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Solar Particle Observations Inside the Magnetosphere during the 7 July 1966 Event*

by

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ABSTRACT

Observations of protons emitted by the 7 July 1966 solar flare at N34, W47 with the low-altitude--high-latitude University of Iowa satellite Injun IV show the following. (a) High energy ($E_p \sim 27$ MeV) protons arrive promptly over the earth's polar caps and decay in a manner consistent with diffusive propagation. (b) The counting rate due to protons in the interval $0.52 \leq E_p \leq 4$ MeV and moving normal to the magnetic vector shows a double plateau as the satellite moves over the polar caps. (c) The position of the "knee" for protons in the above energy interval varies from $L \sim 7.5$ to $L \sim 6.3$ at magnetic local times of ~ 4.5 hours and ~ 11.5 hours, respectively. (d) After the sudden commencement the latitude gap between trapped protons and solar protons disappears, suggesting that some solar protons may become trapped in the earth's radiation belts. (e) Simultaneous observations with similar detectors inside the magnetosphere (Injun IV) and outside the magnetosphere (Explorer 33) show that low energy (~ 0.5 MeV) protons have essentially immediate access from the interplanetary space to the polar caps of the earth. Finally, the theoretical implications of these results are discussed.

I. INTRODUCTION

We report herein observations of protons emitted in the 7 July 1966 solar flare, obtained inside the magnetosphere from 7 to 10 July 1966. These observations were made with detectors onboard the University of Iowa satellite Injun IV which was launched on 21 November 1964 into a nearly polar orbit of 81° inclination, with initial apogee altitude of 2502 kilometers and perigee altitude of 527 kilometers. Data are analyzed during that portion of the satellite orbit for which $L \gtrsim 4$, and the dependence of the counting rate on universal time, invariant latitude, and magnetic local time is examined. Energy spectra for protons and alpha-particles at selected times are computed, and the particle fluxes are compared to those outside the magnetosphere observed simultaneously with Explorer 33. Finally, a comparison of the results with proposed theoretical models is given.

II. THE DETECTOR

The Injun IV detector relevant to these observations is a totally depleted silicon surface barrier one in the form of a thin circular disc, whose thickness is 25 microns and whose frontal area is 1.75 ± 0.2 mm^2 (Nuclear Diodes, Inc.). The detector is located inside a conical collimator with a full vertex angle of 40° and is otherwise shielded by a minimum of 10.2 g/cm^2 of brass, which corresponds to the range of 95 MeV protons. To shield against sunlight a nickel foil whose thickness is 0.21 mg/cm^2 of air equivalent for α-particles, is placed in front of the detector. Four electronic discrimination levels are provided. The first two (channels A and B) are sensitive to protons and heavier nuclei and the last two (channels C and D) are sensitive only to particles heavier than deuterons (Table I). The thin detector, coupled with a double-delay line clipped pulse of 200 nanoseconds full width, renders the detector insensitive to electrons of any energy. The electron insensitivity and the calibration methods that have been used are identical to those described in detail elsewhere [Krimigis and Armstrong, 1966]. The satellite is equipped with a permanent magnet and energy-dissipating hysteresis rods so that it will maintain a particular axis continuously aligned with the local geomagnetic field vector. Thus, for the low energy proton observations reported herein, the axis of the detector collimator was maintained continuously perpendicular ($\pm$ 10°) to the local geomagnetic field vector so that the detector was receiving particles whose pitch angles were 90° $\pm$ 30°.

In addition to the solid state detector, the Injun IV instrumentation includes a shielded GM-tube whose threshold for protons is ~ 27 MeV. This detector has been described previously [Krimigis and Van Allen, 1967].

Table I

Characteristics of the Injun IV Detectors

Detector**	Unidirectional Geometric Factor cm^2 steradian	Omnidirectional Geometric Factor cm^2	Particles to Which Sensitive	Dynamic Range
A	0.0064 ± 0.0007	---	Protons: $0.52 \leq E_p \leq 4^*$ MeV Electrons: None	From inflight source to 10^6 c/sec
B	0.0064 ± 0.0007	---	Protons: $0.90 \leq E_p \leq 1.8^*$ MeV Electrons: None	"
C	0.0064 ± 0.0007	---	α-Particles: $2.09 \leq E_\alpha \leq 15^*$ MeV	"
D	0.0064 ± 0.0007	---	α-Particles: $3.89 \leq E_\alpha \leq 7.6^*$ MeV	"
112-GM	---	8.9^{***}	Protons: $E_p \gtrsim 27^+$ MeV Electrons: Insensitive except via bremsstrahlung for $E_e \gtrsim 1$ MeV	From galactic cosmic ray rate of 30 c/s to 10^5 c/sec

*Upper limit for vertical incidence only; the corresponding limits for incidence at 20° to the collimator axis are 4.2 MeV, 1.9 MeV, 18 MeV, and 8 MeV for A, B, C, and D, respectively.

**A, B, C, D, correspond to different electronic discrimination levels in the same basic detector.

***If exposed in free space; effective geometric factor is smaller by ~ 30% as actually mounted in the satellite.

+ This threshold corresponds to protons incident perpendicular to the axis of the cylindrical-type tube. For protons incident at an angle of 60° to the axis, the threshold is ~ 40 MeV.

III. OBSERVATIONS

a. Energetic Protons

In Figure 1 is plotted the counting rate of the shielded GM-tube for the period 7 to 10 July 1966, averaged over the polar cap for $L \gtrsim 8$. It is observed that during the pass which ended on 0050 U.T. on 7 July, the detector counting rate was accurately equal to the pre-event cosmic ray background rate. Hence the arrival of particles at the earth, due to a flare on the sun, whose onset was at 0023 U.T. [Van Allen, 1967] took place after 0050 U.T. On the following satellite pass at ~ 0234 U.T. the counting rate had already approached its maximum value. It subsequently decreased until, at ~ 1800 U.T. on 9 July, it was indistinguishable from the cosmic ray background. The intensity-time profile is reminiscent of several such events during the previous solar cycle, in that it has a rapid increase to the maximum and a slow non-exponential decay of 2-3 days. Such time behavior may be accounted for in terms of diffusion in the interplanetary medium [cf. Krimigis, 1965]. More complete observations of the present event have shown that this is indeed the case [Heristchi et al., 1967].

b. Low Energy Protons

Figure 2 shows the counting rate of the solid state detector, due to protons in the energy interval $0.52 \leq E_p \leq 4$ MeV, during a northbound Injun IV pass over the polar cap. We observe the following:

(1) Solar protons in the quoted energy interval do not have access to regions where $L < 5.5$, independently of magnetic local time.

