NASA

Technical Memorandum 79624

# Discrepancy in Proton Flux Extrapolation along Field Lines in the Middle Jovian Magnetosphere

A. W. Schardt and T. J. Birmingham

(NASA-TM-79624) DISCREPANCY IN PROTON FLUX EXTRAPOLATION ALONG FIELD LINES IN THE MIDDLE JOVIAN MAGNETOSPHERE (NASA) 39 p HC A03/MF A01 CSCL 03E
N78-31028
Unclas
G3/91 29422



AUGUST 1978

National Aeronautics and
Space Administration

**Goddard Space Flight Center**
Greenbelt, Maryland 20771

# DISCREPANCY IN PROTON FLUX EXTRAPOLATION ALONG FIELD LINES IN THE MIDDLE JOVIAN MAGNETOSPHERE

A. W. Schardt and T. J. Birmingham
NASA/Goddard Space Flight Center, Greenbelt, Maryland 20771

## ABSTRACT

Fluxes of energetic electrons and protons in Jupiter's outer magnetosphere were observed to be modulated with the 10 hour rotation period of the planet. This modulation is due to the concentration of particles at the magnetic equator: the non-alignment of Jupiter's spin and rotation axes causes Pioneer-10 to oscillate between $+20^{\circ}$ and $-19^{\circ}$ magnetic latitude and hence between regions of stronger and weaker fluxes. In this paper we investigate the relationship between electron and proton fluxes observed off the magnetic equator with those measured at the equatorial crossing radii of the same flux tubes. Liouville's theorem is applied with the assumption that particles move conserving their magnetic moments. A magnetic model which matches the intensity and direction of the magnetic field along the Pioneer 10 trajectory is used for determining the positions of the equatorial crossings. Energetic electrons (1.3 MeV) compared in this way appear to be consistently described. Protons, on the other hand, show much weaker fluxes at the off-equatorial points than would be predicted by this simple application of Liouville's theorem. Violation of the first adiabatic invariant is one explanation; other potential explanations depend on slow magnetic field fluctuations which are not included in the magnetic model and which conserve the first invariant or on a large asymmetry in equatorial proton flux as a function of system III longitude.

## Introduction

The Alfven radius for containing the corotating plasma in the Jovian magnetosphere is expected to occur somewhat further than 41 Jupiter radii ($R_J$) from the planet (see Kennel and Coroniti, 1977, for a review of different theories). Inside of this region the equatorial field lines are closed and the average magnetic field can be represented by the Jovian dipole field plus a local perturbation. One might thus expect that the energetic particles trapped in this field have a reasonably long lifetime. In the absence of major perturbations by the solar wind, the behavior of energetic particles should be described by simple adiabatic theory.

A more detailed analysis of data on the proton flux and its angular distribution has shown that protons are probably not permanently trapped at distances much greater than 20 $R_J$. In this region McDonald and Trainor (1976) found protons streaming along field lines towards the planet, and from a more detailed analysis, Northrop et al. (1978) concluded that a source of energetic particles (1.9MeV) must exist in the plasma sheet near the magnetic equator. Another unexpected observation was a proton acceleration event at 32 $R_J$ which lasted for 30 minutes and increased the proton flux by an order of magnitude (Schardt et al., 1978). Perturbations lasting only a few minutes are frequent since two particle flux measurements taken only a few minutes apart often differ by 10 to 30 percent.

The purpose of this paper is to determine whether simple theory can explain the observed changes in electron and proton fluxes along the Pioneer 10 trajectory. Due to the 10.5° offset between the Jovian spin and magnetic dipole axes (Smith et al., 1976), the Pioneer 10 inbound trajectory changes between +2 and -19° in magnetic latitude (Mead 1974). As shown in figure 1 the trajectory followed at times very closely to a dipole field line, or if field lines are distended, Pioneer 10 crossed them at different points. Since the time averaged flux data follow a regular pattern (Fillius, 1976; McDonald and Trainor, 1976; Simpson and McKibben, 1976; and Van Allen, 1976), one should be able to compare average fluxes at different points along a field line even though they were not observed simultaneously.

By the use of Liouville's theorem and adiabatic theory, one can relate the particle distribution functions and consequently the particle fluxes at different points along a field line. If we assume that stable trapping conditions exist, then the total particle energy is constant and pitch angle scattering is sufficiently unlikely that it can be ignored. Under these conditions the relationship is very simple (Northrop 1976); the flux of particles having a given energy and magnetic moment is invariant along the field line. In other words, the flux at pitch angles $\delta$ relative to the magnetic field B is constant along the field line provided the pitch angles at different points are related by $\sin \delta = \sqrt{B/B_o} \sin \delta_o$ where $B_o$ and $\delta_o$ are the equatorial field magnitude and pitch angle. One consequence is that the intensity of an isotropic distribution is invariant along the field line. For non-isotropic distributions, intensities at related pitch angles are the same. For instance, a distribution $A(1+\sin^2\delta_o)$ at the equator transforms into $A(1+(B_o/B) \sin^2\delta)$ at a point where the field strength is B versus $B_o$ at the equator. The observed energetic particle data were organized on the basis of a magnetic field model that fits the observed fields along the Pioneer 10 trajectory in both magnitude and direction.

The Magnetospheric Model

Barish and Smith (1975) developed a general field model which described the qualitative behavior of the magnetic field over a large portion of the dayside Jovian magnetosphere. For the purpose of this paper we needed a model which fits quantitatively the observed field data for the Pioneer 10 inbound trajectory over the restricted region 20 to 35 $R_J$; hence we have developed our own model.

Values of the 1 hr. averaged magnetic field as measured by Smith et al (1976) were first resolved into dipolar $\rho$, $\phi$, and z components and values of the dipolar components $B_\rho^{dip}$, $B_\phi^{dip} = 0$, and $B_z^{dip}$ subtracted from the data. The dipole was taken to be centered with parameters otherwise characteristic of the $D_4$ model (Smith et al. 1976), viz. moment $\mu = 4.225$ Gauss $R_J^3$, $10.8^o$ inclination with respect to ecliptic north, and System III longitude $231^o$ (Dec. 1974). The residual magnetic field $\underline{\Delta B}$ was then fit by a least squares method.

Data were considered for 27 one hour intervals centered on times beginning at 2043 on 12/1/73 and ending at 2243 on 12/2. During this time Pioneer moved from a Jovicentric radial distance of 42.4 $R_J$ to 25.2 $R_J$. It was noted that the primary spatial dependence of $\Delta B_\rho$ seemed to be a parabolic dependence on z, distance from the dipole equator. In fact there seemed to be two distinct parabolic variations with z depending on Pioneer's longitude with respect to the magnetic dipole axis. Allowing for a slower radial variation of $\Delta B_\rho$ by inclusion of the factor $\rho^{-n}$, we then fit the residual $\Delta B_\rho$'s in a least squares manner to two functions of the form

$$\Delta B_\rho = \frac{1}{\rho^n}(A_1 z^2 + A_2 z + A_3)$$

Data were grouped in longitudinal hemispheres of adjustable phasing and $A_1$, $A_2$, and $A_3$ determined separately for each hemisphere. We found that $n = 1.6$, that a division into longitudinal hemispheres separated by System III values $\lambda = 80^\circ$, $260^\circ$ best fit the data, and the following values of the coefficients in each hemisphere:

| | $80^\circ < \lambda < 260^\circ$ | $260^\circ < \lambda < 80^\circ$ |
|---|---|---|
| $A_1$ | 39.8 | 32.4 |
| $A_2$ | 303 | 358 |
| $A_3$ | -2110 | -26.4 |

(With these numerical values and $\rho$ and $z$ in $R_J$, $\Delta B_\rho$ is in units of $10^{-5}$Gauss).

Having thus determined an optimum hemispheric division, we next fit $\Delta B_\phi = B_\phi$, which showed similar parabolic z dependence, to the form

$$\Delta B_\phi = \frac{1}{\rho^m}(C_1 z^2 + C_2 z + C_3)$$

m was determined as 1.2 and the other coefficients found to be

| | $80^\circ < \lambda < 260^\circ$ | $260^\circ < \lambda < 80^\circ$ |
|---|---|---|
| $C_1$ | -4.37 | 6.66 |
| $C_2$ | -60.4 | 46.7 |
| $C_3$ | 294 | -54.7 |

Finally we noted that the residual

$$\Delta\tilde{B}_z = \Delta B_z - \frac{n-1}{\rho(n+1)} \; z\left(\frac{A_1 z^2}{3} + \frac{A_2 z}{2} + A_3\right)$$

(the second term arises from Maxwell's $\nabla\cdot\vec{B} = 0$ and the prescribed form of $\Delta B_\rho$) could be well fit by the juxtaposition of two linear dependences on $\rho$, $B_z$ being continuous but $\partial B_z/\partial\rho$ discontinuous at the joining radius $\rho = 27$. Thus

$$\Delta\tilde{B}_z = (D_1\rho + D_2)\; S\,(27-\rho) + (D_3\rho + D_4)\; S\,(\rho-27)$$

with $S(x)$ the step function: $S = 0$ for $x < 0$, $S = 1$ for $x > 0$.

The values of the coefficients are

| | $80^\circ < \lambda < 260^\circ$ | $260^\circ < \lambda < 80^\circ$ |
|---|---|---|
| $D_1$ | -2.42 | -2.53 |
| $D_2$ | 65.5 | 70.6 |
| $D_3$ | -.341 | -.588 |
| $D_4$ | 9.32 | 18.2 |

The model field, including both dipolar and non-dipolar components, is displayed in Figure 2, along with the experimentally measured field and the dipole component alone. Plotted are $|\vec{B}|$, the inclination of the field with respect to the scan plane (positive toward and negative away from the earth), and phase in the scan plane measured counterclockwise from ecliptic north.

The fit is quite good; however, the reader is cautioned that the fit has been made with a data set which includes a limited sampling of $\rho$, $\phi$, $z$. This fact plus the great arbitrariness in functional form which is available makes extrapolation off Pioneer 10's trajectory quite risky. With this proviso we note several properties of the model. There is a definite stretching of field lines in the radial direction, a stretching which is certainly greater than that of a dipole field but not as drastic as the distension observed on the outbound Pioneer 10 trajectory. The magnetospheric field lines which Pioneer 10 is on while at Jovicentric radial distances of 20-30 $R_J$ are closed (Figure 1). The hemispheric separation based on one hour averaged data is a rough one; however, it is evident that the character of the field depends on whether Pioneer 10 is moving downward ($260^o < \lambda < 80^o$) or upward ($80^o < \lambda < 260^o$) with respect to the dipole equator. When Pioneer is moving toward the dipole equator ($80 < \lambda < 260$), the field is much more distended than when it is moving down. As a measure of the variation between the two hemispheres, the field line passing through $z = -8.6$, $\rho = 26.6$ extends to $\rho = 37.5$ in the one hemisphere and to 32.7 in the other. The range $260 < \lambda < 80$ contains most of the magnetopause and bow shock crossings identified by Dessler (1978), and it is thus tempting to associate it with the "active hemisphere" (Vasyliunas 1975). However, it is in this hemisphere that we find the smaller field line inflation in the region 20-40 $R_J$.

