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RELATION OF ENERGETIC PARTICLES IN THE PLASMA SHEET TO THE AURORAL ZONE*

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This article will review the observational evidence for a relationship between plasma and energetic particle phenomena in the geomagnetic tail and precipitation of particles into the auroral zone. First, the properties of the plasma and energetic particles in the geomagnetic tail will be summarized. A fundamental feature of this region is that it contains a thick slab of hot plasma extending symmetrically northward and southward from the region of field reversal (neutral sheet). The total thickness of the plasma sheet is several earth radii (~ 30,000 km). The plasma sheet thickness is probably variable and the whole sheet at times may move rapidly with respect to a coordinate system such as the solar-magnetospheric. The plasma sheet extends across the tail to the magnetopause and back into the tail to at least distances of 60 earth radii. The plasma particles are highly variable in energy. At a geocentric distance of 18 R_e the peak of the electron energy spectrum ranges from 0.1 to 10 KeV and in the case of the protons the range is 1 to 20 KeV. The proton energy density is about 8 times that of the electrons. The particle density in the plasma sheet is about 1 cm^{-3}. This information on the plasma properties comes from the VELA satellite and is summarized by BAME (1968). VASYLIUNAS (1968) has extended the plasma sheet measurements in closer to the earth. He finds that the plasma sheet extends past the dusk meridian into the sunlit hemisphere. At a Gordon Conference (1968) he showed evidence that the plasma sheet extends to low altitudes on the night side of the earth close to or into the auroral zone. The spatial extent of the plasma sheet and its relationship to the auroral zone is shown in Figure 1. BAME et al (1967) have shown that the plasma may suddenly become strongly heated in the sense that the average particle energy is greatly increased. It is at these times that the energetic (> 20 KeV) fluxes of electrons appear, then slowly decay away. The impulsive acceleration events resulting in electron island fluxes was first reported by ANDERSON, HARRIS and PAOLI (1965) and their properties were more fully discussed by ANDERSON (1965), MONTGOMERY _et al_ (1965) and KONRADI (1966). Many examples of this phenomenon may be found in those articles. Figures 2 and 3 show additional examples. ANDERSON and NESS (1966) showed that the island fluxes appear in a slab-like region straddling the neutral sheet in which the magnetic field was markedly weakened; an effect they attributed to the diamagnetism of a plasma in this region. There is now little doubt that this region is just the plasma sheet discussed by BAME _et al_ (1967) and by VASYLIUNAS (1968). Some of the known properties of the island fluxes are summarized in Figure 4.

A resemblance between electron island fluxes occurring in the tail and auroral zone phenomena has been recognized for some time. This resemblance can be seen by comparing Figure 5 with Figures 2 and 3. In Figure 5, balloon measurements of X-rays due to the _bremsstrahlung_ of electrons with energies > 25 KeV are seen to exhibit fast-slow behavior with characteristic times about the same as island fluxes in the tail. Also at the time of the electron precipitation, an intense negative bay occurs showing that an auroral substorm is in progress.

HUDSON (1966) has studied the energy spectrum of the electrons coming into the auroral zone during auroral breakup. In the few cases measured, he found a progressive softening of the spectrum from an e-folding energy of 10 KeV to about 5 KeV. This is just the behavior of energetic electrons in the tail during island events as shown in

Figure 4. This suggests that one of the phenomena that occur during the complex substorm process is precipitation of particles out of the plasma sheet region into the atmosphere.

Several attempts have been made to more closely relate phenomena occurring in the tail with effects in the auroral zone. PARTHASARATHY and REID (1967) and DRIATSKIY (1967) studied the ionospheric effects produced by precipitating particles and associated them with the appearance of energetic electrons deep in the magnetotail. The combined results for an event which occurred on 28 May 1964 are shown in Figure 6. The Russian arctic stations were at local times between 0200 and 0300 at the appearance of riometer absorption and the South Pole station was also within a few hours of magnetic midnight. It is interesting that the electron flux actually observed in the tail on this occasion was comparatively weak. Many islands have been observed with much higher intensity. However, it is likely that an intense plasma sheet acceleration event (island) did take place at this time. The spacecraft was somewhat to the south of the neutral sheet region at this time and there had been no detectable electron fluxes > 40 KeV for the previous day. Evidently a portion of the plasma sheet suddenly filled with energetic particles and expanded, enveloping the spacecraft. It seems likely therefore that had the spacecraft been near the center of the plasma sheet much greater electron intensities would have been observed. The island event occurs near the beginning of the riometer effect possibly meaning that the plasma sheet has relaxed back to its former configuration. DRIATSKIY (1967) also reported a close correspondence between riometer absorption and appearance of electron fluxes deep in the magnetotail on 14 May 1964. On the other hand he reported occasions when well-developed island fluxes were not associated with riometer effects.

ROTHWELL (1967) has compared electron measurements in the magnetotail with bay-type disturbances in northern hemisphere magnetometers and finds the general correlation that when island activity is high in the magnetotail the chances are high that a negative bay will occur at sites near local magnetic midnight. An example from more recent satellite measurements confirming this result is shown in Figure 7.

Questions that arise concerning the origin of plasma sheet acceleration events are: (1) Do particles become accelerated in the tail, then propagate into the auroral zone? (2) Alternatively, are particles accelerated much closer to the earth (L ~ 3 to 8) then move out into the tail region? (3) As a third possibility, does an instability excite a propagating disturbance which generates charged particles as it moves along? (4) If the latter is the case, in which direction does the disturbance move?

