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ACCELERATION OF PROTONS AT 32 JOVIAN RADII IN THE OUTER MAGNETOSPHERE OF JUPITER

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Abstract.

During the inbound pass of Pioneer 10, a rapid ten-fold increase of the 0.2 to 5 MeV proton flux was observed at 32 Jovian radii (R_J). The total event lasted for 30 minutes and was made up of a number of superimposed individual events. At the time, the spacecraft was in the outer magnetosphere about 7 R_J below the magnetic equator. Before and after the event, the proton flux was characteristic of the low flux level normally encountered between crossings of the magnetic equator. Flux changes at different energies were coherent within 1 minute; a time comparable to the time resolution of the data. Differential travel time would have led to a greater time difference if the sources had been further than 5 to 10 R_J from the spacecraft. The angular distributions were highly anisotropic with protons streaming towards Jupiter. A field-aligned dumbbell distribution was observed initially, and a pancake distribution just before the flux decayed to its pre-event value. The alpha particle flux changed as rapidly as the proton flux but peaked at different times. The energetic electron flux behaved differently; it increased gradually throughout the period. This acceleration event was associated with a double crossing of a current sheet, with most of the acceleration being coincident with the first crossing. The average shape of the proton energy spectrum (0.3 to 5 MeV) remained unchanged during the event and resembled the spectrum observed in the magnetodisk. A superposition

of acceleration processes of this type is probably responsible for maintaining the energetic particle population around 30 R_J in the magnetosphere. Random fluctuations in the occurrence of acceleration events would explain the 10-50% flux changes during less than 15 minutes which were observed most of the time the Pioneer 10 and 11 spacecraft were in the outer Jovian magnetosphere.

Introduction.

In the outer Jovian magnetosphere, Pioneers 10 and 11 recorded cyclic changes in the flux of energetic particles. A regular pattern of the flux maxima and minima can be observed in the time averaged data which is approximately synchronized with the 10-hour planetary rotation period (Filius, 1976; McDonald and Trainor, 1976; Simpson and McKibben, 1976; and Van Allen, 1976). Figure 1 shows the proton counting rates at two energies, measured during the inbound pass of Pioneer 10. The peaks in counting rate at A, B, C and D correlate closely with proximity to the geomagnetic equator. These data can be interpreted in terms of theoretical models developed prior to the encounter and refined since then by numerous authors (for example, Piddington, 1967; Brice and Ioannidis, 1970; Michel and Sturrock, 1974; Carbary et al., 1976; Gleeson and Axford, 1976; Goertz, 1976; Kennel and Coroniti, 1977).

In these models, the centrifugal force acting on the corotating plasma concentrates it near the geomagnetic equator. Due to the 10.5° tilt of the Jovian magnetic field, the spacecraft was at the magnetic equator and about 20° south magnetic latitude once every 10 hours.

The average flux values shown in Figure 1 represent only the overall behavior of the particle population and wash out the fine structure. Two particle flux measurements taken within 3 minutes differ frequently by 10 to 30%. Simpson and McKibben (1976) have interpreted a particularly disturbed period (0:00 to 08:00 hours on December 6, 1973) as evidence for particle acceleration. Their observations were made in the dawn sector of the magnetosphere; this paper is based on data from the inbound pass of Pioneer 10 at about 25° from the subsolar point. An order of magnitude increase, lasting for less than one-half hour, occurred in the proton flux at 32 R_J (Jovian radii) when Pioneer 10 was near its most southern magnetic latitude.

The angular distributions and time histories of proton and alpha particle channels at different energies have been analyzed and support the conclusion that this flux increase, and probably also many smaller ones, are due to local acceleration. It appears that the average particle population found in the outer magnetosphere is due to a dynamic equilibrium between acceleration and loss processes.

<u>Instrumentation</u>.

The data was taken by the GSFC/University of New Hampshire instrument package on Pioneer 10. The detectors have been described previously (Trainor et al., 1974; Stilwell et al., 1975) and the following types of data from these three telescopes were used:

(a) High Energy Telescope (HET): Electron fluxes above 1 MeV.

(b) Low Energy Telescope I (LET I): Proton observations below 2.28 MeV.

(c) LET II: Angular distribution measurements and most of the proton data.

A schematic of the LET I and LET II instruments is shown in Figure 2. Most of the LET II data were taken with an integral threshold on the 50 μm thick surface barrier detector (SI) in anticoincidence with detector SII. These channels are sensitive to protons from the threshold energy up to 2.15 MeV, and to alphas up to 2.05 MeV per nucleon. Sensitivity to electrons was less than 5×10^{-3} above a 200 keV threshold and less than 10^{-6} for higher threshold energies. When pulse pileup is not a problem, alpha particles (0.68 to 2.06 MeV/n) and any heavier ions can be separated from protons because protons falling into this energy window penetrate SI and trigger the anticoincidence detector. Conversely, we can demonstrate that alphas and heavier ions constitute only a moderate fraction of counts in the lower energy channels by inter-comparing counting rates in LET I and LET II. Since LET I is covered by a 0.53 mg/cm^2 mylar foil, it is more sensitive to protons than alpha particles because the threshold energy for the latter is raised. Only the nominally 1.80 to 2.15 MeV proton channel of LET II has a substantial alpha contribution; this occurs because this channel is sensitive to a large range of alpha particle energies (0.45 to 2.05 MeV/n).

Protons from 3.2 to 19 MeV were counted with minimal contribution from other ions in a SI SII coincidence channel. Positive identification of protons above 3.4 MeV was also made on the basis of ΔE vs. E data from LET I; however, at least 15 minutes of data had to be averaged to perform such an analysis.

Angular distributions were measured in eight sectors perpendicularly to the Pioneer spin axis. The plane in which the distributions were measured is referred to as the spin plane. The angle θ_B gives the inclination of the magnetic field relative to this plane and is negative if the field points toward Jupiter. The range of pitch angles from 0 to $|\theta_B|$ and from 180 to 180 - $|\theta_B|$ was not sampled. The clock angle, ϕ_B , of the projection of the magnetic field into the spin plane is measured counterclockwise, as seen from the Earth, and referenced to the north pointing perpendicular to the plane of the ecliptic. Angular distributions were analyzed to first and second order anisotropy by the formula:

$$C = A_0 + A_1 \cos(\phi - \phi_1) + A_2 \cos 2(\phi - \phi_2),$$

where C is the counting rate and ϕ_1 and ϕ_2 are the directions of the first order anisotropy and axis of the second order anisotropy, respectively. The angles α_1 and α_2 designate the angles in the spin plane of the observed anisotropies relative to the projection of the magnetic field, and are measured from the positive field direction.