Note that the gyradius $r_g$ of a 1 MeV proton in a 5γ field is $\sim .4\ R_J$ and hence generally much smaller than the radii of curvature $r_c$ of magnetic field lines (Figure 1). The ratio $r_g/r_c$ is largest near the equator, where $|\vec{B}|$ is weakest and $r_c$ smallest. The situation is not nearly as drastic as on the outbound orbit where the current sheet is much thinner (Goertz et al. 1976). Since magnetic moment conservation depends on the smallness of $r_g/r_c$, the likelihood of its violation is largest in the vicinity of the equator. Under such circumstances it is still legitimate to inter-compare off-equatorial fluxes assuming magnetic moment conservation.

## Particle Instrumentation and Observations

The particle data used in our analysis were taken with the GSFC/ University of New Hampshire instrument package on Pioneer 10 (Trainor et al., 1974; Stilwell et al., 1975). Observations were made in 8 sectors, $45^o$ each, in a plane perpendicular to the Pioneer spin axis. Continuous angular distributions were generated by an interpolation process which preserved the sector averages as well as the Fourier coefficients (with minor changes) up to the 4 $\theta$ term. The angular distributions of protons that would be measured by a corotating spacecraft were calculated from the observed distributions by using a rigid corotation model with the assumption that the plasma velocity has only a $\vec{\phi}$ component around Jupiter corresponding to $\kappa(r) = 0$ in Birmingham and Northrop (1978). The transformation is rather sensitive to the assumed proton energy spectrum. We used the spin-averaged spectrum given by McDonald et al. (1978) as the spectrum in the corotating frame and derived the look angle dependent spectrum in the fixed frame by the appropriate coordinate transformation. The differential rigidity spectrum is of the form $J(R) = K \exp-\{R/R_o\}$, with $R_o$ in the range of 9 to 11 MV during the period of interest. Intensity ratios at each angle were calculated by integrating the proton spectra in each coordinate frame between upper and lower energy thresholds. Look directions were transformed using the mean energy of the window. Both local and equatorial pitch angle distributions were calculated from these distributions by using the observed local magnetic field and the model field at the equator. One hour averages of the data were used to minimize the effect of temporal fluctuations.

All observations came from the LET II telescope which consisted of three well shielded Si detectors of 0.05 mm, 2.5 mm, and 2.5 mm thickness. Electrons were detected in the middle detector in anticoincidence with the front and back detectors. Integral thresholds of 0.37 and 1.02 MeV resulted in the detection of electron energies from threshold to about 2 MeV with monotonically decreasing sensitivity above 1.0 MeV. The effective energy of each channel is close to the threshold and the channels will be referred to as 0.5 and 1.3 MeV electrons. Ions were detected with the 0.05 mm front detector of LET II in anticoincidence with the other detectors. Intercomparison of rates between different telescopes on Pioneer has shown that the counts were predominantly due to protons in the energy range between 0.50 and 2.15 MeV and that the 1.80 to 2.15 MeV channel has a substantial alpha contribution (Schardt et al., 1978). Since our analysis is essentially independent of particle type, the proton alpha ratio is only of secondary importance.

The spin averaged electron fluxes are shown in figure 3. At 1336 on 1 December 1973, Pioneer 10 crossed the magnetopause which had moved inward in response to a fast solar wind stream (Smith, et al. 1978). A regular 10 hour variation in counting rates is clearly visible from 000 on 2 December until Pioneer entered the inner magnetosphere on 3 December. Equatorial electron fluxes increased in magnitude proportionally to $R^{-5.5}$, except that the flux at 40 $R_J$ was substantially higher than would be expected by extrapolating intensities observed at the other equatorial crossings. Although no unique interpretation can be given, it is plausible that Pioneer 10 observed an enhanced particle flux at that time due to the recent perturbation of the magnetosphere by the solar wind.

Most of the time the electron angular distributions were nearly isotropic with only a 5 to 15% $\sin^2\delta$ term. A substantial anisotropy was observed from 0113 to 0413 on 12/3. The most extreme distribution is shown in the insert of figure 3 and corresponds to a $(1-0.80 \sin^2\delta)$ distribution. At $B_o/B = 0.5$, the spin-average flux from this pitch angle distribution would be 1.33 times that from an isotropic equatorial distribution with the same average flux as the actual distribution. However, away from the equator at a higher field strength, the magnetic field made about a $45^o$ angle to the scan plane, and therefore the average flux observed there was increased by only 17%. Since these corrections are relatively small and uncertain, we treated the electron flux as isotropic.

The average proton counting rates are shown in figure 4. The equatorial flux is almost independent of radial distance between 25 and 40 $R_J$. As in the case of electrons, a larger flux was observed at 000 on 2 December than predicted by extrapolating the other flux maxima. Short period variations are superimposed on the regular 10 hour flux modulation. The 1 hour averages eliminate most of these. Still the maximum in the 1 hour averages may occur somewhat displaced from the plasma sheet crossing as deduced from magnetic field data (Kivelson et al. 1977). We estimate the residual flux uncertainty to be 30 per cent or less. This amount is sufficient to explain the apparent discrepancy between the position of the flux maxima and the magnetic equator. Therefore we consider discrepancies larger than this as significant. Figure 5 shows the proton pitch angle distribution observed at the flux maxima near the equator. Both the angular dependence and absolute intensities are almost the same at 35.4 and 30.1 $R_J$; some increase in intensity but little change in shape was observed at 21.6 $R_J$. On this basis we believe that the equatorial proton flux intensities can be approximated by interpolating between the observed proton maxima.

Interpretation

We can be reasonably certain that Pioneer 10 on its inbound trajectory did not cross open field lines after 1500 on 12/2/73. As shown in figure 1, the model field lines are closed, with the longest one extending to 37 $R_J$, well within the Alfven radius. The equator of the model field falls somewhat above the dipole equator for the hemisphere $80 < \lambda < 260^{\circ}$. The centrifugal force on the equatorial plasma would prevent the actual equator from moving as far south or north as the dipole equator. Our model does not reflect this motion; as a result we estimate at most a 1 $R_J$ uncertainty in the radial position at which field lines cross the equator and this is smaller than the inherent uncertainties of a model.

As shown in figure 1, the Pioneer trajectory from 1600 to 2100 on 2 December would have been along a magnetic field line if the field were dipole-like. In that case Liouville's theorem would predict a constant counting rate for electrons rather than the observed decrease of almost an order of magnitude (Fig. 3). If the simple version of Liouville's theorem is applicable, then we can determine the equatorial crossing of the field lines by comparing observed counting rates after 1500 on 12/2 with the equatorial fluxes derived from an interpolation between observations at 0845 and 1645 on 12/2 and 0245 on 12/3. This approach is reasonably good even from 0100 to 0400 on 12/3 when the electron flux is anisotropic (insert Fig. 3) because the required corrections are small compared to the $R^{-5.5}$ slope of the equatorial flux. The major source of error are probably short period intensity fluctuations, which introduce a maximum error of about 5% into the deduced L values. Figu. shows the L values along the Pioneer 10 trajectory as derived from our field model and from electron fluxes at 2 energies. We are using L to represent the radial distance at which the field line through the spacecraft crosses the magnetic equator. The magnetic field model has a discontinuity near $\lambda = 80^{\circ}$ where the two hemispheres are joined. Since this is an artifact of the model, a smooth interpolation was used to join the two hemispheres. A noticable adjustment was required only at 1643 on Dec 2, 1973 and amounted to increasing the model field L value from 33 to 35 $R_J$. The agreement between the model and the values from the 1.3 MeV electrons is as good as can be expected. Near 19 $R_J$ the L value from electrons peaks one hour before the model; this is probably due to a decrease in field sweep back. By definition, the L values derived from 1.3 and 0.5 MeV electrons agree at flux maxima, 29.5 and 22.5 $R_J$. The lower energy electrons, however, predict consistently larger L values near flux minima.

In contrast to the electron data, the equatorial proton flux (Fig. 4) is relatively independent of distance from Jupiter. Since the angular distribution changes substantially between flux maxima and minima, it is important to intercompare observed fluxes at equivalent pitch angles in the corotating coordinate system. Figure 7 shows the observed angular distributions after transformation into this system. In interpreting figure 7 it should be remembered that the distributions are based on 8 sector measurements, each covering $45^o$; thus any features with a higher angular resolution are just one of many ways of interpreting the original measurements. The distributions between 0 and $180^o$ relative to the field projection into the scan plane are not quite symmetrical with those between 0 and $-180^o$. These observations correspond to the same pitch angles but different phase angles around the field. This nongyrotropic feature of the distributions is probably primarily due to a flux gradient perpendicular to $\vec{B}$, but uncertainties in the correction for corotation may also be a significant contributor. The near equatorial distributions at 30.1 and 29.4 $R_J$ are distinctly pancake. In addition the distributions are non-symmetric about $90^o$ pitch angles with slightly more particles moving counter to $\vec{B}$ than along $\vec{B}$. In contrast, the distributions at flux minima, 26.7 and 26.0 $R_J$, are more nearly circular but with a large excess of particles moving down the field line as compared to those returning after having mirrored.

A direct comparison of intensities cannot be made in figure 7 because of differences in field strength and angle between the field and the scan plane. These variables are eliminated in figure 8, which shows the equivalent equatorial pitch angle distributions. For the transformation we used the observed field at the spacecraft and equatorial field values from the model. Figure 8a corresponds to L values over which the equatorial flux of 1.9 MeV protons is essentially constant; thus the different curves should coincide at overlapping pitch angles. Errors due to counting statistics are insignificant but as much as $\pm 30$ percent differences could be caused by temporal fluctuations. Counter to predictions, a 5 to 1 intensity change occurs between the magnetic equator and measurements taken about 8 $R_J$ below the equator. The same pattern, in reverse order, occurs as the magnetic equator dipped down again towards Pioneer (Fig. 8b). During this time period, however, the equatorial flux at the L values crossed by Pioneer 10 increased somewhat (Fig. 4), and the angular distributions shown in figure 8b were normalized to the flux observed at 30.1 $R_J$.

The 0.7 MeV proton channel (0.5 - 2.15 MeV) was analyzed in the same fashion (Fig. 9). To compensate for the dependence of equatorial flux intensity on distance, all fluxes were normalized to 28.9 $R_J$ by using the L values from the model field. The use of slightly larger L values as indicated by the electron observations (Fig. 6) would not have made a significant change. In this case, our observations between 26.7 and 29.4 $R_J$ are in agreement with Liouville's theorem, but this agreement breaks down from 26 to 23 $R_J$. The minimum flux is only about 1/3 of what would be expected.

