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X-660-74-197

PREPRINT

NASA TM X- 70687

INTERPLANETARY Mev ELECTRONS OF JOVIAN ORIGIN

(NASA-TM-X-70687) INTERPLANETARY MeV ELECTRONS OF JOVIAN ORIGIN (NASA) 28 p HC $4.50 CSCL 03B

N74-28315

Unclas G3/30 43322

B. J. TEEGARDEN

F. B. McDONALD

J. H. TRAINOR

W. R. WEBBER

E. C. ROELOF

JUNE 1974

GSFC

GODDARD SPACE FLIGHT CENTER

GREENBELT, MARYLAND

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B. J. Teegarden, F. B. McDonald, J. H. Trainor
NASA Goddard Space Flight Center
Greenbelt, Maryland

W. R. Webber, E. C. Roelof
Department of Physics
University of New Hampshire
Durham, New Hampshire

Abstract

In this paper we report observations of low energy (0.2-8 MeV) electron increases observed in interplanetary space on Pioneer 10 as it approached within 1 AU of Jupiter. These discrete bursts or increases were typically several hundred times the normal quiet-time electron flux, and became much more frequent as one approached Jupiter resulting in the quasi-continuous presence of large fluxes of these electrons in interplanetary space. In view of the likely origin of these electrons at Jupiter, and the similarity of these increases to quiet-time electron increases previously observed at earth we have re-examined the temporal presence of the quiet-time increases. It is found that these increases have a 13 month periodicity indicating a Jovian origin for the events near the earth as well.

It is noted that the integrated flux from quiet-time increase electrons at 1 AU is comparable to the integrated ambient electron flux itself. In addition, the spectrum of electrons observed in Jupiter's magnetosphere, on Pioneer 10 in interplanetary space near Jupiter, for the quiet-time increases near the earth, and for the ambient electron spectrum are all remarkably similar. These two lines of evidence suggest the possibility that Jupiter could be the source of most of the ambient electrons at low energies. At the same time it is difficult to understand how Jovian electrons could be distributed uniformly throughout the inner solar system so as to produce the relatively constant quiet-time spectrum. At this time it is not possible to decide between a galactic knock-on origin coupled with a small residual solar modulation or a Jovian origin for the ambient electron intensity in the 0.2-40 MeV range.

I. INTRODUCTION

The behavior of low energy cosmic-ray electrons (~0.2-30 MeV) has become an important and intriguing aspect of cosmic ray research. These relativistic, low rigidity particles are unique probes for investigating the acceleration, propagation and modulation of both solar and galactic cosmic rays. The first measurements of these electrons (Cline et al., 1964, Simnett et al.,1969) found a flux in the 3-20 MeV region of ~1% of the total cosmic ray flux with an energy spectrum of the form $E^{1.75}$ Further measurements (Webber et al., 1973, Herford et al., 1973) extended the observations down to ~0.2 MeV with essentially the same spectral shape. On the high energy side this was extended to ~40 MeV by L'Heurex et al. (1972). The entire low energy spectrum from 0.2-40 MeV is remarkably different from the relatively flat differential spectra measured from ~40 MeV to ~1 GeV. Above 1 GeV the measurements approach a power law of $\sim E^{-3}$. Since the spectral shape of the low energy component is consistent with that of knock-on electrons produced in interstellar space by higher energy nucleons, it has been generally assumed they were interstellar secondaries. However this model requires that the total solar modulation at low energies be less than a factor of ~5.

In some respects such as Forbush Decreases, the time variations of this low energy component appeared to be qualitatively the same as that of higher energy cosmic rays (McDonald et al., 1972). The 11 year or long term modulation was, however, smaller (~2.5 from solar minimum to solar maximum) than the variation in higher energy electrons (McDonald et al., 1972). A more puzzling feature was the frequent (a total of 18-19 over a four year period) positive increases of these electrons that could not be associated with discrete solar events. These "quiet-time" increases represented a factor of 3-5 increase in intensity and lasted from 5-12 days. They displayed a remarkable anti-correlation with low-energy proton events. Qualitatively their amplitude was observed to diminish toward solar maximum. Webber et al., (1973) have reported that the correlation in quiet time increases observed on two spacecraft tends to disappear when the spacecraft are separated by more than ~20° in heliocentric longitude. Further 2 and 3 spacecraft comparisons will be of great interest in mapping the spatial variations of these electrons.

