local time of nighttime and daytime count rates for events of type 1. Latitude is defined by $R_c = 14.9$ GV $\cos^4 \lambda$ where R_c is the vertical cutoff based upon the earth's internal field only [Shea _et al_. 1968].

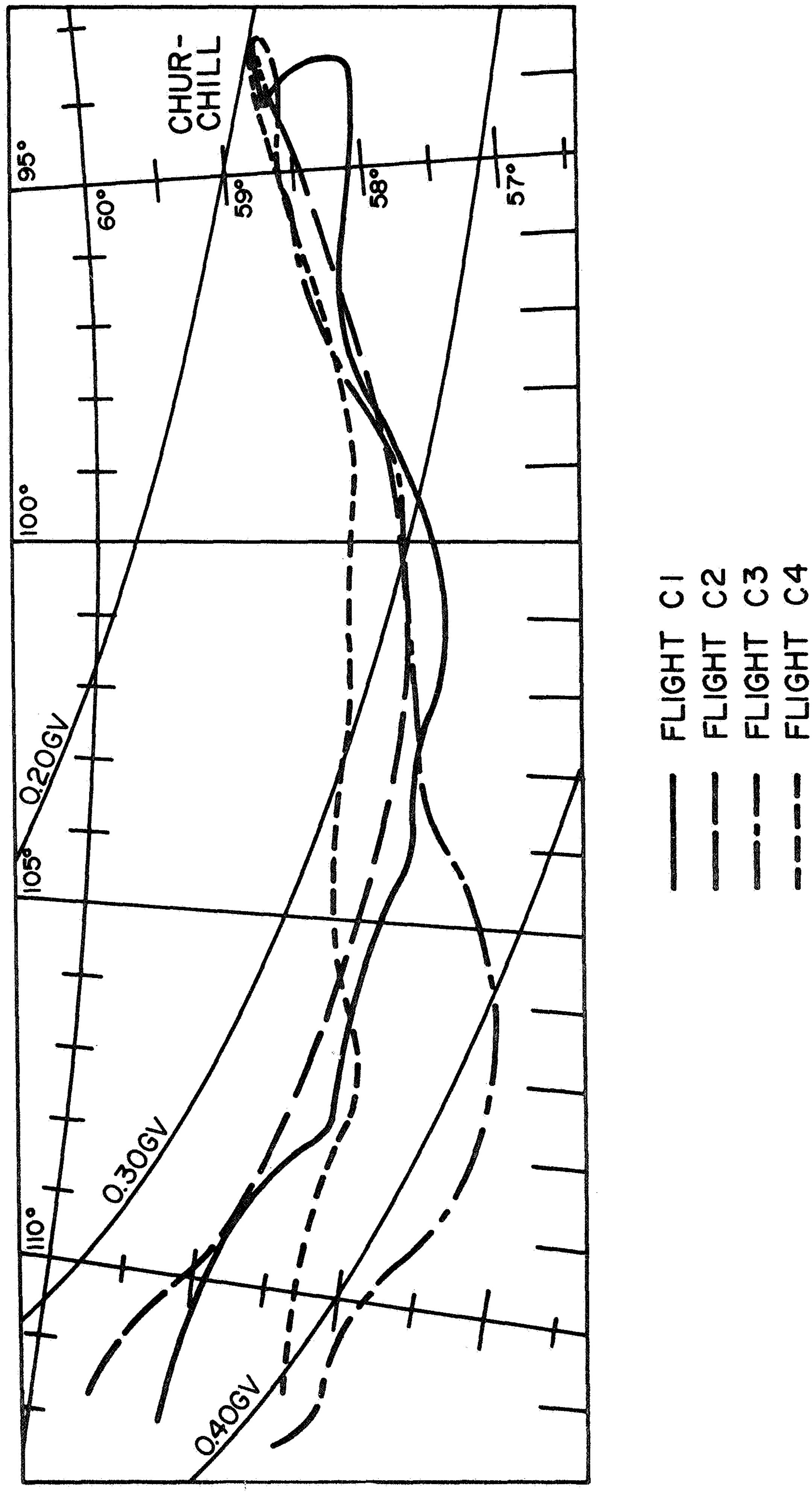
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Figure 1

