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JOVIAN MODULATION OF INTERPLANETARY ELECTRONS AS OBSERVED WITH VOYAGERS 1 AND 2

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ABSTRACT

ORIGINAL PAGE IS OF POOR QUALITY

The release of magnetospheric electrons from Jupiter into interplanetary space is modulated by the Jovian rotation period. This effect was initially discovered by Pioneer 10, and the Voyager 1 and 2 observations permit a more detailed study of this modulation. It was found that the modulation period agrees on the average with the synodic period of Jupiter (9h 55m 33.12s), but over intervals of weeks it can differ from the synodic period by several minutes. The lack of exact synchronization is attributed to changes of the plasma population in the Jovian magnetosphere. Such changes affect the magnetic field sweep-back and departure from exact corotation. However, the magnetospheric asymmetry, which is responsible for the modulation, is always re-established at the same longitude. Thus no long term departures occur from the synodic period. The Jovian modulation appears to be a persistent feature of the interaction between the solar wind and the magnetosphere and the disappearance of the modulation away from Jupiter is attributed to interplanetary propagation conditions. This leads to the following limits on the diffusion coefficient for interplanetary electrons: $\kappa_{\perp} < 8 \times 10^{19}$ cm^2 s^{-1} and $\kappa_{\parallel} > 4 \times 10^{21}$cm^2 s^{-1}. Although modulation could be detected in interplanetary space out to only ~ 10^8 km from Jupiter, it was still detectable at 3.8 A.U. behind Jupiter in the far magnetotail. This requires a mean free path in the tail > 0.75 A.U. and good field connection along the tail to Jupiter. During two intervals, the electron spectrum was softer than the Jovian spectrum and was not modulated by the Jovian period. The time histories of these latter increases are similar to that of 30-60 MeV protons measured simultaneously by the same detector system. They are associated with large solar cosmic ray events at 1 A.U. and appear to be of solar origin.

Introduction

Between 1 and 10 A.U. the Jovian magnetosphere is the dominant source of 0.2 - 30 MeV electrons in the solar system. The time history of electron intensities and spectra provides significant information about interplanetary propagation conditions and solar wind - Jovian magnetosphere interactions. The Jovian origin of interplanetary electrons in this energy range was first established from Pioneeer 10 observations within 1 AU of Jupiter (Chenette et al. 1974, Teegarden et al. 1974). Furthermore, Teegarden et al. (1974) demonstrated that Jupiter is also the source of quiet time electrons near earth. Interplanetary propagation of the Jovian electrons has been studied extensively (see Conlon 1978 and references therein) and can be expressed as an asymmetric diffusion along and across interplanetary magnetic field lines. The cross-field diffusion is greatly reduced by corotating interaction regions (CIR's) which are formed when a fast solar wind stream overtakes a low velocity region (Smith and Wolfe, 1976). As a result, highest electron fluxes are observed when minimal-cross field diffusion is required between Jupiter and the observer and the flux is at a minimum when an interaction region exists between the two.

Near Jupiter, the electron flux and spectrum is often also modulated by Jupiter's rotation period, as first discussed by Chenette, Conlon and Simpson (1974) and Smith et al. (1976). The original observations with Pioneer 10 were confirmed with Pioneer 11 (Simpson et al. 1975) and Voyager 2 observations (Schardt et al. 1981). This modulation is best defined by changes in the electron spectrum which generally, but not always, becomes substantially softer once each rotation of Jupiter. The softening coincides near the magnetosphere with minima in the electron flux, with deeper minima occurring at the higher energies. The spectral rocking is a more sensitive measure of the Jovian modulation than the intensity itself because the electron flux at an appreciable distance from Jupiter is primarily controlled by interplanetary propagation conditions. Although the shape of the spectrum may also be changed during interplanetary propagation, any such effect is considerably smaller than the intensity modulation. The unique feature of the spectral rocking is that its phase appears to be independent of spacecraft position, and softest spectra occur when the subsolar Jovian longitude is about 240° (for a definition of system III, 1965, Jupiter longitudes see Seidelmann and Divine, 1977). For this reason the Jovian modulation is often referred to as 'clock' modulation.

The clock modulation is also present in the subsolar outer magnetosphere at distances beyond 45 R_J (Jovian radii). McKibben and Simpson (1974) proposed that the energetic electron flux in the whole outer magnetosphere may be time dependent and that interplanetary electrons reflect this dependence. Simpson et al. (1975) showed that, based on Jupiter's synodic period, the modulation observed with Pioneer 11 was in phase with Pioneer 10 observations. The Voyager 2 results (Schardt et al. 1981) obtained almost 6 years after the Pioneer 10 encounter were still in phase; this proved beyond any doubt that the phase of the modulation depends on the synodic period (9h 55m 33.12s) rather than the siderial period (9 h 55m 29.71s). The dependence on solar aspect proves that the modulation results from the interaction between the solar wind and the Jovian magnetosphere. Dessler and Hill (1975) proposed that an azimuthal asymmetry in the magnetospheric plasma population could cause the clock modulations. Since then a magnetic-anomaly model of the Jovian magnetosphere has been developed (Dessler and Vasyliunas 1979; Vasyliunas and Dessler 1981), to account for various phenomena which could result from such an asymmetry.

The purpose of this study was to determine whether the Jovian modulation of the electron flux is a general feature of the interaction between the solar wind and magnetosphere or whether it occurs only under special conditions. A detailed definition of the properties of the modulation should provide clues about the mechanism involved. The effect of interplanetary propagation conditions on the electron spectrum can be studied by exploring the region of space over which the Jovian modulation is observable. The Voyager 1 and 2 trajectories were well suited for the purposes of this study. As shown in Figure 1a, the trajectory stayed close to Jupiter's magnetotail for a long time and, because of good magnetic field connection to the tail, the electron flux was substantially larger than during the pre-encounter period. This long observation time permitted us to observe whether or not different interplanetary conditions, such as fast solar streams, effect the modulation. Of special interest was the passage of Voyager 2 near the far magnetotail at ~ 3.8 A.U. behind Jupiter (Fig. 1b). Finding modulation while Voyager 2 was immersed in the far tail would demonstrate relatively scatter-free propagation of electrons along the tail.

Special data-analysis techniques were required to extract the Jovian modulation as manifested by the spectral rocking from the raw data. We "averaged" over many modulation periods by adding counts observed during the same phase of the modulation. This process improves the counting statistics over those of a single period and provides some averaging over interplanetary modulation. If due to Jupiter, the modulation should disappear when this epoch analysis is carried out with periods that differ significantly from the Jovian synodic period. However, the electron modulation is not necessarily synchronized exactly with Jupiter's rotation because a slow drift in longitude of the causative agents, such as a region of enhanced plasma density, could lead to temporary departure from the synodic period of Jupiter.

The two largest electron increases observed when Voyager's 1 and 2 were more than 200 R_J beyond Jupiter (September 1979, May 1981) had different properties then those associated with Jovian electron events. They were accompanied by a simultaneous increase in energetic protons that extended to energies above 100 MeV. These are identified as solar cosmic ray events channeled through high field regions of the interplanetary medium.

Instrumentation and Analysis Techniques

Interplanetary electrons were detected with the High Energy Telescope, HET, (Fig. 2) of the Cosmic Ray Subsystem on the Voyager spacecraft (Stone et al. 1977). This instrument is sensitive to electrons entering through the B detectors, that is from below in Fig. 2. Electrons can be identified on the basis of a three-dimensional pulse height analysis of the energy lost in detectors B1, B2 and the total energy in C2+C3+C4. Events that trigger C_1 or the guard counter G are eliminated to minimize the background from penetrating radiation. In addition, three electron rate channels are formed on the basis of the following coincidence-anticoincidence combinations: $B_1\ B_2\ C_4\ \overline{C_3}\ \overline{G}\ \overline{SL}$, $B_1\ B_2\ C_4\ C_3\ \overline{C_2}\ \overline{G}\ \overline{SL}$, and $B_1\ B_2\ C_4\ C_3\ C_2\ \overline{C_1}\ \overline{G}\ \overline{SL}$; where SL is a slant threshold which is triggered by protons and other ions. This paper is based on the first and last of the three electron channels. Thus the low energy channel includes all electrons with a range between 4 and 10 mm of Si (approximately 2.6 to 5.1 MeV), and the high energy channel covers electrons with a range between 16 and 22mm of Si (approximately 8-12 MeV). The electron rates were chosen over the pulse-height analyzed events because of the better statistics. An analysis of some of the pulse height analyzed events gave similar results as the rate data.

A study of the spectral rocking based on individual Jovian synodic periods (9h 55m 33.12s) is generally inconclusive because of poor counting statistics and the effects of interplanetary modulation. To minimize these effects we "averaged" over many periods by superimposing observations made at the same phase of the modulation. This analysis, which will be referred to as epoch analysis, was performed as follows. Eighteen flux bins were established each covering 20° in phase. Electron intensities, averaged over 30 minutes, were assigned to one of these bins depending on the phase at the time of observation. The length of the intervals analyzed covered between 2 and 50 days. Each interval was analyzed with at least 10 periods, τ, near the expected electron modulation period. If the analysis was performed with the Jovian synodic period τ_0, then the phase was calculated to be equal to λ_{III} of the subsolar point. (For a definiton of system III longitude of 1965, see Seidelman and Divine, 1977.) For other values of the analysis period, the phase is very close to λ_{III} for the first period but can shift by a substantial amount towards the end of the interval. For instance if $\tau = \tau_0$ - 4min, the phase shift is 2.4° in one period but is 20° or one bin in 3.4 days and 60° in 10.25 days. The flux ratio of low to high energy electrons was then calculated from the two "averaged" electron rates.

In order to understand how the epoch analysis affects the data, let us first consider an analysis of ideal data. Assume that the electron flux during a Jovian period has the values shown in Figure 3a; this gives the spectral rocking or flux ratio curve shown as curve 1 in Figure 3b. Now, let the flux in all Jovian periods be identical. When we "average" over 20 modulation periods, the flux ratio curve would remain unchanged (Fig. 3b, curve 1) provided the period τ used to compute the phase equals the Jovian period τ_0 = 9h 55m 33.12s. (This is also the electron modulation period.) However, if τ differs from τ_0, the rocking curve becomes broader and less distinct. Curve 2 of Figure 3b illustrates the result from superimposing 20 periods using $\tau = \tau_0 - 7.5$ min (4.5° slipping per period). Almost the same curve is obtained for $\tau = \tau_0 + 7.5$ min, except that the peak is shifted to a lower rather than a higher phase. If τ is shortened to $\tau = 20\ \tau_0/21$, then the modulation disappears (Fig. 3b, curve 3) because the modulation has equal probability of occurring at all phases between 0° and 360°. In the more general case, the modulation disappears when $\tau = n\tau_0/(n \pm 1)$. If T is the length of observation, then we are "averaging" over $n = T/\tau_0$ periods. This gives

$$\Delta t = |\tau - \tau_0| \approx \frac{\tau_0}{n} = \frac{\tau_0^2}{T} \qquad (1)$$

When the difference between τ and τ_0 is increased beyond Δt, the modulation will reappear but at a reduced magnitude. If the electron fluxes or degree of modulation had been allowed to change between individual periods, then the modulation would not disappear completely but would have minima at $\tau_0 \pm \Delta t$.

For real data, we have to determine whether departures from a constant flux ratio are statistically significant and if significant whether the modulation is due to Jupiter. For this purpose we used the χ^2 test, where χ^2 is defined as

$$\chi^2 = \sum_{i=1}^{18} \frac{(R_i - \bar{R})^2}{\sigma_i^2} \qquad (2)$$

R_i is the counting rate ratio in the ith bin, σ_i is the standard deviation of R_i calculated from counting statistics, and $\bar{R}$ is the weighted average over all phases. With 17 degrees of freedom and no modulation, the expectation value for χ^2 is 17 with a variance of 6, and a 2.5% probability that $\chi^2 >$ 30. Modulation will be present if we can prove that the counting rates do not follow a χ^2 distribution, thus $\chi^2 > 30$ implies a very high probability of modulation; however, a high value of χ^2 does not automatically prove Jovian modulation because other factors contribute to the variability of the electron rates. Interplanetary modulation will contribute to the variability of the flux ratio to the degree that this modulation is energy dependent. The analysis was therefore performed with different periods near the Jovian period, and we required that two minima in χ^2 were $2\Delta t$ apart (Eq. 1) and bracketed the expected maximum. If these conditions were satisfied, plots of flux ratio vs. phase showed the expected trend with a clear maximum. As will be discussed later, however, the maximum did not always occur at 240°, and the modulation period often differed by several minutes from τ_0. In the later case, the true modulation period rather than τ_0 should be used in equation (1), but the difference is insignificant.

The sensitivity of the epoch analysis can be increased significantly by calculating the flux ratio from a running average of the electron flux in 3 20^0 phase bins. This is equivalent to a low pass filter in that it decreases random fluctuations without significantly decreasing the spectral changes. By using a three point running average, we have reduced the degrees of freedom from 17 to 15 because the average rate can now be calculated from three different combinations of running averages (Meyer 1975). Thus in the absence of modulation, the average value of χ^2 has been reduced from 17 to 15. For highly correlated counts, the value of $R_i - \bar{R}$ in equation (2) is almost unchanged when R_i is calculated from the three point running average of the counting rates, but the square of the standard deviation of the running average is only $\sigma_i^2/3$; therefore, the value of χ^2 can be up to three times its former value in the presence of temporal correlation. If calculated from running averages, values of χ^2 as a function of τ are also more consistent. A small change in τ moves points occurring late in the analysis interval into an earlier or later phase bin; by averaging over 3 bins, the fluctuations produced by moving a few points from one bin to the next are smoothed out. This technique was required to detect Jovian modulation of the electron spectrum during the far tail encounter at ~ 9.5 AU in the spring of 1981.

In summary, to establish Jovian modulation, we require that the following conditions be satisfied:

a) $\chi^2 > 30$,

b) a maximum in χ^2 near the Jovian synodic period with a minimum on either side separated by $2\Delta t$,

c) A clear maximum in the flux ratio vs. phase diagram.