Various attempts have been made to answer these questions. If hydromagnetic disturbances play a role they should be recognizable from the rather long delay times involved. The Alfvén speed is ~ 200 km/sec in the tail so that about 15 minutes are needed for a disturbance to propagate over a distance of 30 earth radii. HONES et al (1967) have looked for this time delay using Vela satellite data and ground magnetometers. They first of all find the general correlation discussed above that frequent plasma sheet acceleration events implies frequent magnetic bays for stations near local midnight. The appearance of the energetic electrons at the spacecraft situation at 18 R_e geocentric distance was found to occur coincident with or following the deepest portion of the bay decrease. This result applies to situations when it was believed that the ground magnetometer and the spacecraft were connected within a rather small tube of geomagnetic field lines. This result appears to favor the view that an h-m disturbance travels outward into the magnetotail from an origin inside 18 R_e geocentric distance. No consistent value for a delay time, and hence a velocity, could be determined, however.

A different way of studying the questions raised above is to determine the peak intensity of plasma sheet acceleration events as a function of distance into the tail. The result from one such comparison is shown in Figure 8. The IMP-3 data were taken in the geocentric distance range 20 to 40 R_e while the EXPLORER-35 data all come from close to 60 R_e. The IMP-3 results were obtained uniformly across the tail while the EXPLORER-35 results are biased somewhat toward the dawn side of the tail. Kp conditions are about the same for both sets of data. A large radial effect is seen in Figure 8. Apparently the acceleration process is weakening as a function of distance into the tail. The dawn-dusk asymmetry reported by BAME et al (1967) if it exists as far back as 60 R_e, would serve to make the radial dependence effect even greater than shown in the Figure. The number of acceleration events per unit time above a very low flux threshold does not change greatly as a function of distance into the tail. ANDERSON (1965) previously reported a radial dependence of the number of islands with distance into the tail above a threshold of about 10^5 $cm^{-2}sec^{-1}$ > 40 KeV electrons. This can now be understood as a constant rate per unit time of island events down to flux values as low as 10^3 $cm^{-2}sec^{-1}$.

The h-m waves producing the large modulation of the energetic electron fluxes are a prominent feature of the skirt and plasma sheet regions (LIN and ANDERSON, 1966). They are present at all times.

Their origin has been attributed to surface waves on the magnetopause. In the past it has been tacitly assumed that these waves are an incidental feature of these regions and play no role in determining the properties of the plasma in the regions in which they propagate. However, it appears that their role may be of great importance in the energy balance of the plasma sheet:

1. They may trigger the instabilities that give rise to the plasma sheet acceleration events (particle islands). The plasma sheet is a region of $\beta \sim 1$ so that a relatively small disturbance may be all that is required to begin a transfer of magnetic energy into particle energy (ANDERSON and NESS, 1966).
2. The high particle energies in the plasma sheet may be supplied by the h-m waves. BAME (1968) has shown that even when the plasma is not in its highly heated state the proton temperatures are several hundred electron volts. The energy density is about 500 eV/cm^3 at these times and much higher when the plasma becomes suddenly heated. It has been noted that the trains of h-m waves are rather short-lived (LIN and ANDERSON, 1966). They appear for several cycles then disappear. If it is assumed they dissipate their energy in the plasma (rather than propagating indefinitely along the tail with no loss) the energy loss per unit volume for a typical train of waves may be calculated from the following formula:

$$u = \frac{B_o b_o}{4\pi}$$

where B_o is the strength of the undisturbed field and b_o is the initial amplitude of the wave. For $B_o = 15\gamma$ and $b_o = 5\gamma$ the energy density is 100 eV/cm^3, on the order of the observed plasma energy density. Further heating could be produced by more wave trains. The final temperature of the plasma would then depend on how the plasma loses energy. A typical period for the waves is 300 to 400 seconds and the wave train may last for 5 cycles. This gives a heating rate of about 0.05 eV/cm^{3}sec. Mechanisms have been proposed by which such waves should dissipate their energy in collisionless plasmas (BARNES, 1967).

3. The east-west asymmetry in the appearance of energetic electrons on the VELA orbit observed by BAME et al (1967) may be du to these waves. If the wave activity is greatest on the dawn side of the magnetotail and if the waves are indeed responsible for heating the plasma or triggering the plasma into an instability then energetic particles would be expected more frequently on the dawn side of the tail. There is evidence from the IMP-3 and EXPLORER-35 particle experiments that the energetic electrons are more strongly modulated on the dawn than on the dusk side. Since this modulation is believed to be due to the presence of h-m waves, it does appear that the wave activity is greatest on the dawn side. This might be due to the spiral character of the interplanetary field which would then allow more effective connections to the geomagnetic field on the dawn side of the tail. If this is the case there should be a north-south asymmetry since toward sectors should then connect to the southern half of the magnetotail and away sectors to the north magnetotail.

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FIGURE CAPTIONS

Figure 1: The spatial extent of the plasma sheet as determined by VELA and OGO spacecraft. The plasma sheet comes to the auroral regions on the night side of the earth and the equatorial inner boundary is observed to move toward the earth during magnetic bays.

Figure 2: Examples of energetic electron fluxes in the plasma sheet 60 R_e into the tail. The characteristic fast-slow behavior is apparent. Some of the fluxes do not seem to show this characteristic. All the fluxes are strongly modulated by h-m waves with periods of a few minutes.

Figure 3: Same as Figure 2

Figure 4: Summary of the properties of the particles accelerated in the plasma sheet. The electrons progressively soften with time while the proton fluxes do not do so. The pitch angle distribution is anisotropic early in the event but soon becomes isotropic. The switching off of the particles which occasionally occurs is probably due to sudden contractions of the plasma sheet.

Figure 5: Electron precipitation into the auroral zone during substorms shows the same temporal behavior as island fluxes.

Figure 6: A comparison of particle fluxes observed in the geomagnetic tail with riometer records.