The Pioneer 10 spacecraft was launched toward Jupiter in early 1972. As the spacecraft came within 1 AU of the planet, a marked increase in MeV electron activity was observed, and it became clear that Jupiter was releasing large bursts of energetic electrons into interplanetary space (Trainor et al., 1974; Simpson et al., 1974). Some of these increases were at least two orders of magnitude larger than the quiet-time increases observed at earth. The question then arose, could some fraction of the low-energy electrons observed at earth be coming from Jupiter? We believe that at least part of the puzzling features of the low-energy electrons observed at earth can be explained if some of these electrons are of Jovian origin. We will present evidence in this paper that most of the electron quiet-time increases are of Jovian origin. Furthermore, the source strength appears adequate to supply all the low energy 0.2-40 MeV electrons observed at earth. However, Jupiter is essentially a point source at 5 AU, and it is not clear if the required flux can be distributed around the earth's orbit at 1 AU.

II. PIONEER 10 AND 11 RESULTS

The Goddard-University of New Hampshire cosmic ray experiments on Pioneers 10 and 11 consisted of a coordinated set of three solid state charged-particle telescopes. This paper contains data from two of these, the high energy telescope (HET) and the second of two low energy telescopes (LET-II). The LET-II is sensitive to electrons from ~0.12-2.1 MeV, and the HET covers the range 2.1-8.0 MeV. Both telescopes efficiently reject protons by multiparameter analysis. Schematic diagrams of the detector system are included in a companion paper to this one (Trainor et al., 1974).

Let us first examine the relative locations of Pioneers 10 and 11 and Jupiter during the period of the measurements. The Pioneer 10 and 11 trajectories are shown in Fig. 1. Superimposed on the trajectories are nominal interplanetary magnetic field lines, assuming a constant solar wind speed of 400 km/sec. The location of Jupiter six months prior to encounter is also shown. This figure will be referred to in the following discussion of the data.

The Pioneer 10 and 11 daily average electron counting rates in the energy range 6.2-8 MeV are shown in Fig. 2(a) and (b) for 1973. Due to the presence of radioisotope power generators (RTG's) on the spacecraft, the background in the electron counting rates on both Pioneer 10 and 11 is roughly a factor of 40 larger than that due to true cosmic ray electrons. Increases over background on these plots therefore represent very large increases in the electron intensity (i.e. at least 40 times the expected intensity). This very preliminary analysis is based on the "Rates Data."

Further analysis using the multiple parameter pulse height data will eliminate most, if not all, of the RTG background. Inspection of the pulse-height data show that the counting rate increases are produced by electrons and do not represent some spurious background. It is evident that there is a striking increase in the occurrence of electron events as Pioneer 10 approaches Jupiter. The black boxes indicate times when solar protons were present at Pioneers 10 and 11. The largest solar proton event seen on Pioneer 10 in 1973 was that on 3 May, yet we see that the accompanying electron increase barely exceeded background. It is unlikely then that the other electron increases on Pioneer 10 in 1973 are of solar origin. Furthermore, in marked contrast to Pioneer 10, there is very little activity seen on Pioneer 11. The only two exceptions (28 April and 30 July) are clearly flare associated. The level of activity steadily increases as Pioneer 10 approaches Jupiter. The small size of the flare associated events on Pioneer 10 and 11 and the lack of any significant Pioneer 11 electron increases show that these electrons are not of solar origin. The steady increase as Pioneer 10 approaches Jupiter as well as the thirteen month periodicity observed in quiet time electron increases (as discussed in a later section) indicate these electron bursts are of Jovian origin. Jovian electrons were seen possibly as early as 8 March 1973 and were certainly present by the end of May. During the March-May period Pioneer 10 was between 1.2 and 0.8 AU away from Jupiter. Electrons escaping from Jupiter are therefore seen at quite large distances from the planet.

Let us now refer back to Fig. 1 and examine the relative locations of Pioneers 10 and 11 during the times that Jovian electrons are present. Both Pioneers 10 and 11 are moving roughly perpendicular to the interplanetary magnetic field lines during this time. Pioneer 10 does not cross the nominal field line connecting to Jupiter until the actual time of encounter. In fact, during the March-June period Pioneer 10 and Jupiter nearly line up along the same radius to the Sun. Since the electrons are expected to propagate mainly along field lines, some distortion of the field relative to the nominal spiral is necessary for Jovian electrons to be easily seen at Pioneer 10.

During the latter half of 1973 Pioneer 11 is, on the other hand, much more distant from Jupiter's field line. To permit Jovian electrons to propagate to Pioneer 11 would require a very large deformation of the magnetic field line. It is therefore quite reasonable that no large Jovian electron increases are seen on Pioneer 11 during this time.