The sensitivity to Jovian modulation depends on the constancy of the modulation period over the time-interval being analyzed. We found that τ can deviate from τ_0 by several minutes; our sensitivity to modulation may therefore be substantially different in different intervals. The accuracy with which the average modulation period of an interval can be determined depends both on the width and magnitude of χ^2 because the center of the distributon can be determined more easily if χ^2 is large.

Observation Within 10^8 km of Jupiter

The interplanetary electron flux observed with Voyagers 1 and 2 is shown in Fig. 4. During the pre-encounter period, we observed a periodic modulation of 2 cycles per solar rotation. Late in 1978 and in January and February 1979, when both spacecraft were still inside Jupiter's orbit, the interplanetary modulation of the fluxes observed at the two spacecraft is somewhat similar to that expected from the modulation mechanism proposed by Conlon and Simpson (1977). Great changes occurred in the interplanetary medium between the Pioneer and Voyager encounters. In early 1979, there existed a combination of corotating high speed streams (CRS's) and radially propagating shock waves. At the time of the Pioneer 10 and 11 encounters the CRS's were the dominant feature. There is an absence of long lived recurring increases in the Voyager data except for the one indicated in Figure 5.

The interplanetary modulation changes dramatically between pre- and post-encounter because of the location of Voyager relative to the Jovian tail region (Fig. 1). This difference can be easily seen in Figs. 4 during April, May and June 1979 when one spacecraft was in each region. During this period the flux minima are almost an order of magnitude higher at Voyager 1 than Voyager 2. The minima observed with Voyager 1 generally occur at the same time as the Voyager 2 minima; however, the post-encounter minima are much shorter and generally not as deep. These observations show that the magnetic connection to the Jovian electron source region was much better for the post-encounter period than pre-encounter. This is to be expected because, on the average, the interplanetary magnetic field connects the post-encounter trajectory to the dawn side of the Jovian magnetotail (Fig. 1a) where much of the electron release is expected to occur (Schardt et al. 1981).

Considering the Jupiter-spacecraft distance, relatively large fluxes were observed on August 7 (Voyager 2 only) and in mid-September 1979 (Fig. 5). These are comparable to fluxes observed near the plasma sheet in the magnetotail beyond $80R_J$. The plasma wave and plasma instruments showed that the distant magnetotail engulfed Voyager 2 on August 7 and September 16 (Kurth et al. 1981). The August 7 electron flux was almost certainly due to magnetotail electrons. It was not seen at Voyager 1, and the temporal signature--a rapid increase in intensity followed by an equally fast decrease--is consistent with a brief re-entry into the Jovian magnetotail. The electron increase in September appears to have a different origin. The flux minimum on September 11 preceded by 2 days the compression region ahead of the fast stream, and the large increase started on September 15 after the compression region had passed. Although the Voyager 2 peak flux on September 16 coincided with the encounter of the extended magnetotail, the electrons were not characteristic of normal Jovian electrons. An almost simultaneous increase of comparable magnitude was observed by Voyager 1 and by ISEE-3 at 1 A.U. (Fig. 5). However, the ISEE-3 electrons are produced in a solar flare associated cosmic ray event. An electron event with similar properties was also observed in early May 1981 (Fig. 12). Associated with these two events are proton increases that extend to energies > 150 MeV. In both cases the relative time histories of the 30-60 MeV protons and MeV electrons are essentially identical when plotted on a 10-hours time scale. The spectra of the protons in the range 20-70 MeV is a very flat power law with $\gamma = 0.8 - 1.5$. These flat spectra suggest that the higher energy nucleons have not been significantly energised by the preceeding shocks but have made a direct transit from the Sun along the interplanetary field. The similiarity between the time histories of the 30-60 MeV proton components and the MeV electrons suggest that they have the same origin. Detailed studies of the low energy protons (McDonald et al., 1981) at Pioneer-11 for the September event indicate that ions in the 0.5-20 MeV region are strongly affected by the shock. Furthermore, there is an accompanying very high field region that coincides with the arrival of the high energy particles. This high field region acts as a channel for the direct transmission of solar particles. There are several smaller increases which also appear to be of solar origin but their intensities are comparable to those of Jovian electrons.

The Jovian modulation is superimposed on the much larger interplanetary modulation. The Jovian effect can be enhanced by averaging over many rotations and using a running average over about 60° in λ_{III}. This improves not only the counting statistics but also averages out random intensity fluctuations. To minimize the effects of interplanetary modulation, the initial survey was made with long term averages of up to 100 Jovian periods. Shorter time averages were used to study further detail during interesting periods. Flux ratios observed during the post-encounter trajectory of Voyager 2 are shown in Fig. 6. The electron spectrum already shows a λ_{III} dependence inside the magnetotail. Because of the tilt between the Jovian spin axis and magnetic dipole, the magnetic latitude depends also on λ_{III}; thus it is not possible to separate unambiguously a longitude from latitude dependence. In the magnetosheet region, softest spectra tend to occur near flux maxima (Voyager 2 outbound) and hence near the equatorial plasma sheet; however, some λ_{III} dependence cannot be ruled out because a significant off-set can often be found between maximum flux and softest spectrum.

A substantial spectral modulation as observed in the spectral rocking was present in the boundary layer and sheath, and in interplanetary space out to ~10^8km from Jupiter. In this region, softest spectra tend to coincide with flux minima. As can be seen in Figure 6, the depth of the modulation decreased with distance. In addition to the maximum flux ratio near λ_{III} = 240°, a smaller secondary maximum occurred at λ_{III} = 60°. Such a stable secondary maximum was observed only during the Voyager 2 post-encounter trajectory; however, transient secondary maxima were seen also at other times. Figure 7 demonstrates that this modulation is really associated with the Jovian period. The values of χ^2 curves 7a and b peak at the synodic period of Jupiter and reach minima at $\tau_0 \pm \Delta t$ as predicted by equation (1). The maximum of χ^2 in Figure 7 curve C was offset by 3m 33s from τ_0. Since the curves are symmetrical and narrow, one can conclude that the offset is real. An offset of 4m33s ±40s from τ_0 was present during the post-encounter phase of the Voyager 1 mission (Fig. 8 curve a); fortunately, it occurred just after encounter when electron fluxes were intense and permitted a higher time resolution study of the effect. Later after encounter (Fig. 8, curve b), two periods may have been present with the stronger one equal to τ_0.

Figure 9 shows the flux ratios that go with the χ^2 curves of Figure 8. The near encounter curve was calculated with the shorter period. If the modulation period is really shorter than the synodic period, then the position of softest spectra should drift towards lower values of λ_{III}, and Figure 10 demonstrates that such a shift did occur. Successive two day (5 period) averages are shown which were superimposed with a period that is 4m 33s shorter than τ_0; however, the phase between successive curves was adjusted such that the first rotation of Jupiter is plotted at the correct value of λ_{III} while the 5th rotation is plotted at λ_{III} + 13.3 degrees. The phase shift between curve 1 and 4 is ~45° in 6 days; from this phase shift one can deduce a modulation period which is ~5m shorter than τ_0 and in good agreement with the χ^2 analysis. A small secondary maximum is visible in Figure 10, curve 4 at λ_{III} = 330°; this becomes the primary peak in curve 5. Again a drift to lower values of λ_{III} is discernible (curve 6), but then the phase stabilized with the center of the distribution at $\lambda_{III} \sim 270°$. Apparently, the phase of the spectral rocking can drift to smaller longitudes and then re-establish itself at the original longitude.

The Voyager 2 observations used for Fig. 7, curve c, cover the time period from November 6 to December 23, 1979, or a total of 113 Jovian periods. If the modulation had been uniform during the whole period, the difference in periods of 3m 40s would result in a total drift of 250°. In order to check on this possibility, 8-day averages were analyzed. Although 8 days was long enough to establish the presence or absence of substantial modulation, it did not permit us to establish an exact period of the spectral rocking. From these shorter intervals we found that the spectrum was modulated from November 7 to November 14 with the peak near $\lambda_{III} = 280°$. There was little or no modulation from November 15 to December 7, 1979; strong modulation was again observed from December 8 to December 15, 1979 with the peak near $\lambda_{III} = 190$. No substantial modulation was observed after that date. It appears that the softest spectra can occur between $\lambda_{III} = 330°$ and $\sim 190°$ with the most probable position $\lambda_{III} \sim 240°$.

From the above discussion it is clear that our ability to identify the presence of recurring spectral changes depends on the constancy of the modulation period over the time interval that is averaged by the epoch analysis. Therefore, we may have obtained negative results in our search for modulation during some intervals either because the spectrum was not modulated or because the phase of the modulation was not stable over the averaging interval. A careful search would undoubtedly uncover a number of intervals with small but detectable modulation. With this caveat, our survey of pre- and post-encounter intervals is summarized in Table 1 and Figure 1a, and gives the following results:

a) No significant Jovian modulation was found in the pre-encounter data except between February 16 and March 1, 1979, on Voyager 1, and between June 6 and 11, 1979, on Voyager 2 (Fig. 11). As can be seen in Figure 1a, Voyagers 1 and 2 were already quite close to the magnetopause during these periods. The Voyager 2 electron flux was particularly high between June 6 and 11, 1979 (Fig. 4), which is consistent with favorable magnetic field connection to the Jovian magnetosphere. Typical flux ratio curves for periods with no modulation are shown in Fig. 6 (12-15x10^7 km), Fig. 9 (curve c), and Fig. 11 (curve 2). During these intervals, the value of χ^2 generally was in the range of 20-50 (Fig. 8, curve 3). Although the points fluctuate more than expected from pure statistics, no definite trend is visible which could be ascribed to modulation at or near the Jovian period. The flux ratio is generally near 10 corresponding to $\gamma \sim 2.8$. Thus, prior to encounter, Jovian modulation disappears at about 1.5 x 10^7 km from the magnetopause (Fig. 1b).

b) From September 16 to 27, 1979, the spectrum was unusually soft with a flux ratio of ~ 40 corresponding to $\gamma \sim 4$. No clear Jovian modulation of the spectrum could be observed during this period of strong interplanetary disturbances, and as previously discussed, this increase appears to be of solar origin.

c) No Jovian modulation was observed beyond 10^8km (1,400 R_J) from Jupiter . An exception to this was the Voyager 2 encounter with the far magnetotail at 9.0-9.5 A.U. from the Sun (Fig. 1b).

<u>Observations in the Far Jovian Magnetotail at 9.5 A.U.</u>

Voyager 2 encountered the far magnetotail of Jupiter several times between January and June 1981. These encounters were observed by plasma wave and plasma probe measurements (Scarf et al., 1981), by 1.2 KHz continuum radiation and by the direction of the magnetic field (Lepping et al., 1982).

We investigated five periods in detail when Voyager 2 was, for several days, either in or very close to the far tail. These periods are January 14 to 23, February 17 to 22, March 7 to 13, April 2 to 19 and May 20 to 27 (Lepping, private communication). Electron fluxes at Voyagers 1 and 2 are shown in Figure 12. During this period Voyager 1 was at a substantial distance from the magnetotail and observed most of the time counting rates at the same low value as observed shortly after launch near 1 A.U. At this low level, we believe that the rate is primarily due to various backgrounds such as the RTG (radioactive thermal generator which furnished Voyager's electric power) and high energy cosmic ray interactions rather than to 2.6-5.1 MeV electrons. The large flux increase at both Voyagers 1 and 2 between May 10 and 20, 1981, is associated with the solar activity and resembles the September 16, 1979, event in both spectrum and time history. In contrast to Voyager 1, Voyager 2 recorded a substantial electron flux which was modulated by the solar rotation period (Fig. 12) and resembled interplanetary modulation observed closer to Jupiter (Fig. 4). No specific flux enhancement was observed when Voyager entered the far tail itself. Possible exceptions are the 10 to 30 hr long flux spikes observed in January, February and April which are unusual and might have been associated with filaments in the magnetotail, but it should be noted that the February spike occurred when the other instruments did not indicate immersion in the tail. Because Voyager 1 was only ~ 35 percent further from Jupiter than Voyager 2, the difference in the electron flux must have been due to the proximity of the magnetotail to Voyager 2. Yet, the Jovian electrons were not confined to the tail itself but must have filled an extended region near the magnetotail.

Values of χ^2 vs τ of the spectral rocking curve are shown in Figure 13a for the January far tail encounter and for 10 day periods pre- and post-encounter. While the pre- and post-encounter periods are consistent with no modulation, the far tail encounter period has a distinct peak at 10h 8m with minima on either side spaced 2Δt apart. Running averages over 3 phase bins of the electron flux were used to decrease sensitivity to higher frequency fluctuations and to improve the statistics. The smoothing effect of a 3 point running average is evident in the flux ratio curve (Fig. 14). Because neighboring points are no longer independent of each other, they fluctuate less about the mean curve than would be expected from the error bars. The modulation is less than observed close to Jupiter, but it is quite distinct and peaks at 170°. An attempt to determine whether the modulation differed between the first and second 5 days of this far tail encounter was unsuccessful because of inadequate statistics.

No modulation was observed during the February and March far tail encounters. Modulation as small as the January observation could not have been seen because the encounter lasted only 6 days vs 10 and had poorer statistics.

Modulation was again observed during the April tail passage. The χ^2 curve for the period April 2 to 19, 1981 is centered about the Jovian period but is somewhat wider than would be expected from an 18 day long observation. Such a broadening could be due to a drift in the period during the observations or because most of the modulation occurred during 12 days of the interval. Based on the presence of 30-60 MeV solar protons, we think that some solar electrons may have contributed to the electron flux from April 7 to 11 and decreased the modulation during that period. The flux ratio versus phase (Fig. 14 curve b) resembles the January observations but peaks near 220°. Jovian modulation was also observed during the May far tail crossing. Because interplanetary conditions were still disturbed from solar activity earlier that month, the χ^2 versus τ curve of the May crossing is not symmetric. A broad maximum between τ = 9.7 and 11.1 hrs reflects Jovian modulation; however, we cannot determine an average period for this crossing. The flux ratio vs phase shown in Fig. 14, curve c was calculated with τ = 10h 9m and is marginally more peaked than curves for longer periods. Again, the flux ratio peaks near 230°.