Figure 7: A comparison of particle fluxes 60 R_e into the magnetotail with ground level magnetometers. When island events occur in the tail the station near local midnight shows a disturbance. Conversely, when the station is several hours from local midnight the magnetic disturbance is small during island events in the tail.

Figure 8: The peak flux of plasma sheet acceleration events decreases with radial distance. The IMP-3 measurements were made between 20 and 40 R_e while the EXPLORER -35 measurements came from 60 R_e geocentric distance. The frequency of occurrence of the island events above a low flux threshold does not vary markedly with geocentric distance.

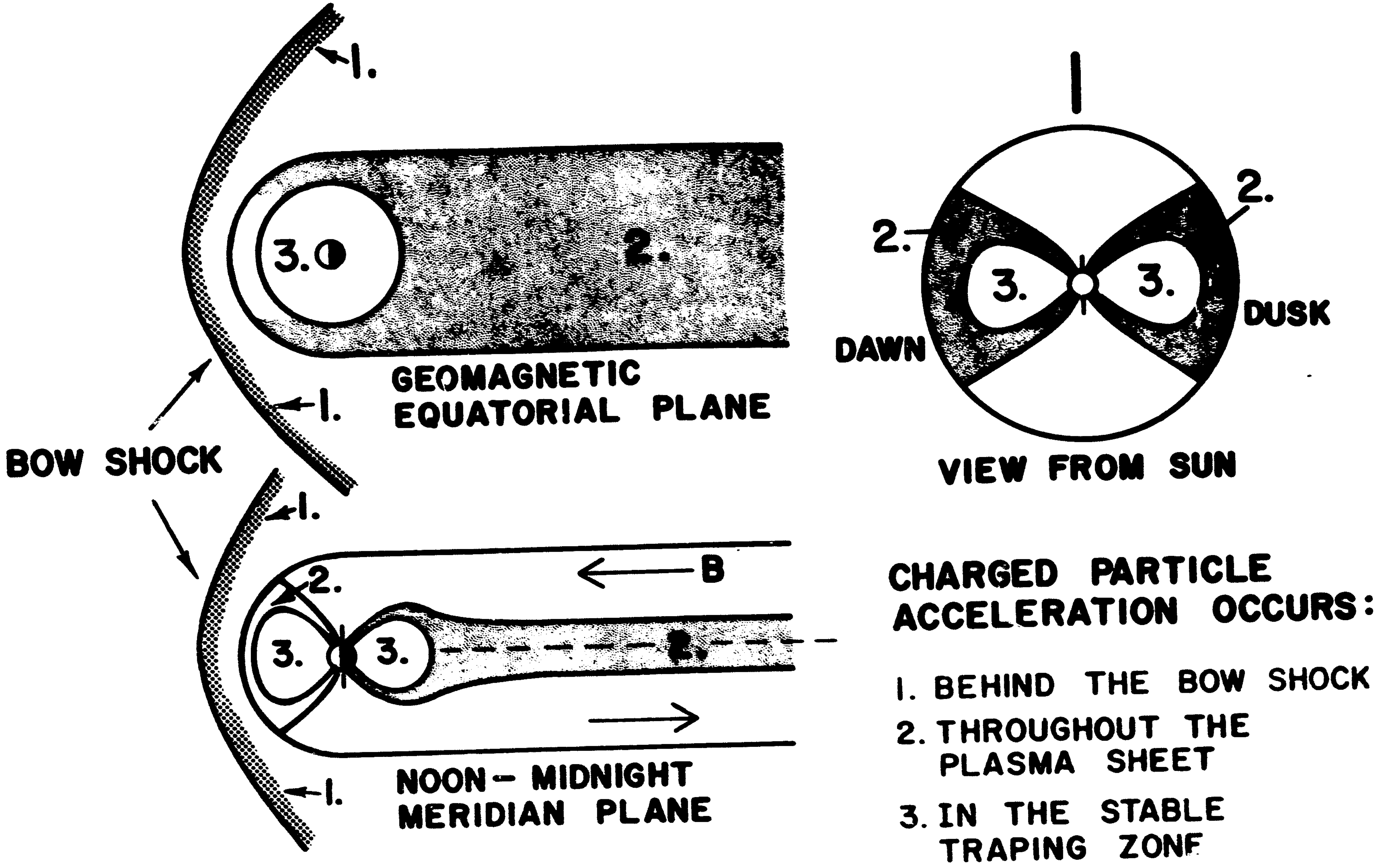
BOW SHOCK
1.
1.
3.0
2.
GEOMAGNETIC
EQUATORIAL PLANE
1.
2.
3.
3.
2.
B
1.
NOON – MIDNIGHT
MERIDIAN PLANE
2.
2.
3.
3.
DAWN
DUSK
VIEW FROM SUN
CHARGED PARTICLE
ACCELERATION OCCURS:
1. BEHIND THE BOW SHOCK
2. THROUGHOUT THE PLASMA SHEET
3. IN THE STABLE TRAPING ZONF