Observations.

Proton peaks B and C in Figure 1 are shown in more detail in Figure 3. In addition to the regular 10-hour pattern, many temporal variations can be observed not only in the integrated flux but also in energy spectrum and composition. For example, between 7:00 and 8:30 the flux at high energy (Curves 4 and 5) decreases much more than at lower energies (Curves 2 and 3), or from 0:30 to 1:30 the high energy proton flux (Curve 5) decreases much more than the alpha particle flux (Curve 4). The general appearance is that the flux at any given time resulted from a superposition of intensity increases which require about 15 minutes to double the flux and then decay almost as rapidly. We are either observing regions with enhanced flux being rotated across the spacecraft, or the particle population is relatively short lived and must be replenished either by local acceleration or cross field transport from other regions of the magnetosphere. Only if the particle population is short lived would we expect to observe time coincidence of enhancements at all energies; otherwise, differential gradient drift would disperse particles falling into different energy channels.

An isolated intensity increase occurred at 13:06 on December 2, 1973 (Figure 3) and offers the opportunity to study the newly created particle population relatively free of leftover fluxes from previous events. At the start of the event, the Jovian magnetic dipole was tilted away from Pioneer 10 and the spacecraft was at a flux minimum. Thus the spacecraft was not at the plasma sheet near the magnetic equator but about 7 R_J below it. The exact position relative to the equator depends on the sweep back of the field and the tilt of the plasma sheet towards the geometric equator (Smith et al., 1974; Hill et al., 1974; Northrop and Goertz, 1974; Goertz, 1976).

Individual observations during the period of interest are shown in Figure 4. The statistical errors for Curves 1, 2 and 3 are contained within the size of the points, thus every inflection is statistically significant. The overall event can be broken down into a number of smaller events. At higher energies where protons can be resolved from alpha particles, we find the two fluxes peak at different times with a tendency for alternate flux maxima. The lower energy channels which respond to both protons and alphas have distinct inflections or peaks at each of these maxima. These features are observed simultaneously at all energies (A, B, C in Figure 4) with no indication of dispersion due to different particle velocities (less than 1 minute). If the maxima are due to impulsive acceleration, then the differences in velocities of protons with the mean energy of each channel requires that the acceleration site must have been within 5 to 10 R_J of the spacecraft.

The possibility that Pioneer 10 moved across a stably-trapped population of energetic protons can be ruled out. The gyroradius in the 25 gamma ambient magnetic field is 0.15 R_J for 3.5 MeV protons; thus it would have taken about 25 minutes to move through a distribution of minimal width. If tubes of enhanced particle flux corotated with Jupiter and passed Pioneer, they could have existed for at most a few minutes prior to being observed. A difference in gradient drift at the extreme energies of less than 0.32 R_J is consistent with observations. In a dipole field, gradient drift would have produced a greater separation in 5 minutes.

The interpretation that our observations are due to in situ particle acceleration is supported by the angular distributions. Typical distributions are shown in Figure 5 and the time histories of the first and second order anisotropies are plotted in Figure 6. The angular distribution prior to the event resembled that normally observed at a flux minimum. At the beginning of the event, Figure 5, Distribution A, the first order anisotropy is greatly enhanced and protons are streaming down the field line towards the planet. During peak flux, Distributions C and D, the angular distribution is very narrowly aligned with the magnetic field with most of the particles streaming towards Jupiter. A possible interpretation is that we observed only particles moving towards Jupiter at A because the half-bounce period is 5 minutes and none could have been mirrored to return back up the field line. During the time the angular distribution at A was measured, however, the magnetic field was at 77° to the spin plane. A very narrow distribution like the one observed at C would not have been sampled; thus this interpretation is not unique.

As the enhanced flux of particles decayed the field aligned part must have decayed more rapidly because at Time F we observe a pancake distribution which resembles the angular distributions normally observed in the plasma sheet near the equator. The first order anisotropy, ϕ_1, indicated a net particle streaming in the opposite direction from corotation. Apparently the local intensity gradients were strong enough to more than cancel out the normally observed effects of corotation. This implies an enhanced flux at a slightly larger distance from Jupiter than the spacecraft.

One-minute averages of the magnetic field (supplied by Dr. E. Smith) are shown in Figure 6 together with the results of the Fourier analysis of the angular distributions. The spacecraft was clearly crossing two current sheets, or possibly the same sheet moved across Pioneer 10 and then back. The alpha flux maxima B and F in Figure 4 were centered on the maximum field depression, while proton maxima A and C occurred apparently on either side of the first current sheet. The first order anisotropy was field aligned, $\alpha_1 \sim 180°$, with particles streaming towards the planet, except during a short period when the flux was decaying. At that time it was nearly perpendicular to B, $\alpha_1 \sim 90°$. The second order anisotropy was relatively small during most of the period except at the peak of the event when it approached 100% and was field aligned, $\alpha_2 \sim 0°$. The field aligned component decayed rapidly and a distinct pancake distribution, $\alpha_2 \sim 90°$, was observed at the time of the second current sheet crossing.

Figure 7 shows 15 minute average proton spectra. The proton spectrum covering the maximum flux period, labeled 13:00, is superimposed on the pre-event spectrum labeled 12:30. The relative intensities at different energies had changed very little, except for the 10 MeV channel; apparently particles were not accelerated up to this high an energy. For comparison, Figure 7 shows also a typical spectrum observed at 7:15 on Dec. 2, 1973, which was taken during the previous flux maximum at the equator. Again the spectrum is quite similar, the major change being that the break in slope occurs at 2 MeV rather than at 1 MeV.

As shown in Figure 8, electrons were not affected in the same way as protons. The low energy electron flux, >0.1 MeV, increased steadily from 12:50 to 13:10, and then remained near its maximum value until the next equatorial crossing. The higher energy electrons flux increased by a small amount at the first current sheet crossing at 13:00, then continued to rise gradually and remained also near its maximum until the next equatorial crossing.

