U. of Iowa 67-51

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Department of Physics and Astronomy

THE UNIVERSITY OF IOWA

Iowa City, Iowa

U. of Iowa 67-51

Observations of Low Energy (~ 0.5 MeV) Trapped Protons with Injun IV

by

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[redacted]

ABSTRACT

The detector complement of the University of Iowa satellite Injun IV, which was launched on 21 November 1964 into a high latitude --low altitude orbit, includes a 25 micron totally depleted surface barrier detector with four discrimination levels, two of which are sensitive to protons in the energy interval $0.52 \leq E_p \lesssim 4$ MeV (channel A) and $0.90 \leq E_p \leq 1.8$ MeV (channel B), and insensitive to electrons of any energy. An analysis of the data for the period 1 March--17 April 1965 has shown the following. (1) Maximum intensities occur at $L \simeq 3.05$ and $|\vec{B}| = 0.16$ gauss of 1.5×10^5 $(cm^2\ sec\ sr)^{-1}$ for A and of 4×10^4 $(cm^2\ sec\ sr)^{-1}$ for B. (2) The intensity maximum moves to higher L values as $|\vec{B}|$ increases. (3) Time variations generally occur for $L \gtrsim 4.5$ and $|\vec{B}| \gtrsim 0.30$, except during major magnetic storms when time variations are observed for $L \gtrsim 2.2$. (4) The energy spectrum may be described by $dj/dE = K/E_o\ e^{-E/E_o}$, with E_o ranging from ~ 0.38 at $L = 2.1$ to 0.13 MeV at $L \approx 4.8$. (5) The boundary is located at $L \sim 5.6$ for protons of $E_p \gtrsim 0.52$ MeV and at $L \sim 4.8$ for $E_p \gtrsim 0.90$ MeV. The data are compared to the model of NAKADA et al. (1965) and found to agree qualitatively with their predictions. Following the 17 April 1965 magnetic storm, the distribution of 0.5 MeV protons became bifurcated with a primary intensity peak at $L \simeq 2.75$ and a secondary one at $L \sim 3.5$.

INTRODUCTION

Since the discovery of the low energy (~ 0.5 MeV) protons trapped in the geomagnetic field by DAVIS and WILLIAMSON (1963) and BAME et al. (1963), several measurements have been reported on the intensities, angular distributions, energy spectra, and time variations of such protons (KATZ, 1965; FILLIUS, 1966; KRIMIGIS and ARMSTRONG, 1966; MIHALOV and WHITE, 1966; ARMSTRONG and KRIMIGIS, 1967). The present investigation extends the measurements to high latitudes (~ 80°) and low L values ($L \gtrsim 1.1$) with data obtained from the University of Iowa polar-orbiting Injun IV satellite. Preliminary data from this experiment have been reported previously (KRIMIGIS and VAN ALLEN, 1965; KRIMIGIS, 1967a, b). In the following, constant intensity contours in $|\vec{B}|$ - L space are presented for protons in the energy intervals $0.52 \leq E_p \leq 4$ MeV and $0.90 \leq E_p \leq 1.8$ MeV. The energy spectrum parameter E_o is computed as a function of L and it is shown that a major departure from the $E_o \propto L^{-3}$ law is found for $L \lesssim 3.5$ at $|\vec{B}| = 0.19$ gauss. The data are compared with those of VERNOV et al. (1967) and MIHALOV and WHITE (1966), at points in $|\vec{B}|$ - L space where the measurements overlap, and are found to agree to within experimental errors. Finally, data are presented on the redistribution of protons in the radiation zones following the 17 April 1965 magnetic storm.

THE DETECTOR

The Injun IV detector relevant to these observations is a totally depleted silicon one of the surface barrier kind in the form of a thin circular disc, whose thickness is 25 microns and whose frontal area is $1.75 \pm 0.2\ mm^2$ (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 $0.21\ mgm/cm^2$ of air equivalent for α-particles, was 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 scheme for energy discrimination is illustrated in Figure 1. It is noted that the maximum energy that an electron may leave in the detector is nominally 60 keV and that it takes seven-fold coincidence of 60 keV electrons to produce a count in channel A. The thin detector, coupled with a double-delay line clipped pulse of 200 nanoseconds full width, renders the detector insensitive to electrons of any

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: Electrons:	$0.516 \leq E_p \lesssim 4^*$ MeV None	From inflight source to 10^6 c/sec
B	0.0064 ± 0.0007	---	Protons: Electrons:	$0.90 \leq E_p \leq 1.8^*$ MeV None	"
C	0.0064 ± 0.0007	---	α-Particles:	$2.09 \leq E_\alpha \leq 15^*$ MeV	"
D	0.0064 ± 0.0007	---	α-Particles:	$3.89 \leq E_\alpha \leq 7^*$ MeV	"
SpB	---	~ 0.4	Protons: Electrons:	$E_p \gtrsim 70$ MeV Insensitive except via bremsstrahlung for $E_e \gtrsim 1$ MeV	From galactic cosmic ray rate of 2 c/s to 2×10^5 c/sec

1* 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.

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

energy. The electron insensitivity and the calibration methods that have been used are identical to those described in detail elsewhere (KRIMIGIS and ARMSTRONG, 1966). Knowledge of the proper operation of the instrument is assured through an inflight ${}_{95}Am^{241}$ source of 5.477-MeV α-particles which was gold plated to obtain a falling spectrum between 0.50 to 3.9 MeV. Thus any change in the detector characteristics and/or drift in the discrimination levels would be immediately noticeable. No such change in the background rate (over the polar caps) by as much as $\pm$ 5% has been observed during the period of the observations on which the present paper is based.

DATA ANALYSIS

The Injun IV satellite 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. 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. Due to a large initial angular velocity at launch and weak damping, magnetic alignment did not occur until the latter part of February

1965. Thereafter, the axis of the detector collimator was maintained continuously perpendicular ($\pm$ 10°) to the local magnetic field vector so that the detector was receiving particles whose pitch angles were 90° $\pm$ 30°. The primary body of data reported in this paper was obtained during the period 1 March to 17 April 1965.

All telemetered data from the satellite are merged with the orbit parameters $|\vec{B}|$, L, and local time and subsequently sorted into subsets specified by selected ranges of $|\vec{B}|$ and L. The L interval used in this study is 0.1 and the $|\vec{B}|$ interval 0.02 gauss. For a given L interval, the directional intensity perpendicular to $\vec{B}$ is plotted as a function of $|\vec{B}|$. From a family of such plots, a graphical display is made of constant intensity contours in $|\vec{B}|$, L space.