FIGURE 1

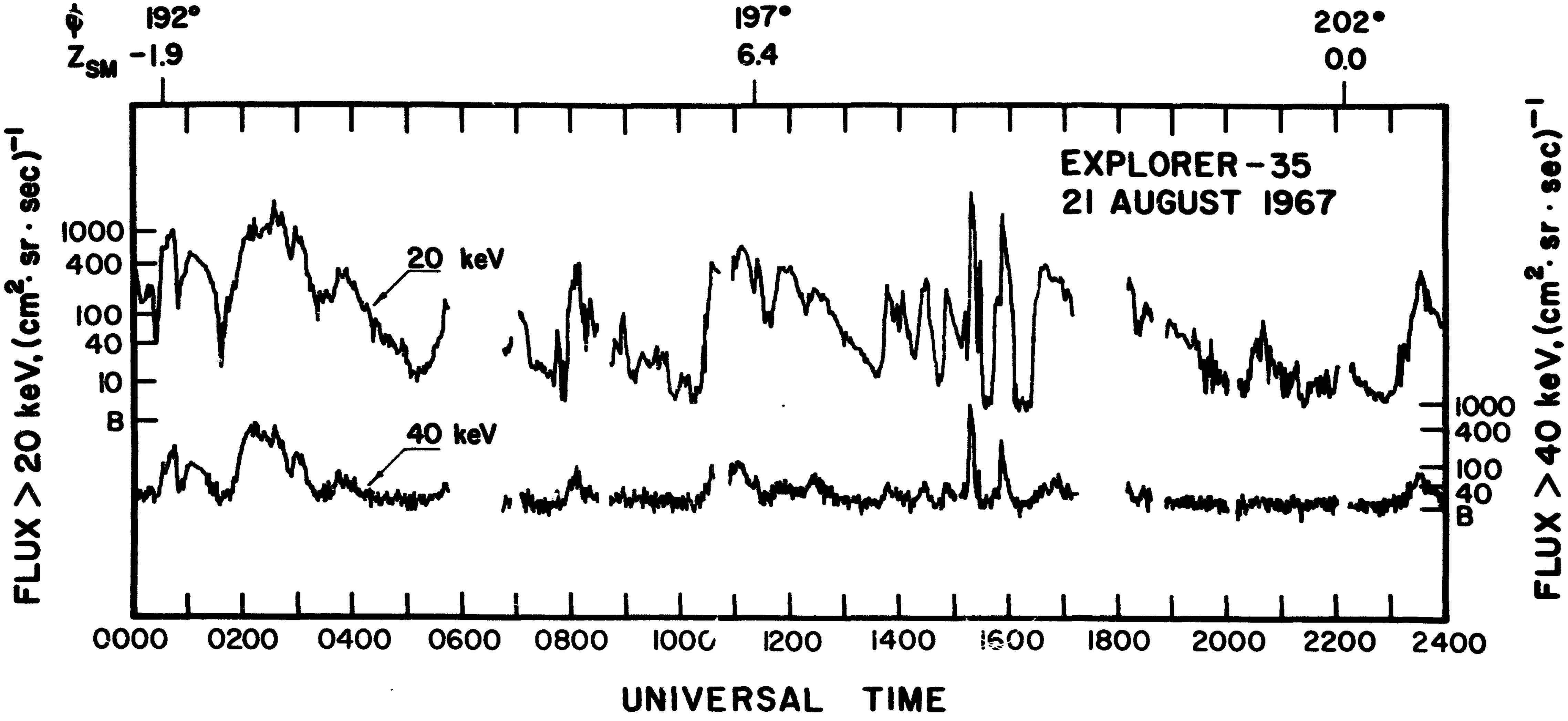
φ
Z_SM
192°
-1.9
197°
6.4
202°
0.0
EXPLORER-35
21 AUGUST 1967
20 keV
40 keV
FLUX > 20 keV, (cm². sr · sec)⁻¹
1000
400
100
40
10
B
FLUX > 40 keV, (cm². sr · sec)⁻¹
1000
400
100
40
B
0000
0200
0400
0600
0800
1000
1200
1400
1600
1800
2000
2200
2400
UNIVERSAL TIME

FIGURE 2

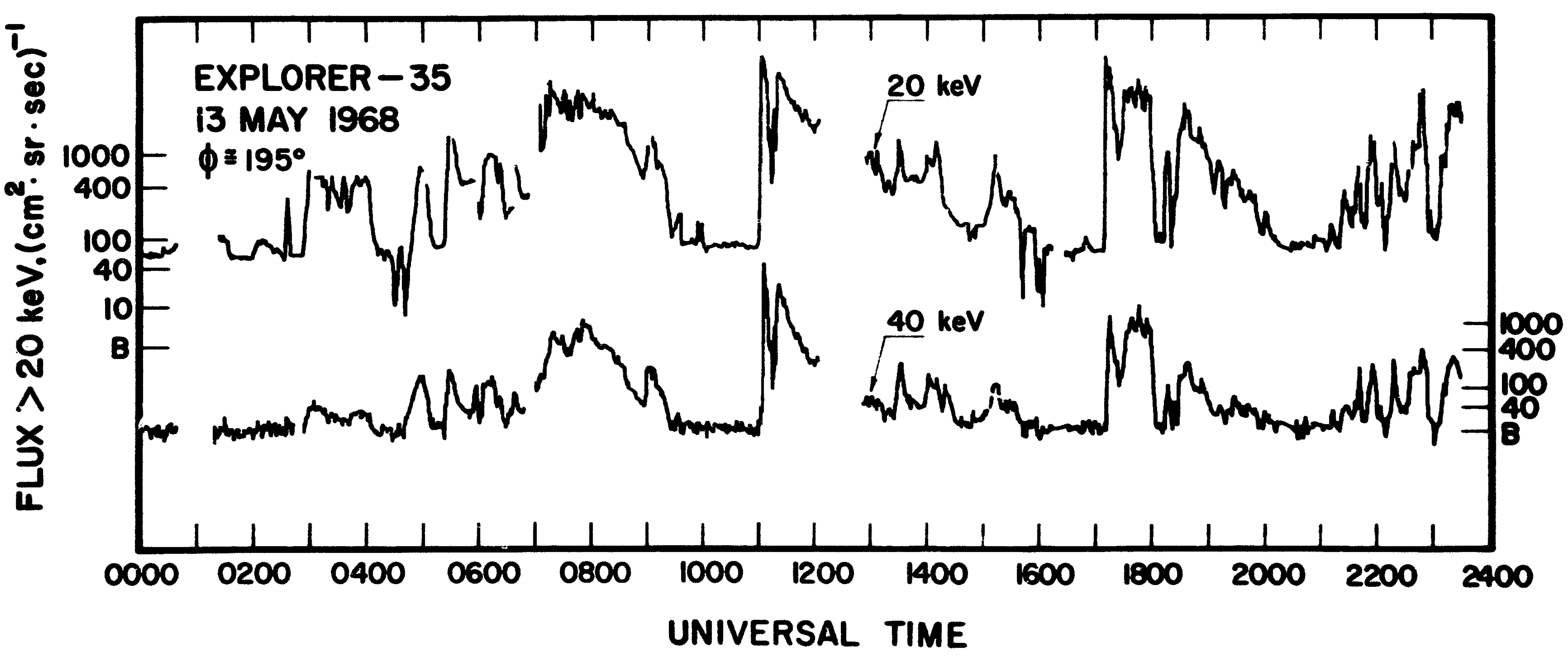
EXPLORER – 35
13 MAY 1968
$\phi \cong 195°$
20 keV
40 keV
FLUX > 20 keV,(cm^2 · sr · sec)$^{-1}$
1000
400
100
40
10
B
FLUX > 40 keV,(cm^2 · sr · sec)$^{-1}$
1000
400
100
40
B
0000
0200
0400
0600
0800
1000
1200
1400
1600
1800
2000
2200
2400
UNIVERSAL TIME