(2) The counting rate shows a double plateau as the satellite moves from a magnetic local time (MLT) of ~ 4 hours to MLT of ~ 11 hours.

(3) The position of the knee for protons in this energy interval is at $L \sim 7.5$ (at 50% of the plateau counting rates) at MLT ~ 4.5 hours and at $L \sim 6.3$ at MLT ~ 11.5 hours.

The double-plateau is found to be a persistent feature of all polar cap passes of the satellite, prior to the occurrence of the sudden commencement at 2102 U.T. on 8 July. To further investigate this effect, four such passes are shown in Figure 3, along with a polar plot of the satellite trajectory for these passes in invariant latitude and MLT. We observe that all four passes show the double-plateau feature at several points in local time. Comparison of the data with the simultaneous measurements of Explorer 33 (see section V of this report) shows that the variation in the counting rate is not due to time variations in the intensity of the primary proton beam.

c. Energy Spectra of Protons and Alpha Particles

The ratios A/B and C/D of the counting rates of proton and alpha detectors, respectively, may be used to determine the energy spectra. During the time interval 0330 to 0540 U.T. on 8 July, the intensity remained relatively constant and the ratios were as follows:

$$\frac{A}{B} = 2.14 \pm 0.1 \qquad \text{protons}$$

$$\frac{C}{D} = 2.70 \pm 0.5 \qquad \text{alpha particles}$$

If one assumes a differential energy spectrum $dj/dE = (K/E_o)\, e^{-E/E_o}$ for $E_p \gtrsim 0.52$ and $E_\alpha \gtrsim 2.1$ MeV, then the values of E_o for protons and alpha particles are $E_{op} \sim 0.8$ MeV and $E_{o\alpha} \sim 2$ MeV, respectively. It is noted that the simultaneous ratio of two proton channels comparable to A and B on Explorer 33 which was located outside the magnetosphere is given by

$$\frac{P2}{P3} = 2.0 \pm 0.01 \qquad \text{protons on Explorer 33}$$

resulting in a comparable value of E_{op} [Armstrong et al., 1967].

IV. REMARKS ON THE LOW ENERGY PROTONS

In the preceding section we pointed out the double plateau feature of the counting rate profile on a polar pass. Although it has been known for some time that the entrance of low energy protons onto the earth's polar caps is not adequately explained by Stormer theory, no adequate theories have been proposed to explain the experimental data of Pieper et al. [1962], Stone [1964], and Harding [1966]. Recently Taylor [1967] has made a calculation using the Taylor-Hones model of the geomagnetic field and finds that the polar plateau is an irregularly shaped region with full accessibility to incoming low energy (~ 1.2 MeV) solar protons in some parts and limited or no accessibility in others. The polar plot in Figure 3 is shown in more detail in Figure 4 where the shaded area for $\Lambda \gtrsim 65°$ is a region of limited accessibility, while the open area is accessible to particles of all pitch angles. Our experimental data show that there is qualitative agreement between Taylor's predictions and the observations. It does appear, however, that the boundary of the region with limited accessibility is at a consistently lower latitude than that predicted by Taylor. It may be possible to use the experimental data to determine more accurately the parameters involved in the calculation.

At this point the question arises as to whether the double-plateau persists after the occurrence of the sudden commencement. Figure 5 shows a pass taken at $\sim$ 2125 U.T., approximately 20 minutes after the sudden commencement. It is observed that the depressed plateau at $\sim$ 11 hours MLT is no longer present; in addition, the latitude gap between trapped protons and solar protons has disappeared and the distinction between solar and trapped protons is no longer apparent. It is suggested that low energy solar protons can enter the relatively ordered region of the magnetic field at high latitudes at L values of $\sim$ 6, and become permanently trapped in the geomagnetic field, although their contribution to trapped proton intensities at comparable energies may not be important.

V. SIMULTANEOUS OBSERVATIONS INSIDE AND OUTSIDE THE MAGNETOSPHERE

Recently, Krimigis and Van Allen [1967] have reported simultaneous observations with Injun IV near the earth and Mariner IV (the latter located ~ 23 x 10^6 km downstream from the earth and near the sun-earth line) and have concluded that the observed delay in arrival time for 0.5 MeV solar protons between the two spacecraft is 0 $\pm$ 2 hrs.

The present measurements make possible a much improved examination of the question of access of particles to the earth through the magnetosphere by use of simultaneous measurements between Explorer 33 and Injun IV for the following reasons: (a) Explorer 33 is in the immediate astronomical vicinity of the earth, but clearly outside of the earth's magnetosphere (Figure 6); (b) the event of 7 July 1966 is of sufficiently high intensity that the statistical accuracy of the Injun IV counting rates is superior to those reported earlier by Krimigis and Van Allen [1967] [see also Williams and Bostrom, 1967]; and (c) the intensity-time structure is rich in detail, thus making possible a refined search for time delays. Because of (a) above, any dissimilarities in the intensity-time profiles between the two spacecraft cannot be attributed to large scale (~ 10^6 km) inhomogeneities in the interplanetary medium, as might have been the case for the Mariner IV and Injun IV comparison.

The University of Iowa detector complement on Explorer 33 is virtually identical to the Injun IV detector [Armstrong and Krimigis, 1967] with discrimination levels set to count protons in the energy ranges $0.3 \leq E_p \leq 10$ MeV, $0.5 \leq E_p \leq 4$ MeV, and $0.82 \leq E_p \leq 1.9$ MeV. The conical collimator of the detector has a half-angle of 30°, and the spacecraft is spinning at the rate of ~ 26 rpm. The absolute value of the unidirectional geometric factor is 0.082 ± 0.003 cm^2-sr.