Discussion and Conclusions

The Voyagers 1 and 2 results have confirmed that Jupiter is a major source of interplanetary electrons and that the electron spectrum is modulated by Jupiter's rotation. This spectral rocking produced softest spectra most frequently when $\lambda_{III} \sim 240^o$ (1965) was in the subsolar position; however, maximum flux ratios of (2.6--5.1)/(8-12) MeV electrons were found at subsolar longitudes as low as $\lambda_{III} \sim 170^o$ and as high as $\sim 330^o$. Jovian modulation of the electron spectrum was almost invariably present after encounter and faded out only at distances between 5 and 10 x 10^7 km (Fig. 1b). This indicates that the Jovian source of interplanetary electrons is normally modulated, and an absence of modulation is due to the properties of the interplanetary propagation path. The modulation of the electron spectrum can be lost if electrons are accelerated or decelerated in traveling from Jupiter to the observer. Such processes do not necessarily preserve the slope of the spectrum, and random changes in γ, when averaged over several Jovian periods, would mask the initial modulation. The other mechanism for losing modulation is based on a dispersion in electron travel time from the source to the observer. Since the softer spectra last for only ~ 2 hours of each period, a 2-hour dispersion in travel time would almost eliminate the effect. We believe that travel time dispersion is the dominant effect during quiescent interplanetary conditions.

The transport of charged particles in the solar wind has been described in terms of the diffusion-convection theory (for a review see Jokipii, 1971). Because of the stochastic nature of the paths followed by individual electrons, a pulse of electrons injected into the solar wind at point A spreads out in time as it travels to point B. Conversely, a dip in electron flux will broaden and fill in until it is no longer recognizable. Rather than applying a pulse, the travel time dispersion can also be estimated by applying a step function at $t = 0$ and calculating the time it takes the intensity to reach half-maximum at a distance s from the source. This approximation holds true as long as the diffusion velocity is small compared to the particle velocity. We use Conlon's (1978) solution to the transport equation which is applicable to the geometry of the interplanetary propagation of Jovian electrons. For the purpose of this discussion, we can neglect the relatively small solar wind convection terms and obtain the following expression for the time t as a function of the distance at which the flux from a step function reaches half maximum:

$$t \approx \frac{1}{4}\left(\frac{S_\perp^2}{\kappa_\perp} + \frac{S_\parallel^2}{\kappa_\parallel}\right) \qquad (3)$$

where the components of the distance perpendicular and parallel to the local magnetic field are given by $S_\perp$ and $S_\parallel$, and the corresponding components of the diffusion tensor are $\kappa_\perp$ and $\kappa_\parallel$. The perpendicular component $\kappa_\perp$ is made up of two parts: $\kappa_{\perp SC}$ is due to scattering at field irregularities and $\kappa_{\perp FM}$ is due to random field line motion. Jokipii and Parker (1969) have shown that $\kappa_{\perp FM}$ should make the major contribution to $\kappa_\perp$. The following relation exists (Jokipii and Parker, 1969) between $\kappa_{\perp SC}$ and $\kappa_{\parallel}$:

$$\frac{\kappa_{\perp SC}}{\kappa_{\parallel}} = \frac{\rho_g^2}{\rho_g^2 + \lambda^2} \tag{4}$$

where ρ_g is the particles gyroradius and λ the mean free path along the field line which is given by

$$\lambda = 3\ \kappa_{\parallel}/v \tag{5}$$

v is the particle velocity. These relations can be used to estimate the diffusion coefficients from our data.

Based on average interplanetary field directions, the post-encounter part of the Voyager 2 trajectory was well connected to the source ($S_{\perp} \sim 0$) and the pre-encounter period required primarily cross-field diffusion ($S_{\parallel} \sim 0$). Thus, it is not surprising that modulation was observable to $\sim 10^8$ km from the magnetopause post-encounter but only to $\sim 1.5 \times 10^7$ pre-encounter. The instantaneous field direction, however, differs greatly from the average; thus a mixture of parallel- and cross-field diffusion must have been present most of the time, and we can place only limits on $\kappa_{\parallel}$ and $\kappa_{\perp}$. Using equation (3), the 2-hour dispersion time for t and the set $S_{\parallel} \sim 10^8$ km, $S_{\perp} \sim 0$; we find $\kappa_{\parallel} > 4 \times 10^{21}\ cm^2 s^{-1}$. Similarly, $\kappa_{\perp} < 8 \times 10^{19}\ cm^2\ s^{-1}$ for $S_{\parallel} \sim 0$ and $S_{\perp} \sim 1.5 \times 10^7$ km. We can estimate the scattering contribution to $\kappa_{\perp}$ from the limit on $K_{\parallel}$ and equations (4, 5). For an average interplanetary field value of 5nT and ~ 10 MeV electrons, we find $\rho_g \sim 7 \times 10^4$ km and $\kappa_{\perp SC} < 1.4 \times 10^{18}\ cm^2\ s^{-1}$. As Jokipii and Parker (1969) have pointed out, the scattering across field lines is not the primary cause for diffusion perpendicular to the average field direction, and diffusion perpendicular to the instantaneous field direction is small. Therefore, it is not surprising that our limit on $\kappa_\perp$ is an order of magnitude higher than the limit on $\kappa_{\perp SC}$. Because the random walk of field lines is primarily responsible for $\kappa_\perp$, one would expect that the diffusion has little effect on particle energies. Scattering by moving field perturbations are the primary cause of energy changes, and the small value of $\kappa_{\perp SC}$ demonstrates that the electrons are not scattered very often.

Our limit $\kappa_\perp < 8 \times 10^{19}$ cm^2 s^{-1} can be compared with 5×10^{20} cm^2 s^{-1} obtained by Conlon (1978) from the decrease of the electron flux as a function of distance. Considering the nature of the estimates, the agreement is reasonable. Hamilton (1977) has derived a radial diffusion coefficient for 1-2 MeV solar electrons near 1 AU and finds it to be in the range (4-9) $\times 10^{21}$ cm^2 s^{-1}. Near Earth, this represents primarily $\kappa_\parallel$. No electron measurements are available at larger heliocentric distances, and we can only state that our lower limit $\kappa_\parallel > 4 \times 10^{21}$cm^{2}s^{-1} appears to be consistent with Hamilton's result.

An exception to the general results discussed above was the period from September 15 to 28, 1979, when Voyager 2 was near Jupiter but no Jovian modulation was observed. During this time, Voyager 2 was magnetically well connected to the magnetosphere and was in the distant tail on September 16, 1979 (Kurth et al. 1981). We concluded, however, that the energetic electrons observed by Voyager 2 during this period were of solar origin. This is based on simultaneous electron observations at ISEE-3 and Voyager 1 and the presence of 30-60 MeV solar protons at Voyager 2. The high solar electron flux can be explained in terms of the channeling of these particles in a high magnetic field region which had formed between two solar wind streams.

The presence of spectral rocking with Jupiter's period in the far tail at

3.8 AU behind Jupiter proves that this tail region is magnetically well connected to the magnetosphere. Using the above equations, we find that the diffusion coefficient is > 10^{23} cm^2 s^{-1} and λ > 0.75 AU or 1540 R_J. Such a large mean-free path requires a surprising integrity of the tail to 3.8 AU behind Jupiter and is consistent with the direction of the magnetic field which pointed predominantly towards or away from Jupiter when Voyager 2 was in the far tail (Lepping et al. 1982). In contrast, the electron intensities appeared to respond to interplanetary modulation (Fig. 12) and did not increase when the spacecraft entered the tail itself. Therefore, the cross-field diffusion near the magnetotail must be sufficiently fast to keep the interplanetary electron population in equilibrium with the flux in the far tail.

The Voyager 2 observations agree with similar Pioneer 10 observations by Pyle and Simpson (1977) at 9.6 A.U. when Pioneer 10 was near the far tail. However, our interpretation of the interplanetary modulation mechanism differs from theirs because the control by a CRS is quite different near the far tail (Voyager 2) than at some distance from it (Voyager 1). Pyle and Simpson concluded that the electron release occurs near Jupiter and that electrons, once released, would not cross a CRS. In 1981, one or more compression regions, often associated with shocks, occurred, in general, in the ~ 4 A.U. between Jupiter and the Voyagers (Fig. 1b). Based on their model, both Voyagers should have observed low electron fluxes most of the time, but Voyager 2 observed considerably higher fluxes than Voyager 1 (Fig. 12). This difference is most easily explained if the far tail is a source of Jovian electrons and the diffusion out of the tail is sufficiently rapid that near to the tail the flux in interplanetary space is in equilibrium with the flux in the tail. One would expect the existence of a boundary layer surrounding the tail in which the average diffusion coefficient falls between $\kappa_{\perp}$ and $\kappa_{\parallel}$ of the undisturbed solar wind. Such a boundary layer would prevent rapid electron flow out of the tail region. The interplanetary modulation of the electron flux at Voyager 2 would then have been due to solar wind modulation of the tail itself. Most likely, expansion of the tail between compression regions accounts for the ~ 27-day recurrence rate of the Voyager 2 encounters with the tail (Fig. 12). Thus, the observed electron intensity modulation by the solar wind could be due to changes in the distance between Voyager 2 and the tail boundary as well as to more favourable propagation conditions when most of the tail was not compressed by a CIR.

The departure of the modulation period from the synodic period of Jupiter and the phase at which softest spectra are observed have to be explained in terms of the modulation mechanism. Any explanation requires a longitudenal asymmetry in the corotating region of the magnetosphere. Dessler and Hill (1975) suggested a Jovian magnetic anomaly as the source of the asymmetry and Vasyliunas (1975) proposed an active hemisphere with an enhanced plasma density. Building on this model, we take the Io torus as the primary plasma source; the expected asymmetry of the torus has been demonstrated with optical S[II] observations (Pilcher and Morgan, 1980). As this plasma diffuses outward, it may produce asymmetries in the energetic particle population (Vogt et al. 1979) and finally an asymmetric interaction at the magnetopause. If the plasma source strength remained constant, then the phase of the electron modulation would be constant and the period the same as Jupiter's synodic period.

Ground-based observations have demonstrated that the plasma density of the Io torus is subject to large temporal variations (Pilcher, 1980; Pilcher and Morgan, 1980 Eviator et al., 1981). An increase in plasma loading can affect the period and phase by producing a larger departure from corotation (Hill, 1980) and therefore a larger than average value of λ_{III} when the plasma arrives at the magnetopause. After the initial enhanced activity, the strength of the plasma source would be much smaller; as the plasma loading decreases, the departure from corotation would decrease also. This would shift the phase of the modulation towards a smaller value of λ_{III}. Such a scenario fits the Voyager 1 post-encounter observations (Fig. 10). The ring currently observed by Voyager 1 was distinctly larger than during the Voyager 2 mission (Connerney et al., 1981) and Eviatar et al. (1981) obtained evidence from ground-based observations that a major injection event took place no more than 6 days prior to the Voyager 1 encounter. Thus, the plasma loading was almost certainly decreasing after encounter.

Another mechanism may also contribute towards shortening the modulation period. After the initial enhancement, the older dense plasma will continue to control the electron modulation until its density has decayed below the density of the newly formed plasma. Much of the older plasma will diffuse outward and some of it will reach temperatures in the keV range (Krimigis et al., 1981). At L = 20, where corotation is still enforced, the drift of a proton plasma with a temperature kT = 24 keV would decrease the modulation period by 3 minutes below the Jovian period; for the same shorter period an O^+ or S^{++} plasma would require kT = 1.5 keV. These energies have not been observed directly but appear to be consistent with the proton plasma having kT = 30-35 keV observed at L = 30 (Krimigis et al. 1981). It should be noted that departure from corotation can shift the phase at most by the value of the sweepback while the prograde drift continues until the old plasma has been dissipated.

Periods longer than the Jovian period can occur only when the plasma density of the Io torus increases. Such an increase might be due to major volcanic activity on Io and would most likely be rapid compared to the decay. In that case, longer modulation periods would occur only a small fraction of the time, and departures from the Jovian period would be substantially larger. This is, in general, consistent with our observations but is hard to pin down because of poor statistics and a less stable modulation during intervals when $\tau > \tau_0$.

The release mechanism controls the phase of the modulation. The initial suggestion was that the electrons are released into the magnetotail and that the flux is a minimum when the inactive hemisphere faces the tail (Vasyliunas, 1975; Dessler and Hill 1975). Because the energetic electrons are initially trapped, the release cannot occur until the plasma has expanded far enough into the tail to permit rapid particle escape. The Voyager post-encounter observations showed that trapping persists to within about 15 R_J of the dawn magnetopause, where the sweepback delay was found to be ~ 2.5 hours or 90^o in phase (Schardt et al. 1981). Because t's sets the time scale for the phase shift of the electron release, the initial model no longer gives the correct phase for the modulation. An alternate suggestion is that partial corotation in the near magnetotail is sufficiently large so that most of the trapped energetic electrons cannot escape until the field lines on which they are trapped have corotated into the dawn magnetopause (Schardt et al. 1981). It was further suggested that the minimum release of electrons and softest spectra occur when the boundary between the inactive and active hemispheres rotates past the pre-dawn magnetopause. The longitude range of this boundary would be characterized by a lower plasma density than other longitudes because the magnetic field sweepback increases due to the gradient in plasma loading. With a lower plasma density inside the magnetosphere, the magnetopause characteristics would resemble those of the terrestrial magnetopause and inhibit the release of electrons. This model is consistent with the phase of the interplanetary modulation. Based on this model, energetic electrons do not fill the tail near Jupiter, but are preferentially released into the boundary layer just inside the pre-dawn magnetopause. This is consistent with no enhancement of the electron flux in the far tail at 3.8 AU behind Jupiter. The brief flux spikes observed between January and May 1981 (Fig. 12) could be associated with filaments that are well connected to the boundary layer.

The electron diffusion time from Jupiter to the observer should shift the phase of the spectral rocking to larger values of λ_{III}. As discussed above, the modulation should disappear only when the propagation time is about 2 hours or $\sim 70°$ in λ_{III}. We were unable to demonstrate this effect because, with the required long averaging interval, the phase of softest spectra becomes too dependent on the value of τ used for the analysis.

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References

Chenette, D. L., T. F. Conlon, and J. A. Simpson, "Bursts of relativistic electrons from Jupiter observed in interplanetary space with the time variation of the planetary rotation period", J. Geophys. Res. 79, 3551, 1974.

Conlon, T. F., "The interplanetary modulation and transport of Jovian electrons", J. Geophys. Res. 83, 541, 1978.