FIGURE 3

INTENSITY

$e > 40$ keV:

UP TO 10^7 $cm^{-2} sec^{-1}$

$p > 125$ keV:

UP TO 10^6 $cm^{-2} sec^{-1}$

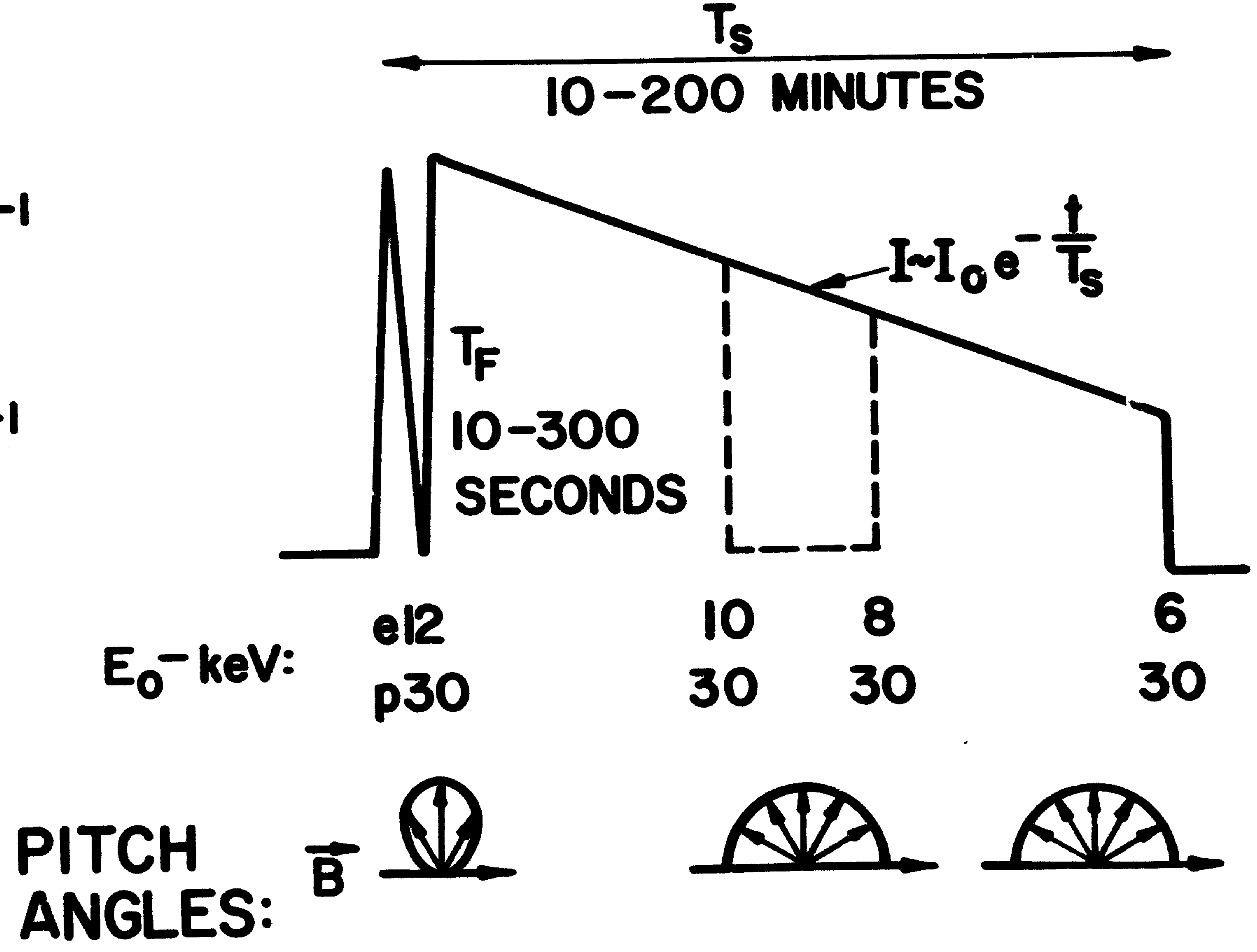

FIGURE 4

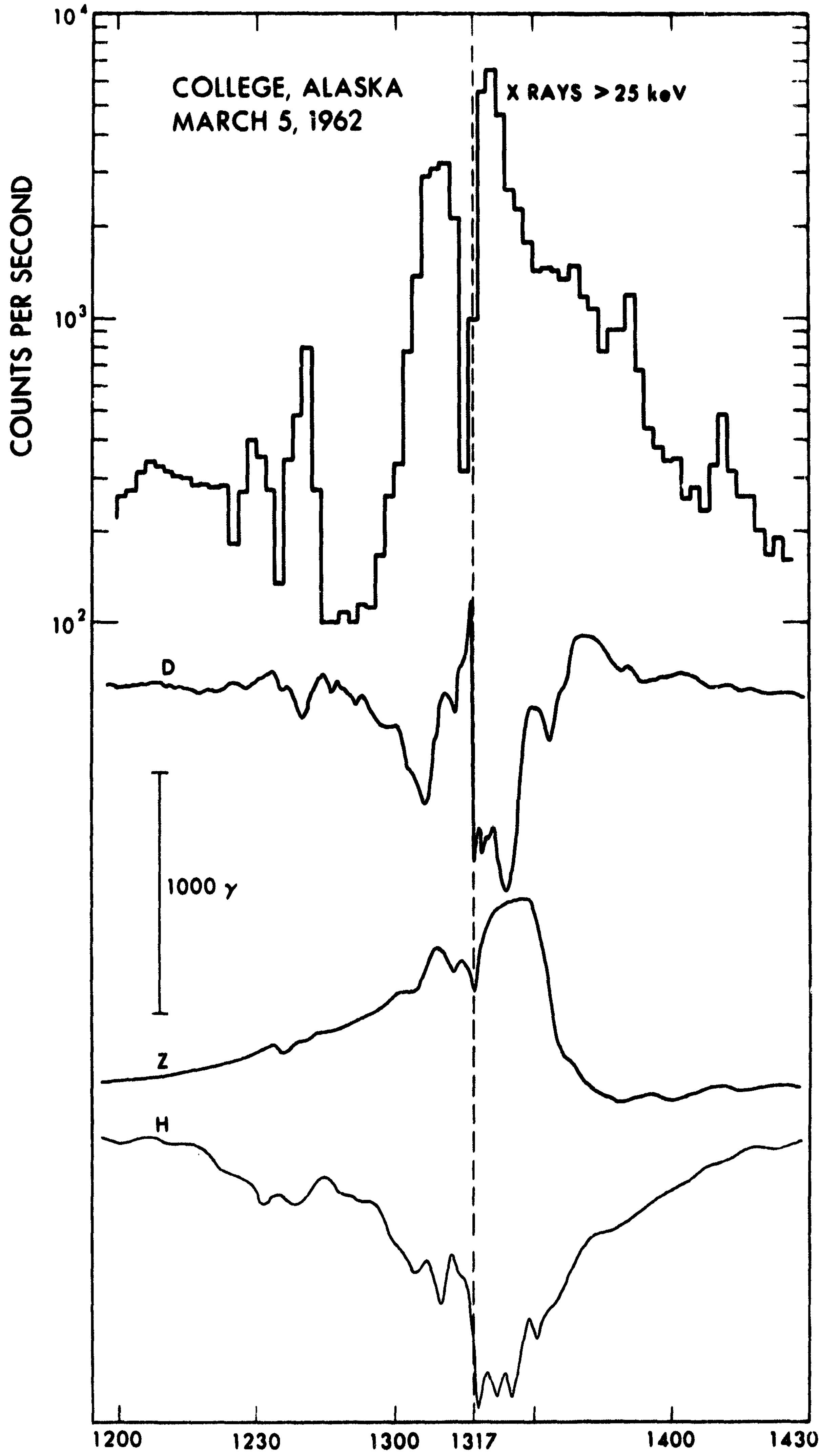
10⁴
10³
10²
COUNTS PER SECOND
COLLEGE, ALASKA
MARCH 5, 1962
X RAYS > 25 keV
D
1000 γ
Z
H
1200
1230
1300
1317
1400
1430
UNIVERSAL TIME