OBSERVATIONS

1. Magnetically Quiet Period. Figure 2 shows the counting rate vs invariant latitude Λ in a typical satellite pass for channels A and B. We observe the following: (a) The maximum intensity occurs at $\Lambda \approx 55°$ or L = 3.05 for both channels A and B. (b) The trapping boundary for $0.52 \leq E_p \leq 4$ MeV protons is located at $\Lambda \approx 65°$ (L $\approx$ 5.6) and for $0.90 \leq E_p \leq 1.8$ MeV at $\Lambda \approx 63°$ (L $\approx$ 4.8), at a

magnetic local time of 4.7 hours. (c) The ratio of the counting rates of A to B increases for $\Lambda > 50°$ or $L > 2.5$ and apparently decreases for $L < 2.5$. Revolution 1818 is typical of many such revolutions in the time interval 1 March to 17 April 1965, a period of relatively low magnetic activity. The data from all such satellite passes during the forementioned period have been averaged for a particular $|\vec{B}|$, L group and the resulting plots have been used in constructing constant intensity contours which are shown in Figures 3 and 4.

It can be seen from Figure 3 that the maximum intensity for $0.52 \leq E_p \leq 4$ MeV proton occurs at $L \simeq 3$ at $|\vec{B}| \simeq 0.19$ gauss and that the intensity maximum moves to higher L values as $|\vec{B}|$ increases. It is also observed that in the region bounded by $L \gtrsim 4.5$ and $|\vec{B}| \gtrsim 0.30$ the constant intensity contours show abrupt changes in form with small variations in $|\vec{B}|$ and L. In several cases the intensity is a multiple-valued function of $|\vec{B}|$ for a constant L. The data suggest that this might be a region in which time variations are important. A detailed examination has revealed that the above impression is correct, namely, in a given $|\vec{B}|$,L group where $L \gtrsim 4.5$ and $|\vec{B}| \gtrsim 0.30$ the intensity changes rapidly as a function of time and responds promptly to time variations in the geomagnetic field.

Figure 4 shows constant intensity contours for protons of energy $0.90 \leq E_p \leq 1.8$ MeV. We observe that the general profile is similar to that of the 0.52 MeV protons, with the intensity maximum moving to higher L values as $|\vec{B}|$ increases. It is apparent that at $L \gtrsim 4.5$ and $|\vec{B}| \gtrsim 0.33$ fluctuations in the intensity occur and are probably attributable to time variations in this region.

In Figure 5, a profile in L at a constant value of $|\vec{B}| = 0.19 \pm 0.01$ is shown for both channels A and B; the data are averaged over the period 1 March to 17 April 1965. It is seen that the features of the averaged L profile are essentially identical to those observed in the single pass shown in Figure 2. The intensity of $0.52 \leq E_p \leq 4$ MeV protons varies from ~ 50 $(cm^2 \text{ sec sr})^{-1}$ at $L = 1.15$ to 1.24×10^5 $(cm^2 \text{ sec sr})^{-1}$ at $L = 3.05$, and that of $0.90 \leq E_p \leq 1.8$ MeV varies from ~ 40 $(cm^2 \text{ sec sr})^{-1}$ at $L = 1.25$ to 3.56×10^4 $(cm^2 \text{ sec sr})^{-1}$ at $L = 2.95$. The position of the high latitude boundary is located at $L = 5.7$ and $L = 4.7$ for protons of 0.52 MeV and 0.90 MeV energy, respectively, if we adopt an arbitrary cutoff value of 1 count/sec which corresponds to a flux of 155 $(cm^2 \text{ sec sr})^{-1}$. We note that the ratio A/B has a minimum value at $L \approx 2.15$ and that it increases monotonically at higher and lower values of L. The increase of the ratio below $L = 2.15$ is in no way correlated to the Starfish electrons, since the peak intensity of these electrons is located at an L-value of 1.3 to 1.4, as measured by a 302 G.M. tube on the same satellite. The significance of the change in the ratio A/B will be discussed in a later section.

Finally we observe from Figures 3 and 4 that for $|\vec{B}| \lesssim 0.22$ the L-value at which the maximum intensity occurs does not decrease as $|\vec{B}|$ decreases. This result indicates that the position of the intensity maximum occurs at the same L value at the equator and at high latitudes where $|\vec{B}| \leq 0.20$. Such impression is verified by the observations of KIRMIGIS and ARMSTRONG (1966) and ARMSTRONG and KRIMIGIS (1967), using data from the Mariner IV and Explorer 33 spacecrafts, respectively, taken close to or at the equator with similar detectors.

2. <u>Time Variations</u>. The observations presented so far were obtained during a magnetically quiet period in the course of which the proton intensities at a given point in $|\vec{B}|$,L space were constant to within $\pm$ 10% (except for $L > 4.5$ and $|\vec{B}| \geq 0.30$). On 17 April 1965 there occurred a sudden commencement at 1312 UT followed by a magnetic storm with $\Delta|\vec{B}| \simeq 160$ gamma at the main phase maximum, which took place at ~ 0830 UT on 18 April. The distribution of 0.52 MeV and 0.90 MeV protons was severely disturbed after

the 17th of April. Figure 6 shows four characteristic passes of Injun IV illustrating the change in the distribution. The first pass was taken prior to the sudden commencement, while the second was taken at the time of the main phase maximum; the 3rd and 4th passes were taken two and twelve days, respectively, after the main phase maximum. We observe the following: (a) The boundary moved from its pre-storm value of $L \sim 5.8$ to $L \sim 4$ during the main phase, and back to $L \sim 5.5$ on April 20. (b) The intensity maximum changed from a broad peak centered at $L \simeq 3.0$ to a narrow peak centered at $L \simeq 2.75$, while the intensity at the peak increased by $\sim 50\%$. (c) On 20 April and at $L \sim 3.5$ there is evidence of the presence of a secondary peak which, on 30 April, appears to be a semi-permanent feature of the proton distribution. Analogous behavior was observed for the 0.9 MeV protons, except that the evidence for a secondary peak in the intensity is not convincing. The distribution shown for 30 April persisted until 15 June, at which time another magnetic storm of moderate magnitude ($\Delta |\vec{B}| \simeq 100$ gamma) changed the distribution to one similar to that existing prior to 17 April.