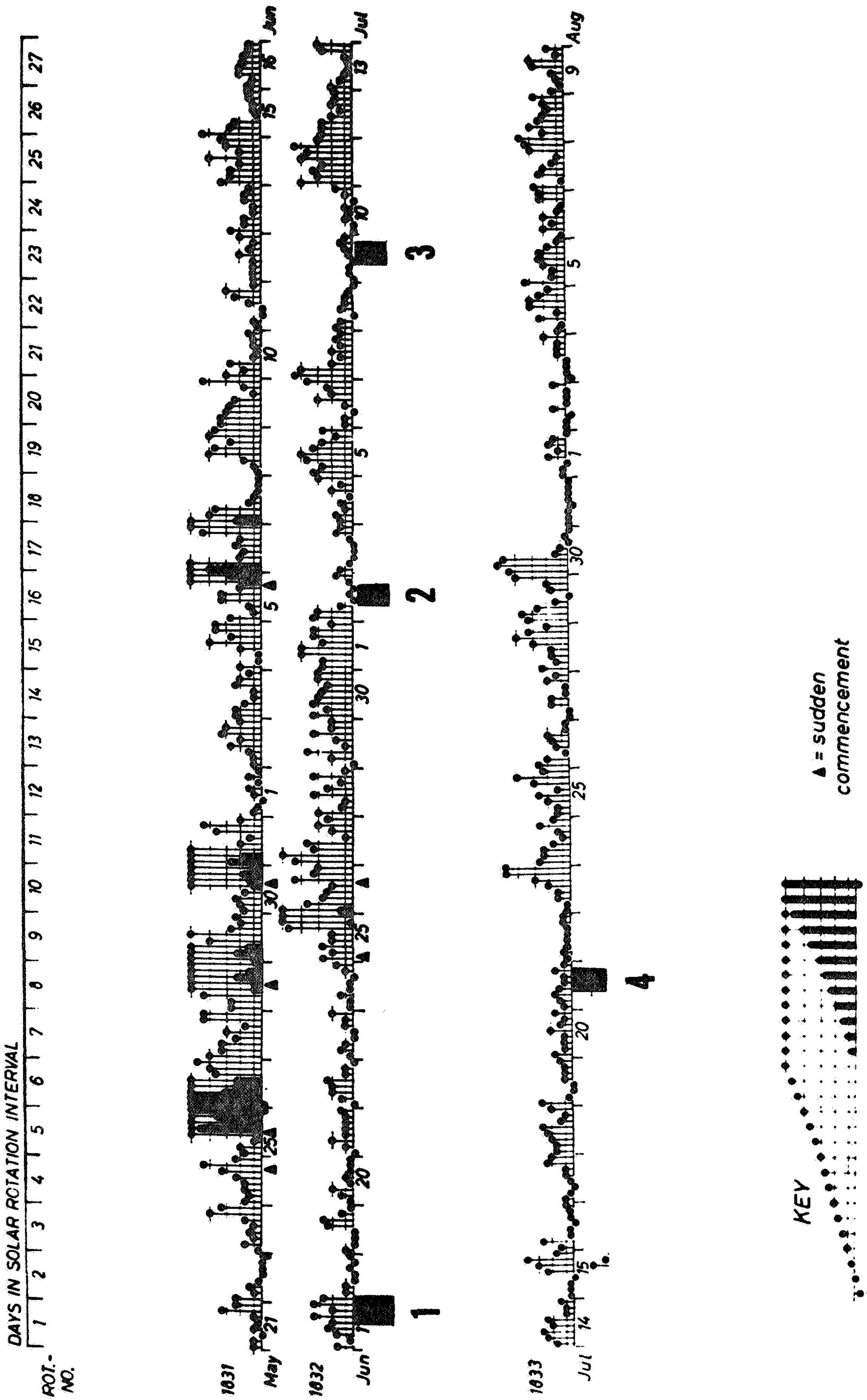
DAYS IN SOLAR ROTATION INTERVAL
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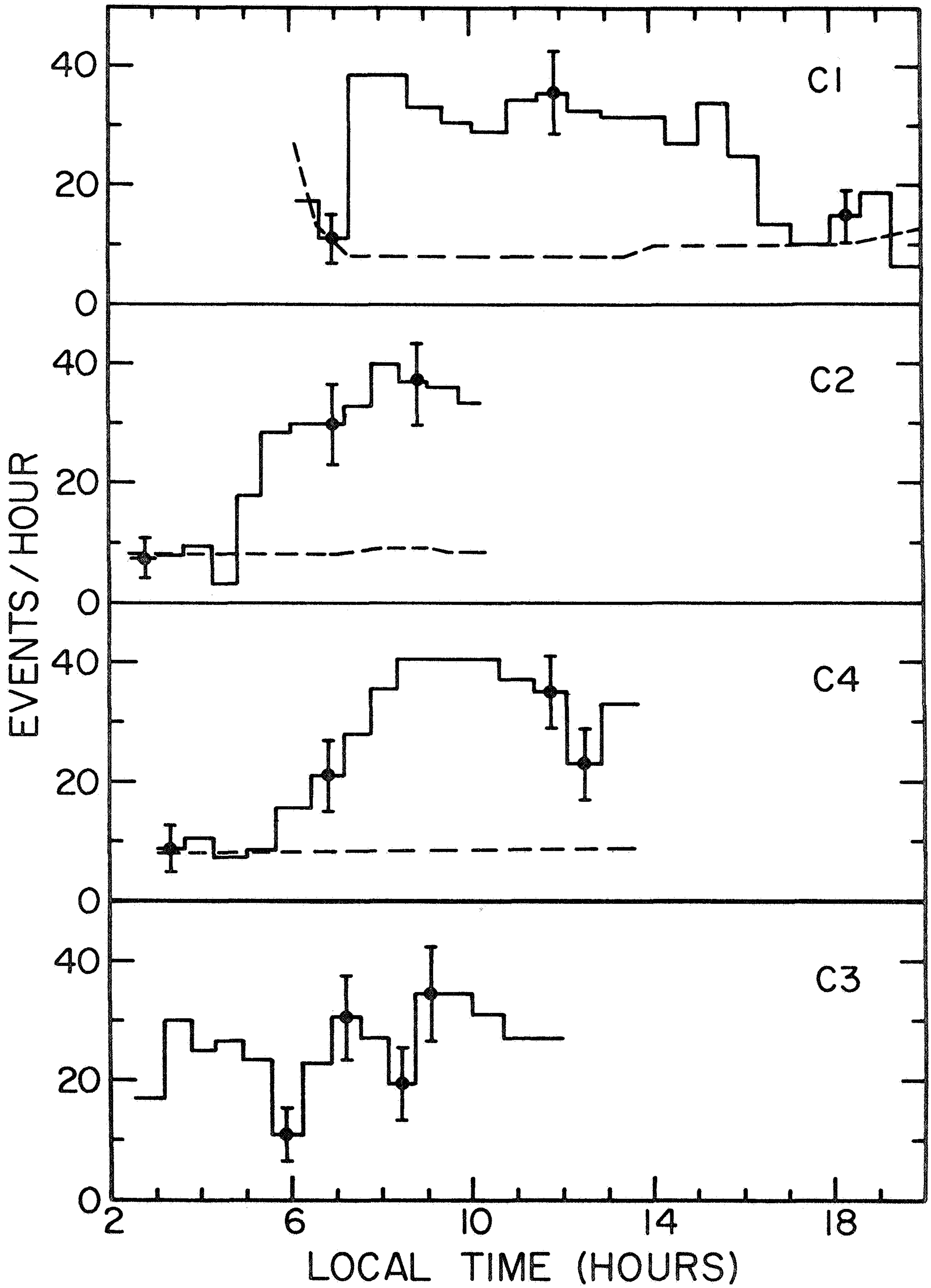