Conlon, T. F. and J. A. Simpson, Modulation of Jovian electron intensity in interplanetary space by corotating interaction regions. Ap. J. (Letters), 211 L45, 1977.

Connerney, J. E. P., M. H. Acūna, and N. F. Ness, "Modeling the Jovian current sheet and inner magnetosphere", J. Geophys. Res. 86, 8370, 1981.

Dessler, A. J. and V. M. Vasyliunas, "The magnetic anamoly model of the Jovian magnetosphere: predictions for Voyager, Geophys. Res. Letters 6, 37, 1979.

Dessler, A. J., and T. W. Hill, High-order magnetic multipoles as a source of gross asymmetry in the distant Jovian magnetosphere", Geophys. Res. Letters, 2, 567, 1975.

Hamilton, D. C., The radial transport of energetic solar flare particles from 1 to 6 A.U., J. Geophys. Res. 82, 2157, L977.

Hill, T. W., "Corotation lag in Jupiter's magnetosphere: comparison of observation and theory", Science 207, 301, 1980.

Jokipii, J. R., and E. N. Parker, "Stochastic aspects of magnetic lines of force with application to cosmic-ray propagation", Ap. J. 155, 777, 1969.

Jokipii, J. R., "Propagation of cosmic rays in the solar wind", Rev. Geophys. and Space Phys. 9, 27, 1971.

Krimigis, S. M., J. F. Carbary, E. P. Keath, C. O. Bostrom, W. I. Axford, G. Gloeckler, L. J. Lanzerotti, and T. P. Armstrong, "Characteristics of hot plasma in the Jovian magnetosphere: results from the Voyager Spacecraft:, J. Geophys. Res. 86, 8227, 1981.

Kurth, W. S., D. A. Gurnett, F. L. Scarf, R. L. Poynter, and J. D. Sullivan, "Voyager observations of Jupiter's distant magnetotail", J. Geophys. Res. 86, 8402, 1981.

Lepping, R. P., L. F. Burlaga, M. D. Desch, and L. W. Klein, "Evidence for a distant (> 8,700 R_J) Jovian magnetotail: Voyager 2 observations", Geophys. Res. Lett. 9, 1982.

McDonald, F. B., J. D. Mihalov, J. H. Trainor, W. R. Webber, and J. H. Wolfe, Energetic storm particles in the outer heliosphere, Proceedings of the 17th International Cosmic Ray Conference, 3, 455-458, 1981.

Meyer, S. L., Chapter 26 in Data analysis for scientists and engineers, John Wiley and Sons, Inc. 1975.

McKibben, R. B., and J. A. Simpson, "Evidence from charged particle studies for the distortion of the Jovian magnetosphere", J. Geophys. Res., 79, 3545, 1974.

Pilcher, C. B., "Images of Jupiter's sulfur ring", Science 207, 181, 1980.

Pilcher, C. B., and J. S. Morgan, "The distribution of S[II] emission around Jupiter", Astrophys. J., 238, 375, 1980.

Pyle, K. R. and J. A. Simpson, The Jovian relativistic electron distribution in interplanetary space from 1 to 11 A.U.: Evidence for a continuously emitting "point" source, Ap. J. (Letters), 215, L87, 1977.

Scarf, F. L., W. S. Kurth, D. A. Gurnett, H. S. Bridge, and J. D. Sullivan, "Jupiter tail phenomena upstream from Saturn", Nature 292, 585, 1981.

Schardt, A. W., F. B. McDonald, and J. H. Trainor, "Energetic particles in the pre-dawn magnetotail of Jupiter", J. Geophys. Res., 86, 8413, 1981.

Seidelmann, P. K., and N. Divine, "Evaluation of Jupiter longitudes in system III (1965)", Geophys. Res. Lett. 4, 65-68, 1977.

Simpson, J. A., D. C. Hamilton, G. A. Lentz, R. B. McKibben, M. Perkins, K. R. Pyle, A. J. Tuzzolino, and J. J. O'Gallagher, "Jupiter revisited: first results from the University of Chicago charged particle experiment on Pioneer-11", Science 188, 455, 1975.

Smith, E. J., and J. H. Wolfe, "Observations of interaction regions and corotating shocks between one and five AU: Pioneer 10 and 11", Geophys. Res. Lett. 3, 137, 1976.

Smith, E. J., B. T. Tsurutani, D. L. Chenette, T. F. Conlon, and J. A. Simpson, "Jovian electron bursts: correlation with the interplanetary field direction and hydromagnetic waves", J. Geophys. Res. 81, 65, 1976.

Stone, E. C., R. E. Vogt, F. B. McDonald, B. J. Teegarden, J. H. Trainor, J. R. Jokipii, and W. R. Webber, "Cosmic ray investigation for the Voyager mission: energetic particle studies in the outer heliosphere--and beyond", Space Sci. Rev., 21, 355, 1977.

Teegarden, B. J., F. B. McDonald, J. H. Trainor, W. R. Webber and E. C. Roelof, "Interplanetary MeV electrons of Jovian origin", J. Geophys. Res., 79, 3615, 1974.

Vasyliunas, V. M., and A. J. Dessler, "The magnetic anomaly model of the Jovian magnetosphere: a post Voyager assessment", J. Geophys. Res., 86, 8435, 1981.

Vasyliunas, V. M., "Modulation of Jovian interplanetary electrons and the longitude variation of decimetric emissions", Geophys. Res. Letters 2, 87, 1975.

Vogt, R. E., W. R. Cook, A. C. Cummings, T. L. Garaud, N. Gehrels, E. C. Stone, J. H. Trainor, A. W. Schardt, T. Conlon, N. Lal, and F. B. McDonald, "Voyager 1: energetic ions and electrons in the Jovian magnetosphere", Science 204, 1003, 1979.

Table 1 Jovian Modulation of Interplanetary Electrons

Interval+	Spacecraft	Distance from Jupiter 10^6 km	R_J	Position	Period++	χ^2 +++ (1)	(2)	Degree of Modulation
12/12-12/23/78	V-1	82 - 71	1150 - 990	Pre	τ_o	46	98	very weak
1/22-1/31/78	V-1	43 - 33	602 - 468	Pre	τ_o	--	70	very weak
2/16-3/2/78	V-1	19 - 4.6	264 - 64	Pre	9h 46m	388	1043	strong
3/14-3/26/78	V-1	10 - 23	140 - 320	Post	9h 51m	2040	--	very strong
3/26-5/4/78	V-1	23 - 60	320 - 843	Post	τ_o	759	--	moderate
4/29-6/7/79	V-2	53 - 24	748 - 336	Pre	τ_o	34	--	very weak
6/4-6/12/79	V-2	28 - 23	396 - 327	Pre	9h 51m	307	--	moderate
7/18-8/7/79	V-2	7.7 - 23	107 - 316	Post	τ_o	2264	5578	strong
8/7-8/19/79	V-2	23 - 31	316 - 435	Post	9h 42m	1110	2746	strong
8/19-8/27/79	V-2	31 - 36	435 - 503	Post	9h 46m	190	98	questionable
8/27-9/12/79	V-2	36 - 48	503 - 667	Post	10h 11m	320	754	moderate*
9/12-9/16/79	V-2	48 - 50	503 - 706	Post	τ_o	88	159	weak
9/27-11/10/79	V-2	58 - 88	810 - 1229	Post	τ_o	210	--	moderate
11/6-12/24/79	V-2	88 - 117	1229 - 1637	Post	9h 52m	94	--	weak
1/14-1/24/81	V-2	413	2.77 A.U.	Tail	10h 7m	--	77	very weak
2/17-2/23/81	V-2	442	2.95 A.U.	Tail	τ_o**	43	28	none
3/8-3/14/81	V-2	459	3.07 A.U.	Tail	9h 57m**	25	17	none
4/2-4/20/81	V-2	488	3.27 A.U.	Tail	τ_o	--	137	weak
5/22-5/28/81	V-2	531	3.55 A.U.	Tail	10h 8m	54	64	moderate

\+ The interval starts and ends at 00 hours of the dates shown.

++ τ_o = 9h 55m 33.12s is Jupiter's synodic period.

+++ Column 1 gives χ^2 for the counting rate ratios and column 2 gives χ^2 for ratios calculated from three point running averages.

* Maximum in flux ratio near 0o phase

** χ^2 reached a local maximum at this period but no clear cut maximum existed in the flux ratio.

Figure Captions

Fig. 1. (a) Ecliptic projections of the Voyager 1 and 2 encounter trajectories relative to the Jupiter-Sun line. A heavy solid or dashed line was used for those parts of the trajectories where Voyager observed substantial Jovian modulation of the electron spectra.

(b) Ecliptic projection of the Voyager trajectories when Voyager 2 encountered the far tail. Voyager 2 was above the plain of the ecliptic and approached the extention of the Sun-Jupiter line only within 375 million km or 535 R_J. The corotating interaction region takes about 11 days (V_s = 500 km/sec) to pass Voyager.

Fig. 2. Schematic drawing of the Voyager and ISEE-3 High Energy Telescope (HET). Electrons were detected on the basis of coincidences between B_1, B_2 and the C_4, C_3, C_2 stack in anticoincidence with C_1 and the guard counters. Differences in the pulse height distributions were used to discriminate against energetic protons and ions.

Fig. 3. (a) Idealized electron fluxes, averaged over 20^o in System III longitude, are shown for one Jovian rotation.

(b) Ratios of (2.6-5.1)/(8-12) MeV electrons using the idealized fluxes shown in (a) above. Curve 1 gives the ratio for one period, or for the superposition of many identical periods if the phase for the superposition is calculated using the exact period τ_0, or 360^o. Curve 2 shows the superposition of 20 τ_0 periods, but the phase for the superposition was calculated using 355.5^o rather than 360^o as a complete period. Curve 3 shows 20 periods superimposed using 342.9^o as a complete period for calculating phases to be superimposed; this corresponds to $\tau_0 - \Delta t$ (equation 1 in text) and should show no modulation.

Fig. 4. Ten-hour averages of electron fluxes observed with Voyagers 1 and 2. For each spacecraft the upper curve gives the 2.6-5.1 MeV flux and the lower curve the 8-12 MeV flux. Intensity changes are due to interplanetary modulation because the 10-hour averaging period eliminates the Jovian modulation. In addition to the strong solar electron event of September 1979, weaker events occurred in July and August 1979, and may have made significant contributions to the Voyager 1 electron flux. The distance from Jupiter is shown in units of 10^6 km; note that 15 x 10^6 km ~ 210 R_J.

Fig. 5. Three-hour averages of electron fluxes observed at ISEE-3 and Voyagers 1 and 2. The September solar electron event was associated with an unusually fast solar wind stream [~ 800 km/s (Kurth et al. 1981)] and was of approximately equal intensity at the three spacecraft. In contrast, the late August event was of the same intensity at ISEE-3 as the September event, but the flux had decayed by at least an order of magnitude before arriving at the Voyager spacecraft.

Fig. 6. Histograms of the ratio of low- (2.6-5.1 MeV) to high- (8-12 MeV) energy electron fluxes versus λ_{III} (1965) of the Jovian subsolar point. For clarity, points from the first 120° have been repeated between 360° and 480°. Voyager 2 observations made after encounter between the indicated distances have been superimposed using the Jovian synodic period of 9 hours 55 min. 33.12 s. For curve c (8.8-12 x 10^7 km) a period of 9h 52m was used; in this case the horizontal axis represents a phase which coincides with λ_{III} only at the beginning of the interval. The spectral index for a power law spectrum of the form $j(E) = KE^{-\gamma}$ was calculated from the ratio of

the two rates. Reevaluation of the spectral indicies given by Chenette et al. (1974) brings their values into general agreement with the values of γ showing here (Chenette, private communication).

Fig. 7. Statistical significance of the spectral rocking observed with Voyager 2 (Fig. 6) expressed in terms of χ^2 as a function of period. Curves a, b, and c correspond to the phase histograms a, b, and c shown in Figure 6. $T \pm \Delta t$ gives the periods at which χ^2 should reach a local minimum. The results are in excellent agreement with the Jovian synodic period until late October 1979 (curve a and b), but a somewhat shorter period is indicated during November-December 1979 (curve c).

Fig. 8. χ^2 as a function of period for the Voyager 1 post-encounter observations. The curve plotted with the symbol x covers the first 12 days after Voyager 1 exited the magnetopause. Notice the significant displacement from τ_0, the Jovian synodic period.

Fig. 9. Histograms of the ratio of low- to high-energy electrons observed with Voyager 1 after encounter. These curves were calculated with periods corresponding maximum values of χ^2 in Fig. 8 (curves a, b, and c). The phase corresponds to the subsolar value of λ_{III} at the beginning of the interval, but drifts relative to λ_{III} when the period used differs from 9h 55min 33.12 s.

Fig. 10. Change of the phase of spectral rocking observed with Voyager 1 shortly after it emerged from the Jovian magnetosphere. A period of 9h 51 min. was used in the analysis. The data were taken at the following dates and distances from Jupiter: curve 1, 3/14 - 3/16/79 at $r \sim 153R_J$; curve 2, 3/16 - 3/18/79 at $r \sim 182\ R_J$; curve 3, 3/18 - 3/20/79 at $r \sim 210\ R_J$; curve 4, 3/20 - 3/22/79 at $r \sim 238\ R_J$;

curve 5, 3/22 - 3/24/79 at $r \sim 265\ R_J$, curve 6, 3/24 - 3/26/79 at $r \sim 293\ R_J$; curve 7, 3/26 - 3/30/79 at $r \sim 326\ R_J$; and curve 8, 3/30 - 4/3/79 at $r \sim 395\ R_J$.

Fig. 11. Ratio of low to high energy electrons observed by Voyager 2 shortly before encounter. Curve 1 spans the period 6/4 - 6/12/1979 ($r = 397 - 317\ R_J$) with $\chi^2 = 300$, and curve 2 covers 6/12 - 6/24/1979 ($r = 317 - 194\ R_J$) with $\chi^2 = 30$. Both curves were calculated with the synodic period of Jupiter.

Fig. 12. Ten-hour averages of electron fluxes observed during the first 6 months of 1981. The 2.6-5.1 MeV flux is shown for both Voyager 1 (*) and Voyager 2 (Δ); the 8-12 MeV flux is shown only for Voyager 2 (o). The shaded areas indicate periods when Voyager 2 was immersed in the far magnetotail (Lepping et al., 1982). The large flux in early May 1981 coincided with major solar activity and a solar electron event observed at ISEE-3. A much smaller solar event may have contributed to the electron population between April 7 and 11, 1981.

