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RING CURRENT PROTON DECAY BY CHARGE EXCHANGE

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ABSTRACT

Explorer 45 (S^3-A) measurements during the recovery phase of a moderate magnetic storm have confirmed that the charge exchange decay mechanism can account for the decay of the storm-time proton ring current. The moderate magnetic storm of 24 February 1972 was selected for study since a symmetric ring current had developed and effects due to asymmetric ring current losses could be eliminated. In this study it was found that after the initial rapid decay of the proton flux, which is a consequence of the dissipation of the asymmetric ring current, the equatorially mirroring protons in the energy range 5-30 keV decayed throughout the L-value range of 3.5 to 5.0 at the charge exchange decay rate calculated by Liemohn (1961). After several days of decay, the proton fluxes reached a lower limit where an apparent equilibrium was maintained, between weak particle source mechanisms and the loss mechanisms, until fresh protons were injected into the ring current region during substorms. While other proton loss mechanisms may also be operating, the results indicate that charge exchange can entirely account for the storm-time proton ring current decay, and that this mechanism must be considered in all studies involving the loss of proton ring current particles.

In studying the complex processes of the proton ring current sources and losses it is important to identify, whenever possible, a single mechanism operating by itself. Various sources and losses such as ion cyclotron resonance, charge exchange, or convective type losses have been described or proposed as occurring during magnetic storms (Frank, 1967; Cornwall, et al., 1970; Russell and Thorne, 1970; McIlwain, 1972; Prölss, 1973; Williams, 1974; Williams and Lyons, 1974; Fritz and Williams, 1975). In this paper we will consider the decay of the proton ring current by charge exchange loss. Previous measurements have been reported in which charge exchange of the ring current protons with neutral hydrogen appeared to be the primary loss mechanism for the tens of keV protons (Frank, 1967; Swisher and Frank, 1968). With the more recent theories and observations pointing to additional mechanisms occurring in the ring current region, it is important to establish the fact that the measurements from Explorer 45 (S^3-A) show that charge exchange must be included as a very basic loss mechanism in the ring current decay process.

The proton ring current during a moderate magnetic storm was selected for study in order to minimize any extreme effects associated with the larger magnetic storms, as shown for example by Hoffman et al., (1975) for the 4-6 August, 1972 storm. The storm under consideration was required to have developed a symmetric ring current in order to eliminate the effects of asymmetric ring current losses. The recovery phase of the storm provides a period where the sources for the ring current protons should be negligible.

In the present paper we examine the charge exchange mechanism as it operates on the ring current protons measured by Explorer 45 (S^3-A) during the recovery phase of the magnetic storm which began on 24 February, 1972. Cahill and Lee (1975) have described some of the Explorer 45 magnetic field observations during this storm and have pointed out that a symmetric ring current had developed at that time. A convection type source mechanism at the beginning of this magnetic storm has been discussed previously (Smith and Hoffman, 1974).

OBSERVATIONS

The hourly values of the equatorial Dst for this storm are shown in Figure 1 (M. Sugiura and D. J. Poros, private communication, 1973). The sudden commencement and main phase of the storm occurred on 24 February, 1972. Following the main phase, Dst recovered fairly gradually for the next several days, but an additional depression in Dst occurred on 28 February, 1972. Selected Explorer 45 orbits which will be discussed later are indicated at the top of the figure. The first five of the six orbits shown are approximately one day apart due to the 7.8 hours orbital period of the spacecraft (Longanecker and Hoffman, 1973). The trajectory of the satellite during this period is shown in Figure 2. Data taken on the outbound leg of the orbits during this storm between L = 3 and L = 5 are pre-dusk, and data on the inbound leg are near 2100h magnetic local time.

The storm-time proton ring current decay at L = 4.25 outbound is shown in Figure 3 for the sequence of differential flux spectra during a four day interval in the recovery phase of this storm. Studies of Explorer 45 proton data have previously shown that the most dynamic energy region of the earth's ring current is from about 10 keV to 100 keV (Smith and Hoffman, 1972; 1973; 1974; Williams, et al., 1973; Fritz, et al., 1974). This fact is substantiated by the spectra in Figure 3.

For the lower energy protons (1 to 5 keV) the fluxes measured on each of the orbits gradually decreased and did so at rather uniform rates. Protons in the energy range (5-30 keV in this case) of maximum storm time enhancement (Smith and Hoffman, 1974) show the most rapid decay, and eventually develop a minimum in the spectrum characteristic of the quiet-time spectrum (Smith, 1973). The high energy protons (>100 keV), which were depleted during the main phase due mostly to adiabatic compression (Williams, 1970), increase in flux during the gradual storm recovery. However, orbit 327 shows a second decrease in flux of these high energy protons in association with the decrease in Dst shown in Figure 1. As we will discuss later a low energy proton enhancement did occur beginning on orbit 325 and was evident at higher L-values.

The proton flux at 25.6 keV had the largest change during this magnetic storm recovery. The flux at near 90^0 pitch angle decreased from about 2.5×10^6 protons/cm^2-sec-ster-keV on orbit 315 to about 2.3×10^5 protons/cm^2-sec-ster-keV on orbit 327. The proton energy density orbital profile in the energy band $22.3<E<30.2$ keV is shown in Figure 4 for each of the six orbits indicated in Figure 1. The proton energy density is computed by integrating the measured proton flux over pitch angle and energy and converting from flux to density. These profiles provide a representation of the L-dependence in this energy band throughout the storm recovery period.

During the main phase (orbit 315) sharp radial gradients were observed just beyond L = 3 outbound and earthward of L = 3.5 inbound, with a maximum near L = 3.5 in each leg of the orbit. The energy density remained fairly constant for the period of time the satellite was beyond L = 4.5. By orbit 318 the maximum in the energy density profile at L = 3.5 was no longer evident. The only significant variations in flux occurred beyond L = 5 outbound where the energy density in this pass band increased by nearly a factor of two. The decay from orbit 318 to orbit 321 and then to orbit 324 was very uniform throughout all L-values for which measurements were possible. As one would expect there does not appear to be any evidence of the spatial distribution of protons with energies of 25 keV receding to higher altitudes and thereby reducing the particle population at a given altitude. The decay does not appear to be strongly L-dependent. A possible exception is the decay between orbits 315 and 318 near L = 3.5, which is most likely the manifestation of the dissipation of the enhanced asymmetric ring current. Orbits 327 and 332 show the remaining evidence at the higher altitudes of the second proton enhancement which was also indicated by the Dst shown in Figure 1.