Figure 2



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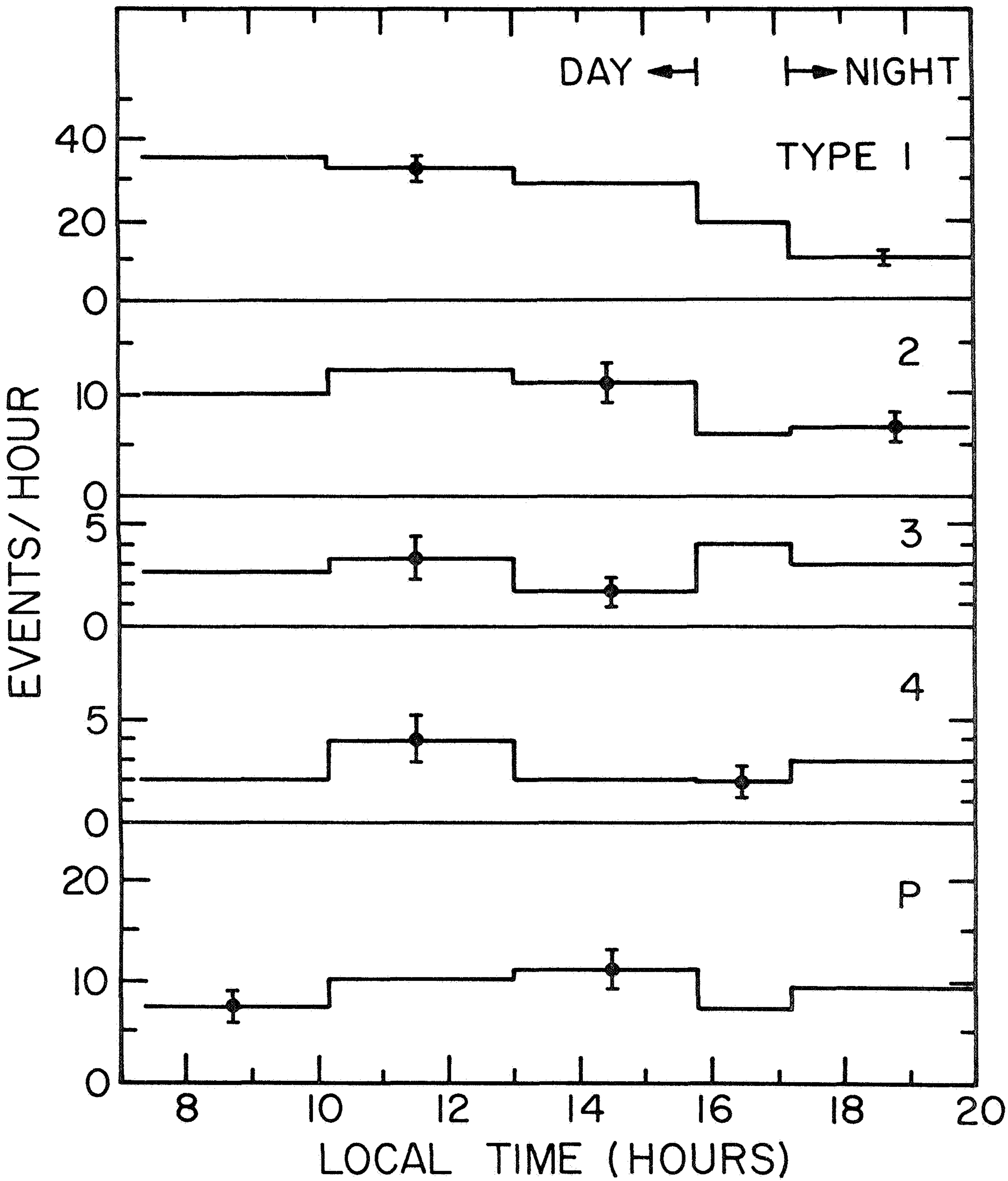

DAY
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LOCAL