Figure 7 shows the counting rate vs time profile of the $0.5 \leq E_p \leq 4$ MeV channel from Explorer 33 (solid curve) and the counting rate vs time profile of the equivalent channel from Injun IV (plotted points) obtained while the latter satellite (orbital inclination 81°) was moving over the earth's polar caps at an altitude ranging from 1500 to 2000 km. The solid curve was drawn by using half-hour averages of the counting rate, while the plotted points represent 8-16 minute averages of the Injun IV counting rate over the polar caps. Since the unidirectional geometric factors of the two detectors differ by approximately a factor of 10 (within 25%), the Injun IV points were moved up one decade in the logarithmic scale so that the absolute values of the intensity at the positions of the two satellites can be compared directly. It is seen that

(a) The absolute intensities of protons in identical energy channels are essentially the same moment-by-moment (within the uncertainties in the geometric factors and the statistics), in interplanetary space and over the polar caps of the earth, during the entire 4-day period of simultaneous observations.

(b) There are statistically significant differences in only two or three instances (e.g., ~ 1800 U.T., 9 July), which are attributed tentatively to marked anisotropies in the interplanetary intensity and/or to strong polar magnetic storms.

We therefore conclude that, on the whole, low energy (~ 0.5 MeV) solar protons have full access to the earth's polar caps from the interplanetary medium, with a delay of 0.5 hour or less. Simultaneous observations of 0.90 MeV protons and 2.1 MeV alpha particles have also been compared and lead to the same conclusion.

Of particular interest is the abrupt decrease in the intensity at about 2300 U.T. on 8 July. A more detailed plot of this period shows that while the counting rate at the position of Explorer 33 is still decreasing, the rate at Injun IV has <u>already</u> decreased to the new level. We infer from this observation that the decrease in intensity at Injun IV <u>preceded</u> that at Explorer 33 by at least 8 minutes, in crude agreement with the concept of a plasma cloud moving radially outward from the sun past the earth and past Explorer 33, in that order, carrying the energetic particles with it.

VI. REMARKS ON SIMULTANEOUS OBSERVATIONS

Although it has been established that the earth's magnetospheric boundary is greatly distorted by the flow of the solar wind, there is essential disagreement regarding the topology of the magnetic field at the boundary between the magnetosphere and the interplanetary medium. Figure 8 illustrates two contrasting models. The model shown in Figure 8a envisions considerable merging [Dungey, 1961; Levy et al., 1964; Axford et al., 1965] between the geomagnetic and interplanetary magnetic fields, such that charged particles approaching the earth on an interplanetary magnetic field line have immediate access to points over the earth's polar caps.

The model shown in Figure 8b envisions no merging between the geomagnetic and interplanetary fields [Dessler, 1964; Michel and Dessler, 1965] near the earth. Proponents of this model suggest that solar-emitted protons having $E_p \lesssim 5$ MeV must diffuse into the very long tail of the magnetosphere and spread slowly from the auroral zone over the polar caps after a delay or "diffusion time" which is a function of, among other parameters, the length of the tail and the energy/unit charge of the particle. For example, applying equation 4 of Michel and Dessler [1965] (wherein E_q is energy/unit charge) [Michel and Dessler, 1967] to a 0.5 MeV proton and a magnetospheric tail length of 1 A.U. (astronomical unit) one calculates a delay time of 30 hours between the arrival of protons in the vicinity of the earth but outside of the magnetosphere and their arrival over the polar caps at the earth. Tail lengths considerably longer than 1 A.U. (and hence longer delay times) are advocated by Michel and Dessler.

It is seen from Figure 6 that Explorer 33 was located clearly outside the shock front [data on shock front location courtesy of K. W. Behannon and N. F. Ness, GSFC]. Hence, our observations (a) provide a specific test of the diffusion calculation [Michel and Dessler, 1965] for solar protons made in the context of a long tail model of the magnetosphere [Dessler, 1964] (Figure 8b) and are in drastic disagreement with its predictions; and (b) appear to favor an "open" magnetospheric model of the sort depicted in Figure 8a [Van Allen, 1965; Van Allen, 1966; Dessler, 1966].

It may be remarked, however, that the foregoing conclusions are based on the concept of non-interacting particles moving in a quasi-stationary magnetic field, and that collective (plasma) phenomena have been ignored. Transport of a fully ionized plasma across a magnetic field at a rate much faster than that attributable to single particle diffusion has been observed in the laboratory. This phenomenon of anomalous diffusion was investigated theoretically by Spitzer [1960] and more recently by Stix [1967], and shown to be due to electric fields. Thus, it may be that interconnection between magnetic lines of force of the interplanetary and geomagnetic fields is not necessary for access of low energy protons to the earth's polar caps, if such particles are only a minor component of a much more dense plasma cloud, and theoretical discussions on the subject of interconnection of lines of force may be irrelevant to this matter.

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FIGURE CAPTIONS

Figure 1. Time history of protons $E_p \gtrsim 27$ MeV as observed over the earth's polar caps with Injun IV.

Figure 2. A characteristic pass of Injun IV over the polar cap, prior to the sudden commencement. Note the well-defined boundary between solar protons and trapped protons.

Figure 3. Data from four Injun IV passes over the polar caps. The satellite trajectory for each pass is shown at the lower right hand corner in invariant latitude and MLT coordinates.

Figure 4. Detail of Figure 3 showing the satellite trajectory. Points on the trajectory are one minute apart and the corresponding U.T. is given for the first and last points. The region in a given trajectory where the second plateau was observed is marked with cross-hatching. The irregularly-shaped contour is the result of Taylor's calculation.

Figure 5. A post-sudden commencement pass. Note the merging of trapped protons and solar protons.

Figure 6. Ecliptic plane projection of the first orbit of Explorer 33 and a segment of the orbit of the moon, both in geocentric solar ecliptic coordinates. The numbers on the orbit correspond to decimal day of the year, with 0000 UT on 1 January denoted by 0.0 days. Note that during

Figure 6. (Cont'd) the period of observations, Explorer 33 was on the sunward side of the shock front [shock front and magnetopause locations courtesy of K. W. Behannon and N. F. Ness].

Figure 7. Simultaneous observations of directional intensities of solar protons with Explorer 33 and Injun IV. The smooth curve is drawn through half-hour averaged counting rates of Explorer 33. Each plotted point represents a polar cap averaged counting rate for Injun IV. The respective sets of data are superimposed on the same absolute intensity basis (to within 25%) by displacing the counting-rate scale of Injun IV data upward by one decade.

Figure 8. (a) Magnetospheric model that envisions merging between the geomagnetic and interplanetary fields [Dungey, 196; Levy, Petschek, and Siscoe, 1964].