Conclusions.

Field aligned acceleration of protons and alpha particles was observed associated with a current sheet crossing when Pioneer 10 was about 7 R_J south of the magnetic equator. Similar current sheet crossings were observed without accompanying flux changes; one of these occurred 1 1/2 hours earlier. The most likely explanation of the observations is that a current sheet moved across Pioneer 10 just when it became unstable. Possibly currents had become sufficiently strong to trigger the two-stream instability, thus disrupting the current flow and producing local field aligned potential differences (Thorne, 1975). After releasing the excess energy the current sheet returned to its earlier position and crossed Pioneer 10 on its way back. The net effect of the currents was to decrease the magnitude of the field from 26 gamma on one side to 21 gamma on the other, and to rotate the field direction through about 60° (Figure 6). Inside the sheet, the field magnitude was depressed to 7 gamma, which is comparable to its lowest values in the equatorial plasma sheet.

The overall acceleration occurred through a number of individual injections during which the flux built up rapidly - a doubling time of only 2 to 3 minutes. The maxima in the proton and alpha particle fluxes occurred at different times with the first alpha peak observed during the maximum field depression (B in Figure 4), and maximum proton acceleration on either side (A and C, Figure 4). Due to the complexity of the overall event, the decay rate of flux from any one event cannot be determined accurately, but the rapid decay observed at 13:12 and 13:30 (Figure 4) would indicate that the same time scale is involved in the decay as build up. Since the proton bounce period is of the order of 10 minutes, we were not observing a stably-trapped population during the few minutes of the event. In view of the many magnetic irregularities, the protons were probably scattered frequently; thus they were detained near the site of acceleration and diffused away over a period of minutes. During this process, the highly anisotropic angular distribution observed at C became first almost isotropic (E to F in Figure 6), and then a higher loss rate of particles with small pitch angles produced the pancake distribution observed at F to G (Figures 5 and 6). It may be worth noting that the angular distribution at F (Figure 5) is typical of distributions observed in the equatorial plasma sheet.

The spectral data from this period show that protons were accelerated up to about 5 MeV and that the energy spectrum was not changed significantly from the pre-event spectrum (Figure 7). It is therefore unlikely that this acceleration event differed greatly from the processes responsible for normally observed proton population. Numerous such acceleration events of various magnitudes may occur with the greatest number near the magnetic equator. Normally, however, we cannot study individual events because the new proton population had been lost in the background from earlier events. Secondly, the site of the acceleration would generally have been sufficiently far away from the spacecraft that the protons had lost their characteristic angular distribution before they were detected.

Electron acceleration was also associated with this current sheet (Figure 8). The temporal characteristics, however, were very different from those of heavy particles. Once accelerated, the higher flux did not dissipate as rapidly, but appears to be localized for at least an hour rather than only minutes. This would be consistent with a substantially smaller cross-field diffusion coefficient for electrons than protons. A difference in diffusion coefficient would also help explain the observation that the proton intensities at magnetic equatorial crossings (Figure 1, Peaks A, B, C and D) show only little dependence on distance from Jupiter over the range from 25 to 45 R_J. This should be contrasted with an R^{-4} dependence of 260 to 460 keV electron intensities observed at the same time by Fillius and McIlwain (1974).

The outer Jovian magnetosphere near 30 R_J in the subsolar hemisphere appears to be in dynamic equilibrium, with particle acceleration and losses balancing each other out, not on a time scale of weeks but minutes to hours. The continuously-changing intensities (Figure 3) reflect the shift in balance between the two processes. Numerous plasma instabilities can be called upon to replenish the loss of energetic particles through wave particle interactions (Kennel and Coroniti, 1974; Michel and Sturrock, 1974; Thorne, 1976; Scarf, 1976). Several energy sources have been identified for driving these instabilities such as solar wind interaction with the magnetosphere, corotation energy of plasma in the magnetic field, and ionospheric winds moving field lines. In the absence of specific knowledge of the plasma parameters, however, we cannot identify uniquely the specific mechanisms responsible for our observations.

Acknowledgements.

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Figure Captions.

Figure 1 - Counting rates in two proton channels of the LET II detector. The dashed line corresponds to the 0.50 to 2.15 MeV channel with a mean energy of 0.7 MeV; solid line, 1.80 to 2.15 MeV, mean 1.94 MeV.

Figure 2 - Schematic cross section of the GSFC Low Energy Telescopes (LET) on Pioneer 10 and 11. Individual Silicon detectors had the following thicknesses: 0.1 mm for DI and DII; 2.5 mm for E and F of LET I; 0.05 mm for SI; 2.5 mm for SII and SIII of LET II. The geometric factors were 1.56 cm^2 ster. for DI and 0.0155 cm^2 ster. for LET II.

Figure 3 - Counting rates averaged over 15 minutes for several LET II channels. Curves 2 and 3 are sensitive to both protons and alpha particles. Curve 2 represents a proton energy channel of 0.76 to 2.15 MeV, mean 1.1 MeV; Curve 3, 1.25 to 2.15 MeV, mean 1.5 MeV for protons; Curve 4, 0.68 to 2.05 MeV/n, mean 0.8 MeV/n for alpha particles; Curve 5, 3.2 to 20.7 MeV, mean 3.8 MeV for protons.

Figure 4 - Counting rates averaged over 24 seconds for several LET II channels. The mean proton energies are: 0.3 MeV, Curve 1; 1.1 MeV, Curve 2; 1.5 MeV, Curve 3; 1.9 MeV, Curve 4; and 3.8 MeV, Curve 6. The mean alpha energy for Curve 5 is 0.8 MeV/n.

Figure 5 - Characteristic angular distributions; each observed during one spacecraft revolution. B denotes the direction of the

magnetic field component in the equatorial plane of Pioneer; ϕ_1 and ϕ_2 are the directions and axis of the first and second order anisotropies, respectively. The dotted circle gives the magnitude of the spin averaged flux.

Figure 6 - One-minute averages of magnetic field magnitude and direction (kindly made available by E.J. Smith); magnitudes of first and second order anisotropies and their angle relative to the projection of the magnetic field into the equatorial plane of Pioneer.