DISCUSSION

1. Comparison with Other Observers. The data presented in the previous sections have been compared to those of VERNOV et al. (1967) and MIHALOV and WHITE (1966). The data of Vernov were taken in February and July 1964 using a solid state detector to measure protons in the interval $0.90 \leq E_p \leq 5.5$ MeV. Those of Mihalov and White were taken in August 1964. Representative points are compared in Table II. It is seen that although the observations were made at different time periods, the agreement is quite good.

2. Energy Spectrum. Figure 7 shows a plot of E_o vs L for the time periods 1 March to 17 April and 25 April--31 May 1965. At the top of the figure is plotted the ratio of A/B from which the values of E_o were derived. We observe that the slope of the ratio undergoes a change in sign at $L \simeq 2.15$ and hence the energy spectrum undergoes a radical change at this value of L. Using the two data channels and making the assumption that the spectrum is falling monotonically in the interval 0.52 to 0.90 MeV, we may compute a value for the parameter E_o in the expression $\frac{dj}{dE} = \frac{K}{E_o} e^{-E/E_o}$. The above assumption is known to be correct for $L \gtrsim 2.1$ (MIHALOV and WHITE, 1966). There are indications, however, that the differential spectrum is rising

Table II

Comparison with Other Measurements

L, $\lvert\vec{B}\rvert$	Vernov et al. (1967)	Mihalov and White (1966)	This Experiment
	$(0.9 \leq E_p \leq 5.5$ MeV$)$	$(0.55 \leq E_p \leq 1.2$ MeV$)$	$(0.9 \leq E_p \leq 1.8$ MeV$)$
2.0, 0.15	5×10^3	---	4.7×10^3
2.0, 0.20	1.5×10^3	---	1.7×10^3
1.8, 0.20	1×10^3	---	0.9×10^3
1.6, 0.15	3×10^3	--	2.3×10^3
3.0, 0.20	---	8×10^4	1.24×10^5 $(0.52 \leq E_p \leq 4$ MeV$)$

in the interval 0.52 to 0.90 MeV with the peak of the spectrum located at 2.5 to 4 MeV for $1.6 \leq L \leq 2.0$ (FILLIUS, 1966; VERNOV et al., 1967). Since the energy passband of the first channel is $0.52 \leq E_p \leq 4$ MeV, we cannot reliably compute a value of E_o for L values in the interval $1.6 \leq L \leq 2$, although it might be possible to derive such values for $L \leq 1.5$ on the assumption that the spectrum is peaked at 4 MeV or higher. With the above limitations in mind, we may now examine the dependence of E_o on L.

a. Pre-Storm Spectrum. We observe that $E_o \propto L^{-3}$ holds in the interval $3.4 \leq L \leq 4.4$ only. The dependence of E_o on L for $L > 4.4$ is reminiscent of the similar behavior observed at the equator with Mariner IV (KRIMIGIS and ARMSTRONG, 1966). It may be connected with the observation that the spectrum is a double exponential described by two different values of E_o (HOFFMAN and BRACKEN, 1965).

For $L < 3.4$ the value of E_o deviates substantially from the $E_o \propto L^{-3}$ dependence. The behavior of E_o in this region may be understood on the basis of the theory of NAKADA et al. (1965). They show that for a given L at the equator, the value of E_o increases as the pitch angle increases, up to 90°. The increase in the value of E_o is quite pronounced at low L values ($L \sim 2$) but is not very important at high L values ($L \sim 4$-5). The data then shows that in the range $3.4 \leq L \leq 4.4$, although we are sampling small equatorial pitch angles ($\alpha_o \sim 10°$), the dependence of E_o on pitch angle is not pronounced and the $E_o \propto L^{-3}$ law holds. At $L < 3.4$ we are observing particles whose equatorial pitch angles vary from $\sim 10°$ at $L \sim 3.4$ to $\sim 30°$ at $L \sim 2$ and hence are sampling regions where the pitch angle dependence of E_o is strong and E_o is expected to decrease.

A further check on this interpretation may be made by observing the dependence of E_o on $|\vec{B}|$. If the theory of NAKADA et al. (1965) is correct, one would expect that at a constant L, E_o would decrease as $|\vec{B}|$ increases, since the equatorial pitch angle of the particle decreases with increasing $|\vec{B}|$. Figure 8 shows a plot of E_o vs $|\vec{B}|$ for $L = 3.05 \pm 0.05$. It is seen that E_o decreases as $|\vec{B}|$ increases to ~ 0.21 but it begins to increase rapidly for $|\vec{B}| > 0.23$. This result is interpreted to mean that at values of $|\vec{B}| \lesssim 0.21$ we are seeing the expected behavior as predicted by NAKADA et al., but for $|\vec{B}| \gtrsim 0.23$ there are important atmospheric effects which cause the spectrum to become harder.

b. Post-Storm Spectrum. Figure 7 also shows the energy spectrum as a function of L for the steady-state proton distribution, following the magnetic storm of 17 April 1965. Several features worthy of note are: (1) The $E_o \propto L^{-3}$ law holds in the interval $2.6 \leq L \leq 4.5$, compared to the interval $3.4 \leq L \leq 4.5$ prior to the storm. (2) The value of E_o is less than its pre-storm value for $3 < L \leq 4.5$, but is higher than the prestorm value in the interval $2.2 \leq L \leq 2.9$, and remains unchanged at $2.9 \lesssim L \leq 3$. (3) The spectrum for $L \lesssim 2.2$ has not changed from its prestorm value. The interpretation of the change in the spectrum must take into account the variation in the intensities of both groups of particles, at 0.52 and 0.90 MeV. Further data show that, although one particle species may have behaved adiabatically in a given $|\vec{B}|$,L interval, another species behaved non-adiabatically in the same $|\vec{B}|$,L interval. Thus it appears that the effects of the storm and the subsequent ring current were, on the whole, non-adiabatic. A detailed study of the data during this storm will be published in a forthcoming paper (BURNS and KRIMIGIS, 1967).

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FIGURE CAPTIONS

Figure 1. ΔE vs E curves for protons and α-particles incident vertically on a 25 micron silicon detector with a 0.21 mg/cm^2 nickel foil in front.

Figure 2. Typical pass of the Injun IV satellite showing the counting rate due to protons in the specified energy intervals. The value of $|\vec{B}|$, magnetic local time, and Universal time are shown at the bottom.

Figure 3. Constant intensity contours for $0.52 \leq E_p \leq 4$ MeV protons.

Figure 4. Same as Figure 3 but for $0.90 \leq E_p \leq 1.8$ MeV protons.

Figure 5. Counting rate profile at constant $|\vec{B}|$ in the indicated energy intervals. Note the change in the spectrum on either side of $L \simeq 2.15$.

