X-612-69-141
PREPRINT

NASA TM X- 63514

PROTON ENTRY INTO THE MAGNETOSPHERE ON MAY 26, 1967

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APRIL 1969

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

FACILITY FORM 602

N69-22805	
(ACCESSION NUMBER)	(THRU)
20	1
(PAGES)	(CODE)
TMX 63514	13
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

Proton Entry into the Magnetosphere
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April, 1969

Abstract

Low energy proton observations over the polar cap and in the interplanetary and magnetosheath regions are compared during May 26, 1967. The results indicate that at this time the entry of low energy solar protons into the magnetosphere was controlled by a diffusion process. It also appears that the protons had access to the entire figure-8 current pattern in the geomagnetic tail and diffused into the two approximately circular cylinders containing the field lines from the northern and southern polar caps. A first approximation value of 10^{15}-10^{16} $cm^2 sec^{-1}$ is obtained for the radial diffusion coefficient, D_{rr}, in the tail. No value can be derived for the diffusion coefficient along the field line, D_{zz}, with the present data. Consequently, in the present case, only a rough upper limit of $L \leq (420\text{-}2400)R_E$ is obtained for the distance to the region where low energy protons are diffused into the tail.

We present evidence in this note that diffusion effects can play a major role in the entry of low energy protons into the magnetosphere. These results also indicate that the entire figure-8 pattern of the geomagnetic tail current system [Axford et al., 1965; Dessler and Juday, 1965] is rapidly exposed to any available solar proton fluxes.

The data of interest are simultaneous proton observations in the interplanetary medium and over the northern polar cap during the solar proton event of May 23, 1967. The interplanetary measurements are from the Explorer 34 satellite and give the intensities of 1-10 Mev protons. The polar cap measurements are from satellite 1963 38C and present the intensities of 1.2-8.5 Mev protons at 1100 km altitude. The local time orientation of both satellites is shown in Figure 1. Data is presented only for times when Explorer 34 was near apogee and statistically significant count rates were observed over the polar cap. This period is indicated by the solid portion of the Explorer 34 orbit in Figure 1.

The time period to be discussed is shown in Figure 2 where both the interplanetary and polar cap proton intensities are plotted. Explorer 34 data are averaged over 15 minutes. The 13 polar cap passes obtained during this period are shown as polar cap averages for invariant latitudes, Λ, greater than 70°. Local times for these passes are also indicated and the passes to be discussed in detail are numbered from one to ten. For reference a plot of D_{ST} values is included in the figure.

In addition we have summarized in Figure 2 the magnetic field configuration external to the magnetosphere at this time. These magnetic field data are from Explorer 33 at ~ 0248 hours local time and at 65 R_E and from Explorer 34 [Fairfield, Behannon, Ness, personal communication; *Behannon et al*., 1968]. During this time the magnetosphere was imbedded in a relatively steady field which changed from strongly southward ($\theta \geqslant -45^\circ$) to strongly northward ($\theta \geqslant 60^\circ$) at ~ 1330 hours.

In spite of an unfortunate gap in the data, Figure 2 indicates that a small increase in the intensity of low energy interplanetary protons began at ~ 0230 hours on May 26. The sequence of five polar cap passes spanning this increase (numbers 1-5) are shown in Figure 3a. The latitude profiles over the polar region are shown along with simultaneous and unnormalized interplanetary fluxes. Figure 3b presents similar data for passes six through 10.

Similarities and discrepancies have been observed previously in comparing the polar cap and interplanetary time histories of low energy proton intensities [*Williams and Bostrom*, 1967; *Krimigis et al*., 1967]. The absolute unnormalized fluxes shown in Figure 2 point out that while general similarities exist between these two regions, significant differences in the respective time histories do occur. In particular it is seen that, a) the ratio of polar cap to interplanetary fluxes varies by a factor of ~ 3 during the period shown, and b) the significant decrease in the interplanetary fluxes occurring at ~ 1120 hours (Figure 2) is not observable over the polar cap except possibly as a slower steady decrease. These features do not support the existence at these times of a readily accessible polar cap region as in an open magnetospheric configuration. They are qualitatively consistent with low energy proton access to the polar cap being controlled by a diffusion process.

These results are further supported when the individual polar cap passes are considered in detail as in Figure 3a where we show a time sequence of five passes (1-5 in Figure 2) obtained during a period in which a slight increase occurred in the interplanetary intensities. Here is clearly seen a time history of polar cap protons which progresses from pass 1 where the intensities tend to increase toward the polar cap, to passes 2, 3, and 4 which show a profile peaked near the auroral regions and having a minimum at the highest latitudes, to pass 5 which shows a distribution much more uniform over all latitudes sampled. Figure 3b continues this polar cap time history (passes 6-10) through an additional small interplanetary increase occurring at ~ 1520 hours (Figure 2).