(b) Magnetospheric model in which merging of lines of force does not occur [Dessler, 1964; Michel and Dessler, 1965].

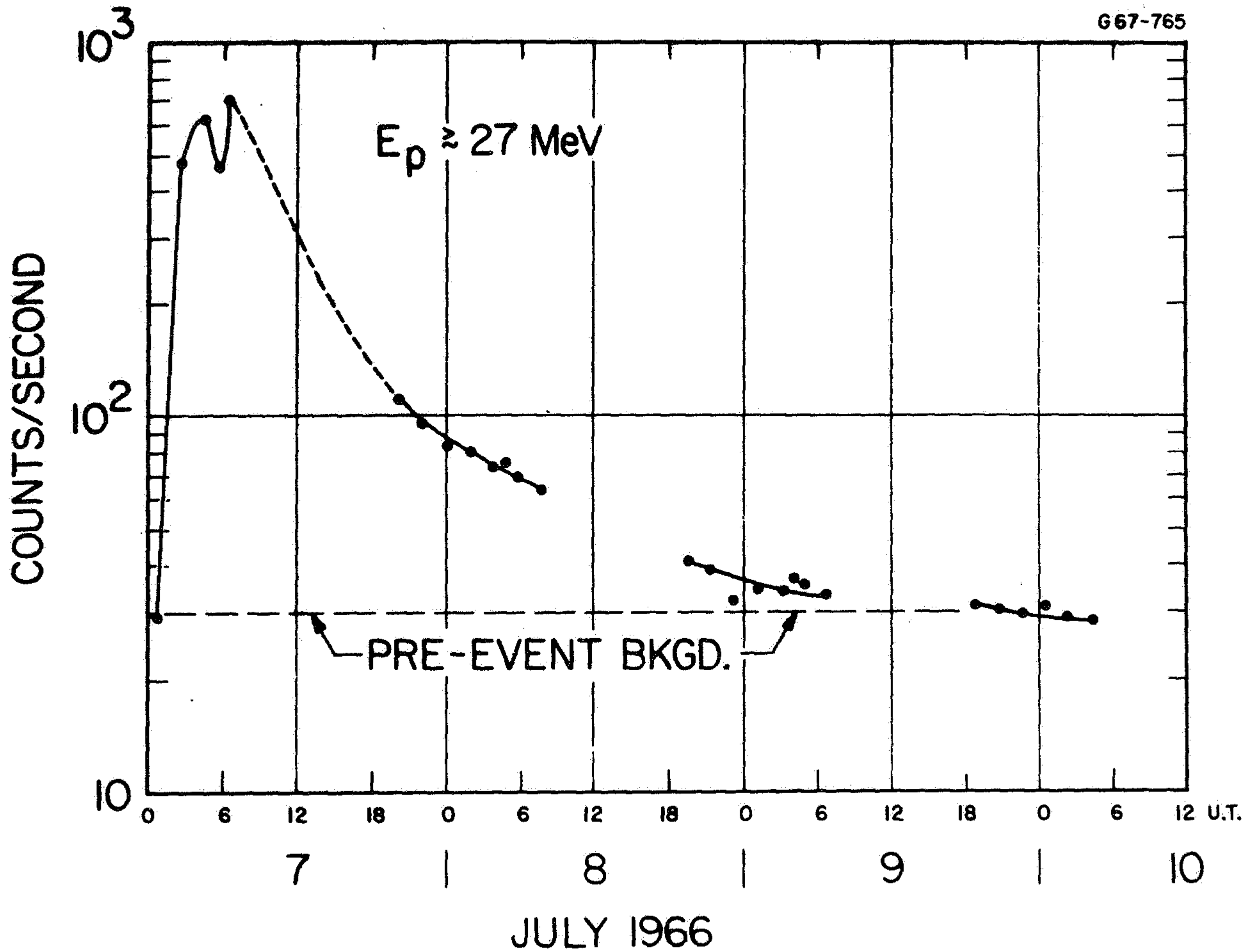

G67-765
10^3
10^2
10
COUNTS/SECOND
$E_p \gtrsim 27$ MeV
PRE-EVENT BKGD.
0
6
12
18
0
6
12
18
0
6
12
18
0
6
12 U.T.
7
8
9
10
JULY 1966