Fig. 13. χ^2 as a function of period for two Voyager 2 far tail encounters. Curve A also shows values of χ^2 for 10 days prior to (o) and 10 days after (x) the January 1981 far tail encounter. The larger value of χ^2 in curve B is primarily due to the longer tail encounter and hence better statistics.

Fig. 14. The ratios of low-to high-energy electrons observed with Voyager 2 during those far tail encounters which exhibited demonstrable modulation. Strongest spectral modulation was observed during the late May encounter, but the period of the modulation and hence phase of softest spectra cannot be determined accurately. This tail encounter followed a major solar event and apparently interplanetary conditions had not yet settled down.

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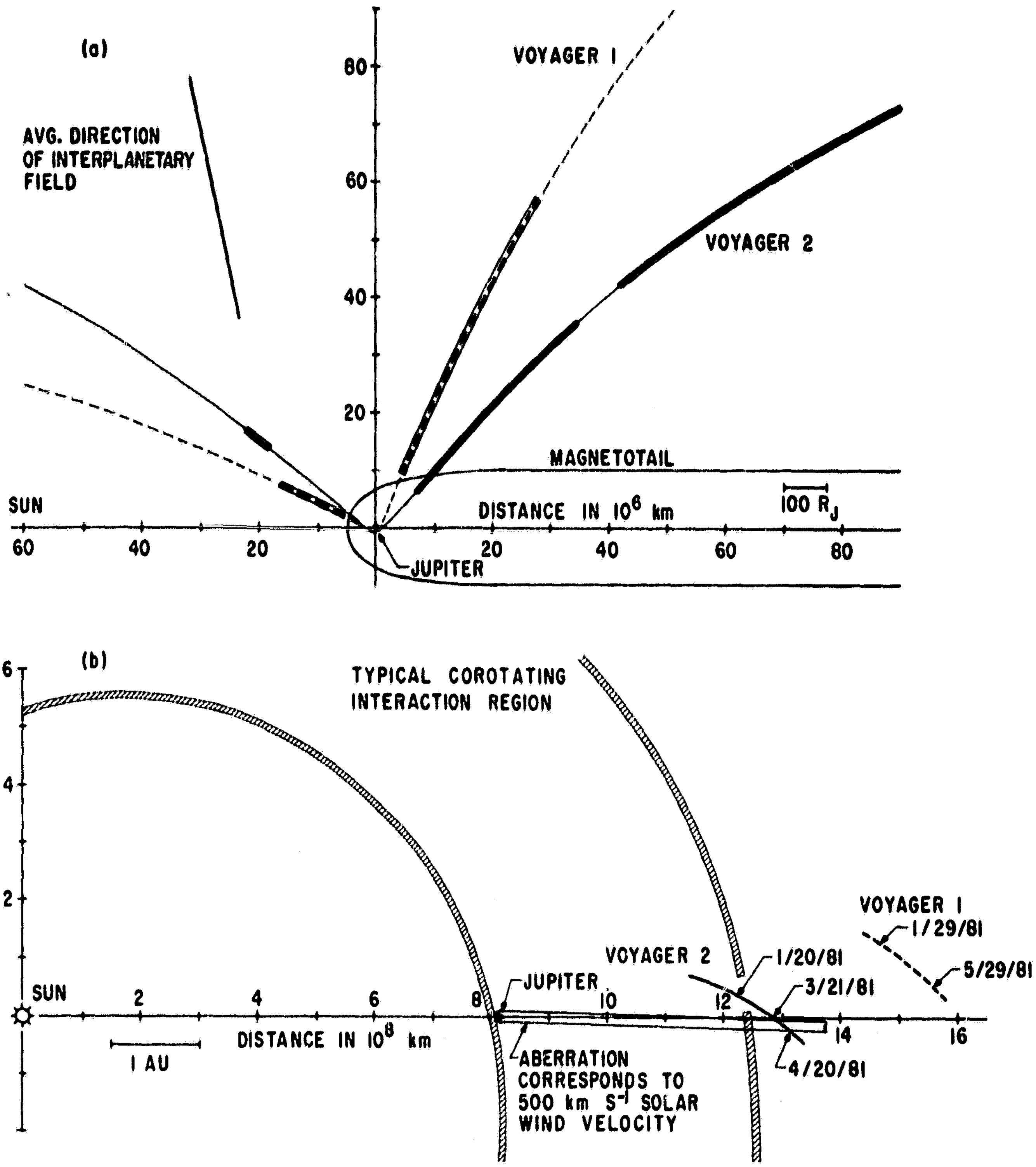

Fig. 1

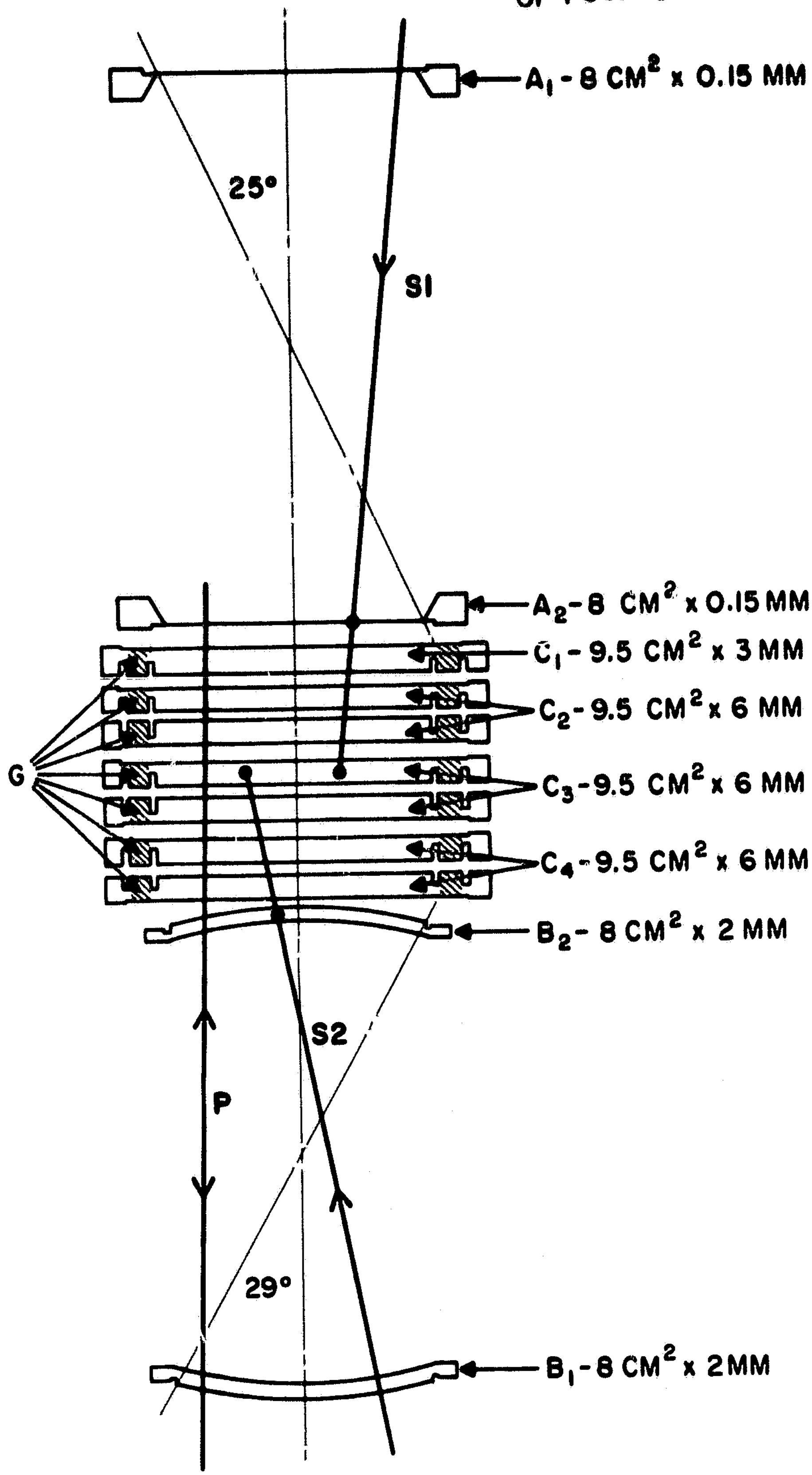
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Fig.2

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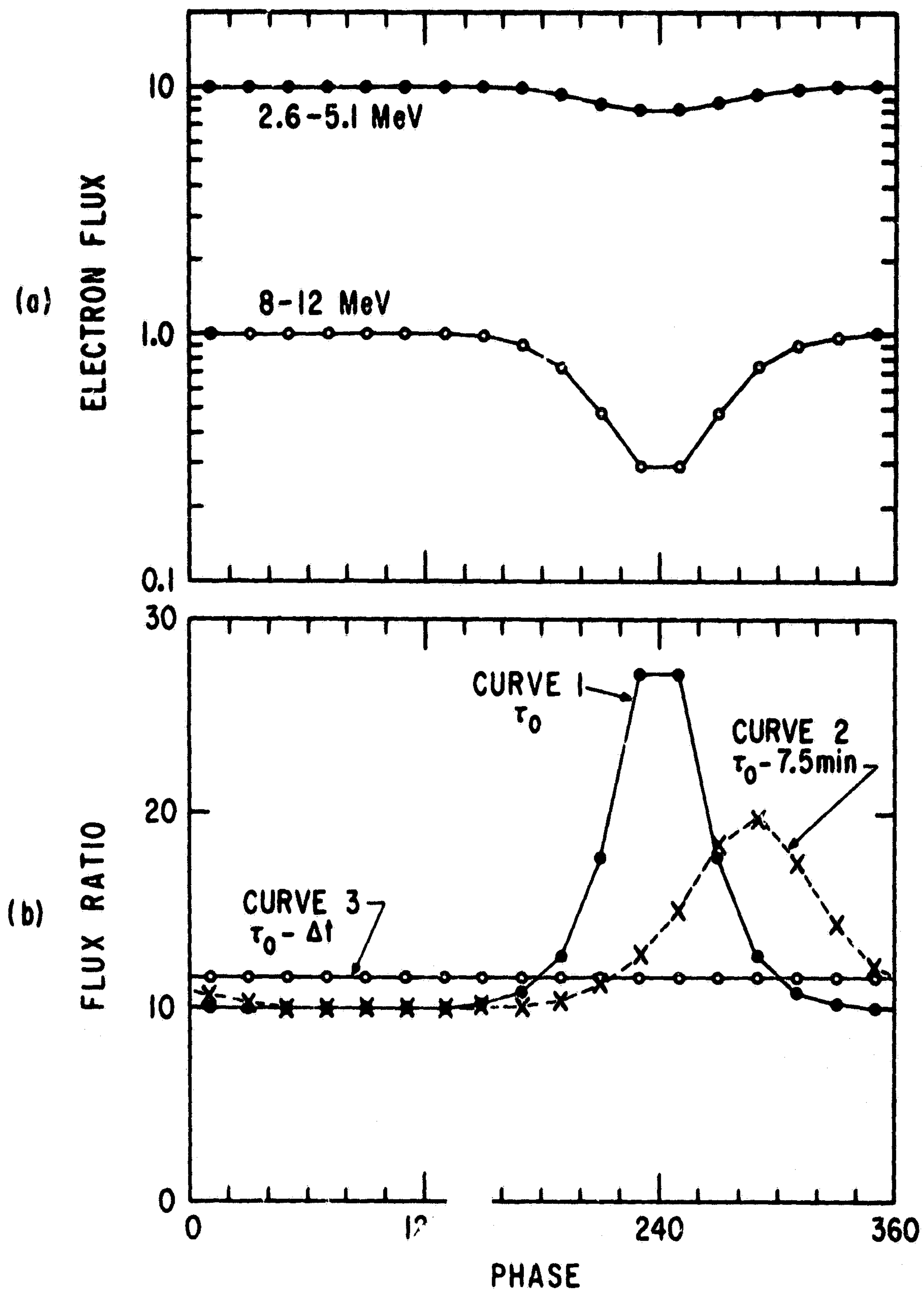
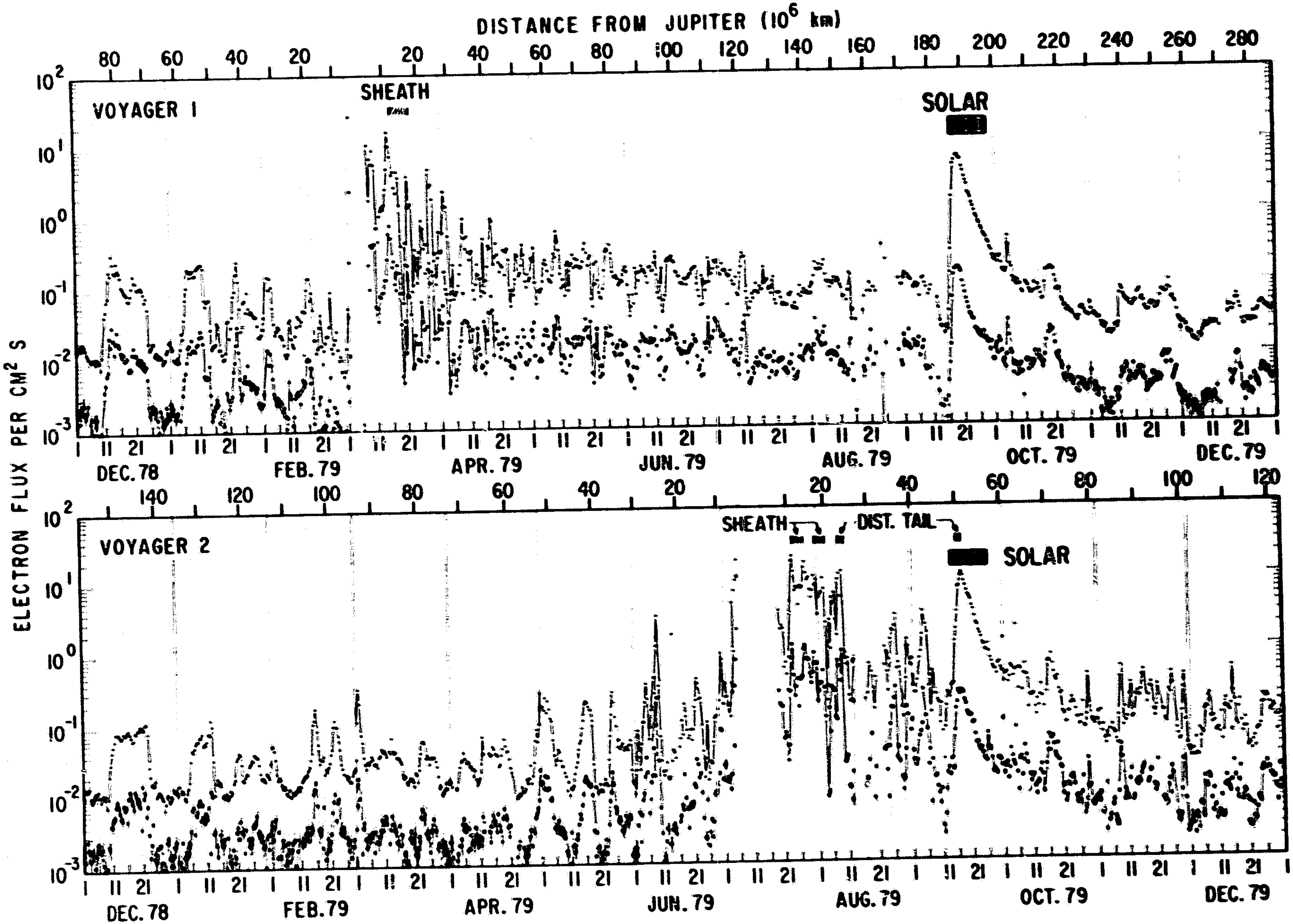