These data are consistent with diffusion into the geomagnetic tail being the primary mode of entry of low energy protons into the magnetosphere at this time. Such a process has been discussed originally by *Michel* [1965] in considering cosmic ray cutoffs and by *Michel and Dessler* [1965] in considering polar cap absorption inhomogeneities. The general features of the polar cap observations can be explained by the magnetotail configuration shown in Figure 4a,b. A figure-8 tail current system defines two approximately cylindrical surfaces which when coupled with the rotation of the earth contain the field lines connecting to the low latitude edge of the northern and southern polar caps [Dessler and Juday, 1965; Axford et al., 1965]. Diffusion into the tail region should produce polar cap profiles which are initially peaked in the auroral regions and which gradually fill in the high latitude polar cap region in much the same manner as shown in Figure 3. Such profiles are not rare and have been reported previously [Bostrom et al., 1967; Zmuda et al., 1967; Blake et al., 1968].

On the nightside hemisphere the magnetopause field lines for the configuration sketched in Figure 4a connect to the auroral oval. The situation is less clear on the dayside hemisphere particularly near the noon meridian. During average geomagnetic conditions, field lines from the dayside auroral oval do seem to be those passing through the magnetopause neutral region and on back to the tail [Fairfield, 1968]. However, it is difficult to move the latitude of the neutral point to the low latitudes where aurora and low energy solar protons are observed during magnetically active periods. The exposure of these low latitude regions to the tail does seem possible in the nightside hemisphere [Williams and Ness, 1966; Williams, 1967].

A rough estimate of the magnitude of the diffusion coefficient may be obtained by considering diffusion into a long cylinder of radius a, (Figure 4a), which has an initial internal density of zero and in which diffusion is purely radial. Figure 4c presents the solution to this problem by showing the radial density profile for several different times following the application of an external and steady source of strength n_o [Crank, 1957].

The similarity of the radial profiles in Figure 4c to the polar cap profiles of Figure 3 is readily apparent. (Note that $r/a = 0$ corresponds roughly to $\Lambda = \pi/2$ and $r/a = 1$ to the nightside auroral oval.) The ratio of polar cap to auroral oval intensities will be assumed to yield n/n_o, the ratio of internal to external densities, at $r/a = 0$. Figure 4c thus yields the appropriate value of Dt/a^2 from which D can be obtained.

Pass 4 in Figure 3 gives a polar cap to auroral region ratio of $n/n_o \approx 0.4$. From Figure 4c we obtain a value of $Dt/a^2 \sim 0.15$. Due to the gap in the Explorer 34 intensities, the appropriate value of t can only be estimated from Figure 2 as $t \approx 1.5$-5 hours. Using $a = 20\ R_E$ gives $D = 1.4\ (10)^{15} - 4.0\ (10)^{15}\ \text{cm}^2/\text{sec}$. This range of values represents an upper limit to the diffusion coefficient as the polar cap to auroral region ratio contains an unknown background intensity from protons present at the time of the interplanetary increase.

Simple diffusion theory gives the following relation between the diffusion coefficient, the mean free path ℓ, and the particle velocity v,

$$D = \frac{1}{3} \ell v$$

If we consider v to be the actual particle velocity, we obtain for a 1 Mev proton ($v_p \simeq 1.3\ (10)^9 \text{cm sec}^{-1}$) with the above values of D,

$$\ell = 3(10)^6 - 9(10)^6 \text{ cm}$$

This value is approximately 100 times smaller than the gyroradius, ρ, of a 1 Mev proton in a 20 γ field ($\rho \simeq 7(10)^8$cm).

The above value of ℓ is misleading in the sense that it physically applies to radial diffusion (i.e., motion across the field lines) and does not take into account the particle's motion down the field line. However, this small value for the mean free path does indicate the difficulty of motion across field lines for these low energy protons in the tail. This can be seen directly in Figure 3 where a polar cap equilibrium distribution is approached only after several hours following an interplanetary disturbance.

An alternative and equivalent description of this diffusion process in the tail is obtained by assuming for effective scattering from magnetic irregularities, a value of ℓ approximately equal to the gyroradius [Parker, 1964]. This yields an effective radial velocity, $v_r \sim .01\ v_p$ and again indicates that these particles travel along the field lines much easier than across field lines.

While these results show the importance of diffusion in the geomagnetic tail, a more accurate description requires the use of a tensor rather than a scalar diffusion coefficient. However, the principal axes of diffusion are defined by the approximate cylindrical geometry of the tail and only the components D_{rr} and D_{zz} should have to be considered. The present data indicate that as a first approximation $D_{rr} \sim 10^{15} - 10^{16}\ cm^2/sec$ in the region where diffusion is a major transport mechanism. The relative magnitude of D_{zz} depends on the assumptions employed in estimating pitch angle scattering effects.