FIGURE 1

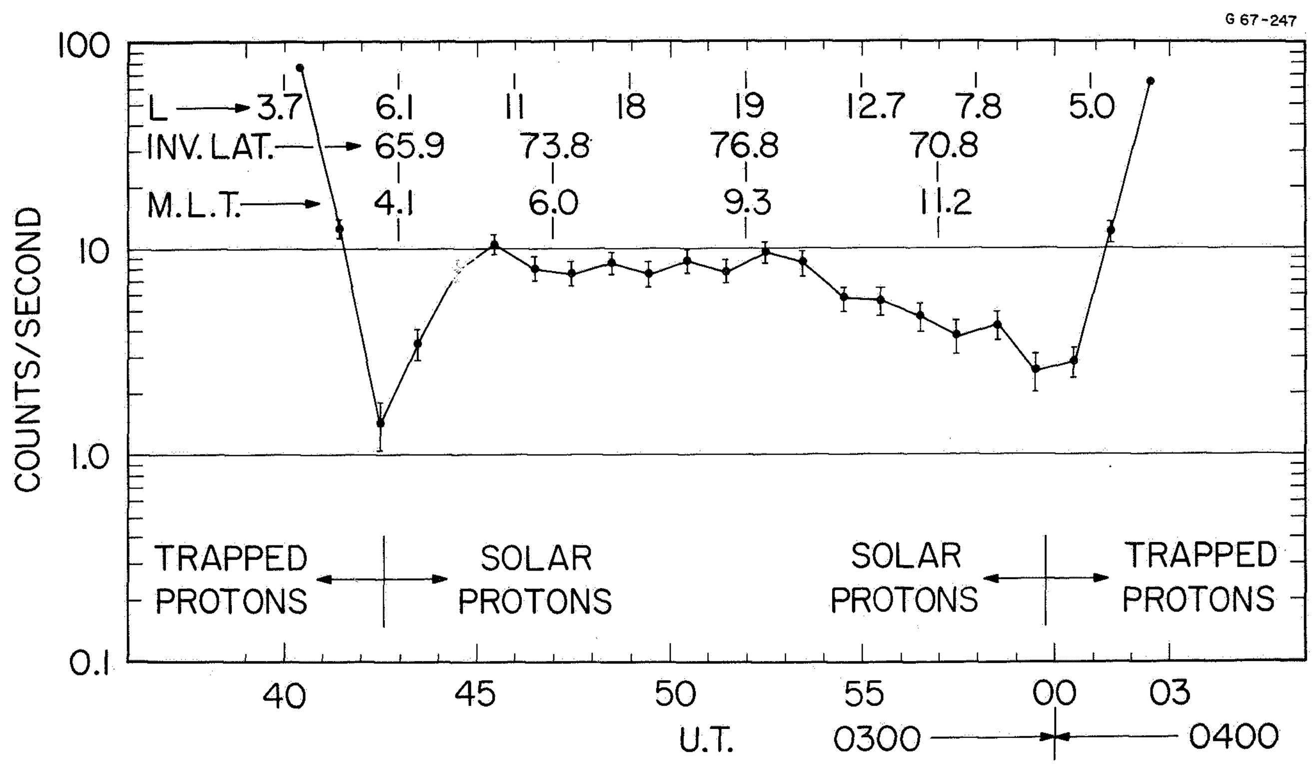

G 67-247
L → 3.7 6.1 11 18 19 12.7 7.8 5.0
INV. LAT. → 65.9 73.8 76.8 70.8
M.L.T. → 4.1 6.0 9.3 11.2
TRAPPED PROTONS
SOLAR PROTONS
SOLAR PROTONS
TRAPPED PROTONS
COUNTS/SECOND
100
10
1.0
0.1
40
45
50
55
00
03
U.T.
0300
0400