Figure 6. Redistribution of trapped protons during and after the 17 April 1965 storm. Evidence for the bifurcated distribution is clear on 20 April. The distribution persisted until 15 June 1965.

Figure 7. Energy spectrum of trapped protons before and after the 17 April 1965 magnetic storm. Values of E_o below $L = 2$ are ambiguous (see text).

Figure 8. Dependence of E_o on $|\vec{B}|$. The effect of the atmosphere is clear for $|\vec{B}| \gtrsim 0.23$.

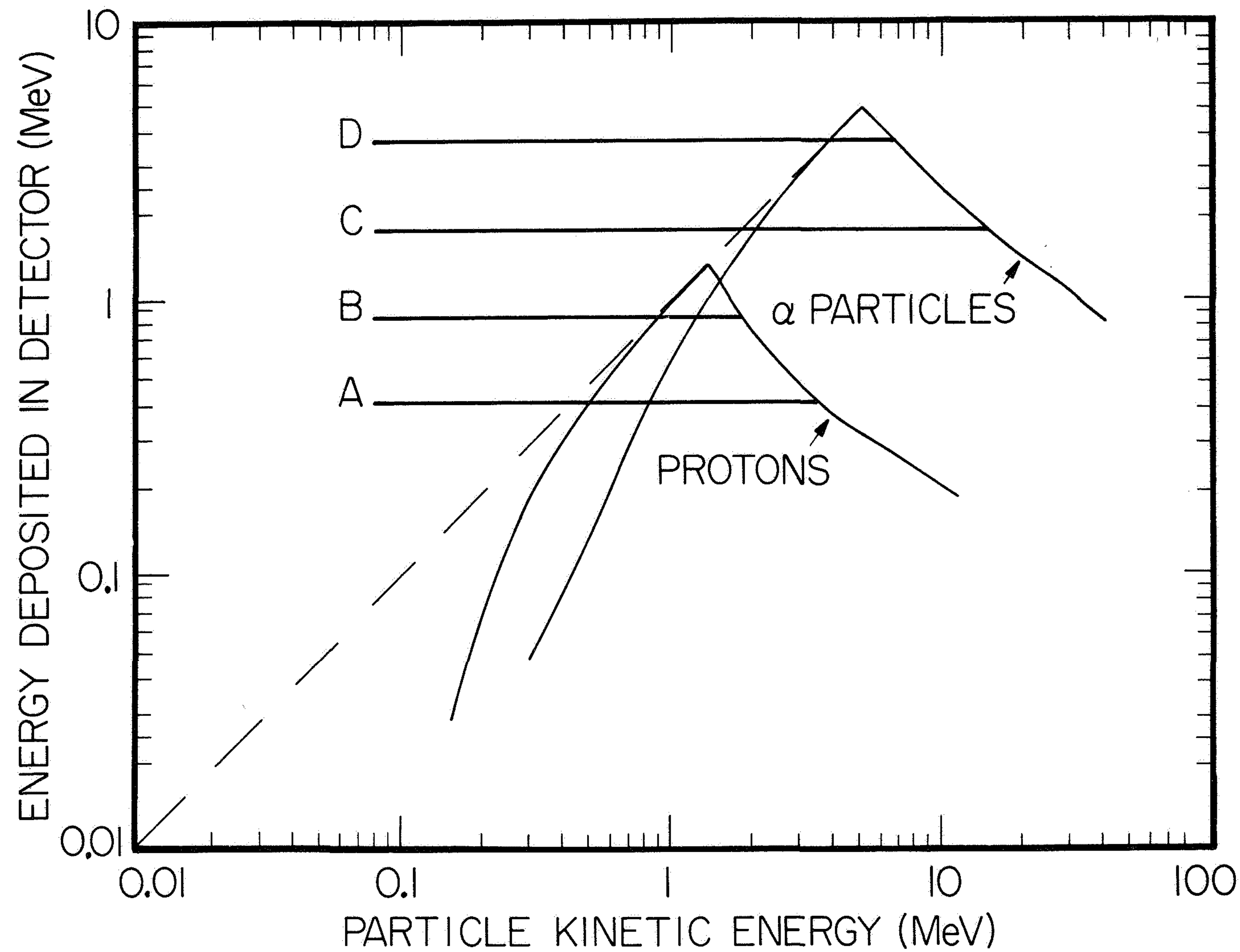
10
1
0.1
0.01
ENERGY DEPOSITED IN DETECTOR (MeV)
D
C
B
A
α PARTICLES
PROTONS
0.01
0.1
1
10
100
PARTICLE KINETIC ENERGY (MeV)