FIGURE 5

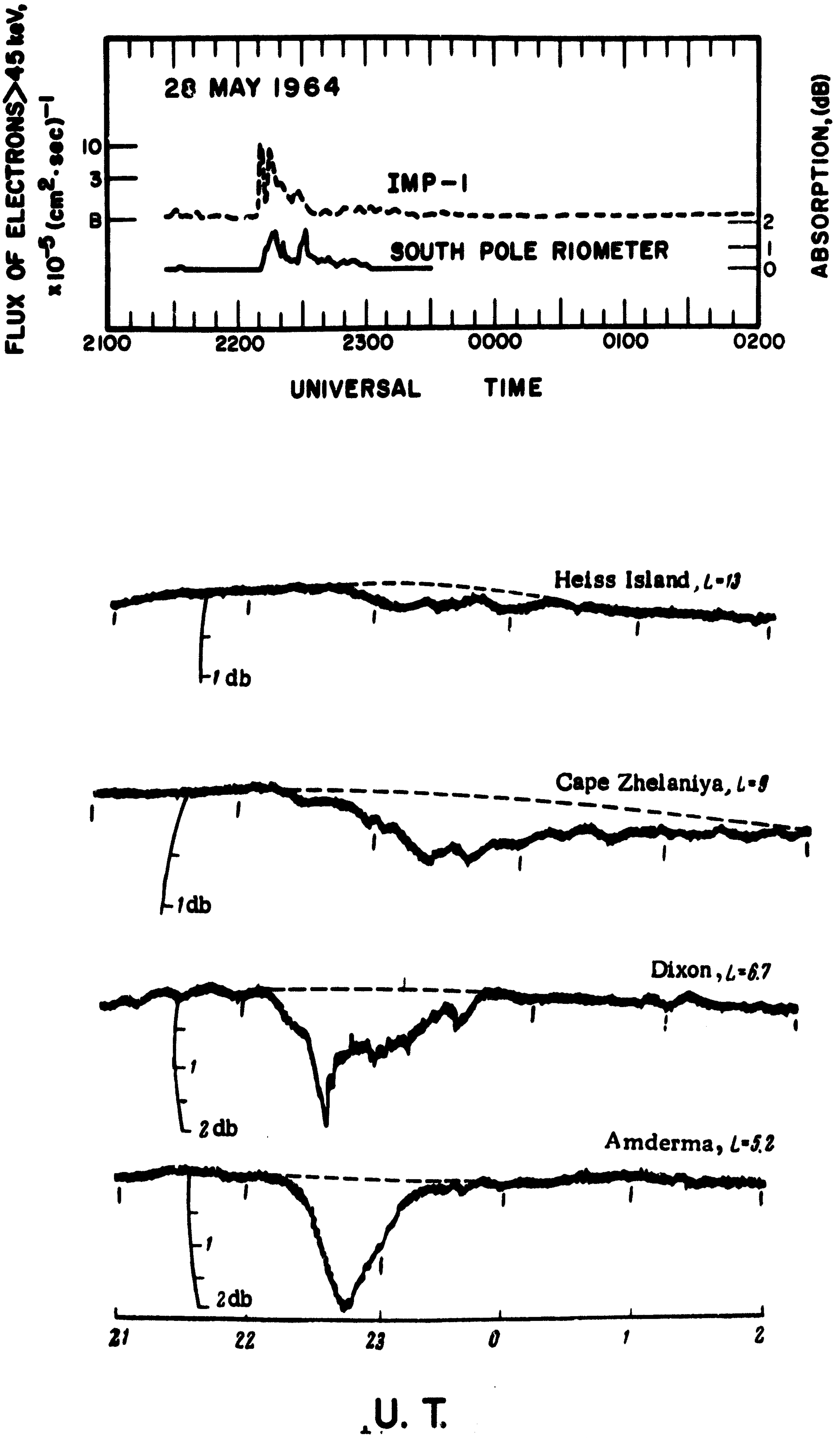
28 MAY 1964
FLUX OF ELECTRONS >45 keV, x10^-5 (cm^2·sec)^-1
10
3
B
IMP-1
SOUTH POLE RIOMETER
ABSORPTION, (dB)
2
1
0
2100
2200
2300
0000
0100
0200
UNIVERSAL TIME
Heiss Island, L=13
1 db
Cape Zhelaniya, L=8
1db
Dixon, L=6.7
1
2 db
Amderma, L=5.2
1
2db
21