Figure 7 - Proton energy spectra derived from 15-minute averages. The spectrum labeled 12:30 covers the time period from 12:30 to 12:45 on Figure 4. Similarly, the 13:00 spectrum is based on data from 13:00 to 13:15. The intensities of the two spectra have been inter-normalized to demonstrate their similarity.

Figure 8 - Electron counting rates averaged over 24 seconds. The times labeled A through G are the same as shown in Figure 4.

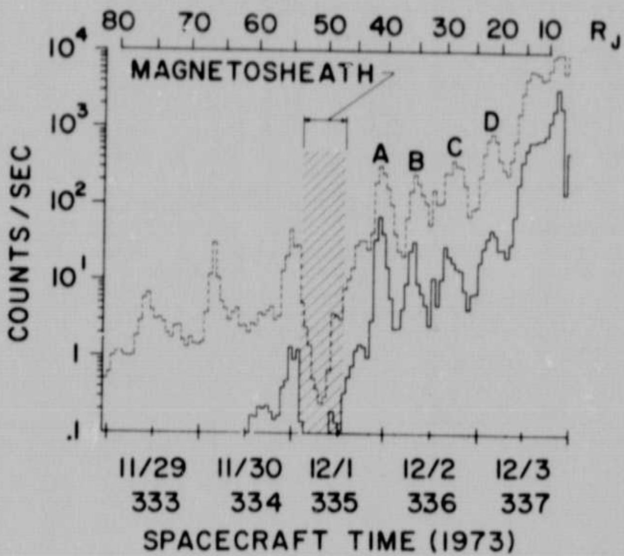

80
70
60
50
40
30
20
10
R_J
10^4
10^3
10^2
10^1
1
.1
COUNTS / SEC
MAGNETOSHEATH
A
B
C
D
11/29
333
11/30
334
12/1
335
12/2
336
12/3
337
SPACECRAFT TIME (1973)

FIGURE 1

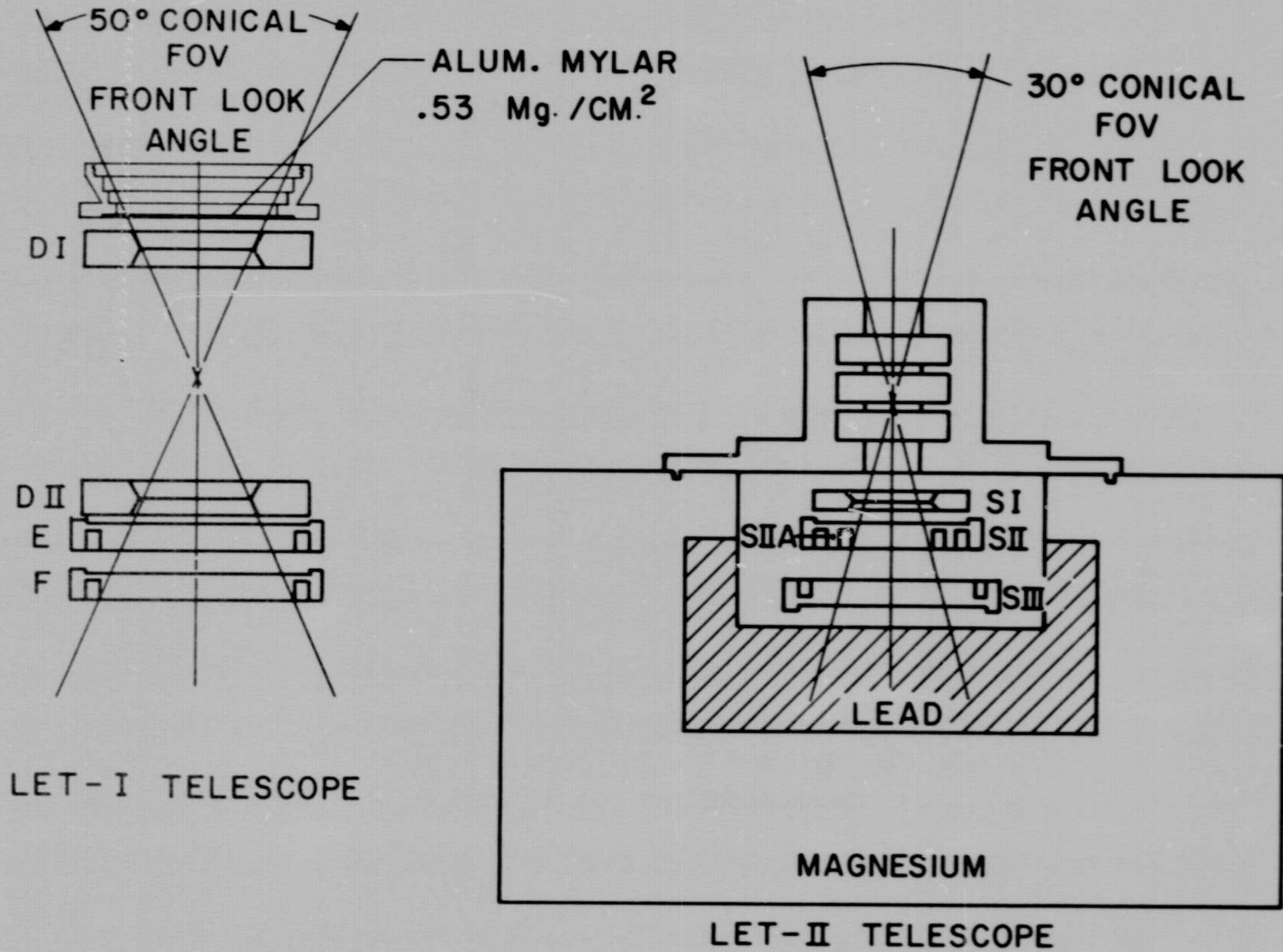

50° CONICAL FOV FRONT LOOK ANGLE
ALUM. MYLAR .53 Mg./CM.²
D I
D II
E
F
LET-I TELESCOPE
30° CONICAL FOV FRONT LOOK ANGLE
S I
S II
S II A
S III
LEAD
MAGNESIUM
LET-II TELESCOPE