Decay Mechanism

The following discussion on the energy and L-value dependence of the decay will be restricted to orbits 317 through 325 (below L = 5 outbound) in an effort to consider only the decay process which occurs after a symmetric ring current is formed and in the absence of any significant source functions.

The charge-exchange decay mechanism is examined by comparing the measured proton lifetimes with the lifetimes predicted from charge exchange. The predicted values which were used are the lifetimes calculated by Liemohn (1961) for the ring current altitudes and ring current energies. This reference has been used consistently in previous work (Frank, 1967; Swisher and Frank, 1968; Russell and Thorne, 1970) on the charge exchange question and was therefore selected on the basis of its historical merit. In his calculation Liemohn used the experimentally measured cross section for charge exchange of protons and atomic hydrogen (Fite, et al., 1960) for the ring current energies of interest, thereby determining the energy dependence of the charge exchange mechanism, and he used the hydrogen density model of Johnson and Fish (1960) to estimate the neutral hydrogen environment, thus providing the L-value dependence. The charge exchange lifetimes as measured by Fite, et al. (1960) are shortest in the proton energy range 5-30 keV.

Other calculated values for the predicted charge exchange lifetimes can be easily compared to those by Liemohn. The basic change in these calculations is that they use hydrogen distribution models which have been improved both through theoretical studies and experimental investigations (Prölss, 1973). The work on the neutral hydrogen distribution is by no means static and it is not the intent of this paper to get into the question of these models. The results of these calculations can also be easily compared to the measured proton fluxes.

Explorer 45 c[illegible] taken at L=3.5, 4.25 and 5.0 outbound and L=3.5 inbound are shown in Figures 5a-5d, respectively. The measured proton fluxes for four energy steps, 6.0, 9.2, 13.5, and 25.6keV, are shown at each location. The energies indicated are the center energies of the bands whose widths are approximately ±15% of the center energy. The particle fluxes shown were measured in a pitch angle interval from 79^0 to 90^0, and were all taken within $\pm15^0$ of the magnetic equator. The error bars represent the statistical error in the counting rate. The slopes of the straight lines through the data are determined from the charge exchange lifetimes calculated by Liemohn (1961) for the equatorially mirroring protons at these given energies and L-values.

The agreement between the measured fluxes and the predicted decay rates is overall remarkably good with the best agreement at L=4.25. This means that both the energy and L-value dependence of the measured decay are consistent with the charge exchange decay mechanism. Not only does charge exchange provide a consistent mechanism for the decay of the storm time ring current protons, but in fact the lifetimes predicted from charge exchange are slightly shorter than the observed lifetimes. Thus at these L-values and under the described conditions charge exchange easily accounts for all the proton decay and, therefore, no additional decay mechanisms are required.

The plasmapause locations (N. C. Maynard, private communication, 1974) shown at the bottom of Figure 5 were determined by the DC Electric Field sensor on Explorer 45. The technique for determining the plasmapause from Explorer 45 measurements has been described (Maynard and Cauffman, 1973; Cauffman and Maynard, 1974; Morgan and Maynard, 1975). The location of the plasmapause varied between L=3.2 and 5.4 for these orbits. No significant change in the decay rate of the proton flux appears to be correlated with the plasmapause location. This is as would be expected from pure charge exchange considerations which depend on the neutral hydrogen environment and not the plasma density.

There does exist some scatter of the data points around the predicted decay slope as is particularily evident in the data at L=3.5 inbound (Figure 5d). This is principally the result of two effects. First, there is a systematic variation in the proton flux caused by the change in magnetic latitude of the measurements taken at the same L-value. The magnetic latitude variation for three orbits is shown as a function of L-value in Figure 6. This three-orbit cycle is approximately repeated in time due to the 7.8 hour orbital period of the spacecraft and the 24 hour rotation period of the earth's magnetic field axis. In order to do a proper correction for this latitude effect one must have a detailed understanding of the magnetic field configuration and the pitch angle distribution during this entire time period. The second effect producing a scatter in the data is caused by small substorm injection. An examination of the AE index during this time period revealed several periods of enhancements. A more comprehensive investigation of this effect requires an understanding of detailed substorm timing and of the trajectories of injected particles. Both of these effects do produce a scatter in the data, but do not significantly affect the general decay pattern. Significant particle injections as occurred on February 28, 1972, however, must be considered separately. The effect of small substorm injections is that the proton flux does not appear to decay as fast as is predicted by the decay mechanism.

INTERPRETATION

For this moderate magnetic storm beginning on 24 February, 1972, it is evident, as the data presented in the previous section demonstrates, that the decay of the storm time ring current protons can totally be accounted for by the charge exchange mechanism for 90^0 pitch angle protons in the energy range 5 to 30 keV and in the equatorial plane at L-values from $3.5R_E$ to $5.0R_E$. The understanding of how these observational facts fit in with other supplementary and/or competing mechanisms requires a more definitive study. However, losses of ring current protons by charge exchange with the neutral hydrogen must be included in all such definitive studies if we are to arrive at any consistent representation of the enhancements and decays of protons during magnetic storms.

An interpretation of several additional aspects of this storm is presented in order to place the described mechanism in the proper context of the entire storm process.

The enhancement of the storm-time ring current protons have been shown by Smith and Hoffman (1974) to be consistent with flow patterns resulting from a combination of inward convection, gradient drift and corotation and in that paper they presented data taken during the beginning of this February storm.

The decay after the main phase maximum proceeded in what appears to be a two step process, as shown in the top panel of Figure 7. The measured flux of the 25.6 keV protons taken at L=4.25 outbound is shown for each orbit from 3?5 to 332 for this six day period. At the beginning of the decay there is a rapid decrease in the proton flux lasting less than 1 day, with a crude fit to the data indicating a lifetime of $\tau = 3.8 \times 10^4$ sec. For the next 3 days the decay proceeded steadily but at a much smaller rate. Here the least square fit to the data indicates a lifetime of $\tau = 1.6 \times 10^5$ sec. This lifetime is in excellent agreement with the lifetime of 1.4 x 10^5 sec. calculated by Liemohn (1961) for charge exchange. By 28 February a lower limit to which the flux can decay appears to be reached. This is evidenced by the flattening of the decay slope and the agreement with the flux levels measured during the five day quiet period before the storm which are indicated by the open triangles However, the change in slope at this time could be due to increased enhancement of the protons associated with the second depression in Dst which is shown again in the bottom panel of Figure 7.