As the above analysis gives no information about D_{zz}, it can give no accurate estimate on the "length" of the tail, i.e., the distance to the region where particles begin to be diffused into the magnetosphere. However, an order of magnitude upper limit may be obtained by assuming rectilinear motion of the protons down the "length" of the tail to the auroral regions where they first appear. Passes 8 and 10 in Figure 3 occur after proton intensity increases are observed at Explorer 34. The auroral region data of passes 8 and 10 were obtained ~ 40 minutes and 7 minutes respectively from the attainment of maximum fluxes at Explorer 34. Pass 8 shows a peak intensity in the auroral region and thus has responded to the interplanetary increase. Pass 10 shows no such response. Consequently, assuming <u>rectilinear</u> propagation for 1 Mev protons, we obtain an <u>upper limit</u> for the tail length, L, of

$$L \leq (420 - 2400)R_E$$

Evidence for the existence of a geomagnetic tail has been obtained in this range [<u>Ness et al</u>, 1967; <u>Wolfe et al</u>, 1967; <u>Mariani and Ness</u>, 1969]. However, the region of entry for low energy solar protons into the tail may be closer to the earth and in the present case depends on the unknown magnitude of D_{zz}.

The observation by <u>Montgomery and Singer</u> [1969] that low energy solar proton fluxes are much more isotropic within the magnetotail than those outside the magnetopause also supports the existence of a diffusive process acting within the geomagnetic tail. The polar cap proton fluxes shown in Figures 2 and 3, and reported polar cap electron fluxes [Vampola, 1969] are also isotropic outside of the loss cone and are indicative of diffusive processes.

Delayed access of low energy solar protons to the geomagnetic tail has been reported [Kane et al, 1968; Montgomery and Singer, 1969]. The lack of a strong energy dependence in the observed delay times [Montgomery and Singer, 1969] may be evidence against diffusion effects. However, it is not clear that the radial diffusion coefficient should exhibit a pronounced energy dependence in the energy range where the proton gyroradius is much smaller than the radius of the tail (for example, if $\ell \sim$ constant, $D_{rr} \sim \sqrt{E}$).

Vampola [1969] has recently reported observations of energetic electrons over the polar regions which are characterized by a featureless polar cap profile. It is difficult to interpret the electron data at this time in terms of a magnetospheric configuration due to a lack of sufficient simultaneous electron data in the interplanetary medium. Structural effects might be easily missed if electron diffusion could proceed much more rapidly than proton diffusion. Note that the proton profiles become flat and featureless (Passes 5 and 6, Figure 3) as equilibrium is approached.

The rapid access of low energy protons to the entire figure-8 current pattern and resulting diffusion into the cylinders (arrows in Figure 4b) can qualitatively account for the appearance of peak proton intensities in the auroral regions and the latitude spread ($\sim 10^{\circ}$) of this peak. However, it should be noted that such a configuration is unable to quantitatively account for observed low energy proton cutoffs, particularly on the dayside hemisphere.

The ready access of low energy solar protons to 6.6 R_E [Lanzerotti, 1968] may be directly related to their appearance in the neutral sheet. The diffusion effects discussed by Lanzerotti [1968] may in this case be related to diffusion through the "cusp" region and not to radial diffusion through the tail.

In summary we have presented data for a time period in which the entry of low energy protons into the geomagnetic tail and their appearance over the polar regions was governed by a diffusion process. However, as discussed previously [Williams and Bostrom, 1968], the access of these low energy solar protons to the geomagnetic tail and polar cap regions depends strongly upon the magnetospheric configuration, which in turn depends upon the external boundary conditions imposed by the interplanetary medium. We thus expect to observe strong variations in the manner in which low energy solar protons enter the magnetosphere. Immediate access, delayed access, and even a mixed mode [Montgomery and Singer, 1969] are possible at different times.

Of interest is the fact that the present evidence for diffusive effects occurred during a period when a strong southward interplanetary field was present (Figure 2). It thus seems that a southward interplanetary field may not be sufficient cause for immediate access of solar protons into the magnetosphere.

References

Axford, W. I., H. E. Petschek, and G. L. Siscoe, "The tail of the magnetosphere", J. Geophys. Res., 70, 1231-1236, 1965.

Behannon, K. W., D. H. Fairfield, and N. F. Ness, "Trajectories of Explorers 33, 34, and 35, July 1966 - July 1968", Goddard Space Flight Center Report X-616-68-372, September 1968.

Blake, J. B., G. A. Paulikas, and S. C. Freden, "Latitude intensity structure and pitch angle distributions of low energy solar cosmic rays at low altitude", J. Geophys. Res., 73, 4927-4934, 1968.

Bostrom, C. O., J. W. Kohl, and A. J. Zmuda, "The solar proton events of August 29 and September 2, 1966", Trans. Am. Geophys. Union, 48, 178, 1967.

Crank, J., "The mathematics of diffusion", Oxford University Press, 1957.

Dessler, A. J. and R. D. Juday, "Configuration of auroral radiation in space", Planet. Space Sci., 13, 63-72, 1965.

Fairfield, D. H., "Average magnetic field configuration of the outer magnetosphere", J. Geophys. Res., 73, 7329-7338, 1968.