FIGURE 2

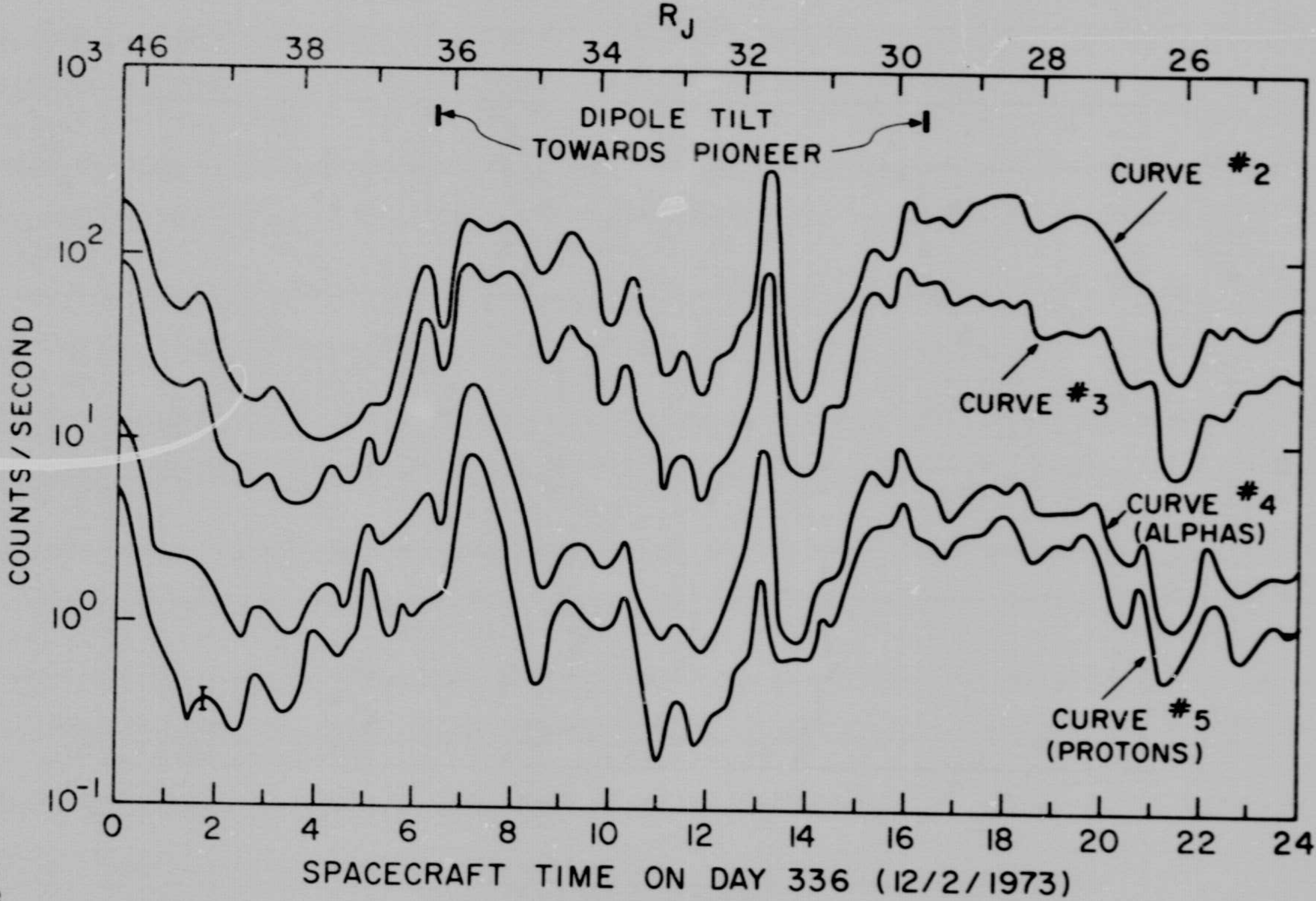
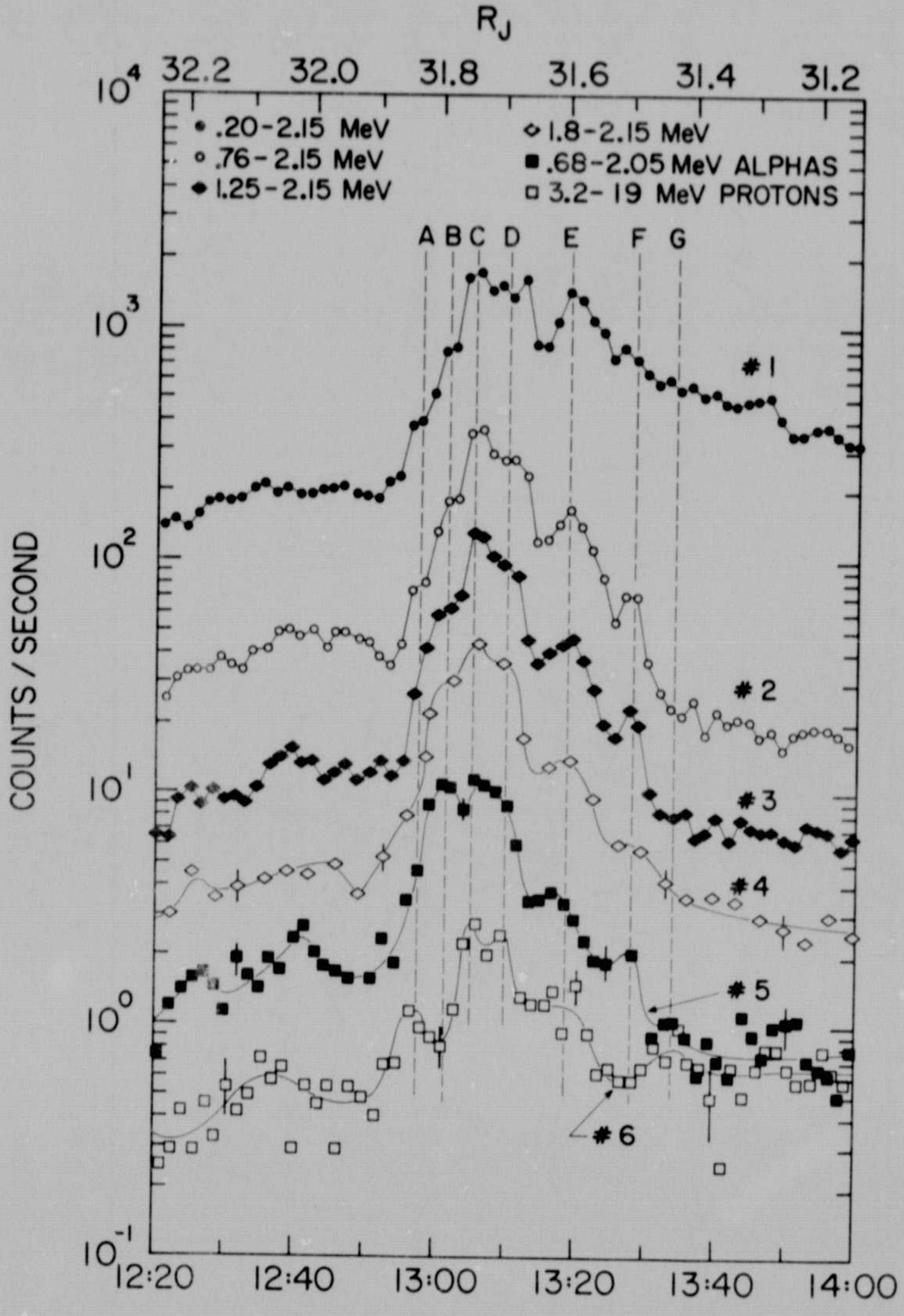