A proton enhancement did occur on orbit 325 (Figure 8) with the observation of the enhancement beginning near L=5 outbound. The energy density in the energy band 22.3keV to 30.2keV increased by approximately an order of magnitude near L=5 outbound. This represents a significant event and therefore any discussion on the decay of the ring current must take into account the fact that a new event occurred at this time. As can be seen, however, from Figure 8, the lower altitudes on the outbound leg of this orbit do not appear to be affected, and are therefore included in the data presented in the previous section.

The picture which has evolved from the ring current particle measurements made during this storm is that the enhancement of the magnetic storm time protons is due to an injection process. The initial rapid decay of the proton flux in the dusk hours after the main phase maximum is probably a consequence of the dissipation of the asymmetric ring current. Whether ion cyclotron resonance interactions contribute significantly to this initial rapid decay, as theoretical work on this mechanism has suggested, (Cornwall, et al., 1970) has not as yet been demonstrated, although some observations of ion cyclotron waves measured by Explorer 45 during magnetic storms have been reported (Taylor, et al., 1975). In the second slower decay phase, as we have shown in this paper, charge exchange appears as the dominant decay mechanism for the near-equatorially mirroring protons. The situation with the off-90^0 pitch angle protons is more involved. First, these protons do not appear to decay as rapidly as the charge exchange decay would predict and therefore suggest fresh substorm injections (Smith, 1974), which complicate the analysis. Second, Williams (1974) and Williams and Lyons (1974) have described the evolution of the changes in the pitch angle distributions during the recovery phase of a large magnetic storm in terms of the ion cyclotron instability. The manner in which the ion cyclotron instability, the charge exchange decay and the electrostatic loss-cone instability (Coroniti, et al., 1972) collectively explain the Explorer 45 observations is a topic for further investigation. Fritz and Williams (1975) in a review paper have identified the important aspects pertaining to this problem of understanding the particle and wave observations during magnetic storms. In addition, the question of particle sources either from (1) substorm injection, (2) inward radial diffusion, and/or (3) outward flow from the ionosphere needs to be considered further for completing this overall picture. The contribution from the results presented in this paper is that charge exchange is a very basic background phenomena which must be considered in all studies involving ring current particles. Not only is this charge exchange mechanism constantly operating but it can account for the major energy loss from the ring current.

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FIGURE CAPTIONS

Figure 1. Dst from February 23, 1972 to March 1, 1972 showing the magnetic storm on February 24, 1972. The number and duration of several Explorer 45 orbits are indicated. The orbital period is approximately 7.8 hours.

Figure 2. Explorer 45 (S^3-A) orbit trajectory in L vs. MLT coordinates for the equatorial orbit 315. This trajectory is nearly identical for all the orbits during this storm period.

Figure 3. Differential proton flux spectra for 90^0 pitch angle particles at L=4.25 for four orbits associated with the recovery of the magnetic storm which occurred on February 24, 1972.

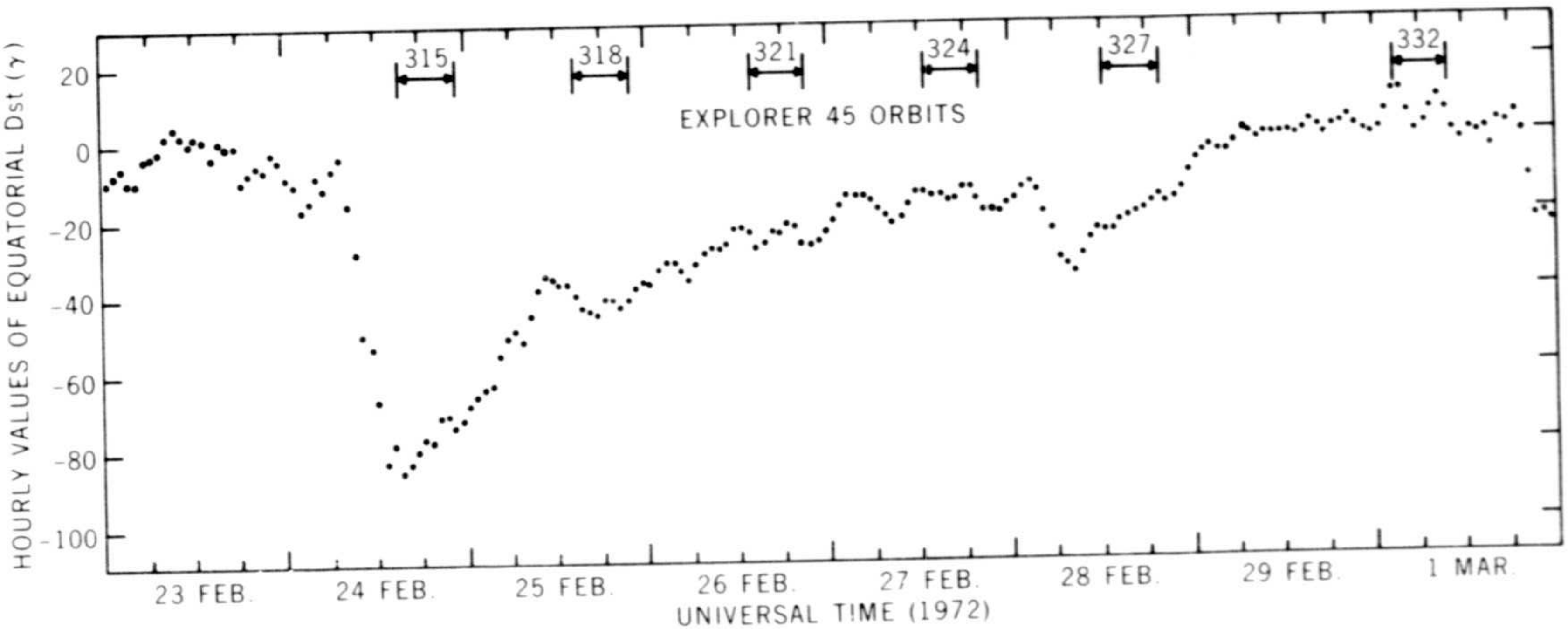
Figure 4. Proton energy density orbital profiles (in ergs/cm^3) in the energy band 22.3 keV $<$ E $<$ 30.2 keV for the six Explorer 45 orbits indicated.