FIGURE 1

G67-328

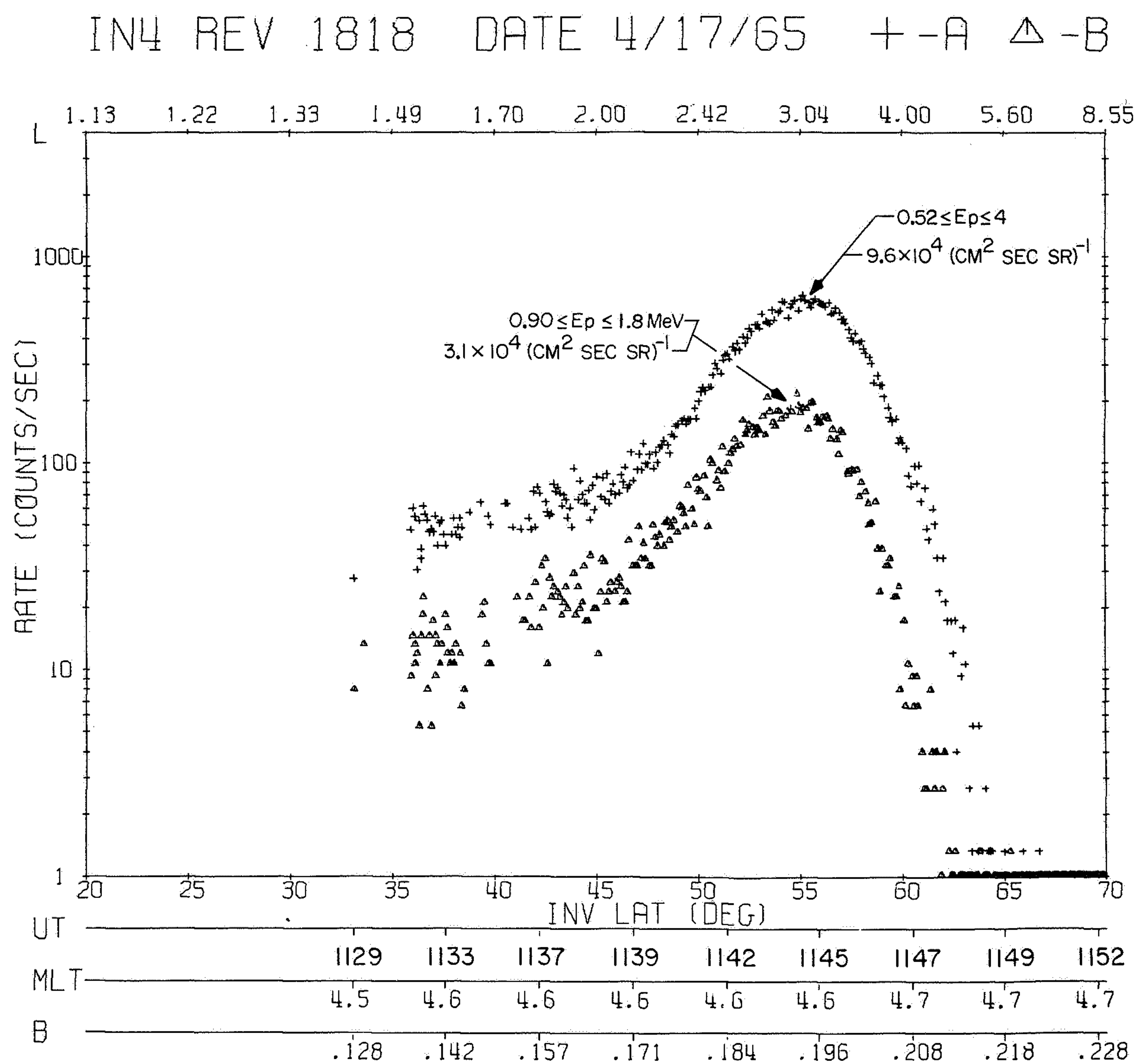

FIGURE 2

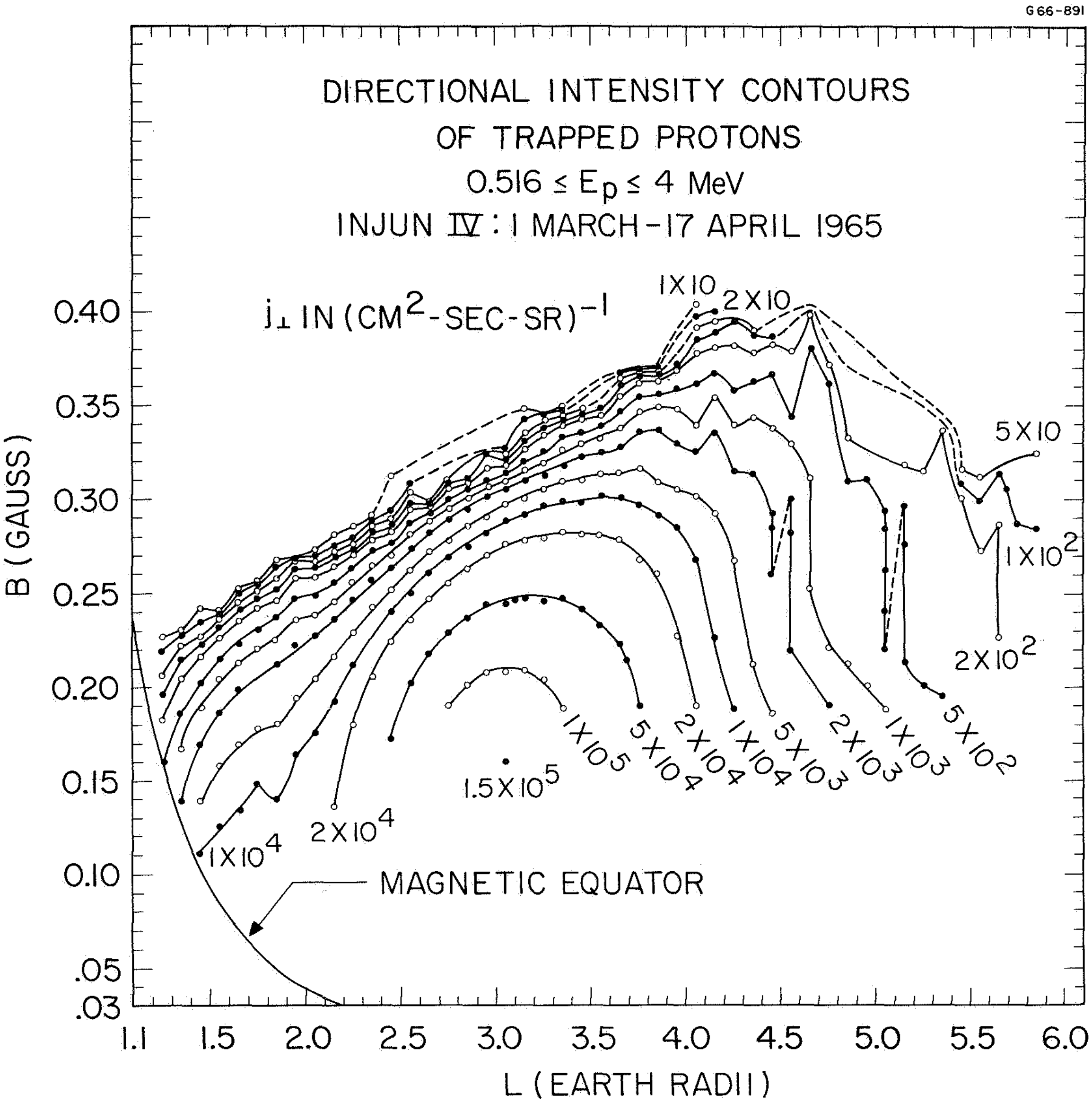
G66-891
DIRECTIONAL INTENSITY CONTOURS
OF TRAPPED PROTONS
0.516 ≤ E_p ≤ 4 MeV
INJUN IV: 1 MARCH-17 APRIL 1965
$j_\perp$ IN $(CM^2\text{-SEC-SR})^{-1}$
1X10
2X10
5X10
1X10^2
2X10^2
5X10^2
1X10^3
2X10^3
5X10^3
1X10^4
2X10^4
5X10^4
1X10^5
1.5X10^5
MAGNETIC EQUATOR
B (GAUSS)
L (EARTH RADII)
0.40
0.35
0.30
0.25
0.20
0.15
0.10
.05
.03
1.1
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0