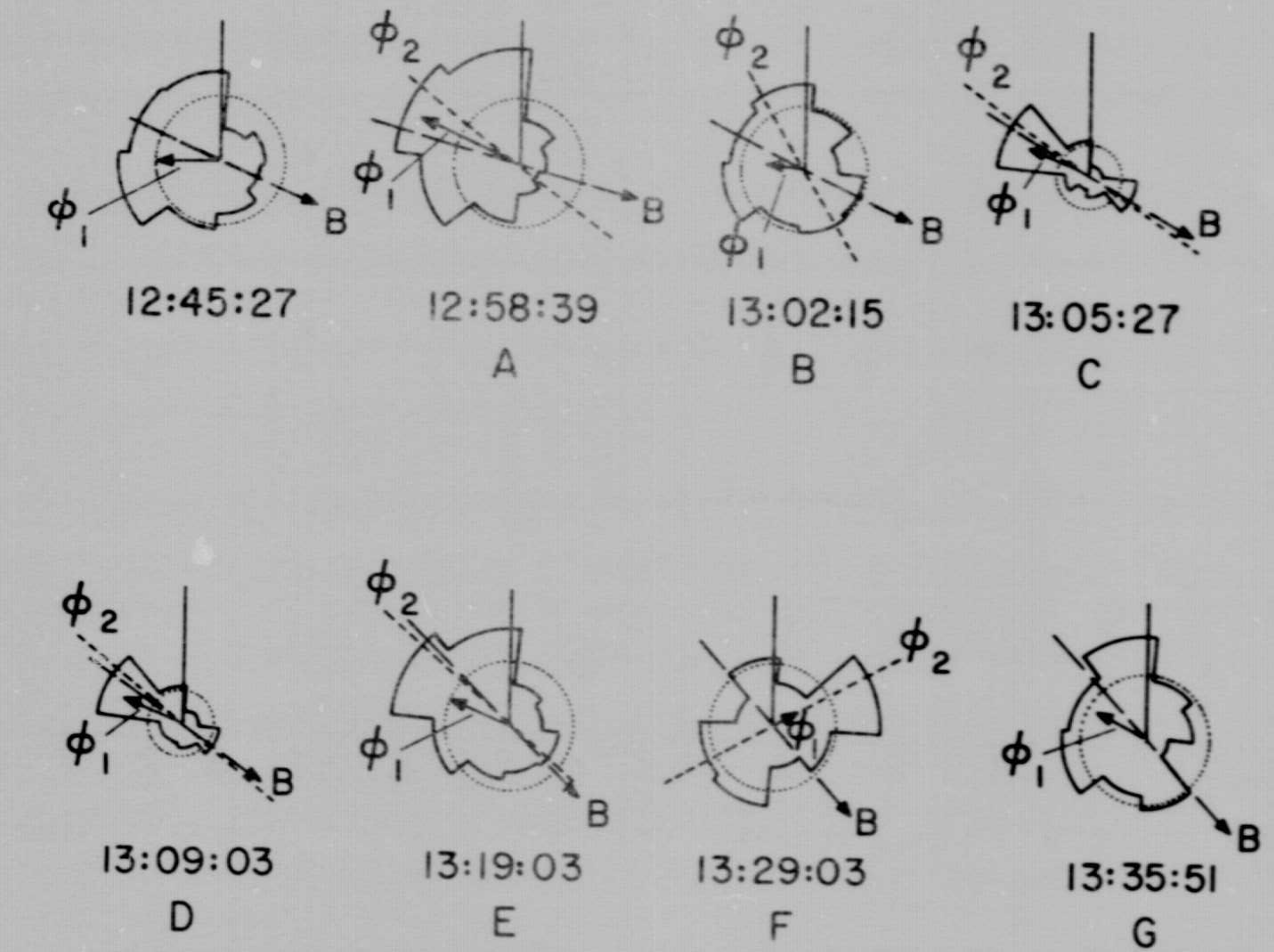
FIGURE 3

ORIGINAL PAGE IS
OF POOR QUALITY



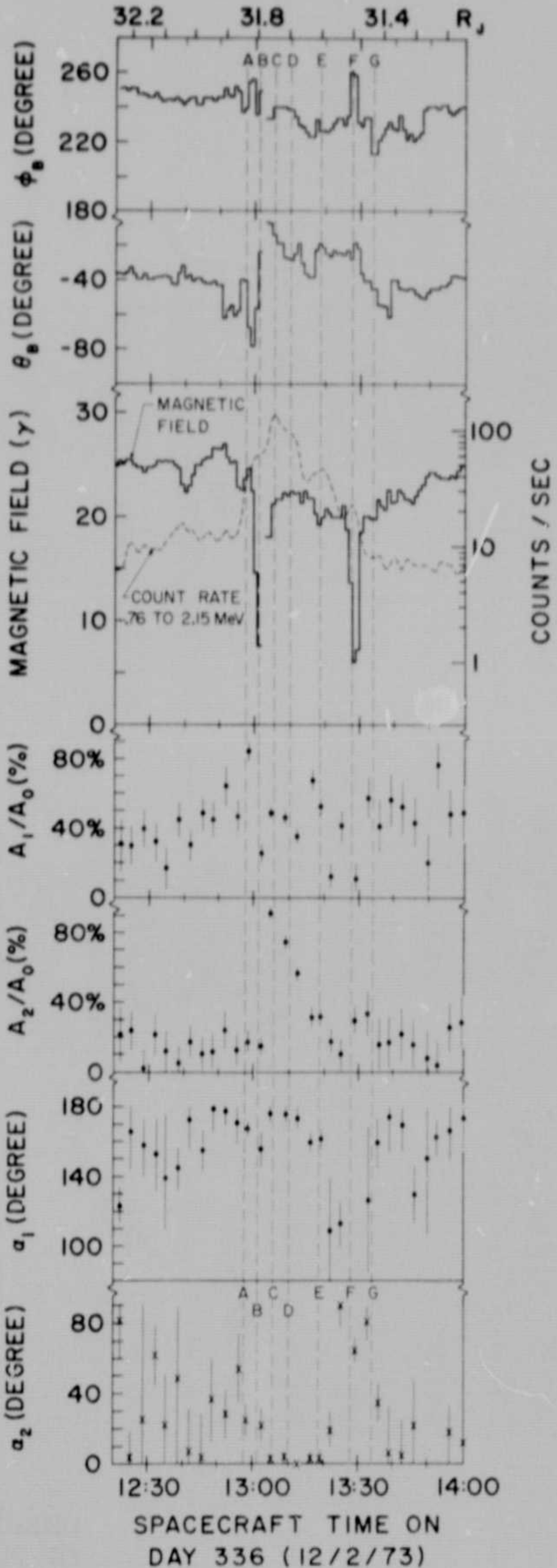
R_J
32.2
32.0
31.8
31.6
31.4
31.2
• .20-2.15 MeV
○ .76-2.15 MeV
◆ 1.25-2.15 MeV
◇ 1.8-2.15 MeV
■ .68-2.05 MeV ALPHAS
□ 3.2-19 MeV PROTONS
A B C D E F G
#1
#2
#3
#4
#5
#6
COUNTS / SECOND
10^4
10^3
10^2
10^1
10^0
10^{-1}
12:20
12:40
13:00
13:20
13:40
14:00
SPACECRAFT TIME ON DAY 336 (12/2/73)

FIGURE 4



PIONEER 10 DAY 336 (12/2/73) 1.15 TO 2.15 MeV PROTONS

FIGURE 5



32.2
31.8
31.4
R_J
A B C D E F G
φ_B (DEGREE)
260
220
180
θ_B (DEGREE)
-40
-80
MAGNETIC FIELD
COUNT RATE .76 TO 2.15 MeV
MAGNETIC FIELD (γ)
30
20
10
0
COUNTS / SEC
100
10
1
A_1/A_0 (%)
80%
40%
0
A_2/A_0 (%)
80%
40%
0
a_1 (DEGREE)
180
140
100
A B C D E F G
a_2 (DEGREE)
80
40
0
12:30
13:00
13:30
14:00
SPACECRAFT TIME ON
DAY 336 (12/2/73)