FIGURE 2

SOLAR PROTONS OBSERVED WITH INJUN IV
ON 8 JULY 1966
$0.516 \le E_p \le 4$ MeV

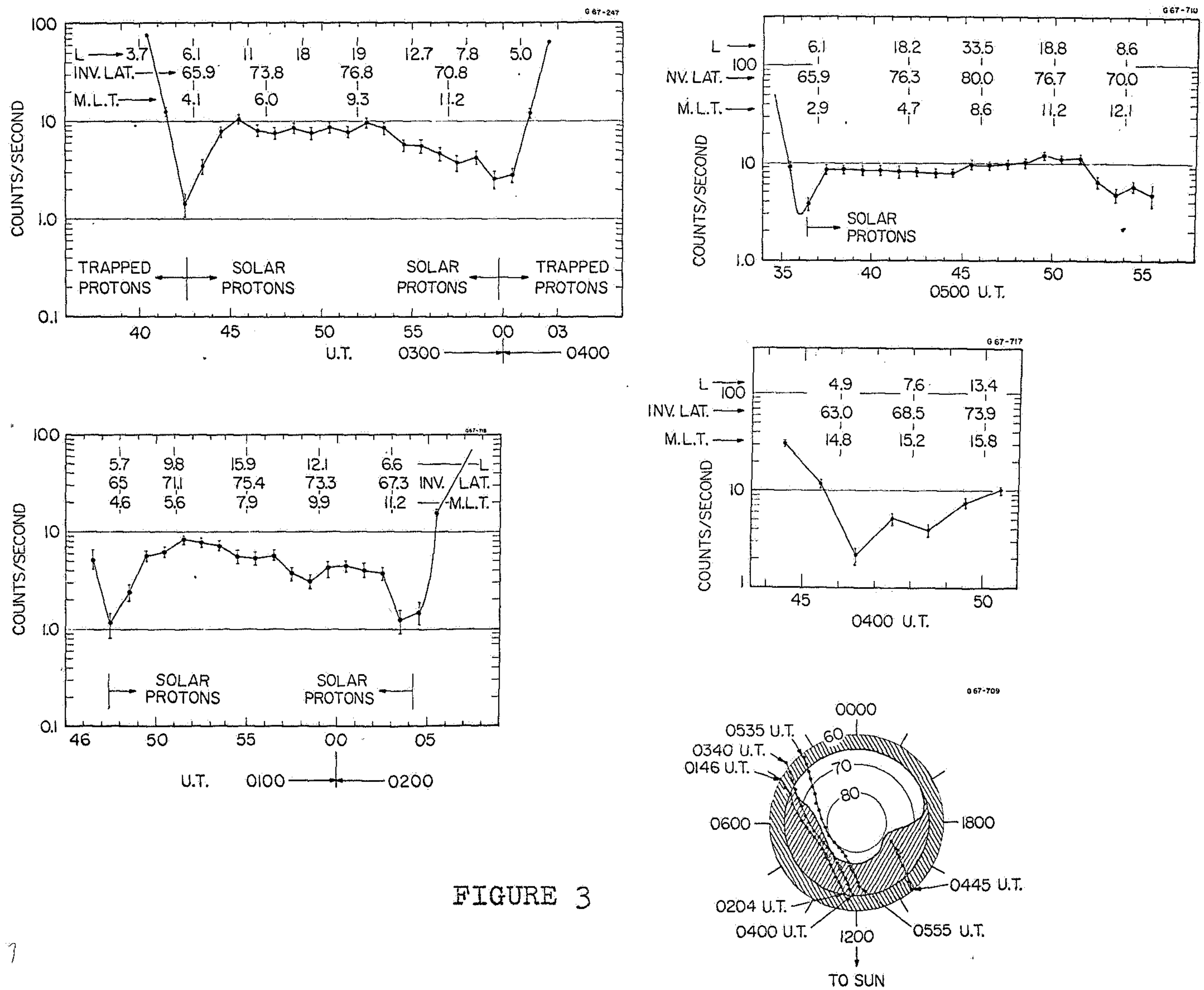


FIGURE 3

G 67-709

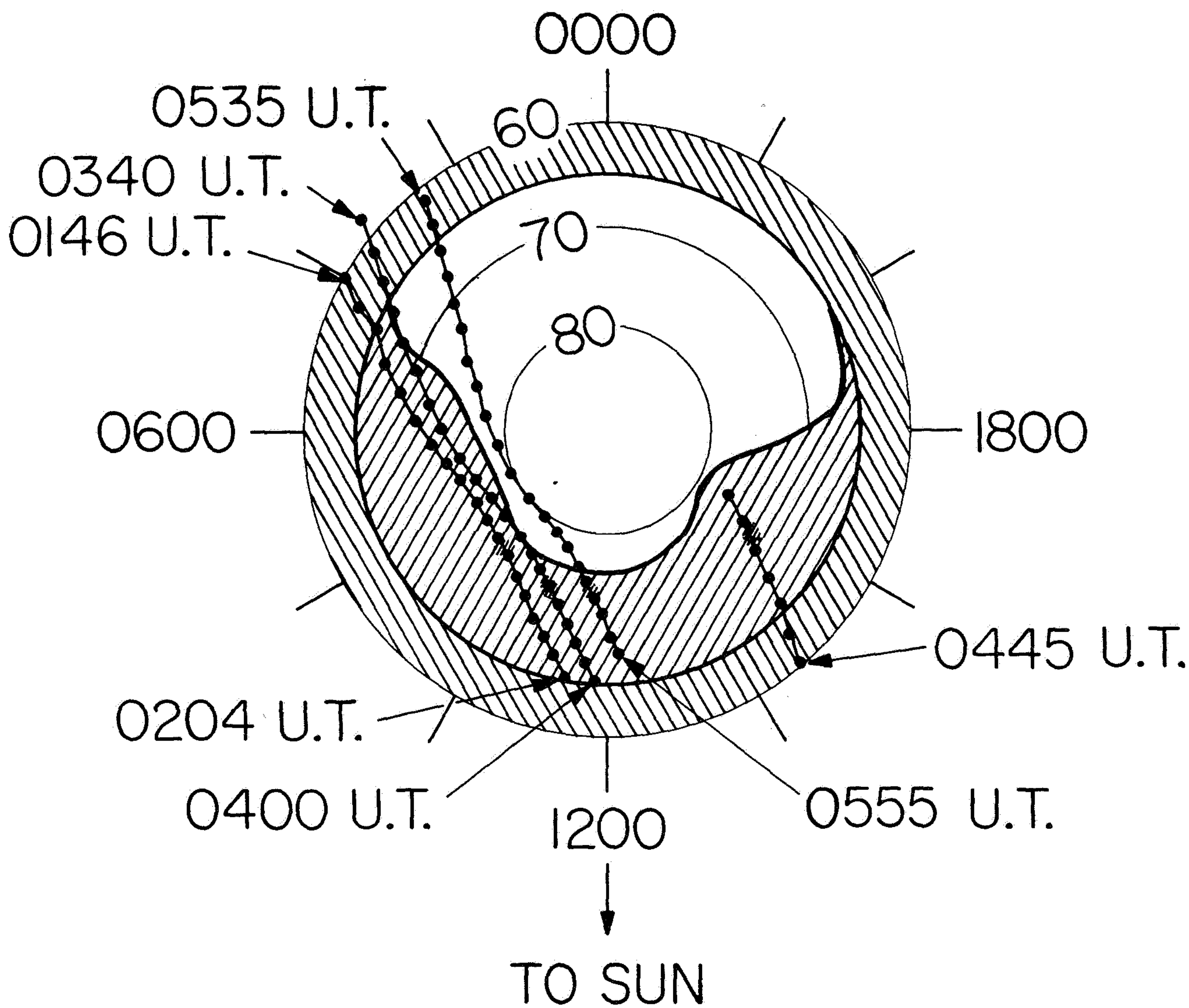