These results are summarized in figure 10, which shows relative equatorial intensities in a $5^{o}$ pitch angle range centered at 37.5 and 180-37.5 degrees. Observations at the two phase angles were averaged and divided by their value at 30.1 $R_J$. The solid line labeled model represents the ratios that would be expected on the basis of Liouville's theorem. L values derived from the magnetic field model were used to interpolate between flux maxima at these pitch angles. Substantial disagreement with theory exists for both energy groups between 23 and 27 $R_J$. This distance happens to coincide with the position of Callisto at 26.6 $R_J$ but the L values along the trajectory are mostly larger than 26.6 (Fig. 1 and 6) and cross field diffusion in this region should be too rapid to permit a major depression in the average flux. Good agreement exists between model and observations inside of 23 $R_J$.

Conclusions

We have tried to explain the observed 10 hour modulation of the electron and proton fluxes between 20 and 30 $R_J$ on the basis of adiabatic theory and assumed symmetry with jovigraphic longitude. Such symmetry might be expected if particles can complete several drift orbits. The L values (field line crossings of actual magnetic equator) for the Pioneer 10 inbound trajectory from 20 to 30 $R_J$ can then be derived in two ways; a) from electron flux intensities, Liouville's theorem, and adiabatic theory and b) from a magnetic field model that fits the observed field in both direction and magnitude. The rms difference of 1.5 $R_J$ between the L values derived from 1.3 MeV electrons versus the field model is not significant in view of the uncertainties involved. Short term variation in flux may be as much as 30 percent which corresponds to a 2 $R_J$ error in the deduced L value. The consistent difference between L values derived from 1.3 and 0.5 MeV electrons is probably most easily explained in terms of a change in the electron spectrum. Latitudinal dependent changes in the electron spectrum were already noted by several authors (Simpson and McKibben 1976, Baker and Van Allen 1976). Relatively large changes occur above 5 MeV and have been attributed to differences in the equatorial pitch angle distributions. For the two energy groups used here, however, the equatorial pitch angle distributions are essentially identical and we have to look for a different explanation. One such explanation would be a dependence of the energy spectrum on System III longitude which is co-rotating with Jupiter. Such a dependence might arise if the electron spectrum depends on equatorial plasma parameters which in turn depend on the magnetic field strength at low altitudes and the consequent structure of the ionosphere (Dessler, 1978; Hill and Dessler, 1976). Note that the Pioneer positions at $2^{\circ}$ magnetic latitude and $-19^{\circ}$ magnetic latitude are separated by $\sim 180^{\circ}$ in System III longitude.

Alternatively, the electron spectrum may vary with azimuth defined in the Jovigraphic equatorial plane with respect to the Jupiter-sun line and independent of Jupiter's rotational phase. Magnetic field lines in the region traversed by Pioneer 10 are swept back, and according to our model the furthest field lines intercept the equator about $10^{\circ}$ towards the dawn. Thus while Pioneer 10 sampled equatorial electrons in situ at 20 to $25^{\circ}$ from the Jupiter sun line, it sampled electrons at 30 to $35^{\circ}$ when it was furthest away from the magnetic equator.

The large discrepancy between expected and observed intensities of energetic protons implies either that the equatorial flux is not independent of System III longitude or that the simple form of Liouville's theorem is not applicable. Off hand, a 5 to 1 change in 1.9 MeV proton flux due to the asymmetry in the planetary magnetic field appears unlikely but not impossible. Voyager with its lower inclination trajectory should be able to resolve this point.

It would not be surprising if a realistic theory of energetic proton motion has to allow for changes in proton energy and/or pitch angle. This is consistent with the result of Northrop et al. (1978) who found that the magnetic equator must be a source of energetic particles. Other observations such as rapid flux changes are also consistent with the presence of acceleration or deceleration processes. The larger effect in the 1.9 MeV proton channel may be due to the substantial admixture of alpha particles in this channel, or just due to the larger rigidity relative to the 0.7 MeV channel.

A contributing factor to the lower flux away from the equator may be slow magnetic field fluctuations. The one minute average field strength often changes over periods of 5 to 10 minutes by 30 to 50%. If such fluctuations occur randomly along a field line, then at any given time there may be a stronger field region between Pioneer 10 and the equator than the local field at the spacecraft. If of sufficient spatial extent, such a magnetic enhancement would block equatorial particles in a whole range of otherwise allowed pitch angles. McDonald and Trainor (1976) have shown that protons stream along field lines toward Jupiter. Northrop et al. (1978) found that as much as 25% of the population may be lost out of the energy channel in 1/2 of a bounce period which is 2.5 to 3.8 minutes for 1.9 MeV protons at L = 27 and a dipole field. Consequently the proton flux would decrease rapidly in the blocked off section of the flux tube. Such an effect would not be significant for electrons because no field aligned streaming has been observed. In summary, a unique process responsible for our observations cannot be identified on the basis of the available data. It appears probable, however, that substantial changes occur in proton energy and/or pitch angle during one-half bounce period.

Acknowledgements

The authors are greatly indebted to Dr. F. B. McDonald for granting us free access to the energetic particle data and to Dr. E. Smith for 1 minute and 1 hour average magnetic field data. Illuminating discussions with Dr. T. G. Northrop are gratefully acknowledged.

Baker, D. N. and J. A. Van Allen, Energetic Electrons in the Jovian Magnetosphere, J. Geophys. Res. 81, 617, 1976.

Barish, F. D. and R. A. Smith, An Analytical Model of the Jovian Magnetosphere, Geophys. Res. Lett. 2, 269, 1975.

Birmingham, T. J. and T. G. Northrop, Theory of Flux Anisotropies in a Guiding Center Plasma, to be published in J. Geophys. Res. 1978.

Dessler, A. J., Longitudinal Control of Jovian Magnetopause Motion to be published 1978.

Fillius, R. W., The Trapped Radiation Belts of Jupiter, T. Gehrels, ed., Univ. of Arizona Press, p.896, 1976.

Goertz, C. K., D. E. Jones, B. A. Randall, E. J. Smith and M. F. Thomsen, Evidence for Open Field Lines in Jupiter's Magnetosphere, J. Geophys. Res. 81, 3393, 1976.

Hill, T. W., and A. J. Dessler, Longitudinal Asymmetry of Jovian Magnetosphere and the Periodic Escape of Energetic Particles, J. Geophys. Rev. 81, 3383, 1976.

Kennel, C. F. and F. V. Coroniti, Jupiter's Magnetosphere, published in Annual Reviews of Astronomy and Astrophysics 15, 389, 1977.

Kivelson, M. G., P. J. Coleman, Jr., R. L. Rosenberg, E. J. Smith, Jupiter's Magnetospheric Field from Measurements of the Helium Vector Magnetometers on Pioneers 10 and 11 - A Compendium of Plots, U.C.L.A. Publication number 1702, 1977.

McDonald, F. B., A. W. Schardt, and J. H. Trainor, A Study of Energetic Ions in the Jovian Magnetosphere, to be published, 1978.

McDonald, F. B. and J. H. Trainor, Observations of Energetic Jovian Electrons and Protons, in Jupiter, T. Gehrels ed., Univ. of Arizona Press, p. 961, 1976.

Mead, G. D., Magnetic Coordinates for the Pioneer 10 Jupiter Encounter, Journal Geophys. Res., 79, 3514, 1974 and private communications.

Northrop, T. G., T. J. Birmingham, A. W. Schardt, Anisotropies in the Flux of Pioneer 10 Protons, to be published in J. Geophys. Res. 1978.

Northrop, T. G., Angular Distribution of Particle Fluxes in Rotating Systems, J. Geophys. Res. 81, 5150, 1976.

Schardt, A. W., F. B. McDonald, J. H. Trainor, Acceleration of Protons at 32 Jovian Radii in the Outer Magnetosphere of Jupiter, J. Geophys. Res. 83, 1104, 1978.

Simpson, J. A. and R. B. McKibben, Dynamics of the Jovian Magnetosphere and Energetic Particle Radiation, in Jupiter, T. Gehrels, ed., Univ. of Arizona Press, p.738, 1976.

Smith, E. J., L. Davis, Jr., D. E. Jones, P. J. Coleman, Jr., D. S. Colburn, P. Dyal, C. P. Sonett, and A. M. Frandsen, The Planetary Magnetic Field and Magnetosphere of Jupiter: Pioneer 10, J. Geophys. Res., 79, 3501, 1974.

Smith, E. J., R. W. Fillius and J. H. Wolfe, Compression of the Jovian Magnetosphere by the Solar Wind, to be published in J. Geophys. Res. 1978.

Smith, E. J., L. Davis, Jr., and D. E. Jones, Jupiter's Magnetic Field and Magnetosphere, in Jupiter, T. Gehrels, ed., Univ. of Arizona Press, p.788, 1976.

Stilwell, D., R. M. Joyce, J. H. Trainor, H. P. White, Jr., G. Streeter, and J. Bernstein, Pioneer 10/11 and Helios A/B Cosmic Ray Instruments, IEEE Trans. Nucl. Sci. 22, 570, 1975.

Trainor, J. H., F. B. McDonald, B. J. Teegarden, W. R. Webber and E. C. Roelof, Energetic Particles in the Jovian Magnetosphere, J. Geophys. Res. 79, 3600, 1974.

Van Allen, J. A., High Energy Particles in the Jovian Magnetosphere, in Jupiter, T. Gehrels, ed., Univ. of Arizona Press, p.928, 1976.

Vasyliunas, Vytenis M., Modulation of Jovian Interplanetary Electrons and the Longitude Variation of Decametric Emissions, Geophys. Res. Lett. 2, 87, 1975.

## Figure Captions

Figure 1 The Pioneer 10 inbound trajectory is represented in magnetic dipole coordinates with 1 hour tick marks; also shown are the L = 30 dipole field line and model field lines. Model field lines intersecting the trajectory between 18 and 21 on 12/2/73 correspond to $260 < \lambda < 80^{o}$, and those between 21 on 12/2 and 01 on 12/3/73 correspond to $80 < \lambda < 260^{o}$.

Figure 2 The Jovian magnetic field observed during the inbound pass of Pioneer 10 is shown in a histogram. The $D_4$ field is shown as the second histogram. The points were calculated from the field model. The direction angle $\theta_B$ is the inclination of the field relative to the scan plane (positive toward earth, negative away), and $\phi_B$ is the angle in the scan plane measured counterclockwise from North.

Figure 3 The histogram gives one hour averaged counting rates of the 1.3 MeV electron channel of LET II. Inserts show pitch-angle distributions over the range of angles sampled. The two pitch-angle distributions shown in each insert differ by $180^{o}$ in gyro-phase angle.