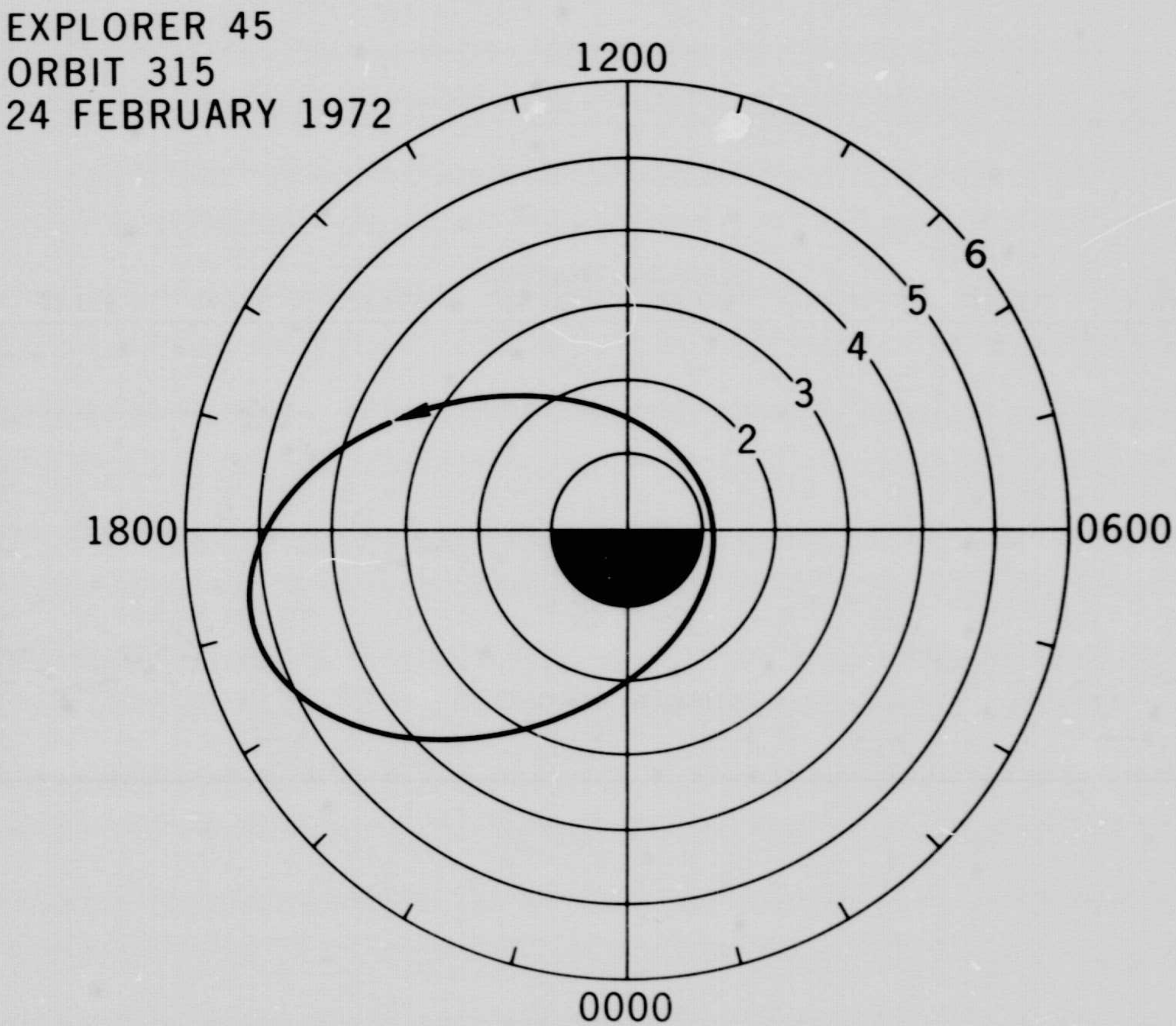
Figure 5. Proton flux decay for locally mirroring particles at the four L-values (L=3.5 outbound, 4.25, 5.0 and 3.5 inbound). Figure 2 indicates the local time of these near equatorical measurements. Fluxes measured at four energies for 6.0 to 25.6 keV are shown for orbits 317 to 325. The solid lines have the charge exchange decay slopes (Liemohn, 1961) for the indicated L-values, energies and pitch angle. The plasmapause locations at the bottom of the figure were determined by the DC Electric Field sensor on Explorer 45 and the L-values indicated are for the outbound leg of the orbit.