FIGURE 3

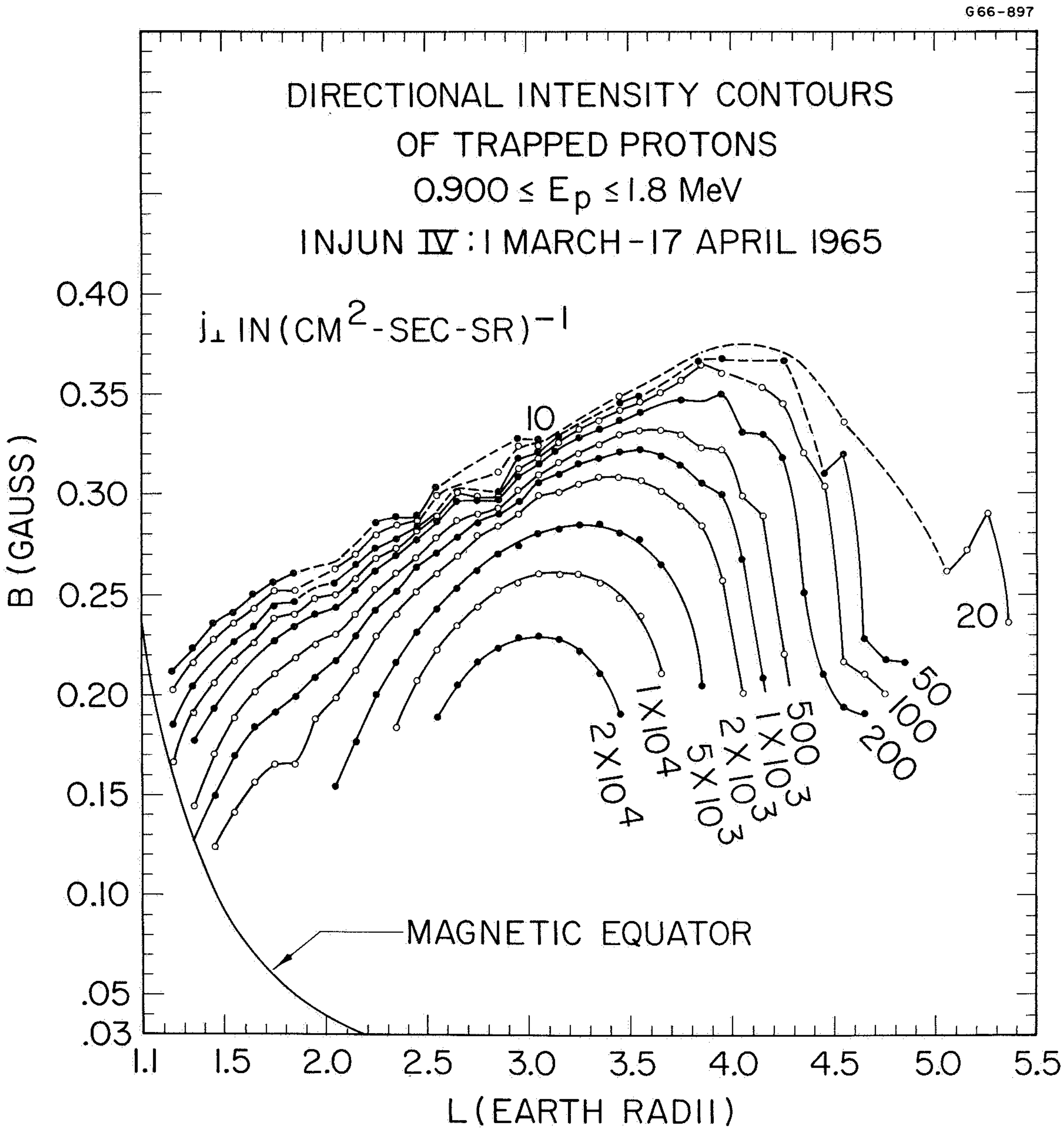
G66-897
DIRECTIONAL INTENSITY CONTOURS
OF TRAPPED PROTONS
0.900 ≤ E_p ≤ 1.8 MeV
INJUN IV: 1 MARCH - 17 APRIL 1965
$j_\perp$ IN $(CM^2\text{-SEC-SR})^{-1}$
B (GAUSS)
0.40
0.35
0.30
0.25
0.20
0.15
0.10
.05
.03
10
20
50
100
200
500
1 X 10^3
2 X 10^3
5 X 10^3
1 X 10^4
2 X 10^4
MAGNETIC EQUATOR
1.1
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
L (EARTH RADII)