Figure 4 One hour averaged counting rates are plotted for protons in the energy ranges from 0.50 to 2.15 MeV and 1.80 to 2.15 MeV, with mean energies of approximately 0.7 and 1.9 MeV, respectively.

Figure 5 Pitch-angle distributions of 1.9 MeV protons at the equator are shown as they would be observed by a detector corotating with Jupiter.

Figure 6 The L values of the Pioneer 10 trajectory derived from 0.5 MeV electrons are shown as solid dots and those from 1.3 MeV electrons as X's. The solid line represents model field values with a smooth interpolation used to join values in different hemispheres.

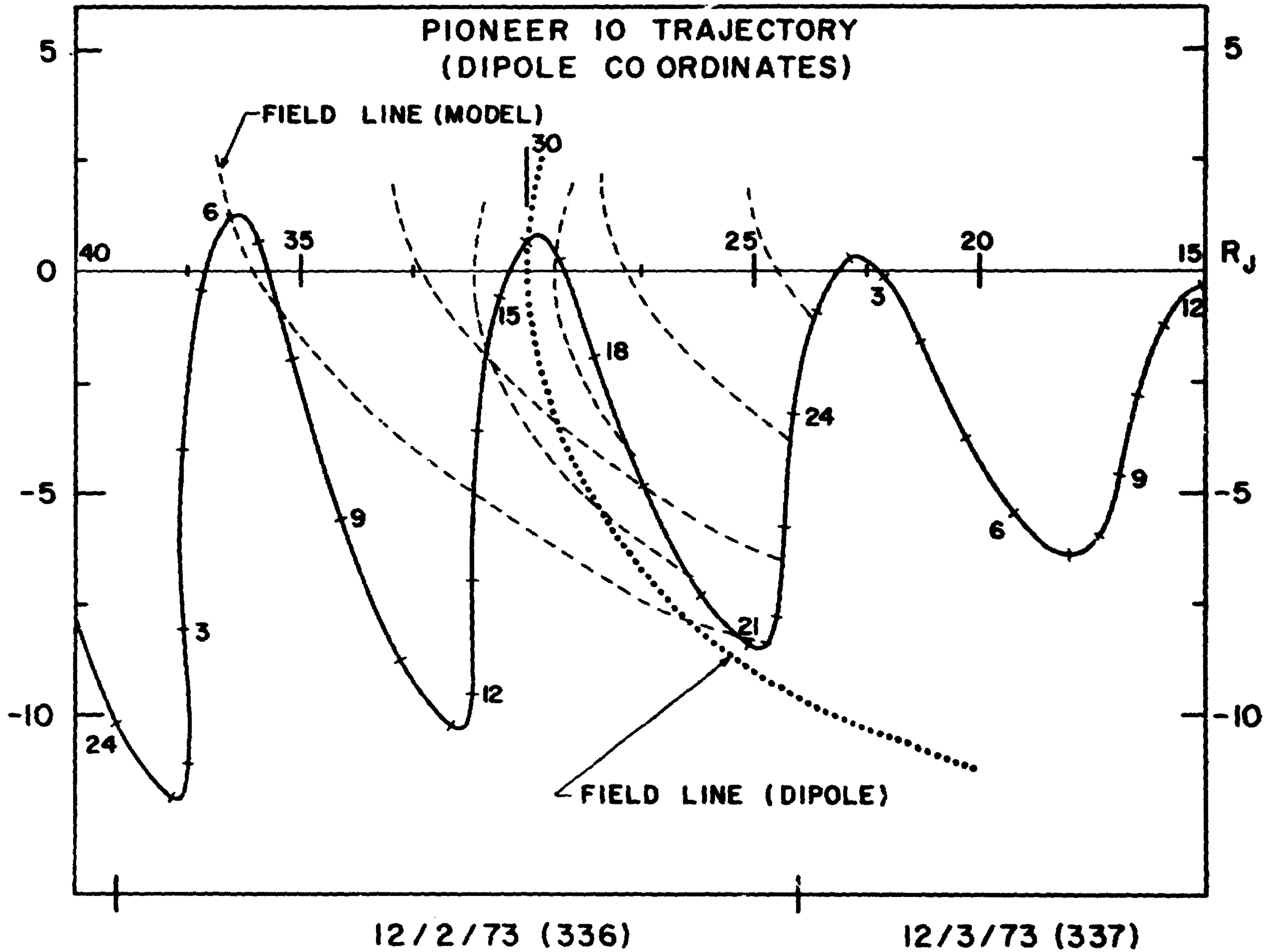
Figure 7 Angular distributions of 1.9 MeV protons corrected for corotation are shown relative to the projection of the magnetic field into the scan plane. Horizontal and verticle tick marks correspond to 10 counts/sec.

Figure 8 Corrected angular distributions of 1.9 MeV protons are shown transformed to their equatorial pitch angles. Intensities have been normalized to average equatorial intensities for $L \geq 29$ $R_J$. Normalization factors are 1.00 for $R \geq 25.3$ $R_J$ and 1.16, 1.44, 1.51, 1.54 for R = 23.8, 23.1, 22.4 and 21.6 $R_J$, respectively.

Figure 9 Corrected angular distributions of 0.6 MeV protons are shown transformed to their equatorial pitch angles. Equatorial intensities were first normalized to the intensity at 28.8 $R_J$. By using L values for the Pioneer trajectory derived from the field model, we found normalization factors by which the observed fluxes had to be divided.

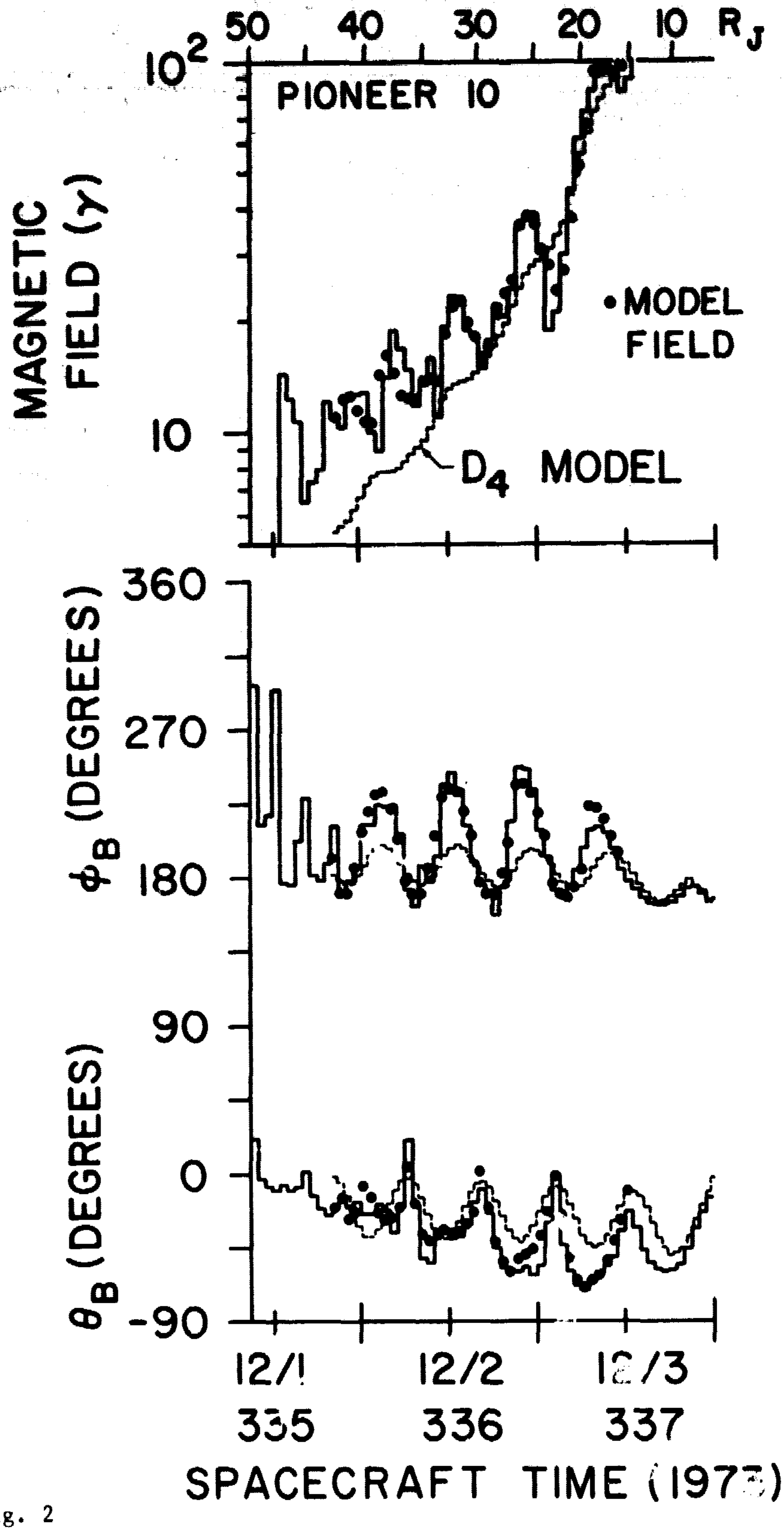
Normalization factors for 9a are 0.94 at 29.4 $R_J$, 0.81 at 27.4 $R_J$, 0.66 at 26.7 $R_J$, and 0.62 at 26.0 $R_J$. Factors for 9b are 1.00 at 25.3 $R_J$, 1.22 at 23.8 $R_J$, 1.70 at 23.1 $R_J$, 1.80 at 22.4 $R_J$ and 2.08 at 21.6 $R_J$. Tick marks on x and y axis are shown every 100 counts/sec.

Figure 10 Relative equatorial fluxes in a $5^o$ pitch angle range centered at $37.5^o$ are shown with solid dots and $142.5^o$ with X's. If no observations were available in these two ranges, values in a range $5^o$ on either side were used and are indicated by encircled symbols. Values at the two phase angles were averaged and divided by their average at 30 $R_J$. The solid line was derived from field model L values and equatorial fluxes at these pitch angles.