22
23
0
1
2
U. T.

FIGURE 6

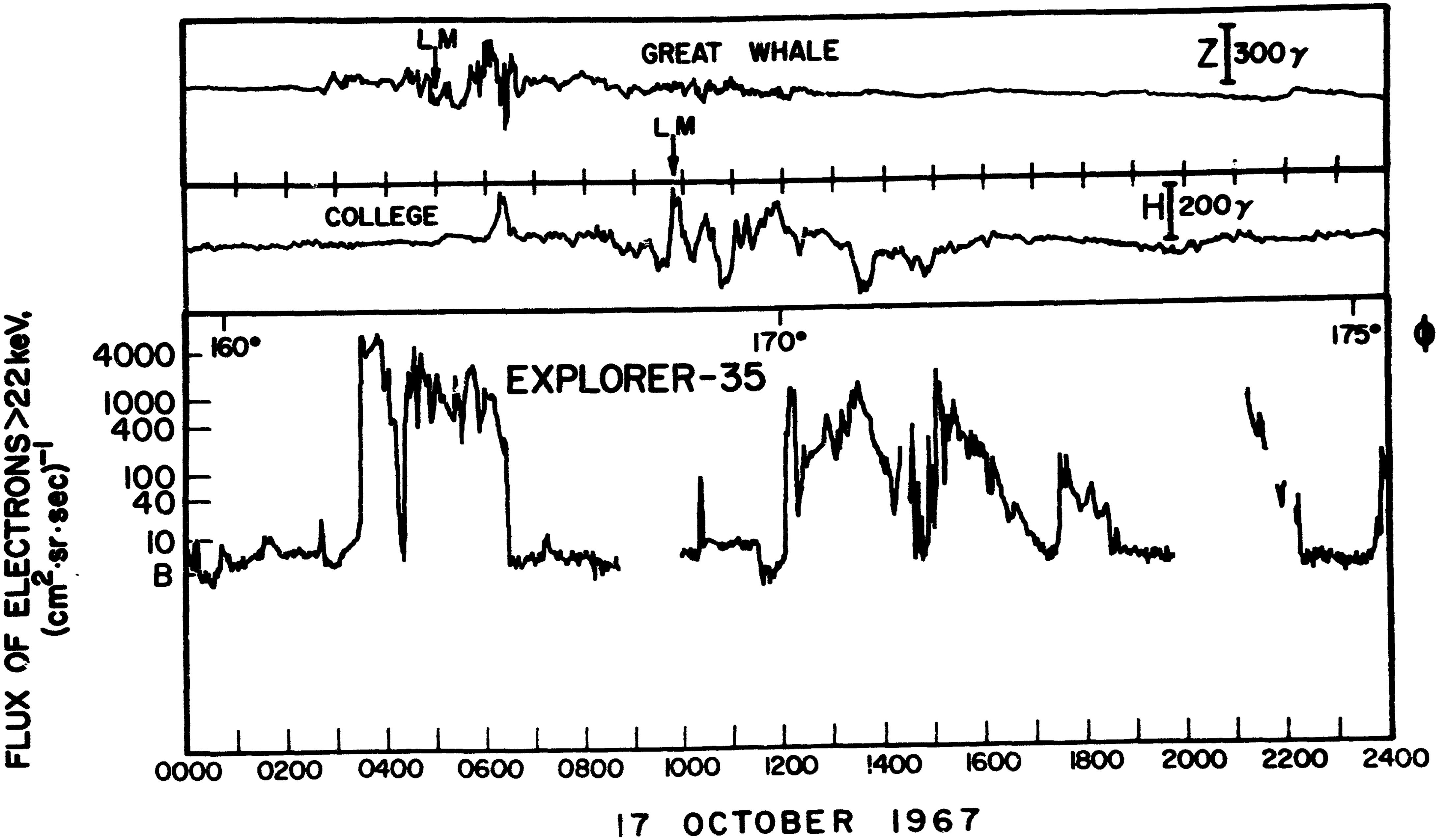
GREAT WHALE
L M
Z 300γ
L M
COLLEGE
H 200γ
EXPLORER-35
160°
170°
175°
Φ
FLUX OF ELECTRONS>22keV, $(cm^2 \cdot sr \cdot sec)^{-1}$
4000
1000
400
100
40
10
B
0000
0200
0400
0600
0800
1000
1200
1400
1600
1800
2000
2200
2400
17 OCTOBER 1967