Kane, S. R., J. R. Winckler, and D. J. Hoffman, "Observations of screening of solar cosmic rays by the outer magnetosphere", Planet. Space Sci., 16, 1381-1404, 1968.

Krimigis, S. M., J. A. Van Allen, and T. P. Armstrong, "Simultaneous observations of solar protons inside and outside the magnetosphere", Phys. Rev. Letters, 18, 1204-1207, 1967.

Lanzerotti, L. J., "Penetration of solar protons and alphas to the geomagnetic equator", Phys. Rev. Letters, 21, 929-933, 1967.

Mariani, F. and N. F. Ness, "Observation of a filamentary geomagnetic tail at 500 earth radii by Pioneer 8", Goddard Space Flight Center Report X-616-69-54, 1969.

Michel, F. C., "Effect of magnetospheric tail on cosmic-ray cut-offs" Planet. Space Sci., 13, 753-760, 1965.

References (Continued)

Michel, F. C. and A. J. Dessler, "Physical significance of inhomogeneities in polar cap absorption events", J. Geophys. Res., 70, 4305-4311, 1965.

Montgomery, M. D. and S. Singer, "Penetration of solar energetic protons into the magnetotail", J. Geophys. Res., 74, June 1969.

Ness, N. F., C. S. Scearce, and S. C. Cantarano, "Probably observations of the geomagnetic tail at 10^3 R_E by Pioneer 7", J. Geophys. Res., 72, 3769-3776, 1967.

Parker, E. N., "The scattering of charged particles by magnetic irregularities", J. Geophys. Res., 69, 1755-1758, 1964.

Vampola, A. L., "Energetic electrons at latitudes above the outer-zone cutoff", J. Geophys. Res., 74, 1254-1269, 1969.

Williams, D. J., and N. F. Ness, "Simultaneous trapped electron and magnetic tail field observations", J. Geophys. Res., 71, 5117-5128, 1966.

Williams, D. J., "On the low-altitude trapped electron boundary collapse during magnetic storms", J. Geophys. Res., 72, 1644-1646, 1967.

Williams, D. J. and C. O. Bostrom, "The February 5, 1965 solar proton event. 2. Low energy solar protons and their relation to the magnetosphere", J. Geophys. Res., 72, 4497-4506, 1967.

Wolfe, J. H., R. W. Silva, D. D. McKibbin, and R. H. Mason, "Preliminary observations of a geomagnetic wake at 1000 earth radii", J. Geophys. Res., 72, 4577-4581, 1967.

Zmuda, A. J., J. W. Kohl, and C. O. Bostrom, "The solar proton event of September 2, 1966: day and night latitude profiles", Trans. Am. Geophys. Union, 48, 178, 1967.

Acknowledgements

We gratefully acknowledge the helpful discussions held with Doctors J. F. Arens, D. H. Fairfield, and S. M. Krimigis. We also thank Doctors D. H. Fairfield and N. F. Ness and Mr. K. W. Behannon for the use of magnetic field data from Explorers 33 and 34.

This work was supported in part by the National Aeronautics and Space Administration under DPR No. R21-009-004(021), and in part by the Naval Ordnance Systems Command, Department of the Navy, under contract NOw 62-0604-c.