Fig.3



DISTANCE FROM JUPITER (10^6 km)
ELECTRON FLUX PER CM² S
VOYAGER 1
SHEATH
SOLAR
DEC.78
FEB.79
APR.79
JUN.79
AUG.79
OCT.79
DEC.79
VOYAGER 2
SHEATH
DIST. TAIL
SOLAR

Fig.4

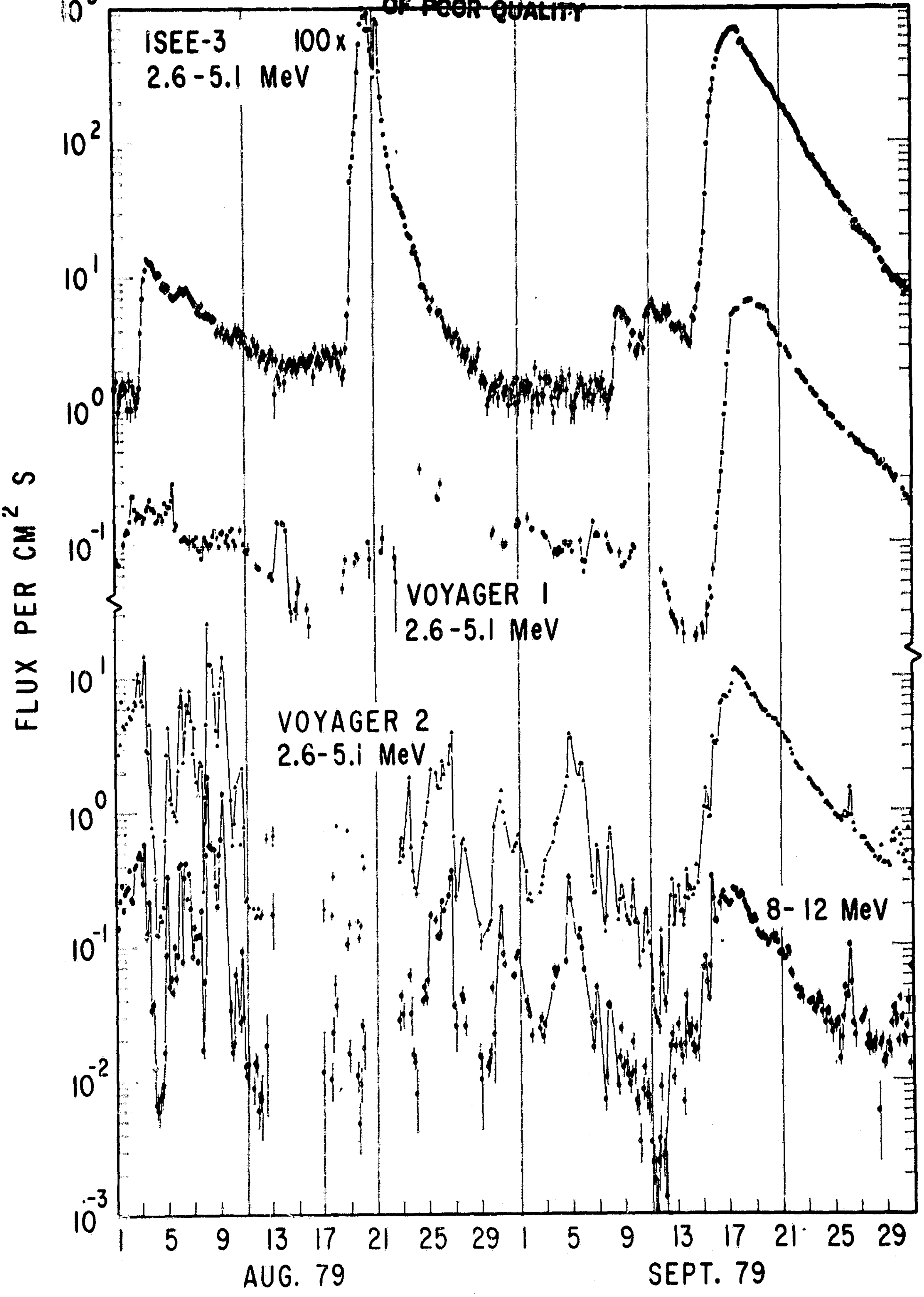
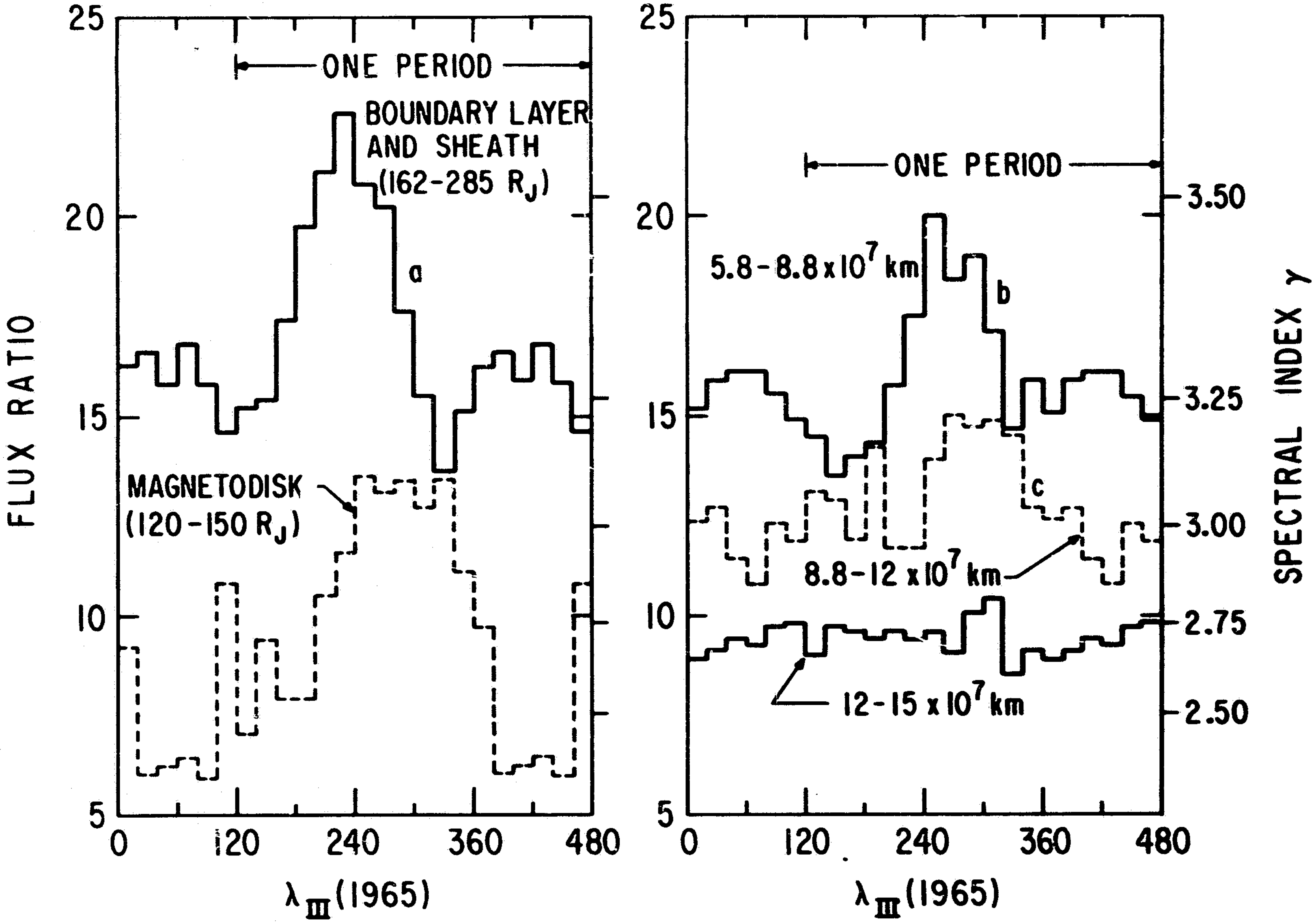

ISEE-3 100x
2.6-5.1 MeV
VOYAGER 1
2.6-5.1 MeV
VOYAGER 2
2.6-5.1 MeV
8-12 MeV
FLUX PER CM² S
10³
10²
10¹
10⁰
10⁻¹
10¹
10⁰
10⁻¹
10⁻²
10⁻³
1 5 9 13 17 21 25 29 1 5 9 13 17 21 25 29
AUG. 79
SEPT. 79

Fig.5



FLUX RATIO
ONE PERIOD
BOUNDARY LAYER AND SHEATH (162-285 R_J)
a
MAGNETODISK (120-150 R_J)
λ_{III}(1965)
ONE PERIOD
5.8-8.8 x 10^7 km
b
c
8.8-12 x 10^7 km
12-15 x 10^7 km
SPECTRAL INDEX γ

Fig.6

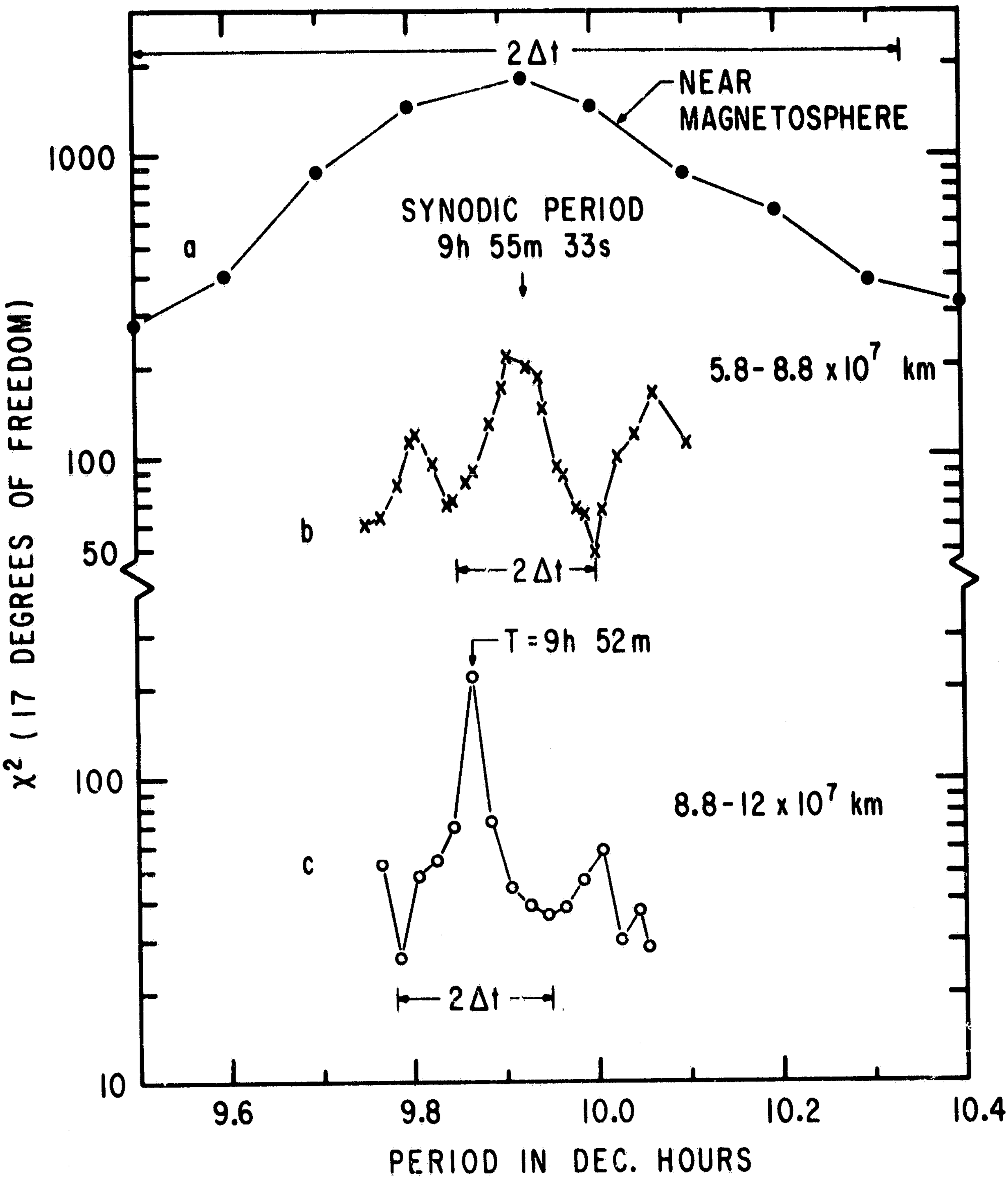

2 Δt
NEAR MAGNETOSPHERE
1000
a
SYNODIC PERIOD
9h 55m 33s
5.8 - 8.8 x 10⁷ km
100
b
50
2 Δt
T = 9h 52m
100
8.8 - 12 x 10⁷ km
c
2 Δt
10
9.6
9.8
10.0
10.2
10.4
PERIOD IN DEC. HOURS
χ² (17 DEGREES OF FREEDOM)