FIGURE 4

G67-716

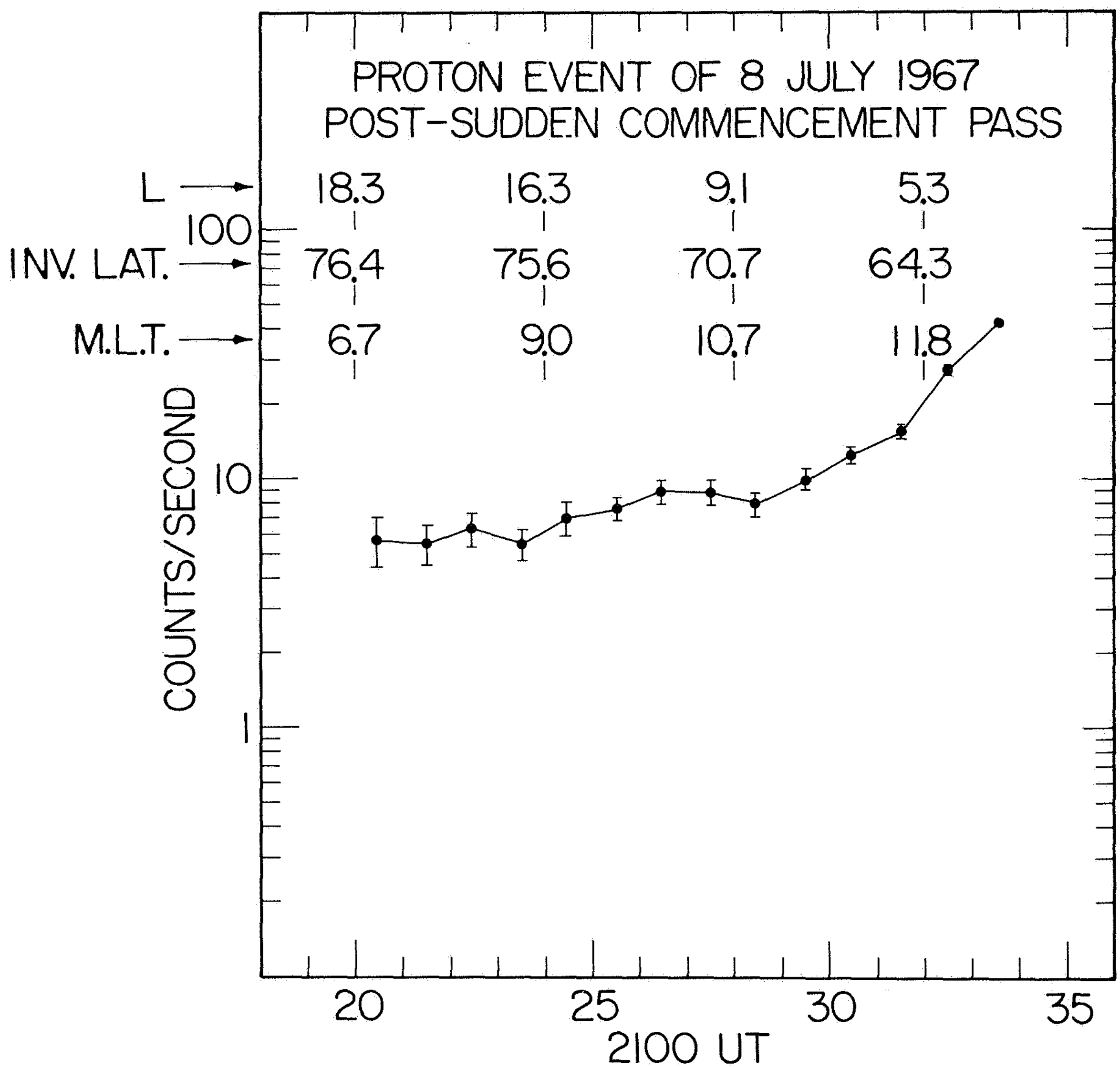


FIGURE 5

G 66-762

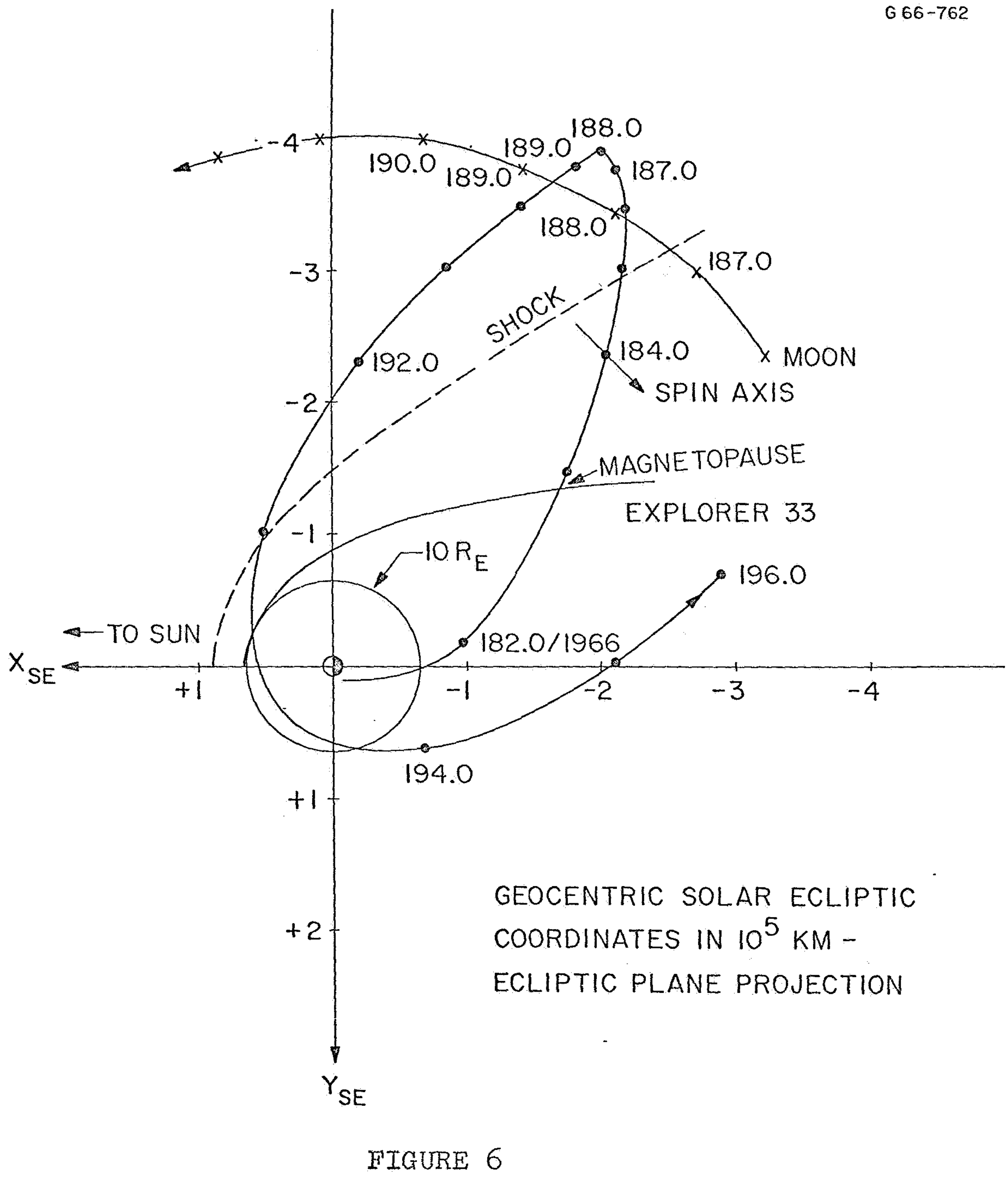
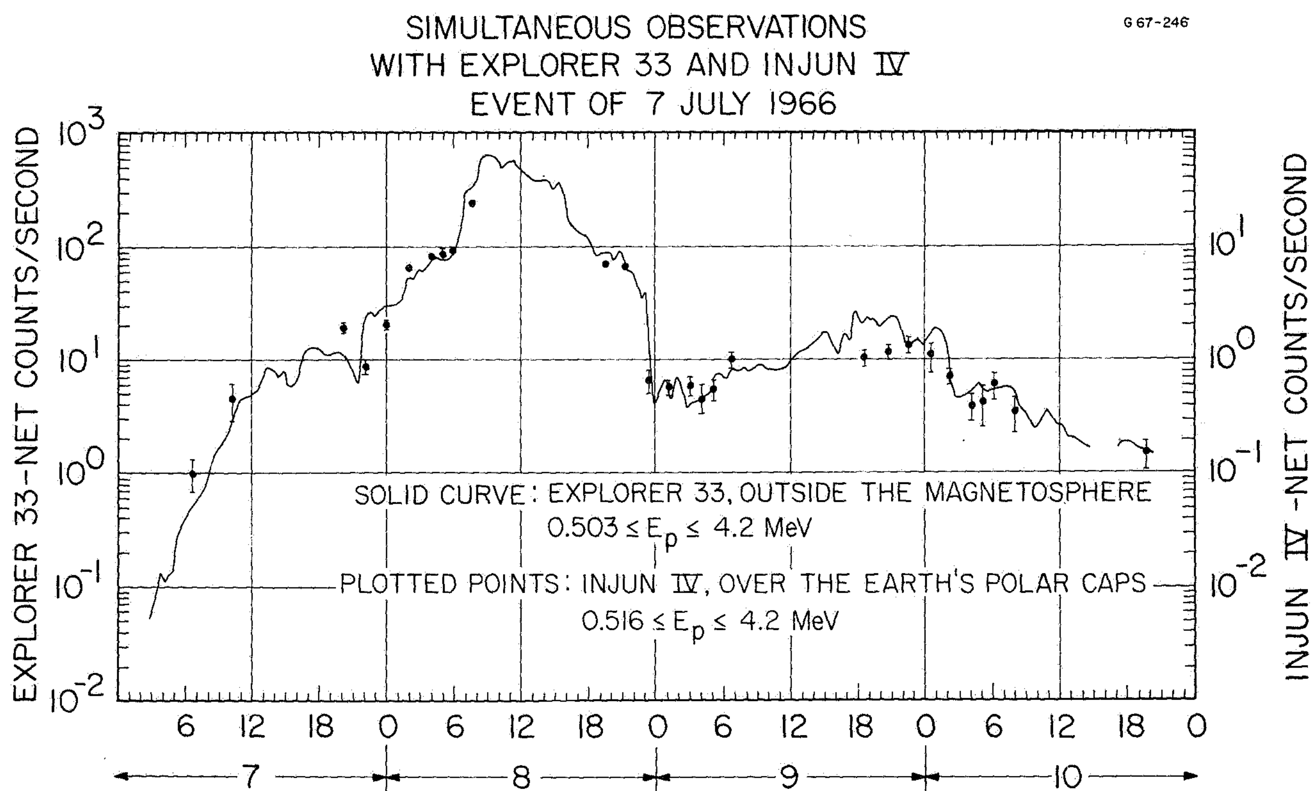