FIGURE 6

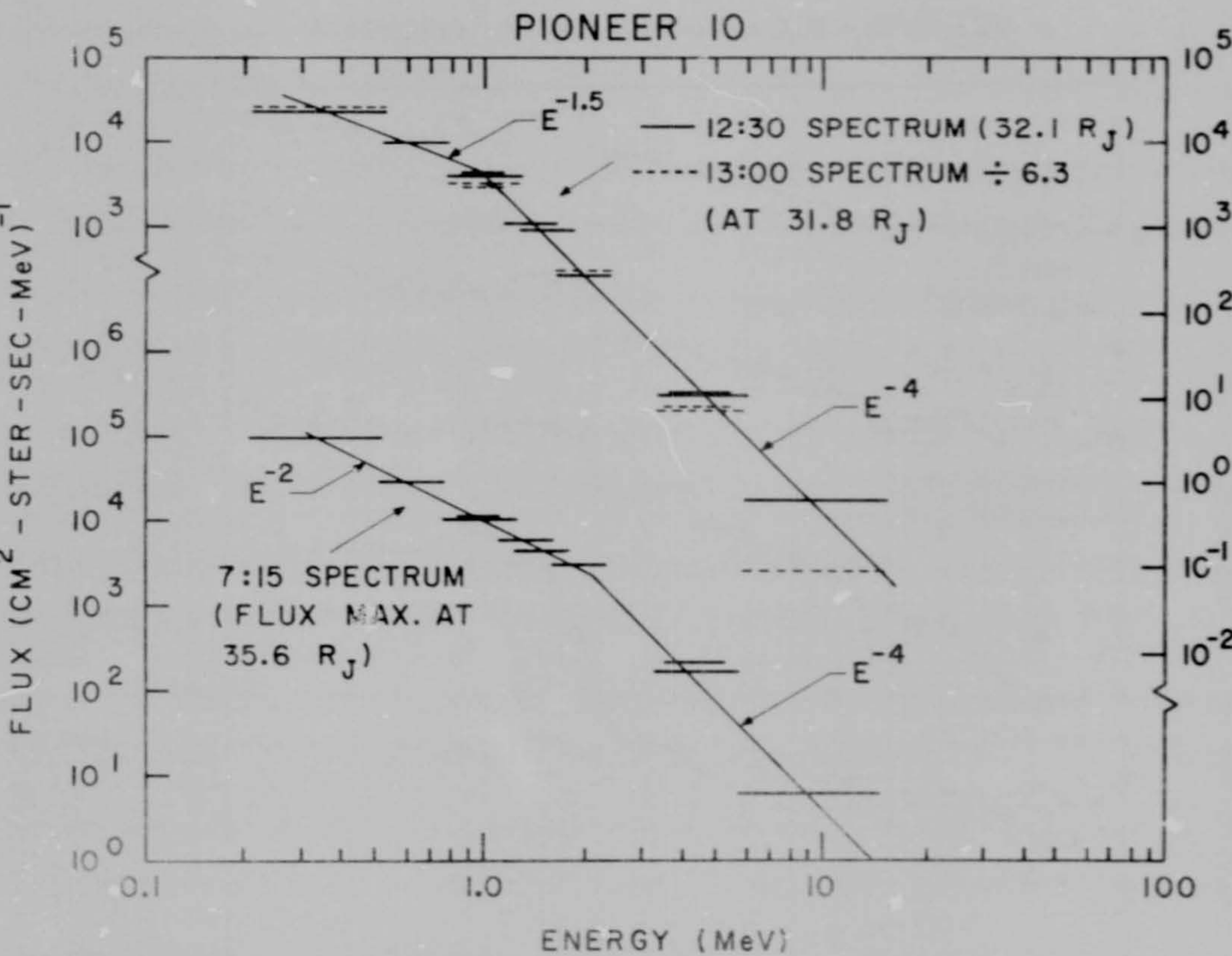
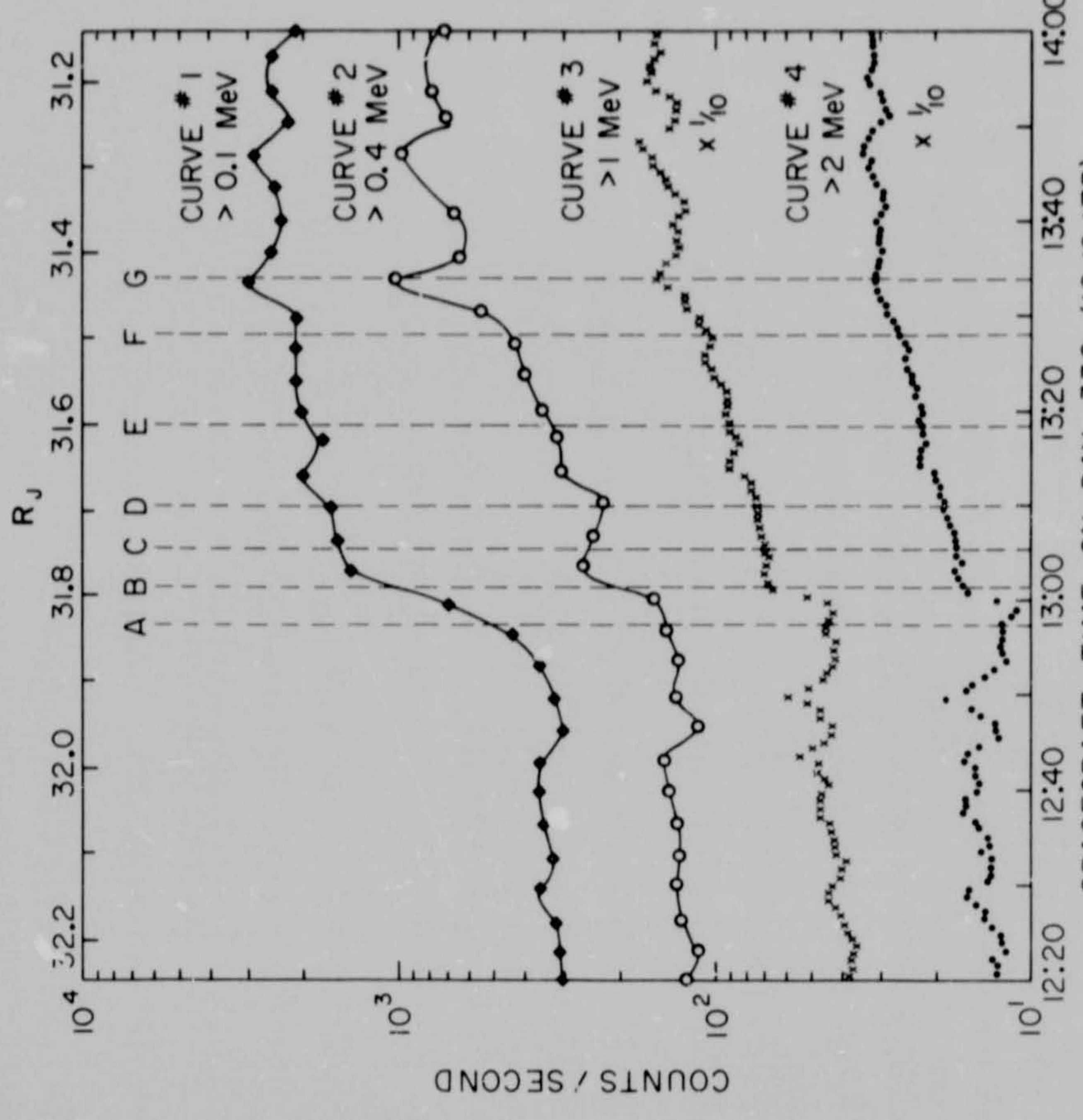

PIONEER 10
10^5
10^4
10^3
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
FLUX $(CM^2 - STER - SEC - MeV)^{-1}$
$E^{-1.5}$
— 12:30 SPECTRUM (32.1 R_J)
----- 13:00 SPECTRUM ÷ 6.3
(AT 31.8 R_J)
E^{-4}
E^{-2}
7:15 SPECTRUM
(FLUX MAX. AT
35.6 R_J)
E^{-4}
0.1
1.0
10
100
ENERGY (MeV)

FIGURE 7

FIGURE 8



R_J
32.2
32.0
31.8
31.6
31.4
31.2
A B C D E F G
CURVE # 1 > 0.1 MeV
CURVE # 2 > 0.4 MeV
CURVE # 3 >1 MeV x 1/10
CURVE # 4 >2 MeV x 1/10
10^4
10^3
10^2
10^1
COUNTS / SECOND
12:20
12:40
13:00
13:20
13:40
14:00
SPACECRAFT TIME ON DAY 336 (12/2/73)