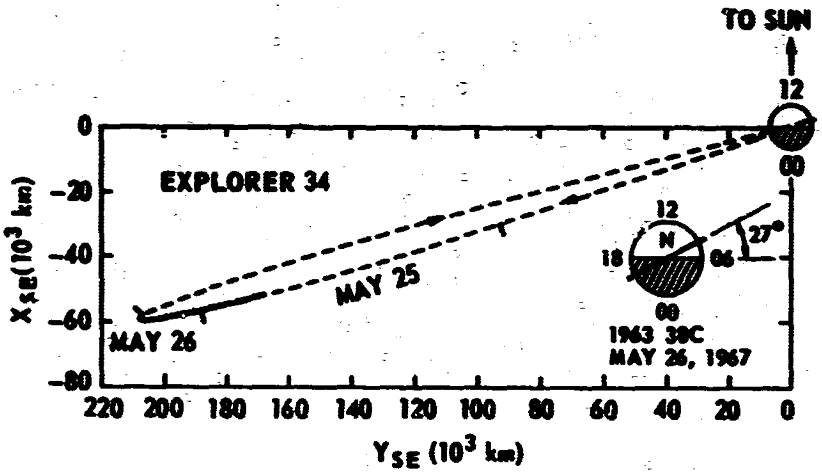
Figure Captions

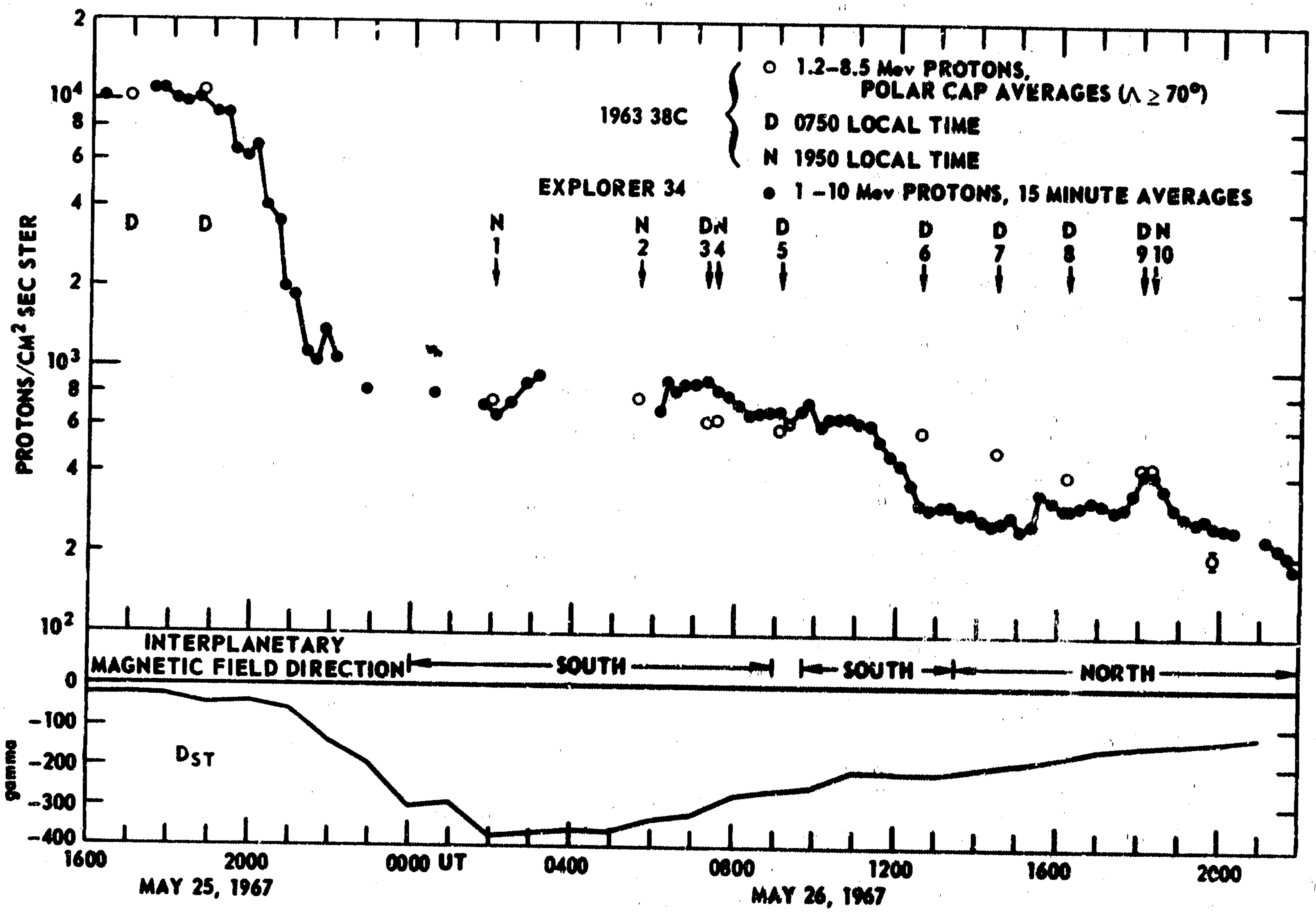
Figure 1: Explorer 34 and 1963 38C orbital data for May 25-27, 1967. Solar ecliptic coordinates shown for Explorer 34 orbit. Period of interest indicated by heavy line.

Figure 2: Time history of 1-10 Mev protons observed at high altitudes ($\geq 28.2\ R_E$) and 1.2-8.5 Mev protons observed at 1100 km over the northern polar cap. The high altitude data are plotted as 15-minute averages and the polar cap data are averages for invariant latitudes $> 70^\circ$. The data shown are absolute and unnormalized fluxes. Orientation of the interplanetary magnetic field with respect to the ecliptic plane is indicated. Numbered polar cap passes are those discussed in detail.

Figure 3: High latitude proton intensity profiles from 1963 38C for (a) passes 1-5 and (b) passes 6-10 from Figure 2. Simultaneous Explorer 34 data shown where available. Flux values are unnormalized. Explorer 34 altitude $\geqslant 32\ R_E$. Error bars show statistical uncertainties.

Figure 4: (a) Sketch of magnetospheric configuration; (b) The current pattern in the tail region (after <u>Axford et al.</u>, 1965, and <u>Dessler and Juday</u>, 1965). Heavy arrows indicate current flow and light arrows indicate proton diffusion; (c) Resulting radial diffusion pattern in a long cylinder of radius a, with initial internal density of zero, following application of an external density, n_o. The internal density distribution, n/n_o, is shown as a function of r/a for various values of Dt/a^2 where D = diffusion coefficient and t = time following application of the external density, n_o. From (a) it can be seen that these radial profiles transform to polar cap latitude profiles in the following approximate way: $r/a = 0$ corresponds to $\Lambda = \pi/2$ and $r/a = 1$ corresponds to the auroral region.