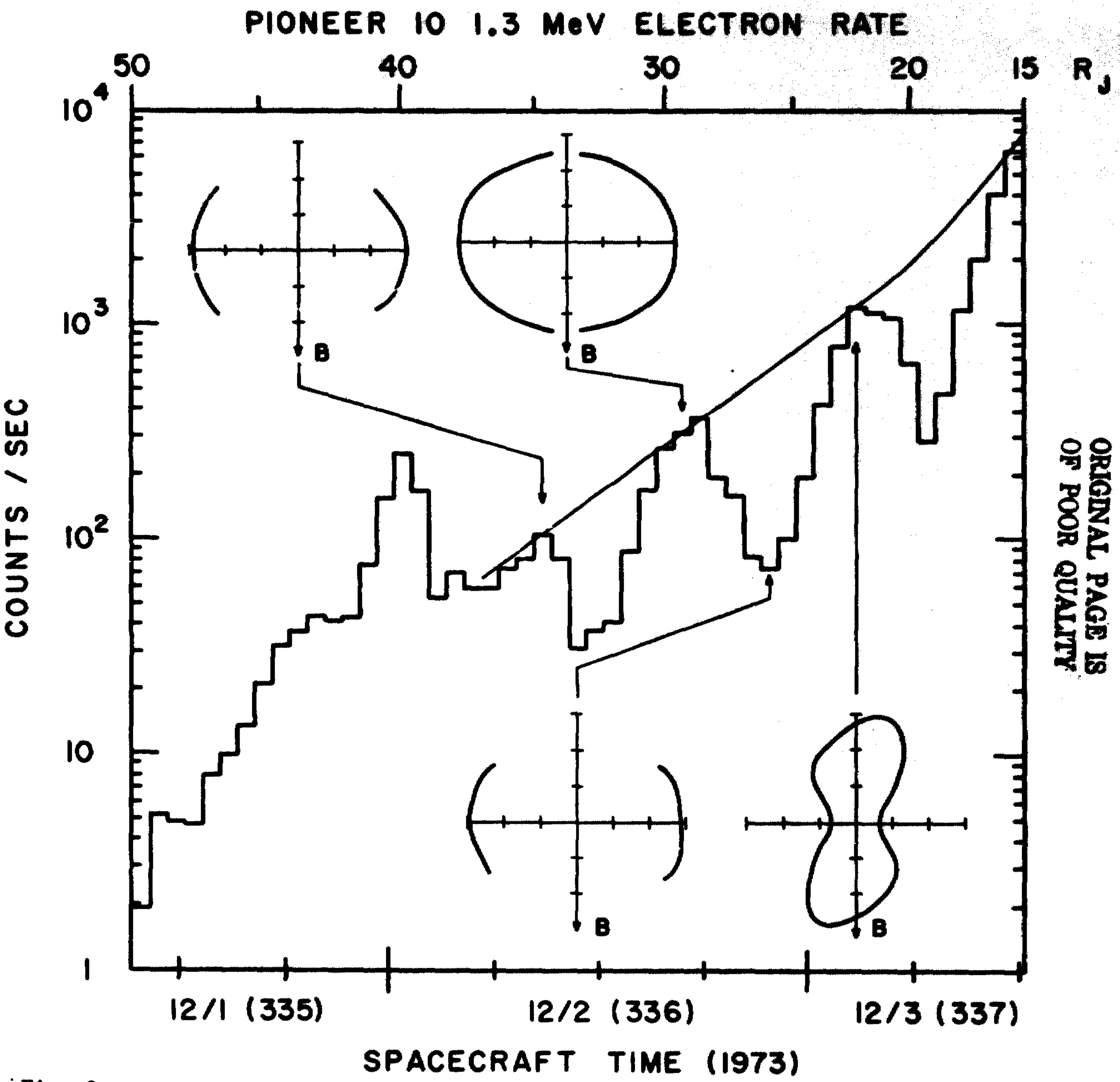

ORIGINAL PAGE IS OF POOR QUALITY

Fig. 1



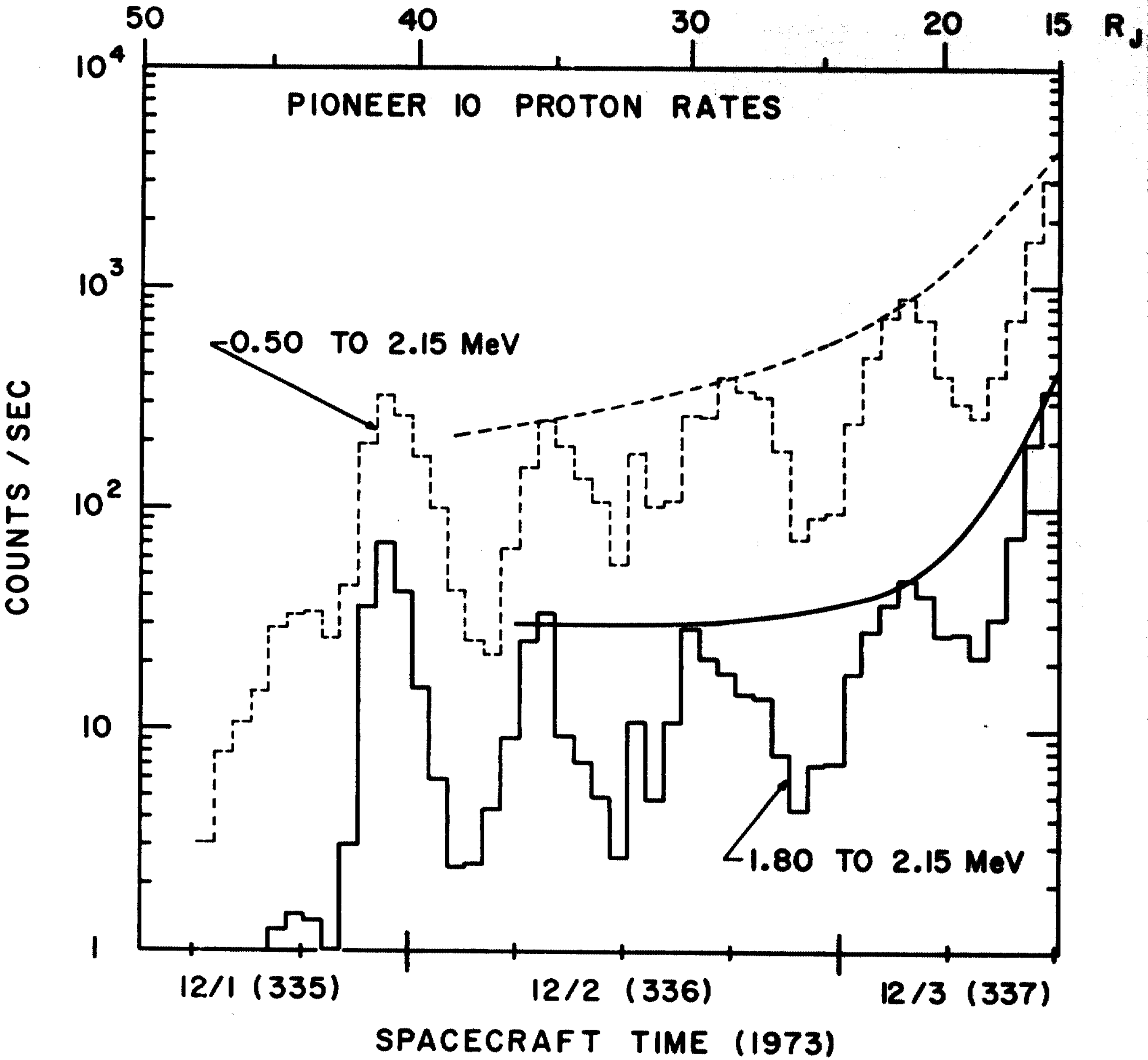
50
40
30
20
10
R_J
10^2
PIONEER 10
MAGNETIC FIELD (γ)
• MODEL FIELD
10
D_4 MODEL
360
270
φ_B (DEGREES)
180
90
θ_B (DEGREES)
0
-90
12/1
335
12/2
336
12/3
337


Fig. 2



PIONEER 10 1.3 MeV ELECTRON RATE
50
40
30
20
15
$R_J$
$10^4$
$10^3$
$10^2$
10
1
COUNTS / SEC
B
B
B
B
12/1 (335)
12/2 (336)
12/3 (337)
SPACECRAFT TIME (1973)


Fig. 3



PIONEER 10 PROTON RATES
50
40
30
20
15
R J
10^4
10^3
10^2
10
1
COUNTS / SEC
0.50 TO 2.15 MeV
1.80 TO 2.15 MeV
12/1 (335)
12/2 (336)
12/3 (337)
SPACECRAFT TIME (1973)


Fig. 4

PIONEER 10 PITCH ANGLE DISTRIBUTION AT EQUATOR
(1.80-2.15 MeV PROTONS)