TIME (HOURS)

Figure 4

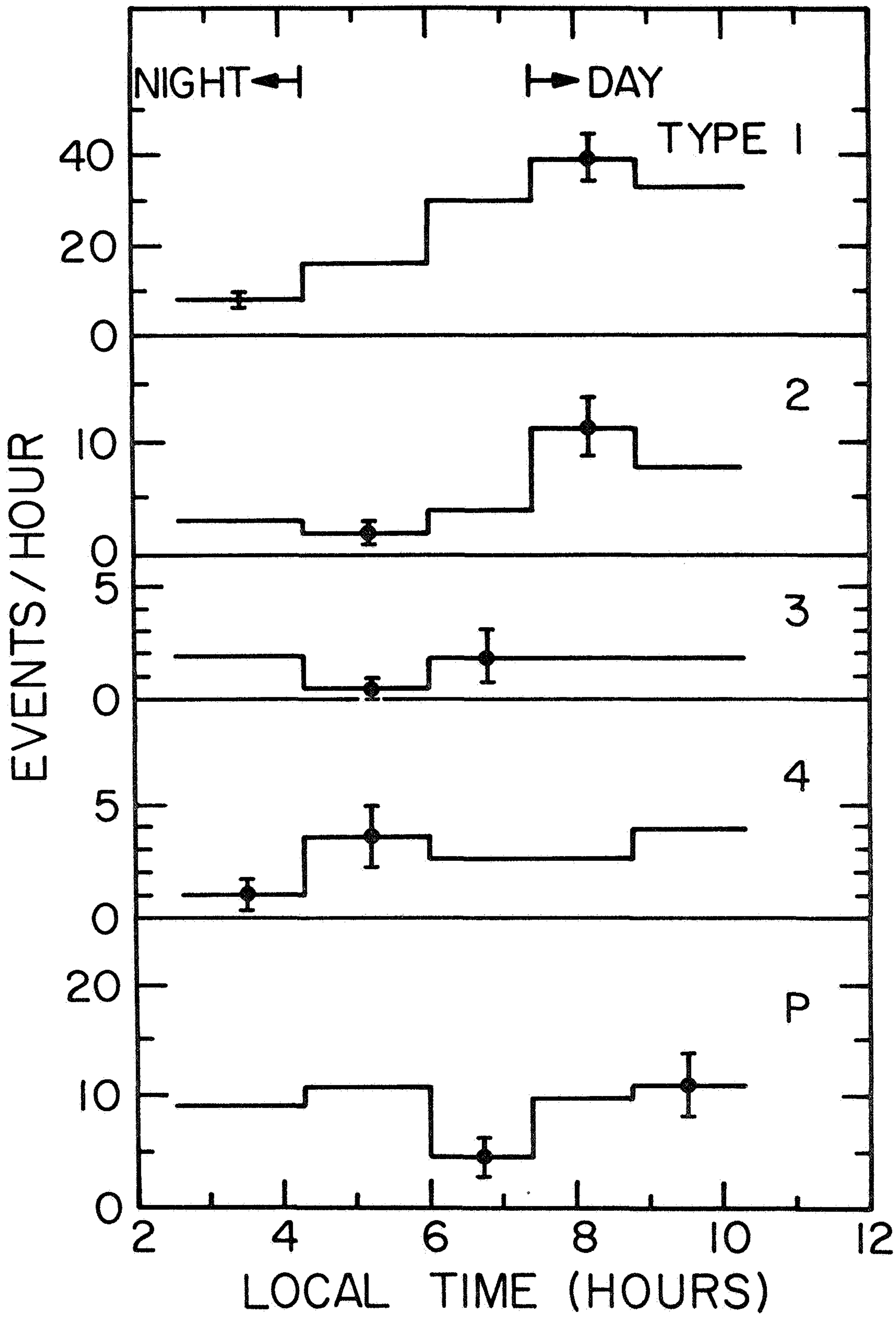
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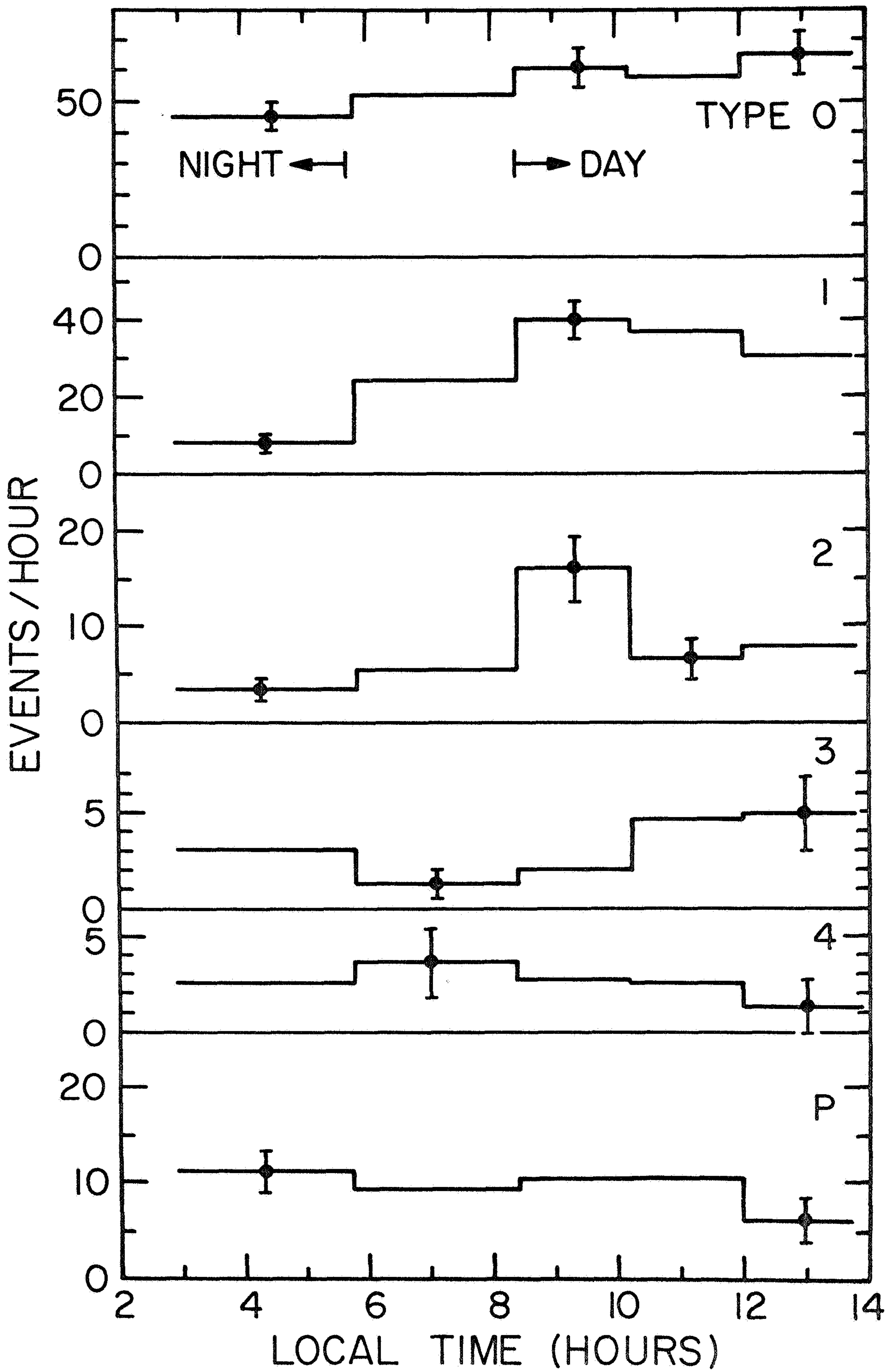