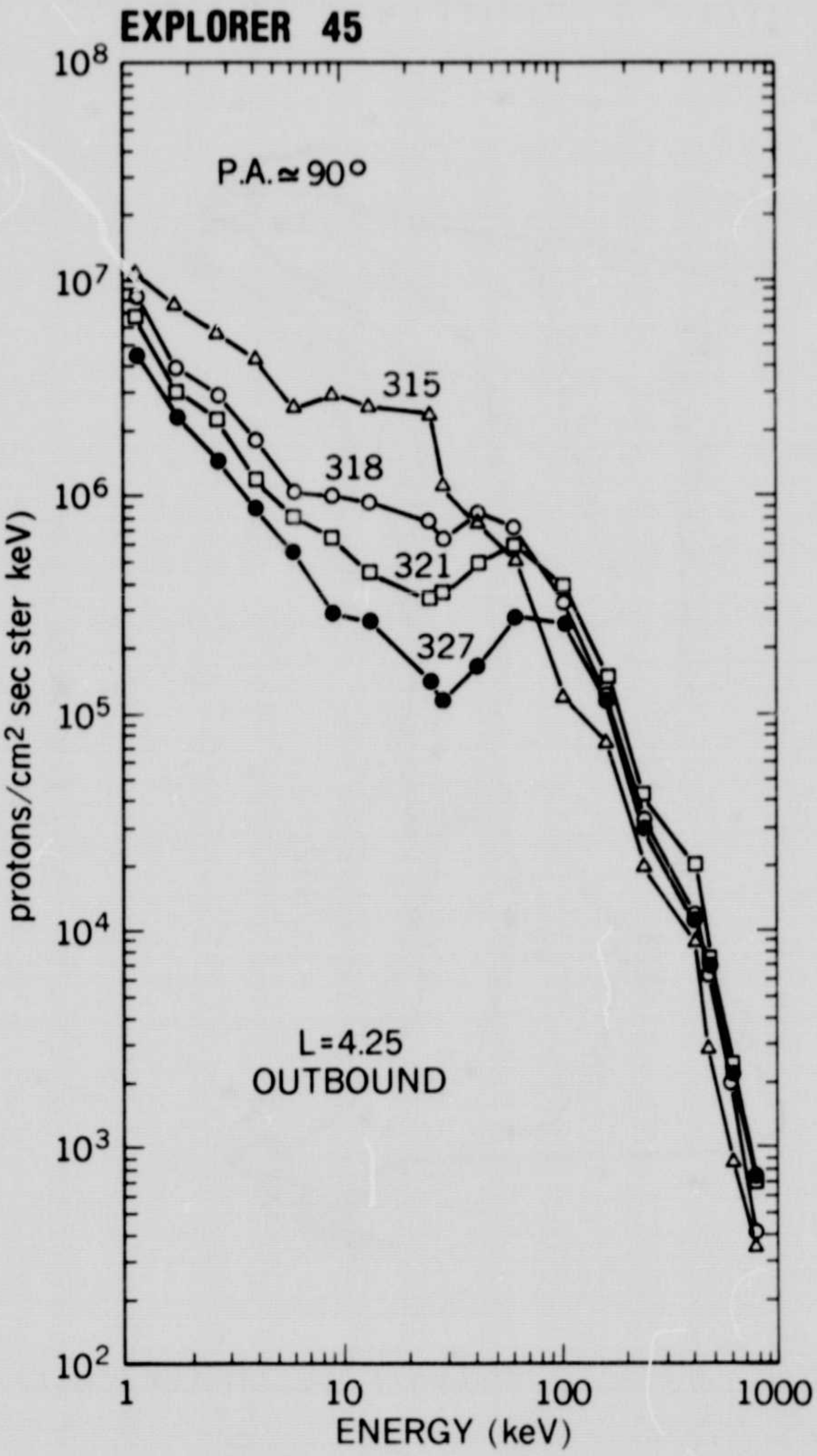
Figure 6. Magnetic latitude variation as a function of L-value for three Explorer 45 orbits. These variations are representative of the three orbit cycles in magnetic coordinates experienced by the satellite.

Figure 7. Flux decay near dusk at L=4.25 for the locally mirroring 25.6 keV protons. The solid lines indicate least square fits to the data points through which the lines are drawn. (Orbit 330 on 29 February is not shown due to the unavailability of data at the time of this writing). The open circles (the time scale is shifted by six and a half days) indicate flux values measured prior to the sudden commencement of this storm and may therefore indicate a steady-state flux level. Dst for the six day storm recovery period, a subset of the data shown in Figure 1, is shown at the bottom of the figure.

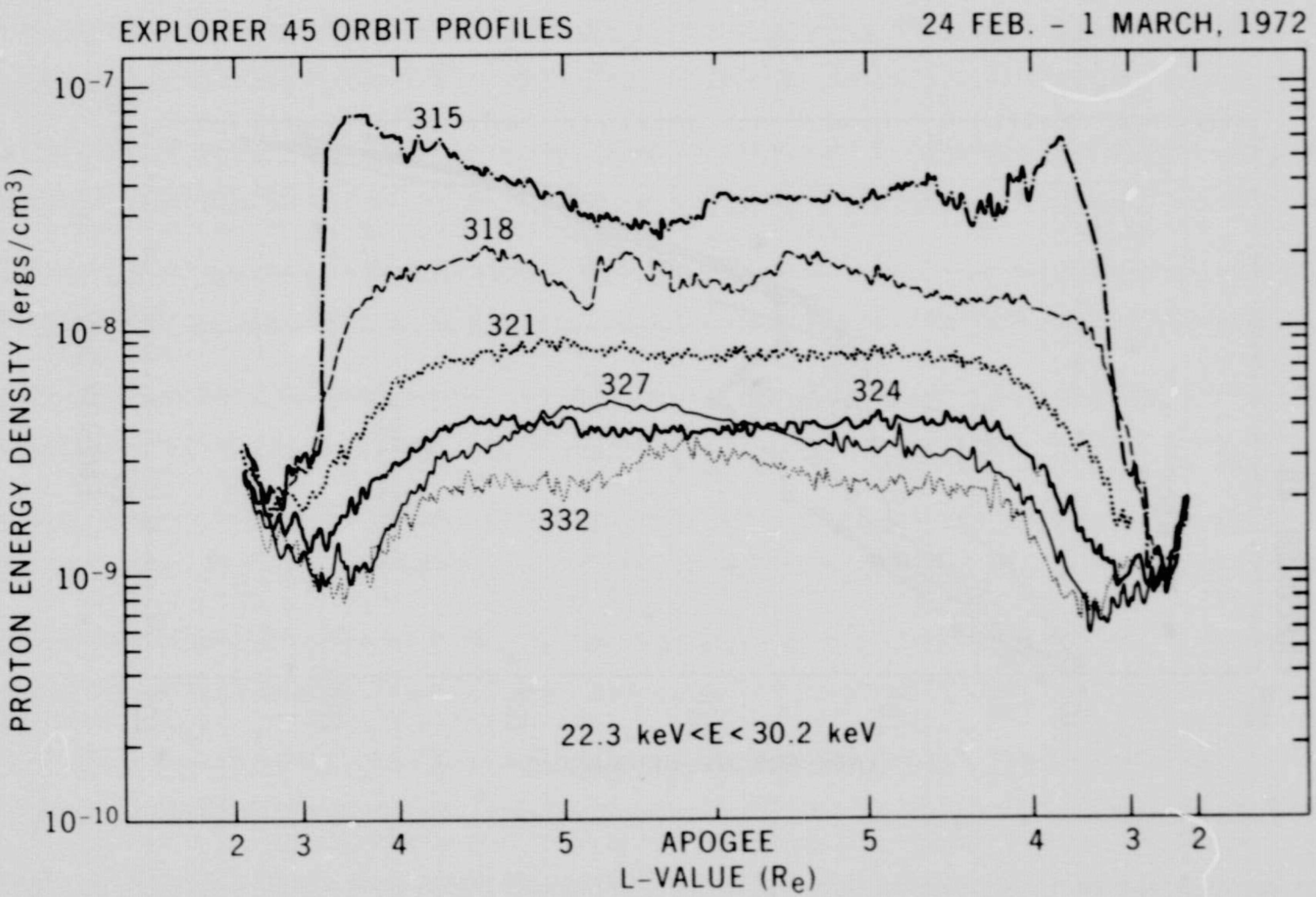
Figure 8. Energy density orbital profile for orbit 325 for protons in the energy range $22.3 < E < 30.2$ keV.