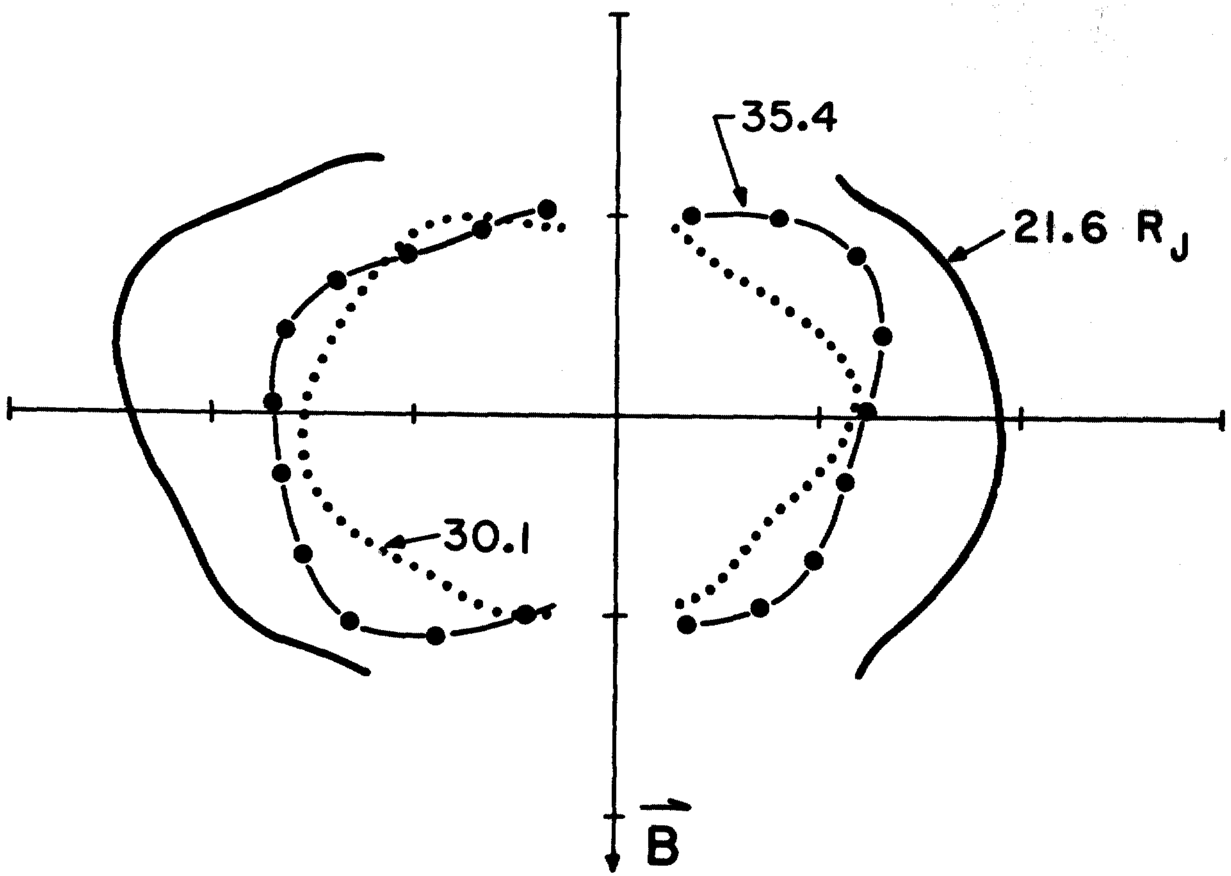
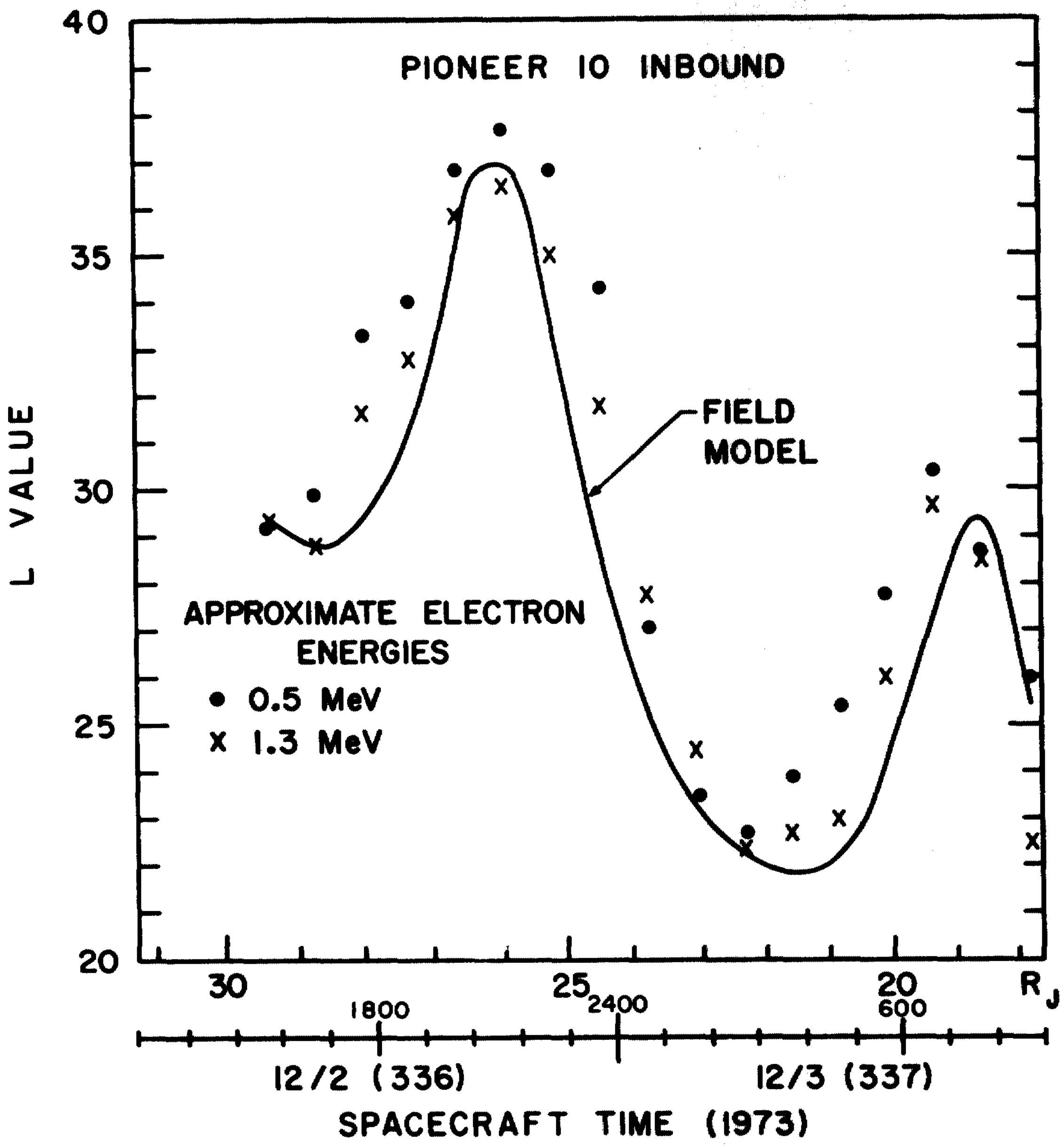


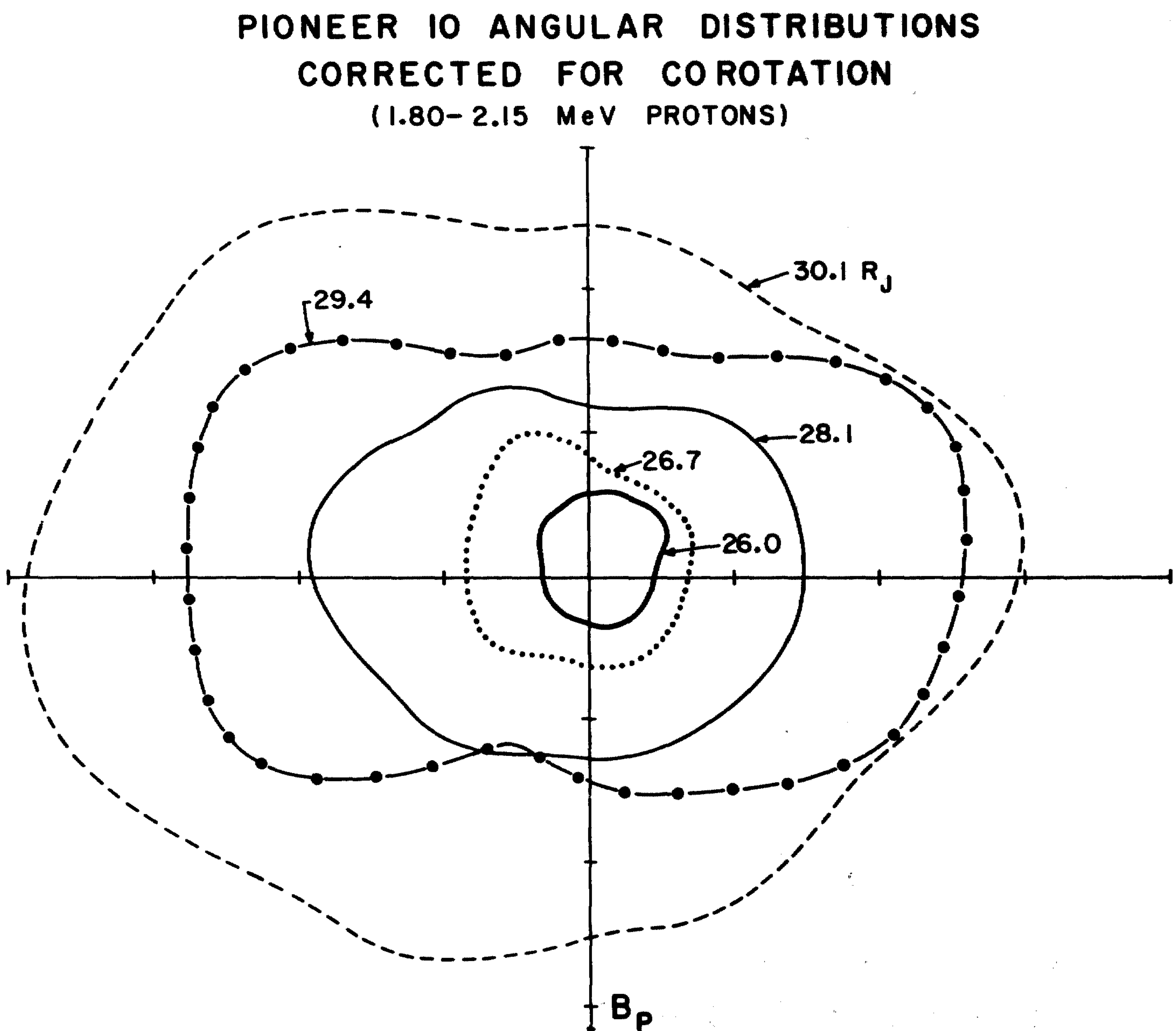



Fig. 5



PIONEER 10 INBOUND
FIELD MODEL
APPROXIMATE ELECTRON ENERGIES
● 0.5 MeV
X 1.3 MeV
L VALUE
40
35
30
25
20
30
25
20
RJ
1800
2400
600
12/2 (336)
12/3 (337)
SPACECRAFT TIME (1973)