Figure 5



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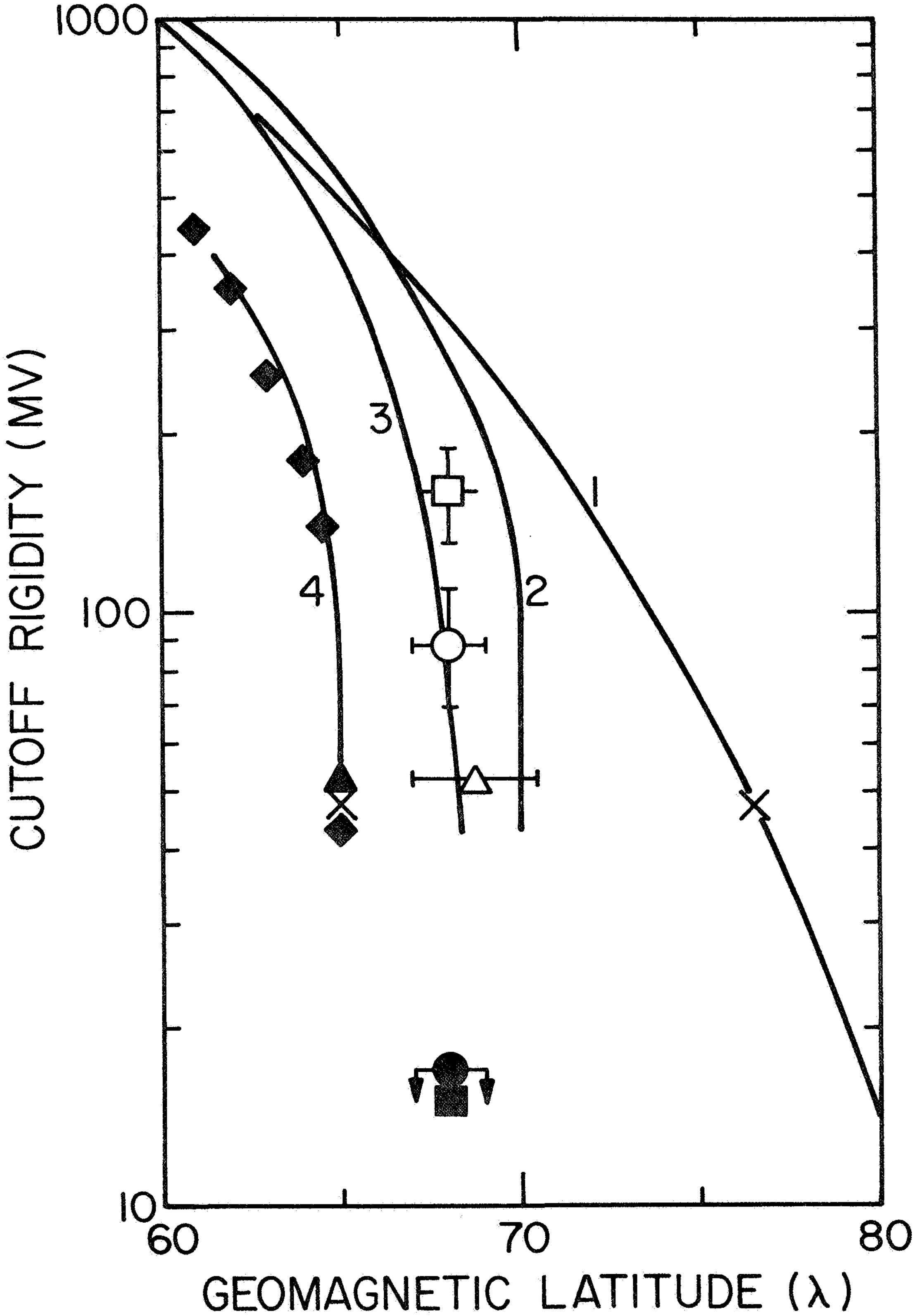
20
0
20
10
0
5
0
5
0
20
10
0
TYPE 0
NIGHT
DAY