315
318
321
324
327
332
EXPLORER 45 ORBITS
HOURLY VALUES OF EQUATORIAL Dst (γ)
20
0
-20
-40
-60
-80
-100
23 FEB.
24 FEB.
25 FEB.
26 FEB.
27 FEB.
28 FEB.
29 FEB.
1 MAR.
UNIVERSAL TIME (1972)

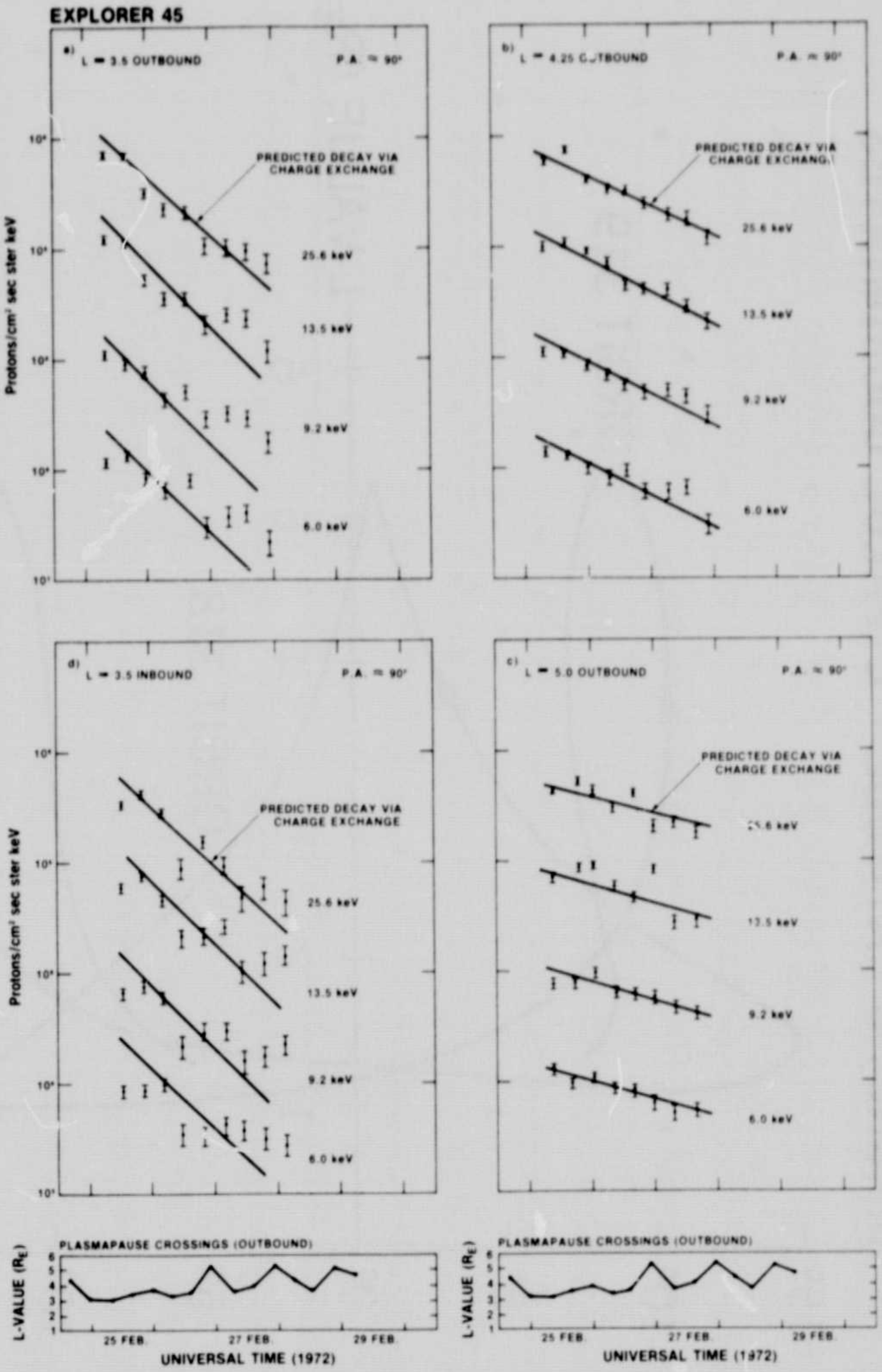

EXPLORER 45
ORBIT 315
24 FEBRUARY 1972
1200
1800
0600
0000
2
3
4
5
6



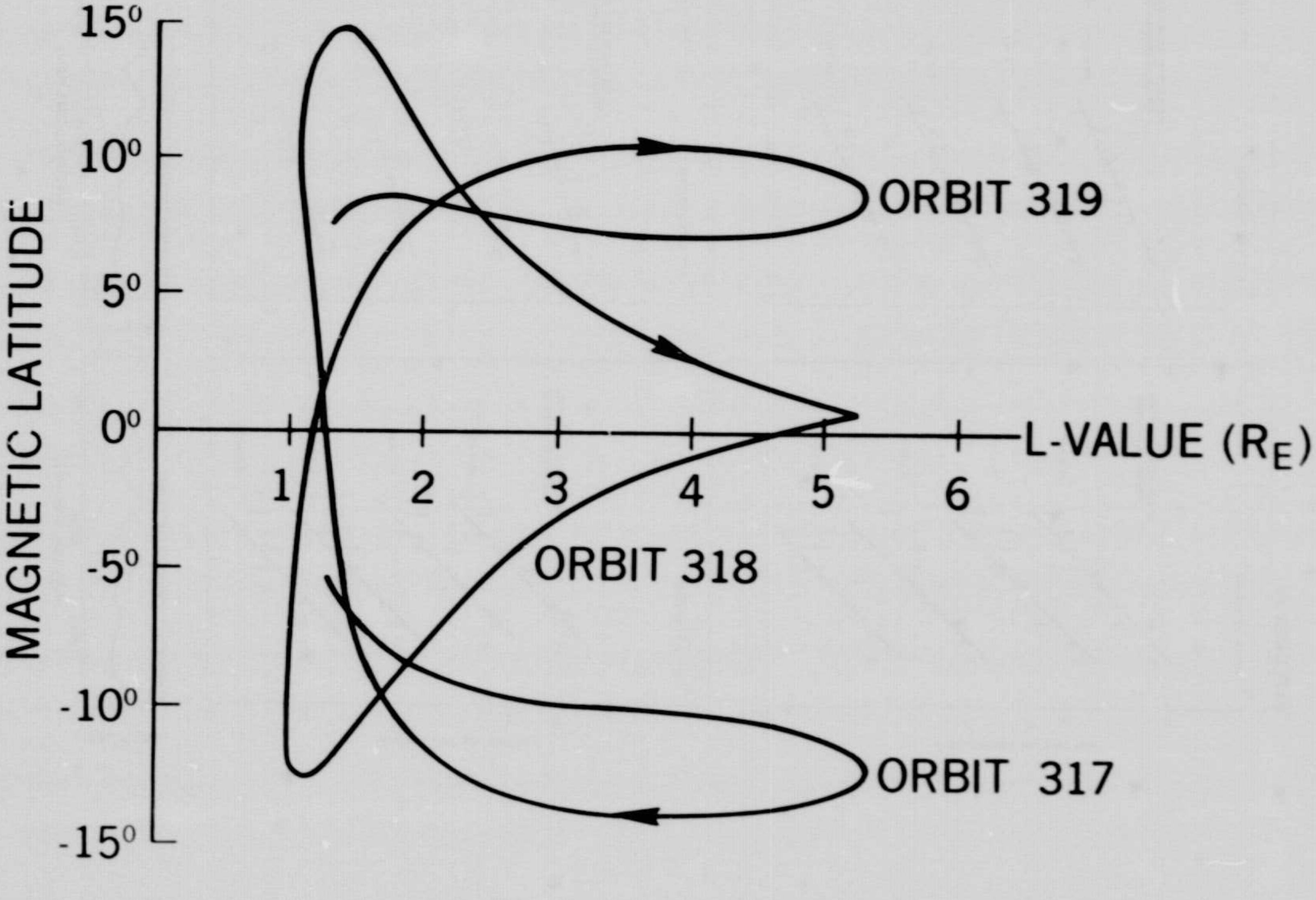