Fig. 6



PIONEER 10 ANGULAR DISTRIBUTIONS
CORRECTED FOR COROTATION
(1.80-2.15 MeV PROTONS)
30.1 $R_J$
29.4
28.1
26.7
26.0
$B_P$


Fig. 7

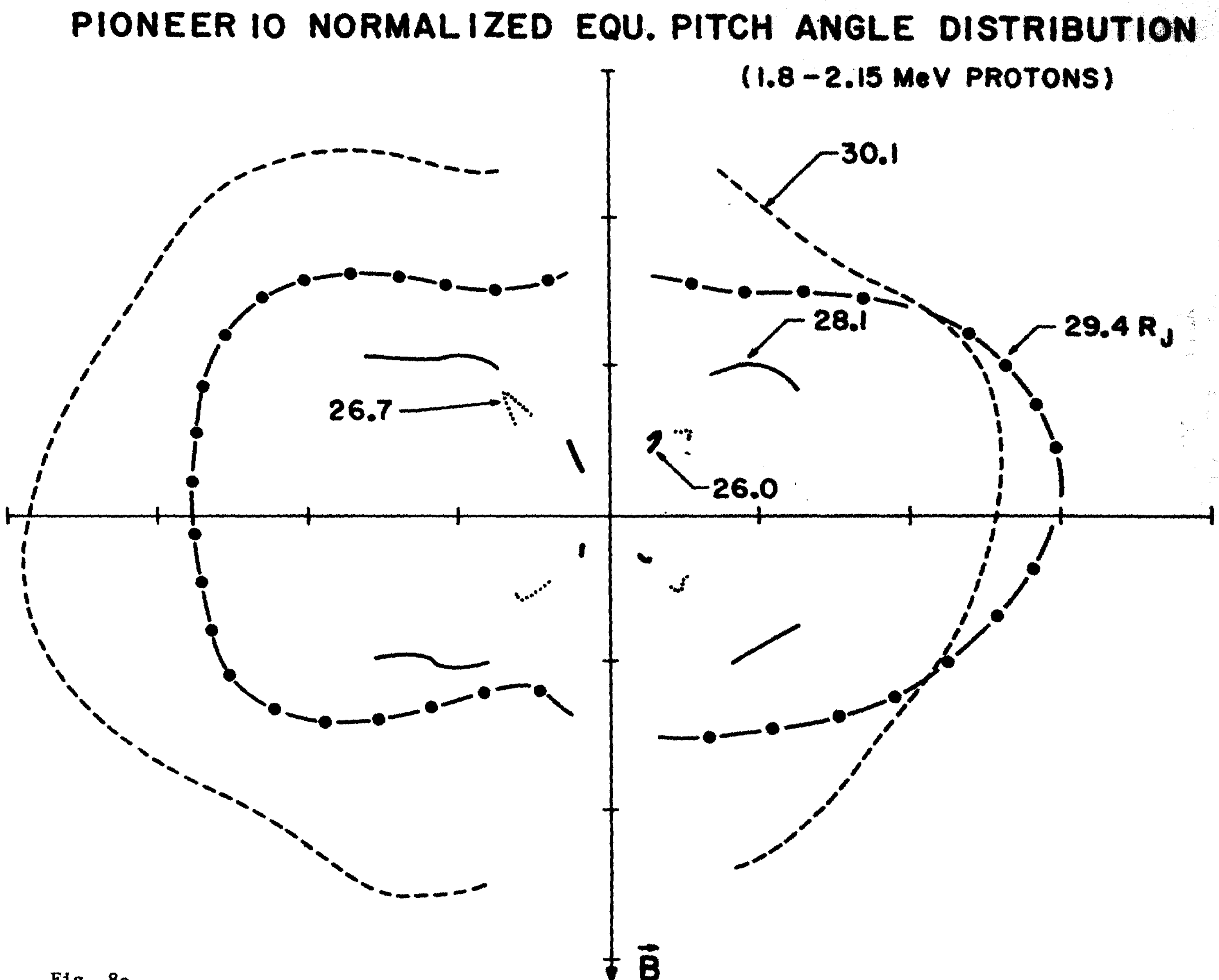

PIONEER 10 NORMALIZED EQU. PITCH ANGLE DISTRIBUTION
(1.8 - 2.15 MeV PROTONS)
30.1
28.1
29.4 R
J
26.7
26.0
B

Fig. 8a

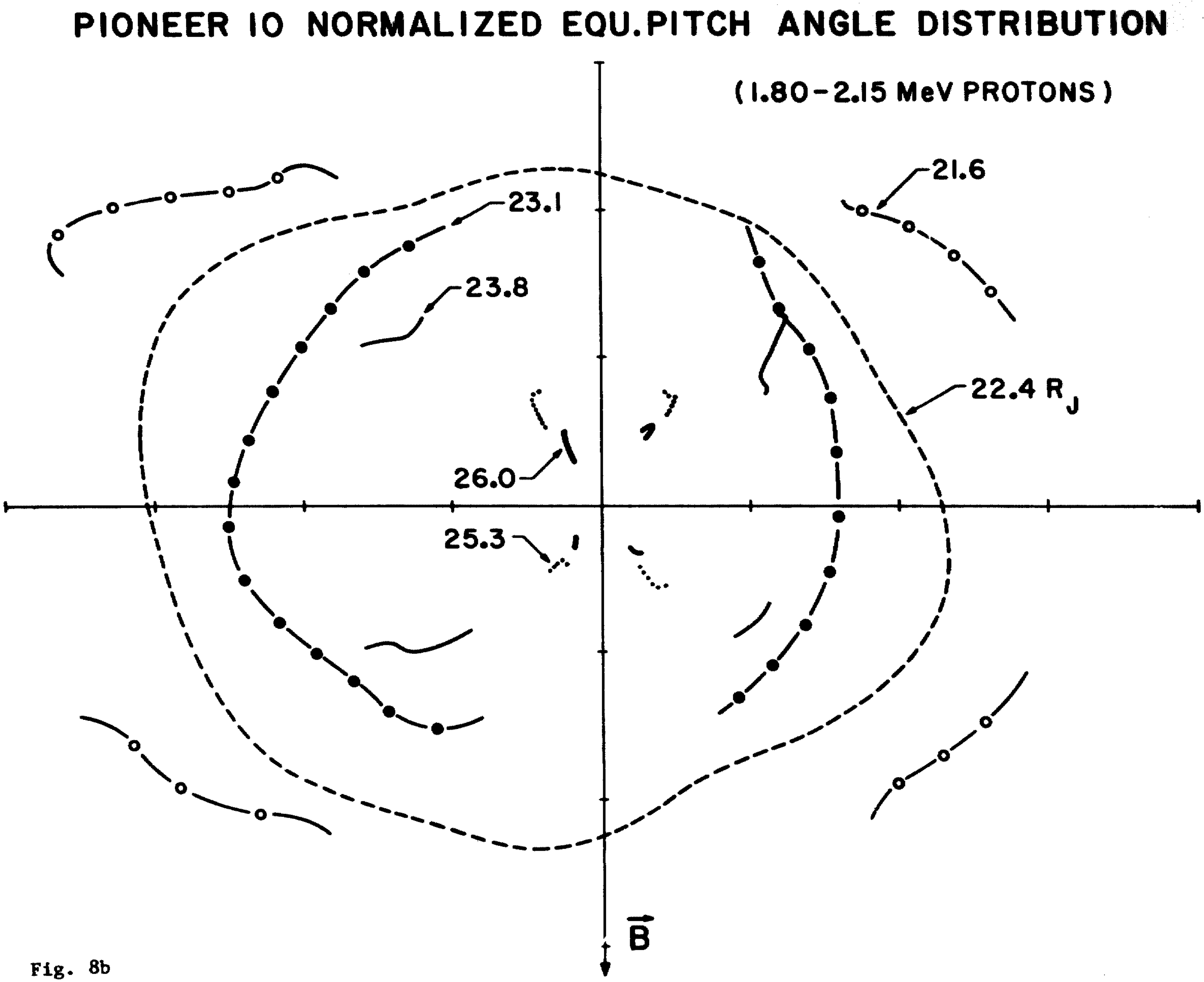

PIONEER 10 NORMALIZED EQU. PITCH ANGLE DISTRIBUTION
(1.80-2.15 MeV PROTONS)
21.6
23.1
23.8
22.4 $R_J$
26.0
25.3
$\vec{B}$

Fig. 8b

# PIONEER 10 NORMALIZED EQU. PITCH ANGLE DISTRIBUTION

(0.50 – 2.15 MeV PROTONS)

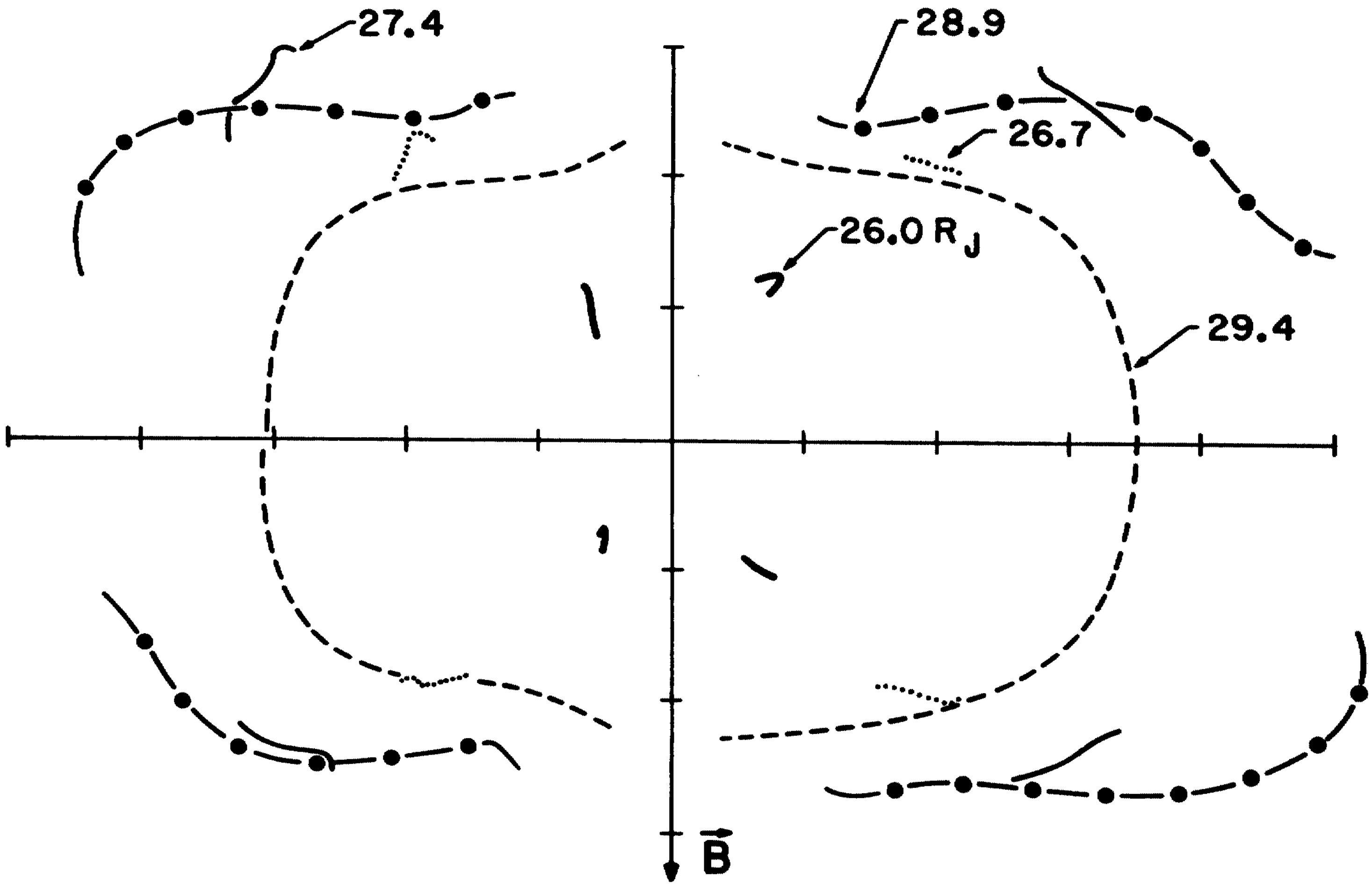



Fig. 9a

# PIONEER 10 NORMALIZED EQU. PITCH ANGLE DISTRIBUTION

(0.50-2.15 MeV PROTONS)