FIGURE 7

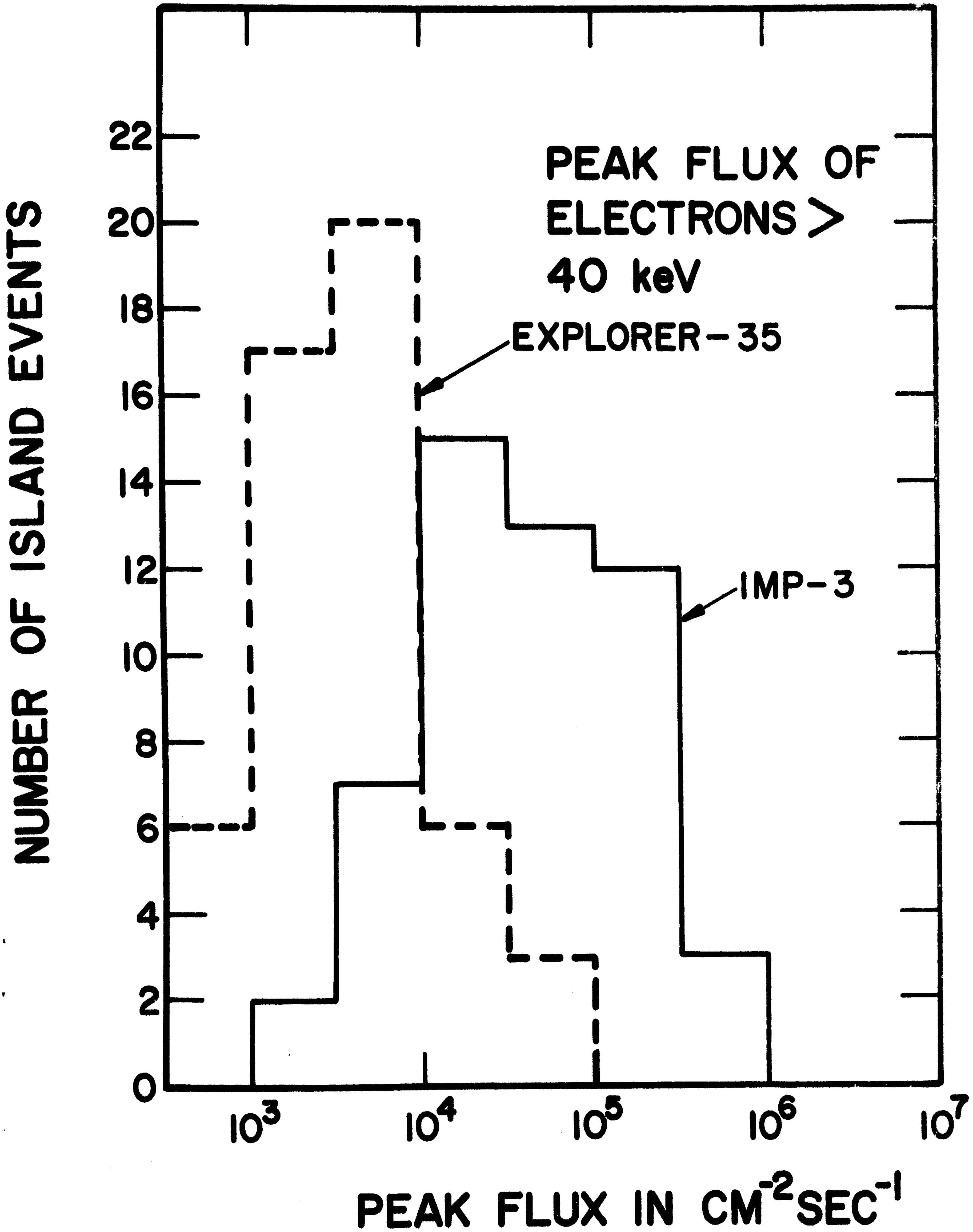
PEAK FLUX OF ELECTRONS > 40 keV
EXPLORER-35
IMP-3
NUMBER OF ISLAND EVENTS
0
2
4
6
8
10
12
14
16
18
20
22
10^3
10^4
10^5
10^6
10^7
PEAK FLUX IN $CM^{-2}SEC^{-1}$

FIGURE 8