EXPLORER 45
P.A.≃90°
315
318
321
327
L=4.25
OUTBOUND
protons/cm2 sec ster keV)
ENERGY (keV)

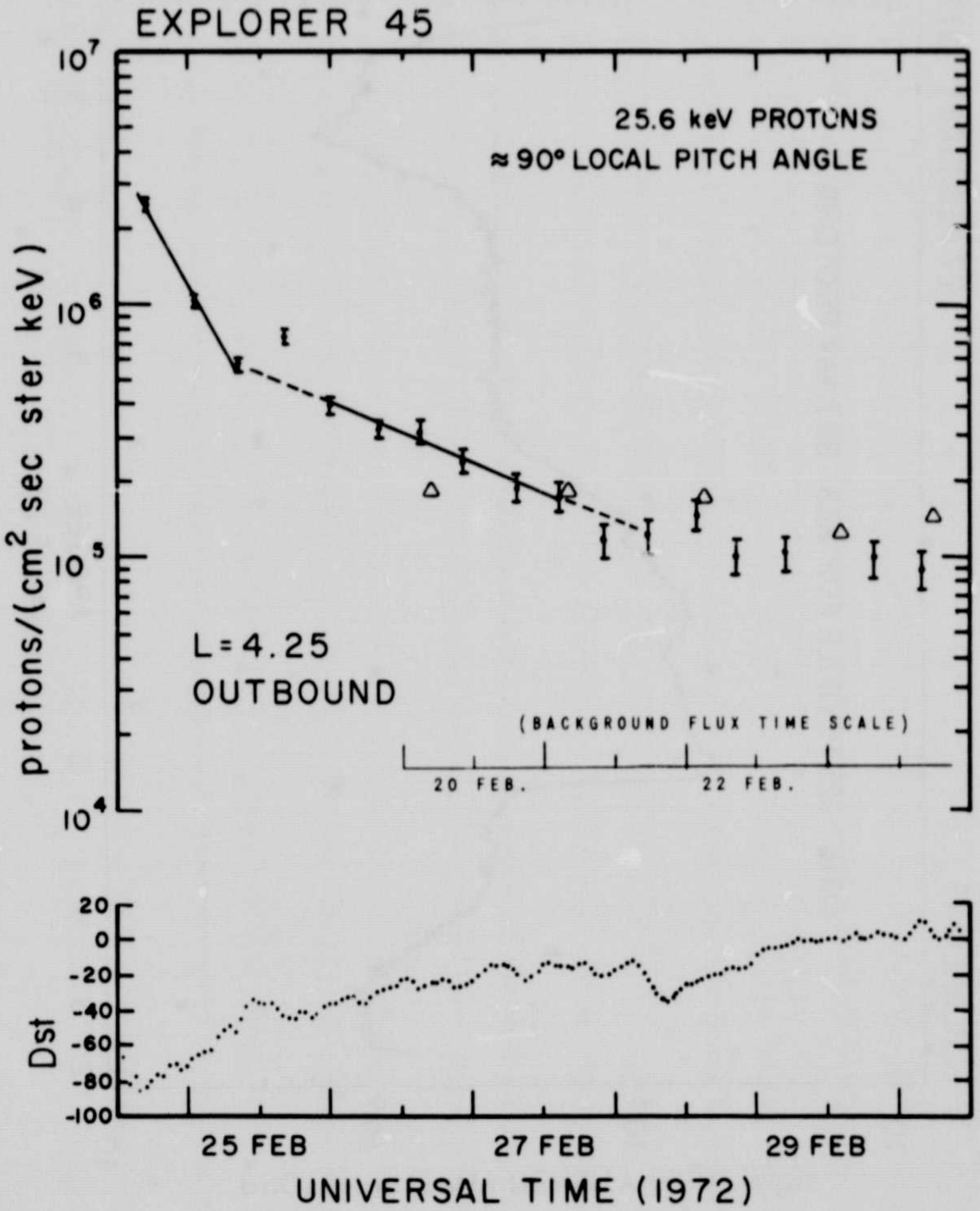


EXPLORER 45 ORBIT PROFILES
24 FEB. - 1 MARCH, 1972
PROTON ENERGY DENSITY (ergs/cm3)
10-7
10-8
10-9
10-10
315
318
321
327
324
332
22.3 keV<E< 30.2 keV
2
3
4
5
APOGEE
5
4
3
2
L-VALUE (Re)