TO SUN
12
00
EXPLORER 34
X_{SE} (10^3 km)
0
-20
-40
-60
-80
MAY 25
MAY 26
12
N
18
06
00
27°
1963 38C
MAY 26, 1967
220
200
180
160
140
120
100
80
60
40
20
0
Y_{SE} (10^3 km)


1963 38C
○ 1.2–8.5 Mev PROTONS, POLAR CAP AVERAGES (Λ ≥ 70°)
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N 1950 LOCAL TIME
EXPLORER 34
● 1 –10 Mev PROTONS, 15 MINUTE AVERAGES
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N 2
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D 5
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D 7
D 8
DN 9 10
PROTONS/CM² SEC STER
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8
6
4
2
10³
8
6
4
2
10²
INTERPLANETARY MAGNETIC FIELD DIRECTION
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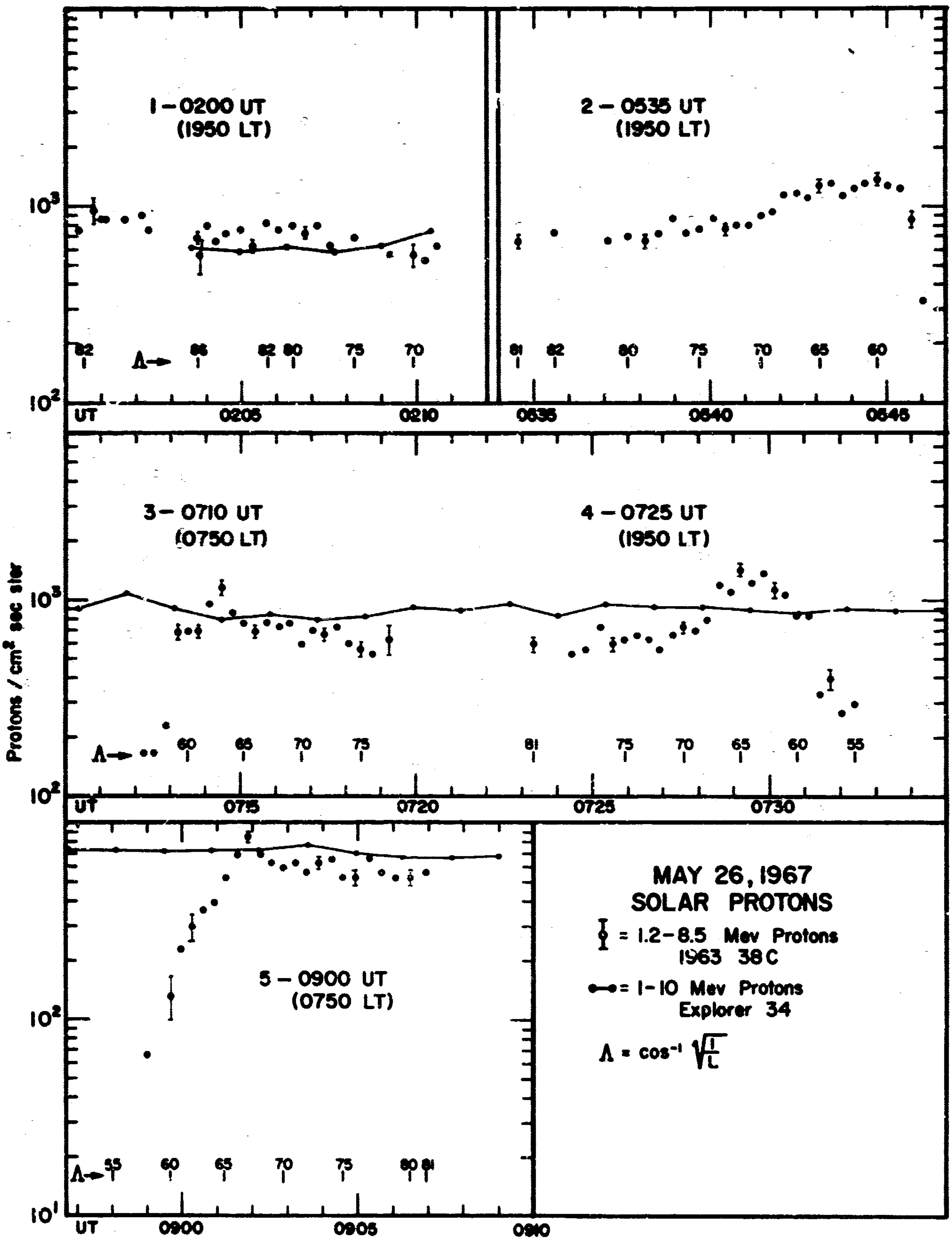