1
2
3
4
P
EVENTS / HOUR
2
4
6
8
10
12
14
LOCAL TIME (HOURS)

Figure 6



1000
100
10
60
70
80
CUTOFF RIGIDITY (MV)
GEOMAGNETIC LATITUDE (λ)
1
2
3
4

Figure 7

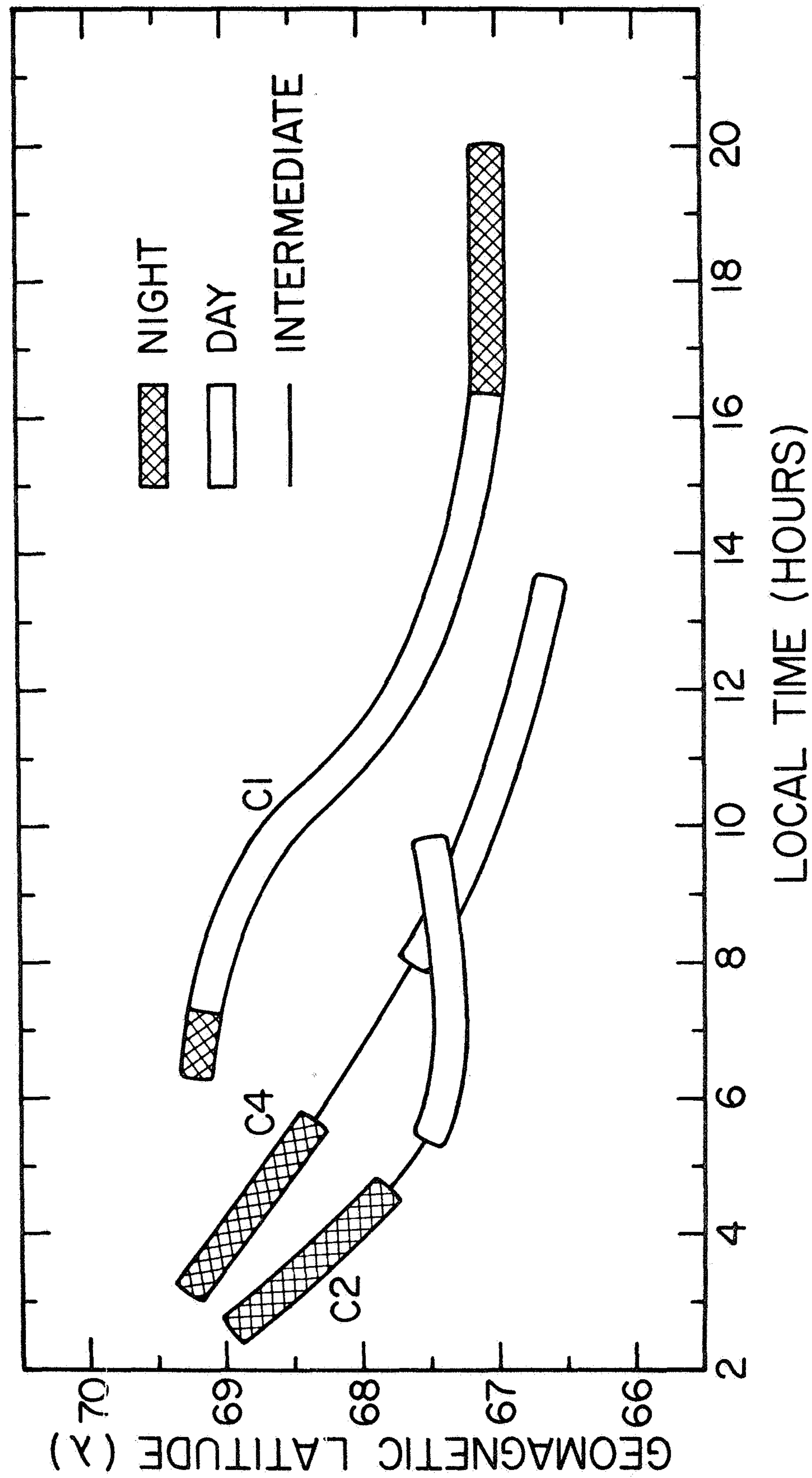

NIGHT
DAY
INTERMEDIATE
C1
C4
C2
LOCAL TIME (HOURS)
2
4
6
8
10
12
14
16
18
20
GEOMAGNETIC LATITUDE (λ)
70
69
68
67
66

Figure 8