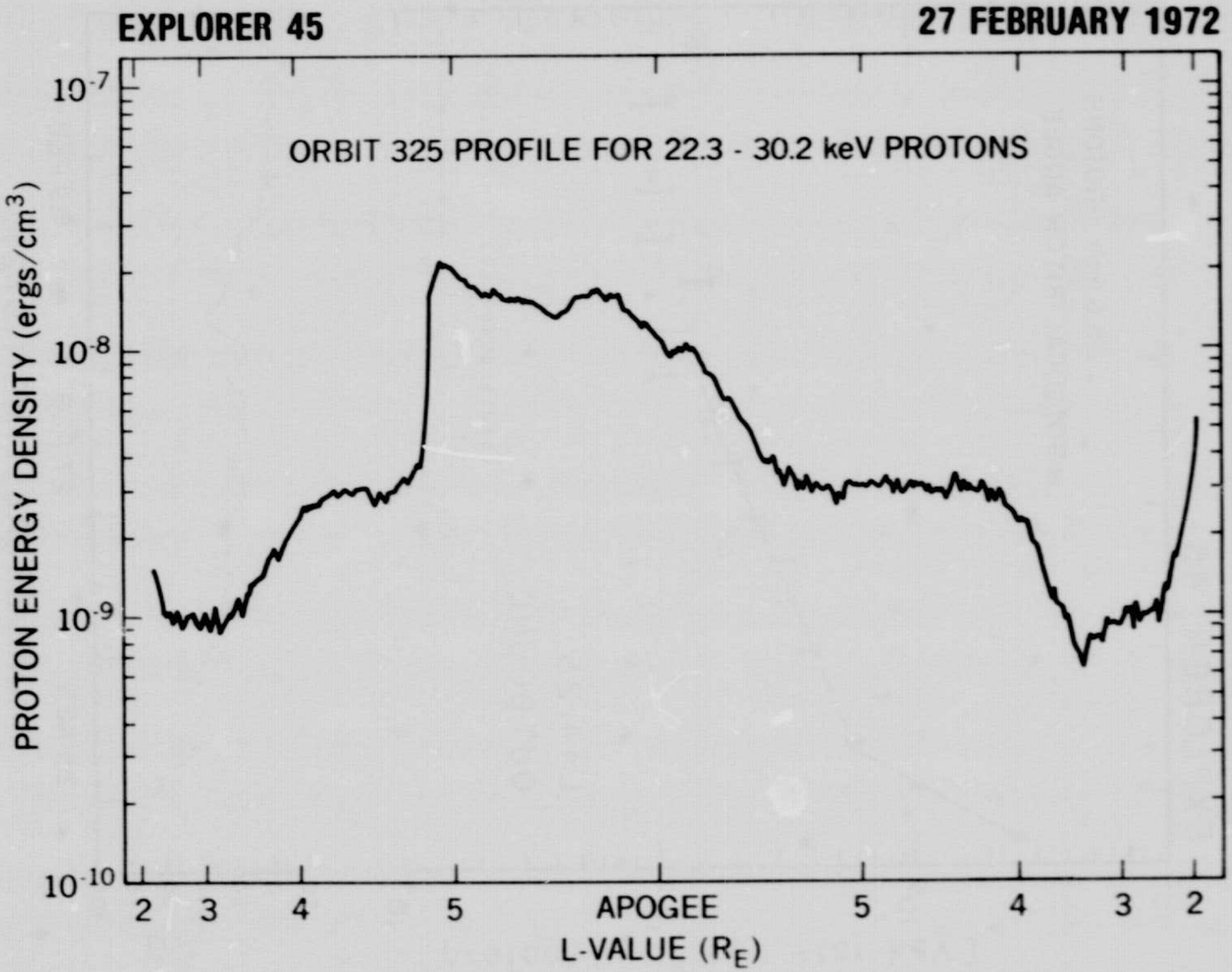

EXPLORER 45
a) L = 3.5 OUTBOUND
P.A. ≈ 90°
PREDICTED DECAY VIA CHARGE EXCHANGE
25.6 keV
13.5 keV
9.2 keV
6.0 keV
b) L = 4.25 OUTBOUND
P.A. ≈ 90°
PREDICTED DECAY VIA CHARGE EXCHANGE
25.6 keV
13.5 keV
9.2 keV
6.0 keV
d) L = 3.5 INBOUND
P.A. ≈ 90°
PREDICTED DECAY VIA CHARGE EXCHANGE
25.6 keV
13.5 keV
9.2 keV
6.0 keV
c) L = 5.0 OUTBOUND
P.A. ≈ 90°
PREDICTED DECAY VIA CHARGE EXCHANGE
13.5 keV
9.2 keV
6.0 keV
Protons/cm² sec ster keV
PLASMAPAUSE CROSSINGS (OUTBOUND)
L-VALUE (R_E)
25 FEB.
27 FEB.
29 FEB.
UNIVERSAL TIME (1972)

EXPLORER 45 TRAJECTORIES IN MAGNETIC LATITUDE - L VALUE COORDINATES





EXPLORER 45
25.6 keV PROTONS
≈90° LOCAL PITCH ANGLE
protons/(cm² sec ster keV)
10⁷
10⁶
10⁵
10⁴
L=4.25
OUTBOUND
(BACKGROUND FLUX TIME SCALE)
20 FEB.
22 FEB.
Dst
20
0
-20
-40
-60
-80
-100
25 FEB
27 FEB
29 FEB
UNIVERSAL TIME (1972)



EXPLORER 45
27 FEBRUARY 1972
ORBIT 325 PROFILE FOR 22.3 - 30.2 keV PROTONS
PROTON ENERGY DENSITY (ergs/cm3)
10-7
10-8
10-9
10-10
2
3
4
5
APOGEE
5
4
3
2
L-VALUE (RE)