FIGURE 4

G 66-877

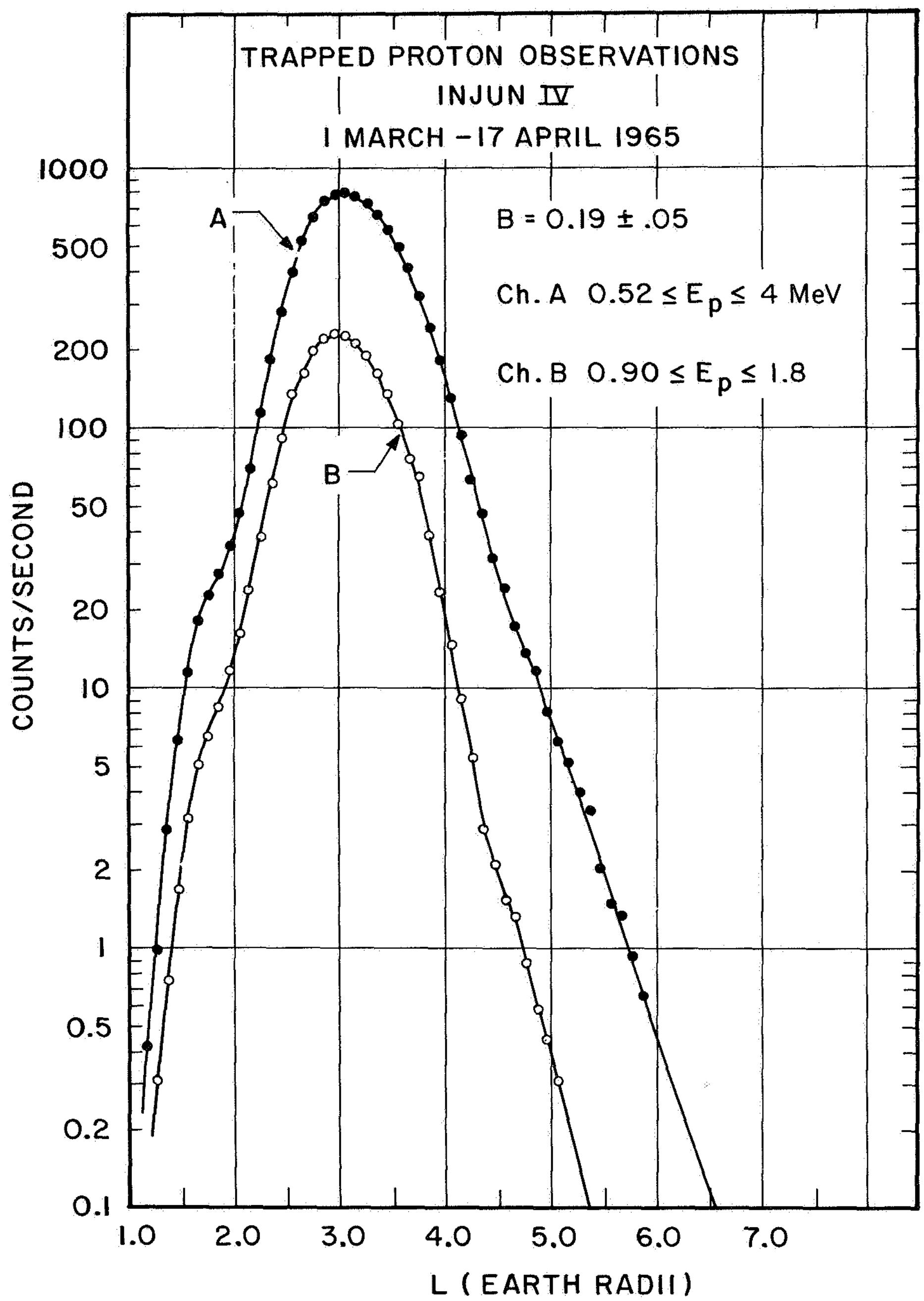

FIGURE 5

G67-312

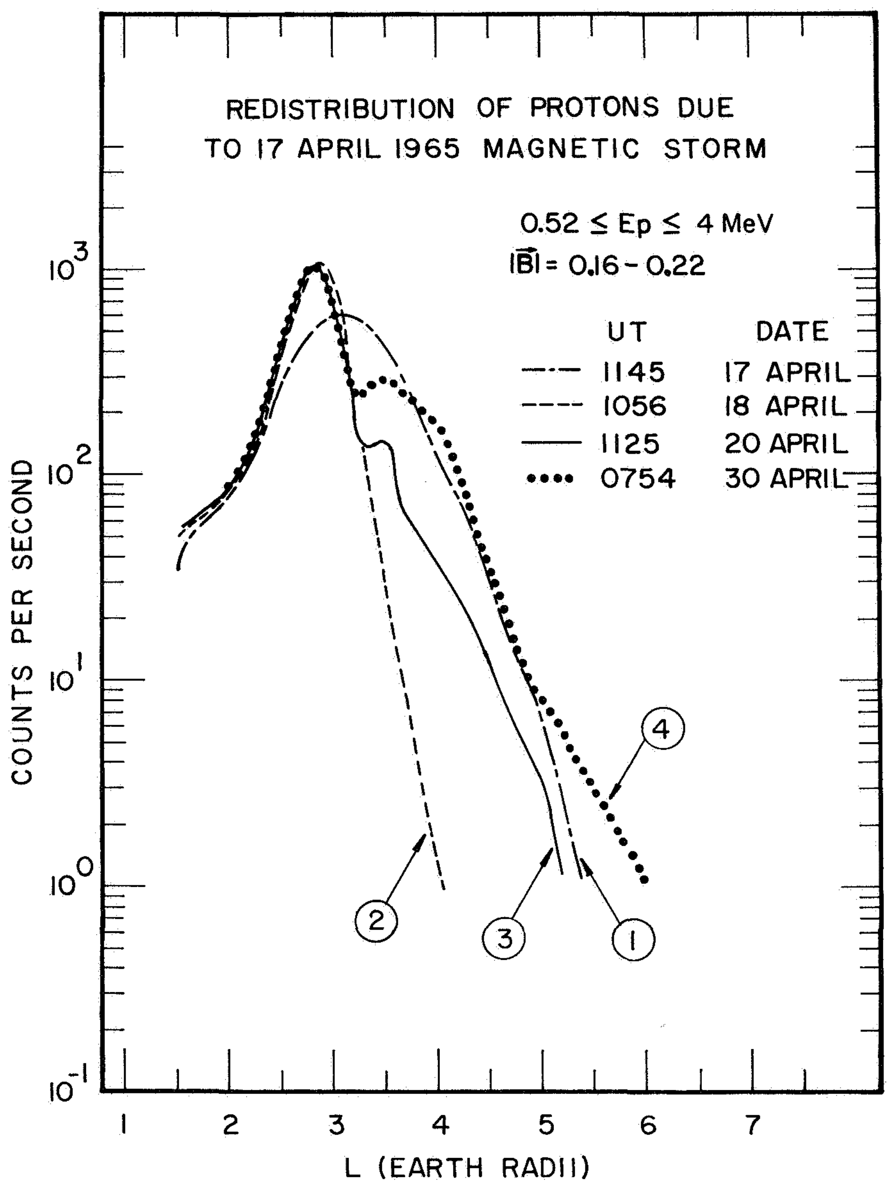

FIGURE 6

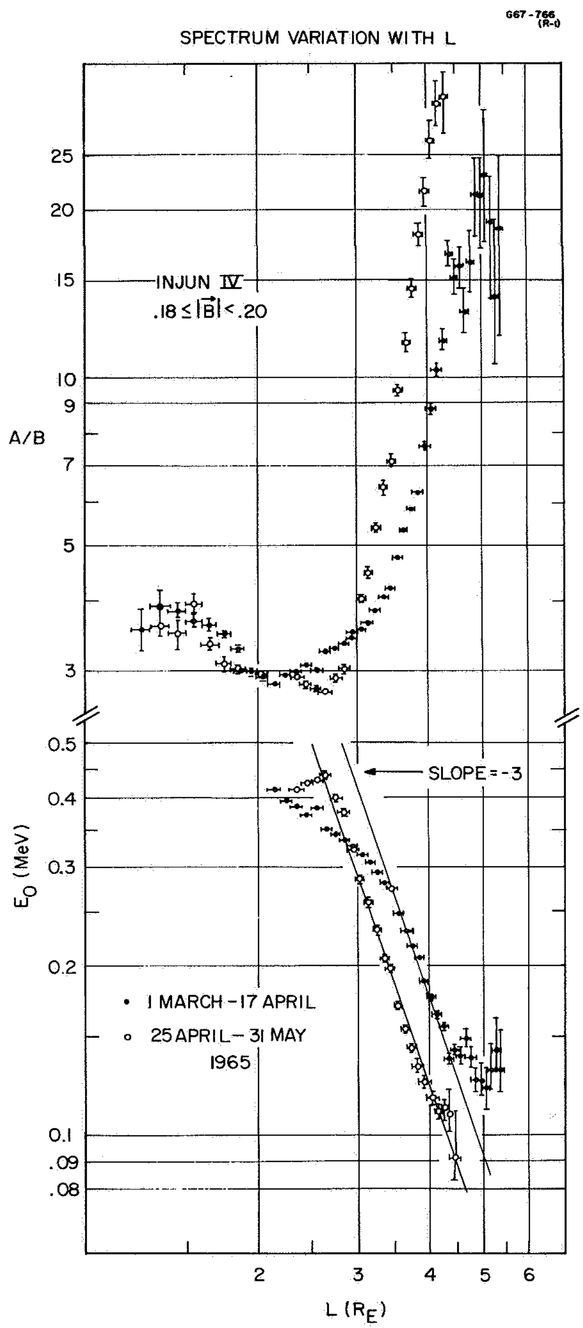
G67-766 (R-I)
SPECTRUM VARIATION WITH L
INJUN IV
.18 ≤ |B| < .20
A/B
SLOPE = -3
E$_O$ (MeV)
• 1 MARCH - 17 APRIL
o 25 APRIL - 31 MAY
1965
L (R$_E$)

FIGURE 7

G66-893

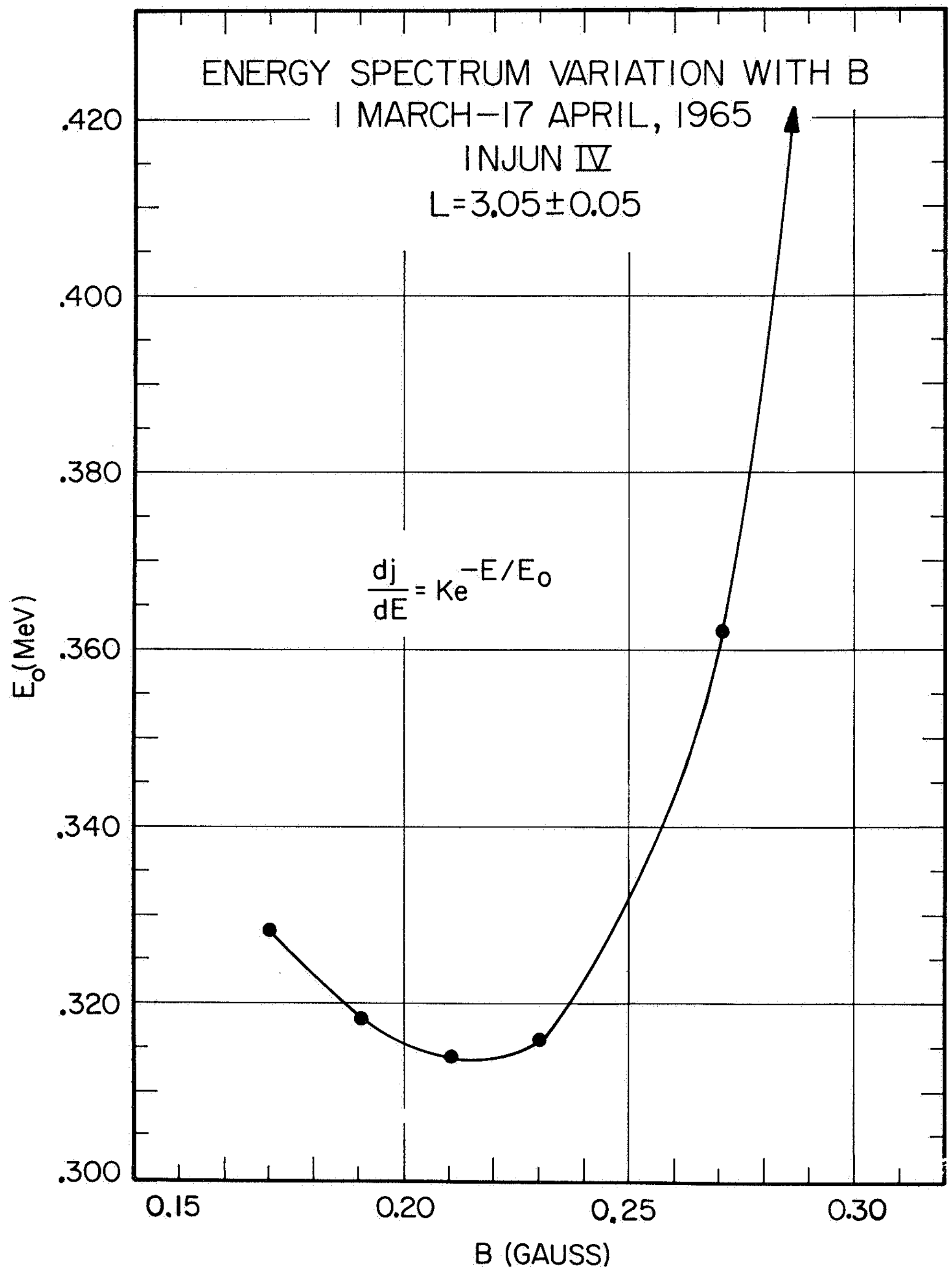

FIGURE 8

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) University of Iowa Department of Physics and Astronomy	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE

Observations of Low Energy (~ 0.5 MeV) Trapped Protons with Injun IV

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Progress July 1967

5. AUTHOR(S) (Last name, first name, initial)

Krimigis, S. M.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
July 1967	29	14

8a. CONTRACT OR GRANT NO. Nonr 1509(06) b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) U. of Iowa 67-51 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. AVAILABILITY/LIMITATION NOTICES

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
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13. ABSTRACT

[See page following]

UNCLASSIFIED
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Trapped Protons						
Radiation Belts						

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