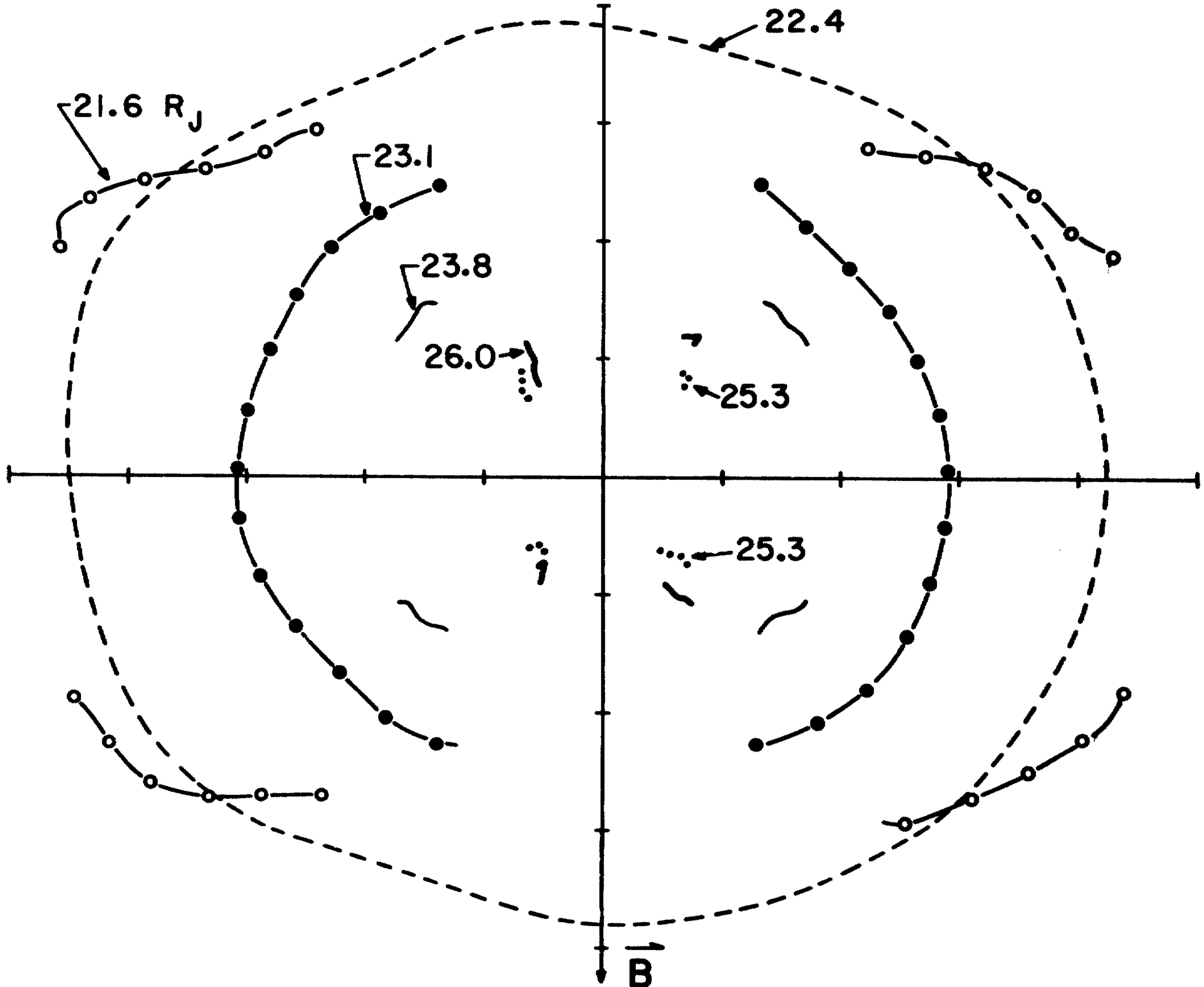



Fig. 9b

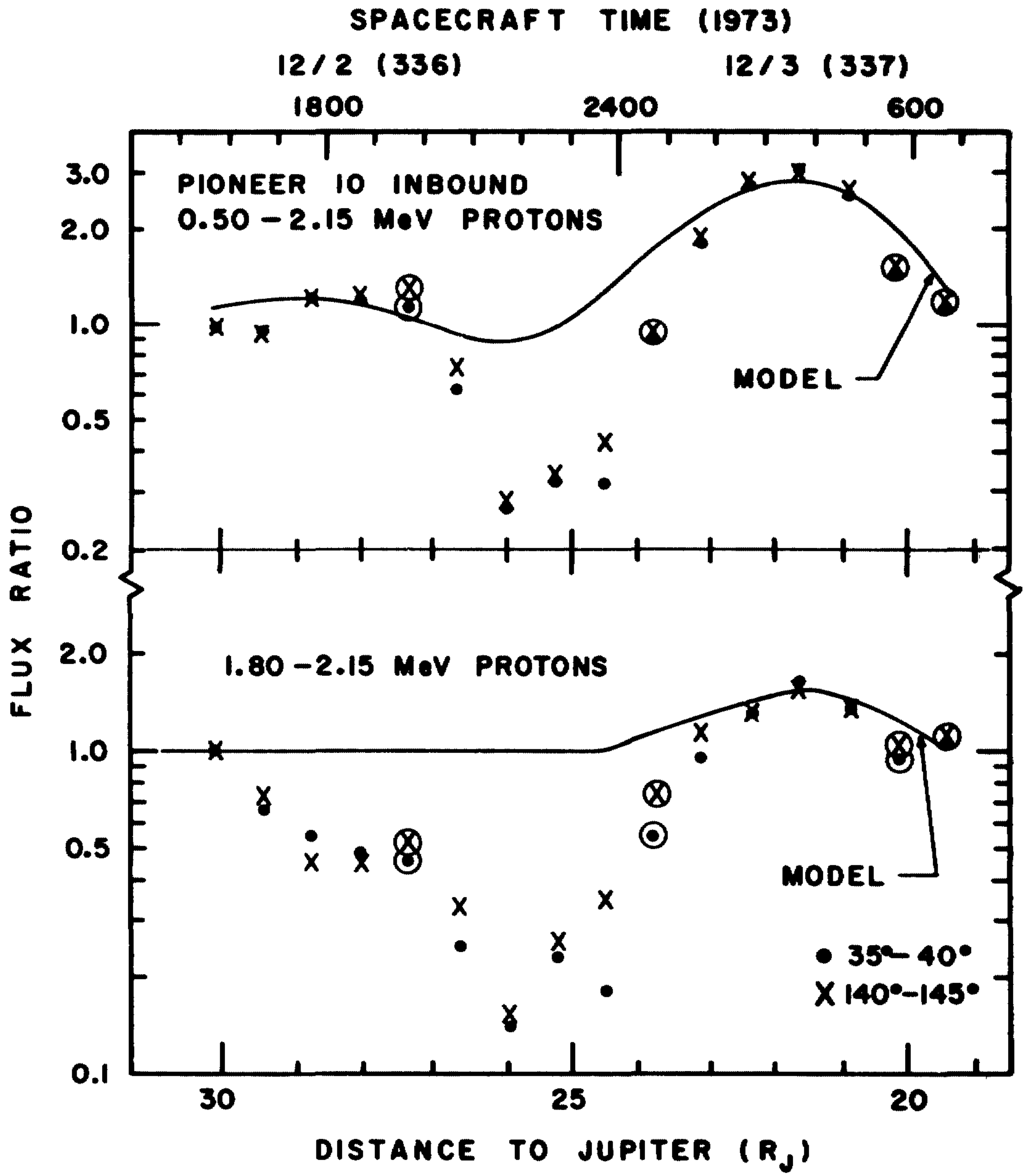

SPACECRAFT TIME (1973)
12/2 (336)
12/3 (337)
1800
2400
600
PIONEER 10 INBOUND
0.50 – 2.15 MeV PROTONS
MODEL
1.80 – 2.15 MeV PROTONS
MODEL
● 35°– 40°
X 140°–145°
FLUX RATIO
3.0
2.0
1.0
0.5
0.2
2.0
1.0
0.5
0.1
30
25
20
DISTANCE TO JUPITER ($R_J$)

Fig. 10

# BIBLIOGRAPHIC DATA SHEET

| | | |
|---|---|---|
| 1. Report No.<br>TM 79624 | 2. Government Accession No. | 3. Recipient's Catalog No. |
| 4. Title and Subtitle<br>Discrepancy in Proton Flux Extrapolation Along Field Lines in the Middle Jovian Magnetosphere | | 5. Report Date<br>August 1978<br>6. Performing Organization Code<br>660 |
| 7. Author(s)<br>A. W. Schardt and T. J. Birmingham | | 8. Performing Organization Report No. |
| 9. Performing Organization Name and Address<br>Code 660<br>Laboratory for High Energy Astrophysics<br>Greenbelt, MD 20771 | | 10. Work Unit No.<br>11. Contract or Grant No. |
| 12. Sponsoring Agency Name and Address | | 13. Type of Report and Period Covered<br>14. Sponsoring Agency Code |

15. Supplementary Notes

To be published in Journal of Geophysical Research

16. Abstract

Fluxes of energetic electrons and protons in Jupiter's outer magnetosphere were observed to be modulated with the 10 hour rotation period of the planet. This modulation is due to the concentration of particles at the magnetic equator: the non-alignment of Jupiter's spin and rotation axes causes Pioneer-10 to oscillate between +20° and -19° magnetic latitude and hence between regions of stronger and weaker fluxes. In this paper we investigate the relationship between electron and proton fluxes observed off the magnetic equator with those measured at the equatorial crossing radii of the same flux tubes. Liouville's theorem is applied with the assumption that particles move conserving their magnetic moments. A magnetic model which matches the intensity and direction of the magnetic field along the Pioneer 10 trajectory is used for determining the positions of the equatorial crossings. Energetic electrons (1.3 MeV) compared in this way appear to be consistently described. Protons, on the other hand, show much weaker fluxes at the off-equatorial points than would be predicted by this simple application of Liouville's theorem. Violation of the first adiabatic invariant is one explanation; other potential explanations depend on slow magnetic field fluctuations which are not included in the magnetic model and which conserve the first invariant or on a large asymmetry in equatorial proton flux as a function of system III longitude.

| | |
|---|---|
| 17. Key Words (Selected by Author(s))<br>Trapped particles, adiabatic theory, jovian magnetosphere, magnetic field model | 18. Distribution Statement |

| | | | |
|---|---|---|---|
| 19. Security Classif. (of this report)<br>UN | 20. Security Classif. (of this page)<br>UN | 21. No. of Pages<br>36 | 22. Price* |

*For sale by the National Technical Information Service, Springfield, Virginia 22151.

GSFC 25-44 (10/77)