Fig.7

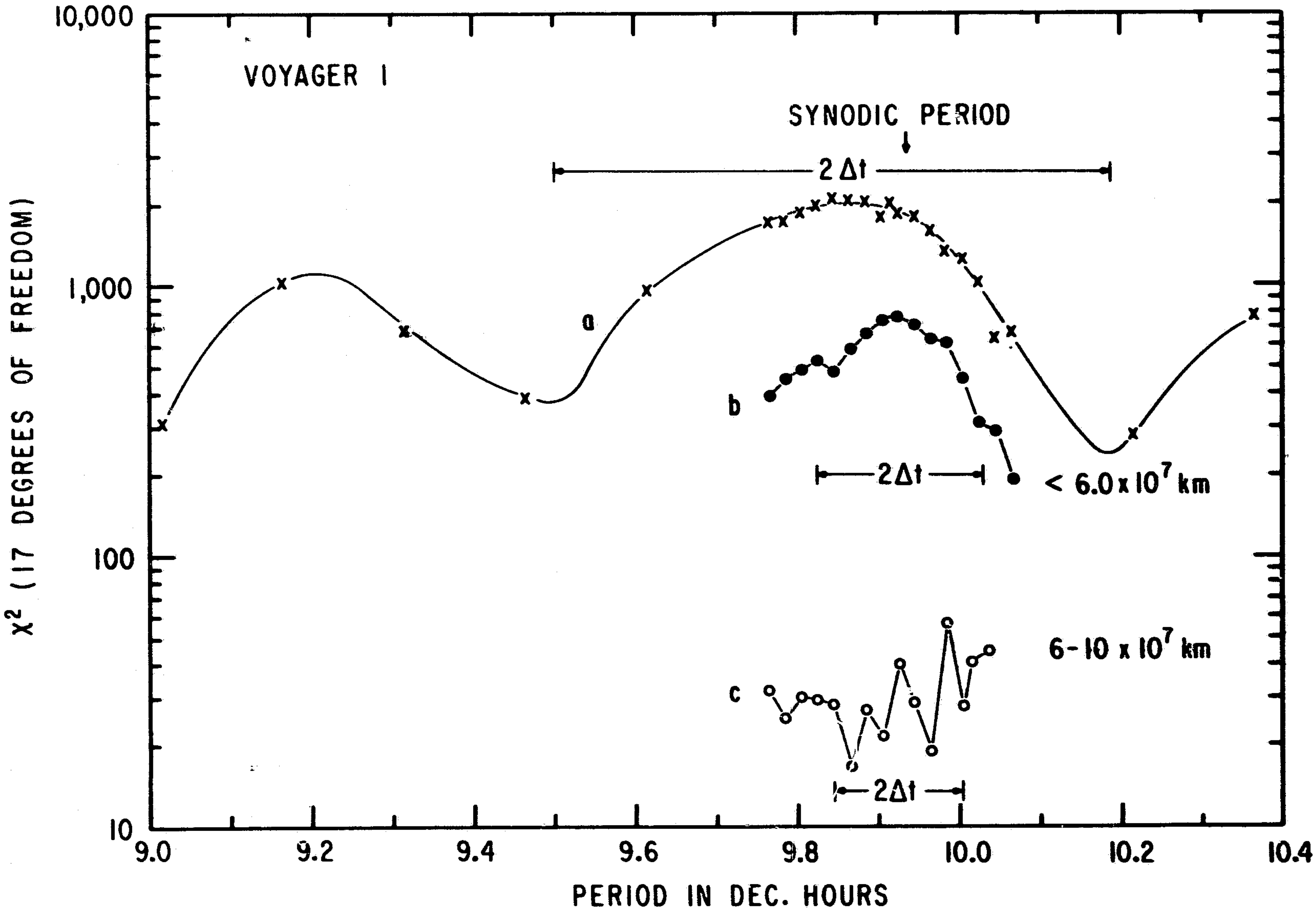

10,000
1,000
100
10
X² (17 DEGREES OF FREEDOM)
VOYAGER I
SYNODIC PERIOD
2 Δt
a
b
2Δt
< 6.0 x 10⁷ km
6-10 x 10⁷ km
c
2Δt
9.0
9.2
9.4
9.6
9.8
10.0
10.2
10.4
PERIOD IN DEC. HOURS

Fig.8

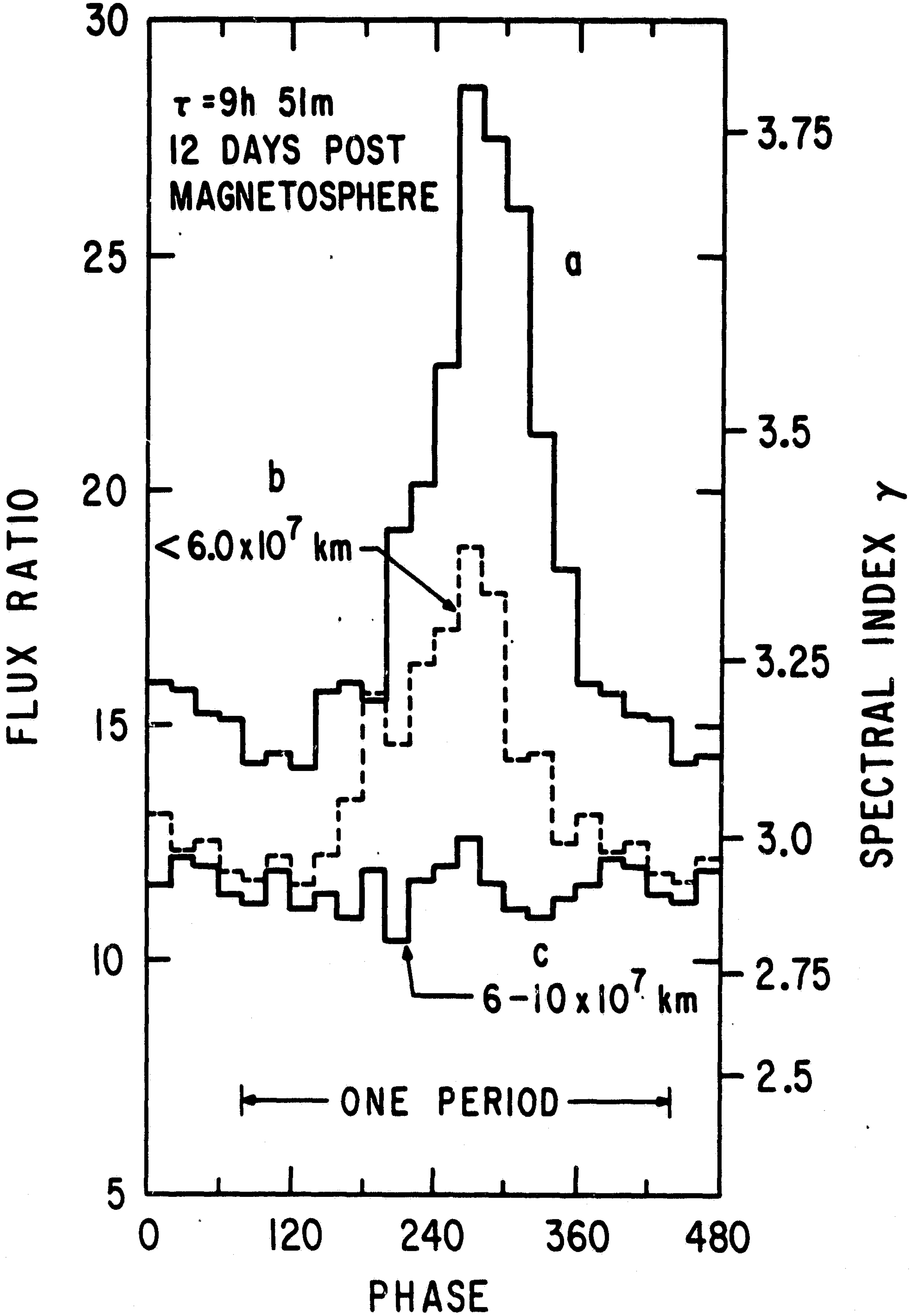

30
25
20
15
10
5
0
120
240
360
480
PHASE
FLUX RATIO
SPECTRAL INDEX γ
3.75
3.5
3.25
3.0
2.75
2.5
τ =9h 51m
12 DAYS POST
MAGNETOSPHERE
a
b
< 6.0 x 10⁷ km
c
6-10 x 10⁷ km
ONE PERIOD

Fig.9

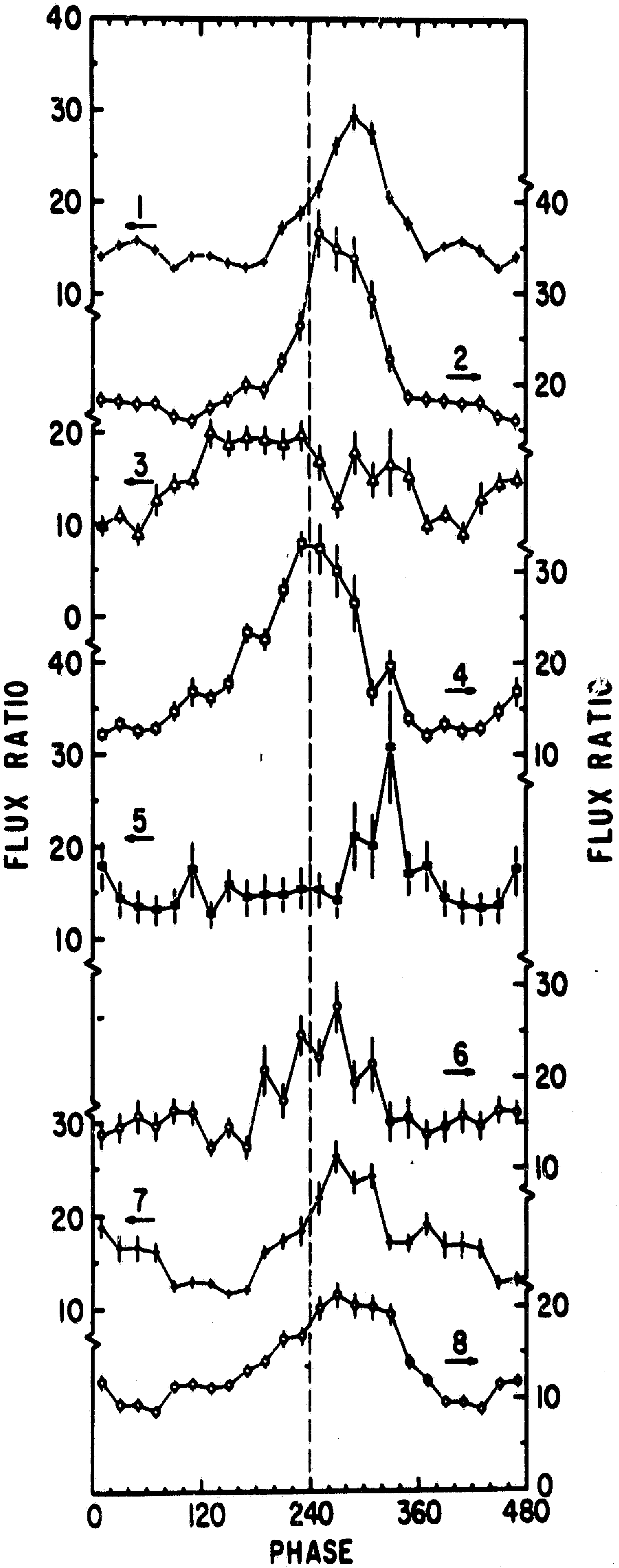


Fig 10

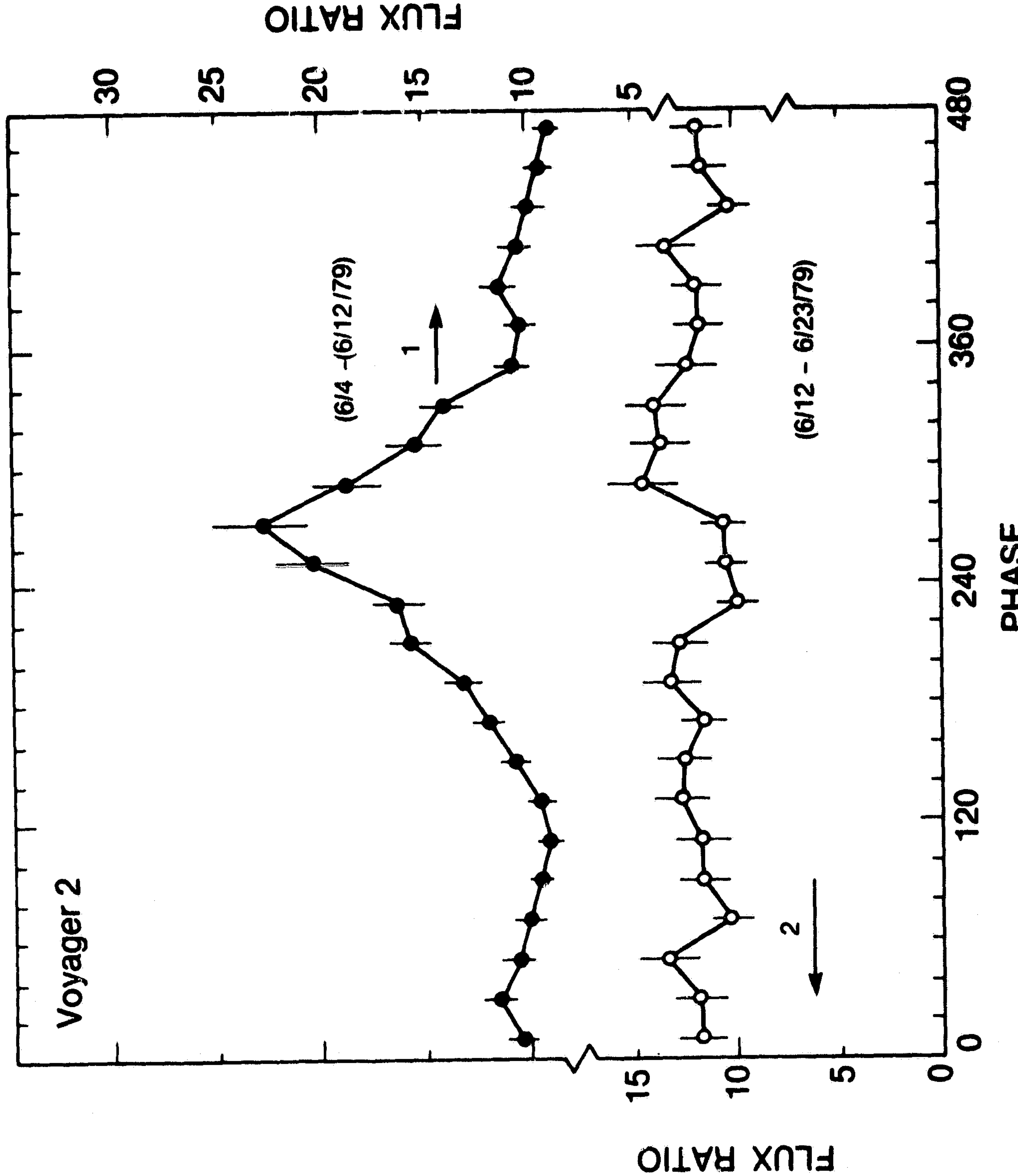

Voyager 2
FLUX RATIO
30
25
20
15
10
5
(6/4 -(6/12/79)
1
(6/12 - 6/23/79)
2
FLUX RATIO
15
10
5
0
PHASE
0
120
240
360
480