SOUTH
NORTH
DST
gamma
0
–100
–200
–300
–400
1600
2000
0000 UT
0400
0800
1200
1600
2000
MAY 25, 1967
MAY 26, 1967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(1950 LT)
2 – 0535 UT
(1950 LT)
3 – 0710 UT
(0750 LT)
4 – 0725 UT
(1950 LT)
5 – 0900 UT
(0750 LT)
MAY 26, 1967
SOLAR PROTONS
= 1.2-8.5 Mev Protons
1963 38C
= 1-10 Mev Protons
Explorer 34
$\Lambda = \cos^{-1}\sqrt{\frac{1}{L}}$
Protons / cm² sec ster
10^3
10^2
10^1
UT
0205
0210
0535
0540
0545
0715
0720
0725
0730
0900
0905
0910
Λ→
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86
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80
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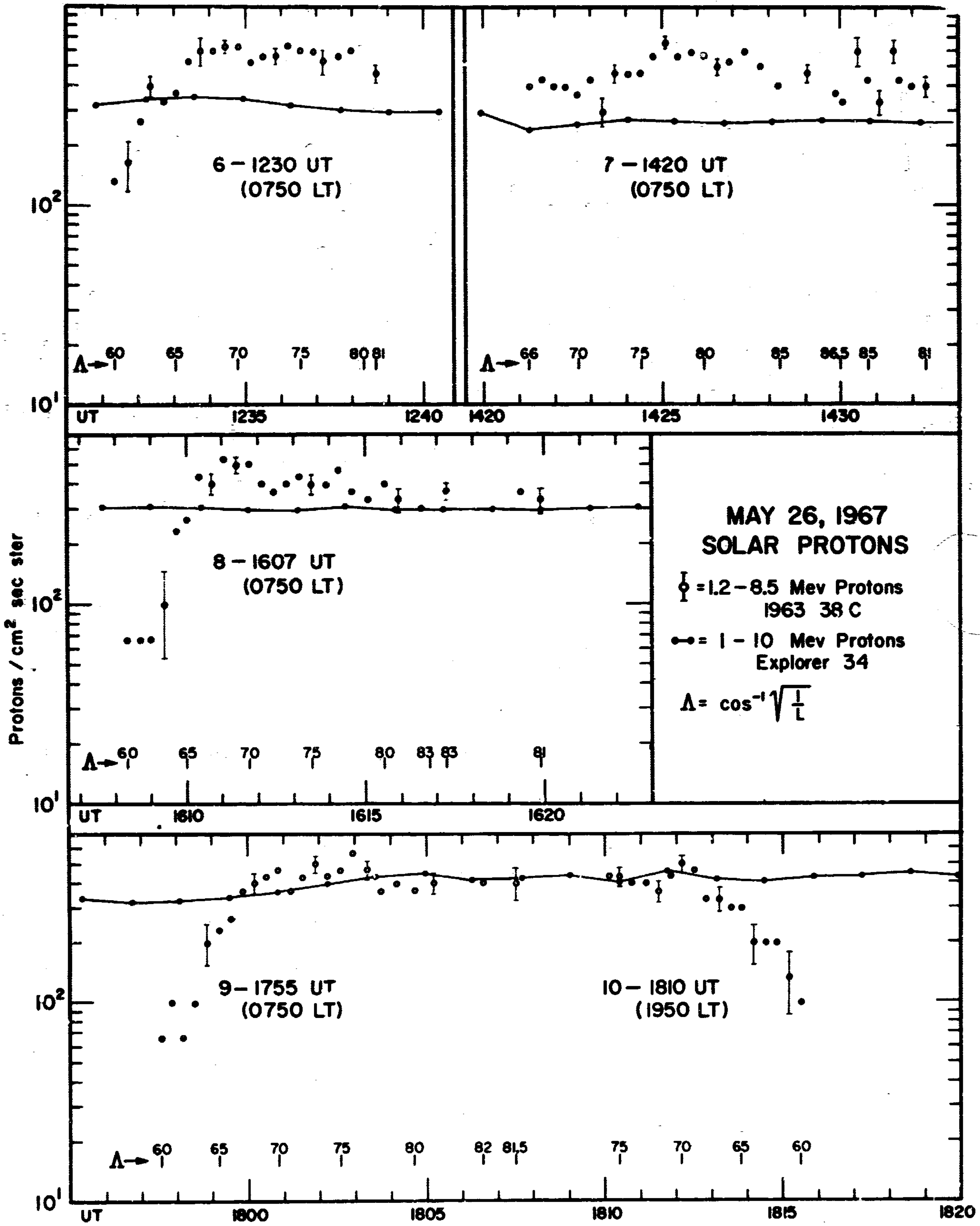
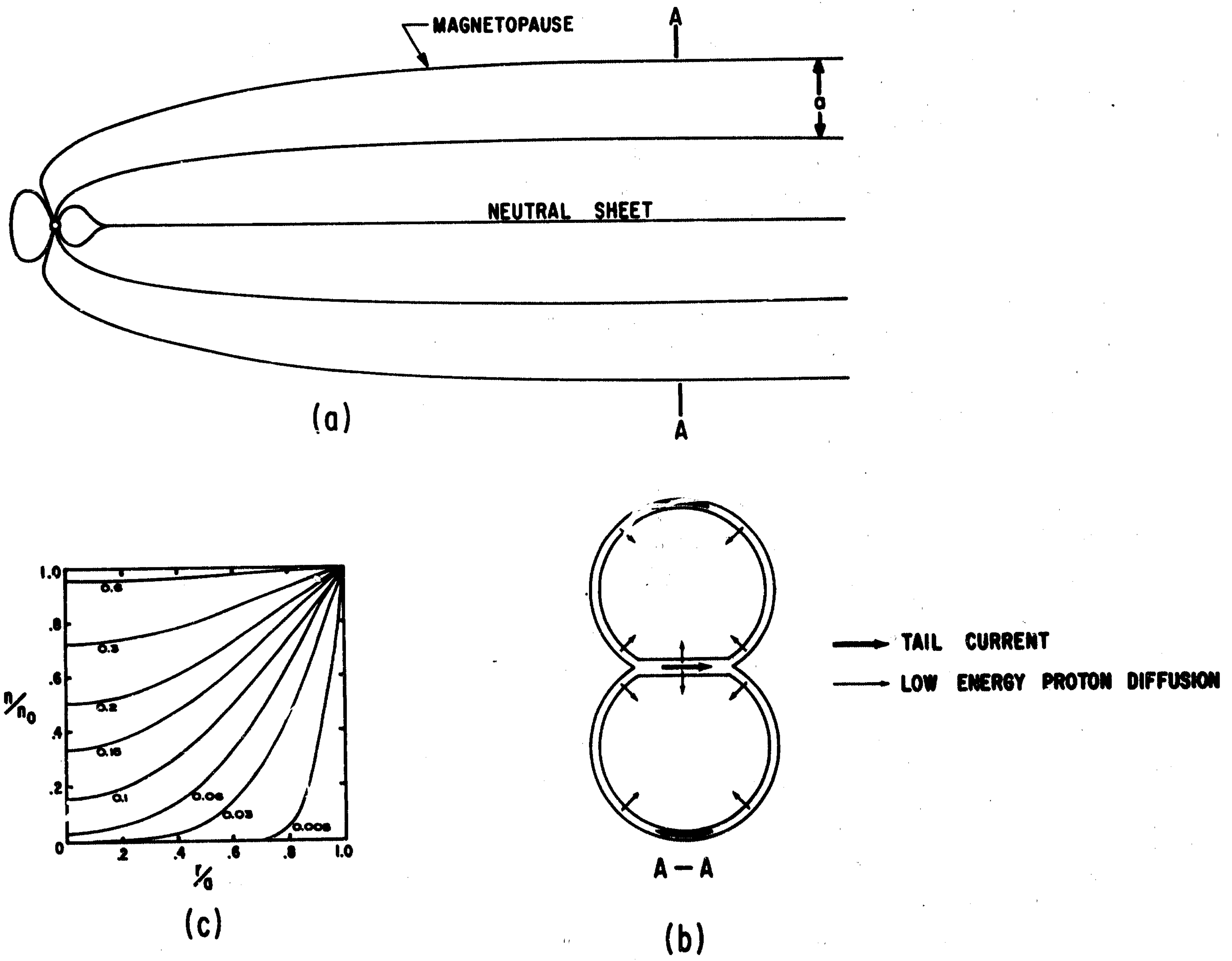
81


MAY 26, 1967
SOLAR PROTONS
= 1.2 – 8.5 Mev Protons 1963 38 C
= 1 – 10 Mev Protons Explorer 34
$\Lambda = \cos^{-1}\sqrt{\frac{1}{L}}$
Protons / cm² sec ster
6 – 1230 UT (0750 LT)
7 – 1420 UT (0750 LT)
8 – 1607 UT (0750 LT)
9 – 1755 UT (0750 LT)
10 – 1810 UT (1950 LT)
10²
10¹
UT
1235
1240
1420
1425
1430
1610
1615
1620
1800
1805
1810
1815
1820
Λ → 60 65 70 75 80 81
Λ → 66 70 75 80 85 86.5 85 81
Λ → 60 65 70 75 80 83 83 81
Λ → 60 65 70 75 80 82 81.5 75 70 65 60


MAGNETOPAUSE
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a
NEUTRAL SHEET
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(a)
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.6
.4
.2
0
n/n₀
0.6
0.3
0.2
0.15
0.1
0.06
0.03
0.008
.2
.4
.6
.8
1.0
r/a
(c)
TAIL CURRENT
LOW ENERGY PROTON DIFFUSION
A — A
(b)