FIGURE 6



G 67-246
SIMULTANEOUS OBSERVATIONS
WITH EXPLORER 33 AND INJUN IV
EVENT OF 7 JULY 1966
EXPLORER 33-NET COUNTS/SECOND
INJUN IV -NET COUNTS/SECOND
SOLID CURVE: EXPLORER 33, OUTSIDE THE MAGNETOSPHERE
0.503 ≤ Ep ≤ 4.2 MeV
PLOTTED POINTS: INJUN IV, OVER THE EARTH'S POLAR CAPS
0.516 ≤ Ep ≤ 4.2 MeV
7
8
9
10

FIGURE 7

G 67-282

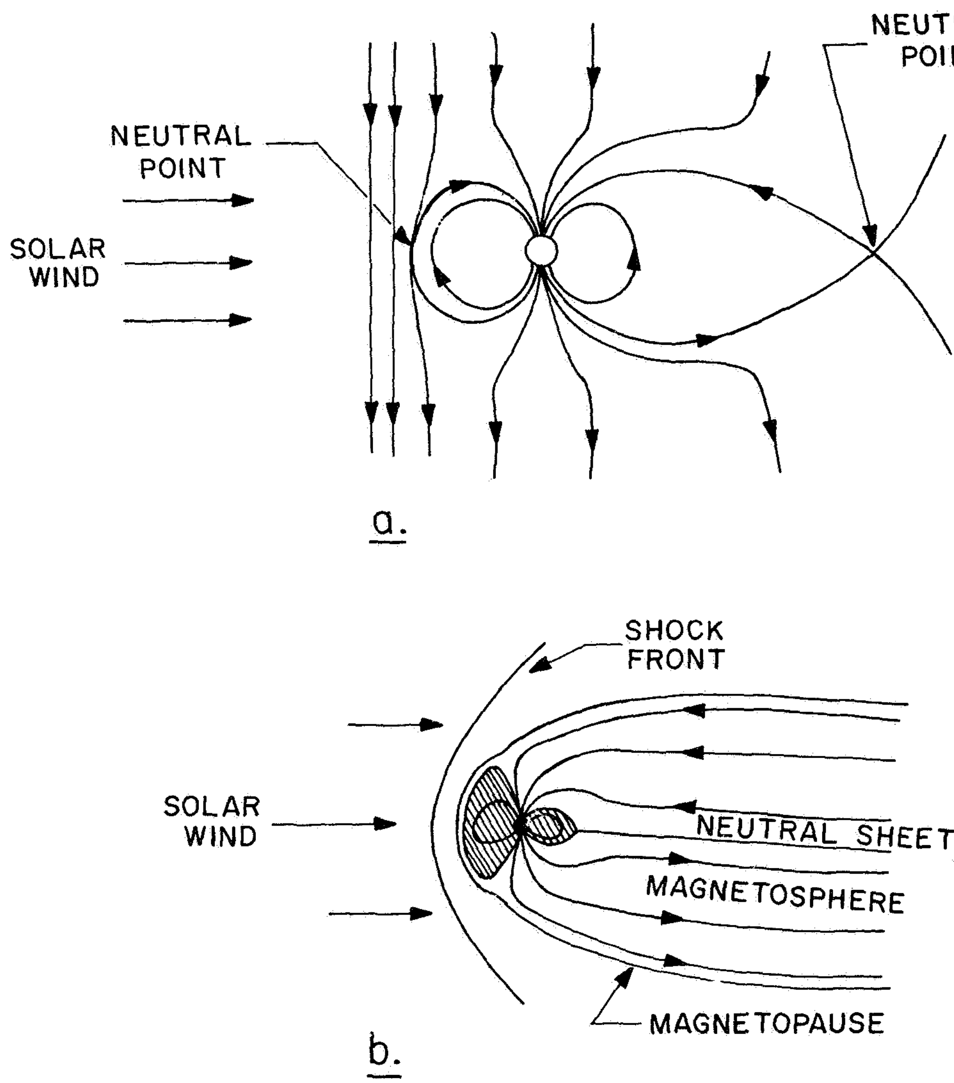


FIGURE 8

UNCLASSIFIED
Security Classification

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Solar Protons						
Simultaneous Observations						
7 July 1966 Event						
Low-Energy Latitude Cut-Off						

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