Fig. 11

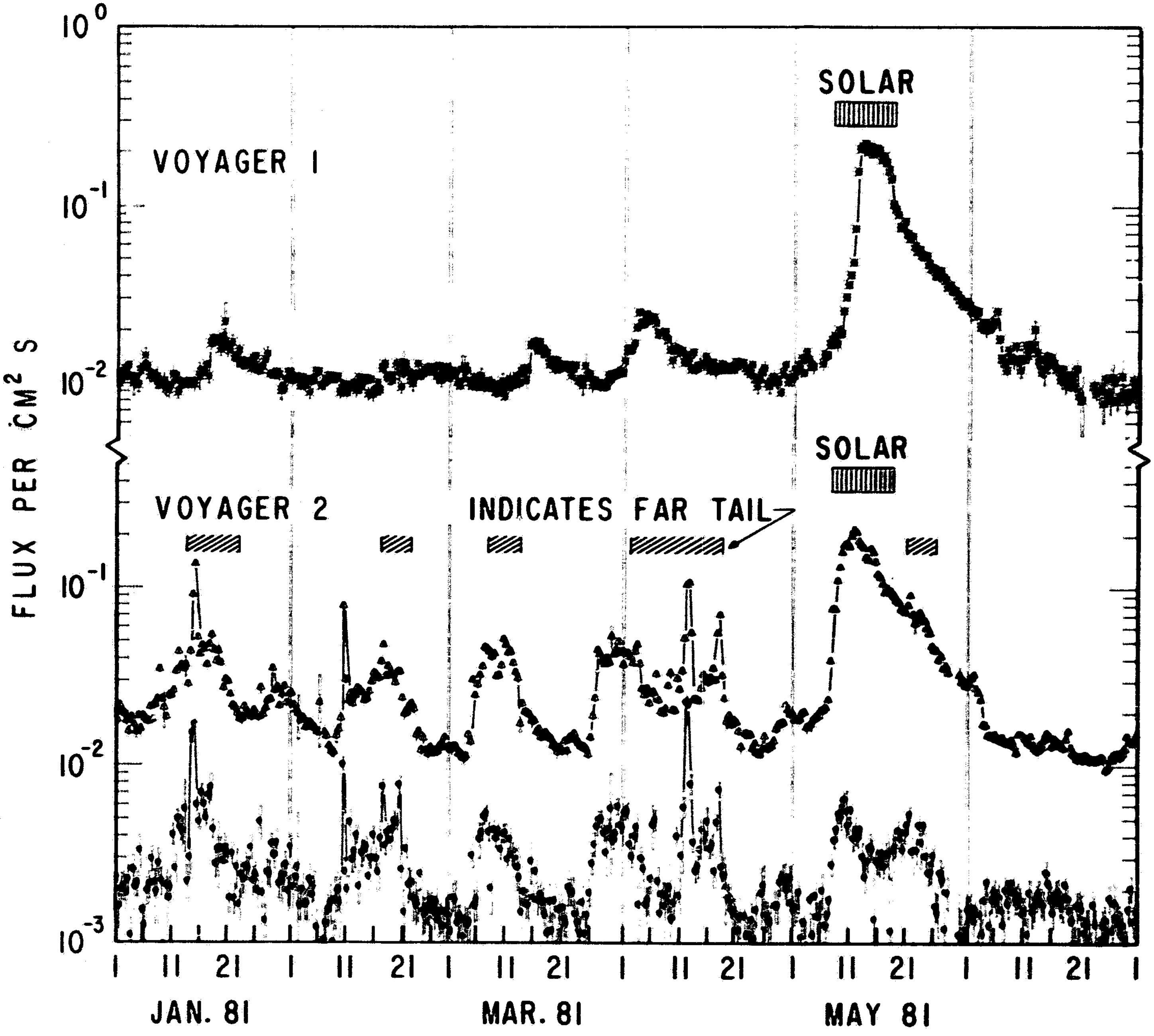


Fig.12

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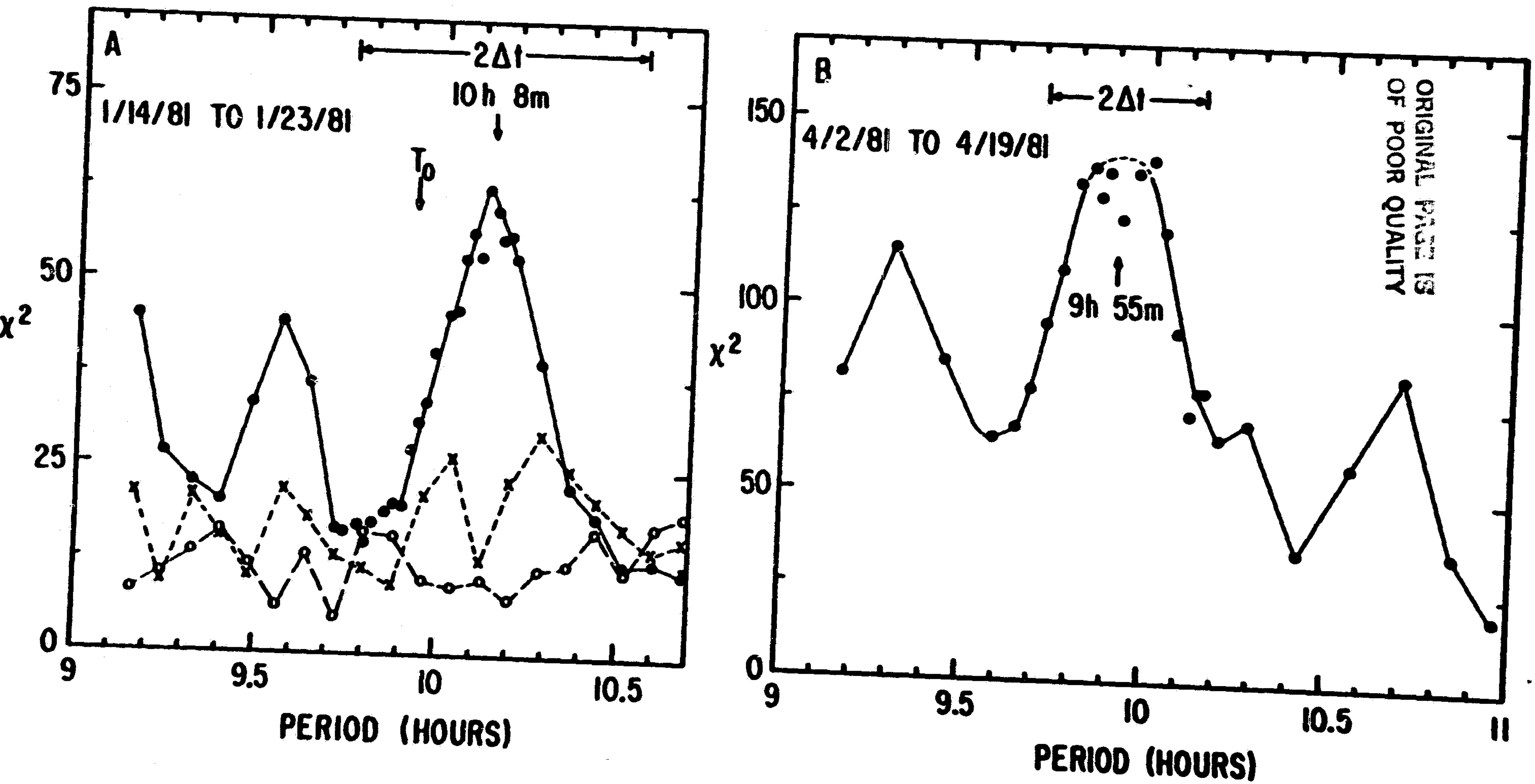
A
1/14/81 TO 1/23/81
2Δt
10h 8m
T_0
75
50
25
0
χ^2
9
9.5
10
10.5
PERIOD (HOURS)
B
4/2/81 TO 4/19/81
2Δt
9h 55m
ORIGINAL PAGE IS
OF POOR QUALITY
150
100
50
0
χ^2
9
9.5
10
10.5
11
PERIOD (HOURS)

Fig.13

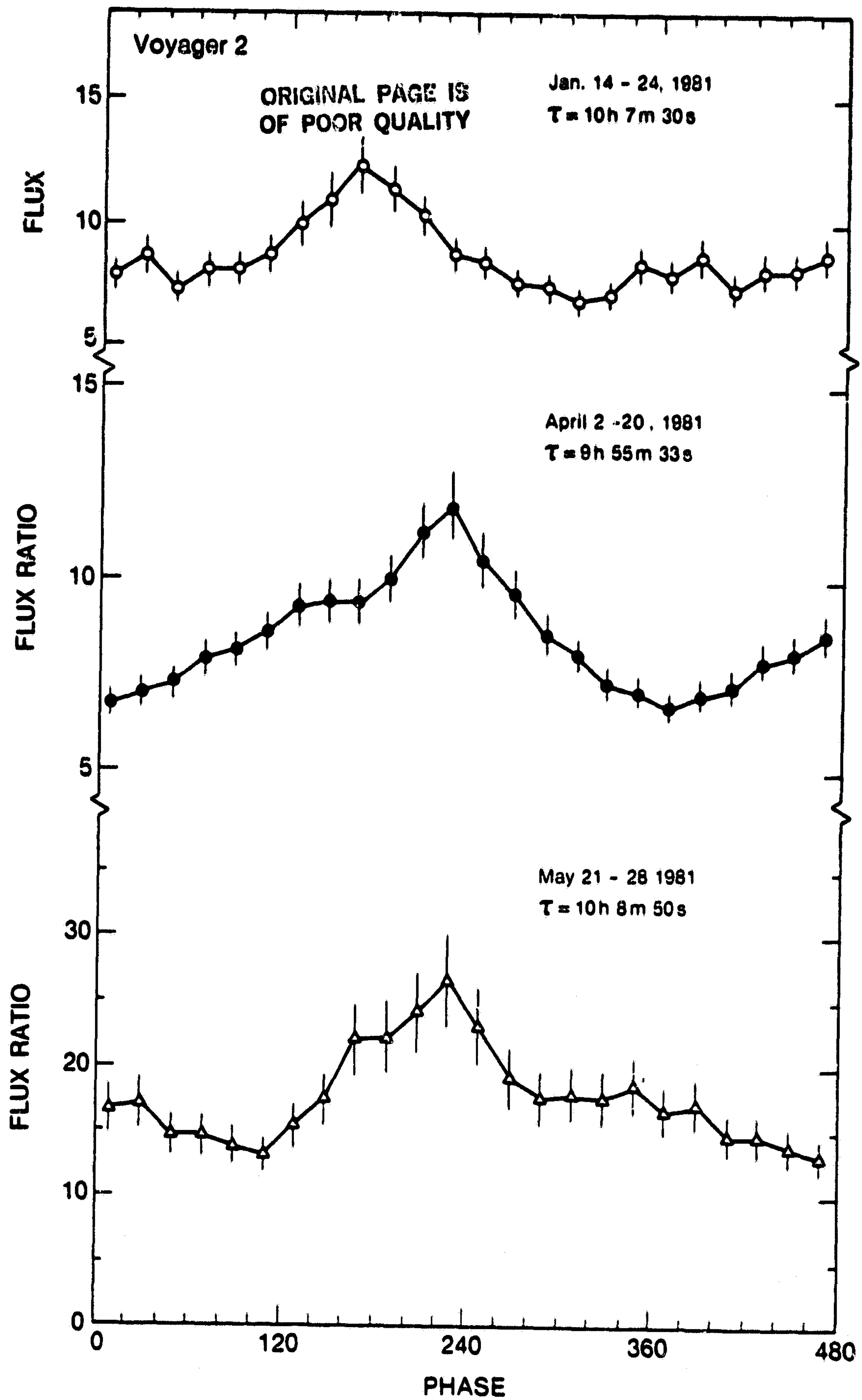
Voyager 2
ORIGINAL PAGE IS
OF POOR QUALITY
Jan. 14 - 24, 1981
τ = 10h 7m 30s
April 2 - 20, 1981
τ = 9h 55m 33s
May 21 - 28 1981
τ = 10h 8m 50s
FLUX
FLUX RATIO
FLUX RATIO
15
10
5
15
10
5
30
20
10
0
0
120
240
360
480
PHASE

Fig.14