To show in more detail the time structure and energy dependence of these events we have plotted three electron counting rates at different energies on an expanded scale (6 hr. avg.) in Fig. 3. Solar proton events, which are principally low-energy co-rotating types, are again indicated by black boxes. Details of the time structure of these electron events are more evident in this figure. They appear to have roughly equal rise and decay times - typically of the order 1-2 days. The duration of an event is generally of the order of 2-4 days. The longer events, particularly in August and September 1973, appear to be superpositions of shorter events. At this point it is not possible to determine whether this time structure is a feature of the escape process or is a result of varying connection conditions due to changes in the interplanetary magnetic field. The general increase in electron activity in the vicinity of Jupiter is even more strikingly apparent in this figure than in Fig. 2. Keeping in mind that the counting rate background level is ~40 times the nominal electron intensity, it is evident that Jovian electrons are strongly dominating a region around the planet at least 0.5 AU in extent.

The electron spectrum during the increase of 5 November is shown in Fig. 4. It was necessary to choose one of the largest events to derive a spectrum in order to insure that the lowest energy points significantly exceeded the radioisotope power supply background. We therefore cannot be certain that this spectrum represents the behavior of all events, particularly the smaller ones at large distances from the planet. The data are consistent with an $E^{-1.5}$ power law over the .12-8.0 MeV range. This is a preliminary analysis and present uncertainties in the calibration of the detector are responsible for an error of $\sim \pm 0.3$ in the power law exponent. Also shown in Fig. 4 is a representative spectrum of electrons in the outer part of the Jovian magnetosphere taken from the companion paper (Trainor et al., 1974). In that paper it is shown that the index of the differential electron spectrum in the outer part of the Jovian magnetosphere ($> 30\ R_J$) is always in the 1.5-2.0 range in the energy interval 0.12-8.0 MeV. The relative similarity of the two spectra in Fig. 4 further confirms the Jovian origin and shows that the escape of these electrons from the Jovian magnetosphere is an energy-independent process. As discussed in the accompanying paper the electrons in the outer Jovian magnetosphere do not appear to be stably trapped with most of them diffusing into interplanetary space.

III. OBSERVATION OF JOVIAN ELECTRONS AT THE EARTH

We have seen in the preceding section that Jupiter is a copious source of MeV electrons. Furthermore, we have established that these electrons are present at least as far as 1 AU away from the planet. The question logically arises, could Jovian electrons be reaching the earth, and, in particular, could they be responsible for the quiet-time increases at 1 AU? Let us first assume that electrons from Jupiter are strongly tied to field lines intersecting the Jovian magnetosphere. Such electrons would be seen at earth mainly at times when the earth crossed field lines connecting with Jupiter. If the field were a perfect Archimedean spiral, this would occur every 13 months (since Jupiter's period is 11.86 yr. the earth's synodic period with respect to Jupiter is 13 months). The question then arises, do 13 month periodicities exist in the quiet-time increases at the earth? In Fig. 5 we have plotted the 3-12 MeV electron counting rate from the earth orbiting satellites IMPs III, IV, (McDonald et al., 1972) and IMP V (Van Hollebeke, private communication) on 13 month epochs over the period 1965-1972. Using >20 MeV protons as an indicator, periods when solar activity was present have been removed. However, there appear to be significant solar MeV electrons present from large co-rotating events in mid-1966. The large increase in Nov. 1967 may also have some solar contribution. The 13 month periodicity in the electron intensity is immediately obvious. The increases are most pronounced during the first three years (1965-1967) and are generally a factor of 2-5 over the normal background level. The maxima in the envelopes of these increases is separated by roughly 13 months. The data in 1969 are incomplete due to a gap between IMP IV and IMP V coverage and the presence of solar activity. The existing data are, however, consistent with the picture developed for the first three years. During 1970 the effect has almost disappeared. Nonetheless a significant enhancement during the middle of the 13 month period still exists. In 1971 and 1972 the 13 month variation has increased in magnitude, but has not yet returned to the level of the 1965-1967 period. As has been previously suggested (McDonald, et al., 1972) it is apparent that the quiet time increases are anti-correlated with the long-term level of solar activity. The increases were largest near solar maximum, (1965-66), nearly vanished near solar maximum (1969-70), and began to increase as the next solar minimum was approached (1971-72).

In Fig. 6 the time of the year that the earth crosses Jupiter's field line is plotted for each year from 1964-1974. The vertical bars in the plot give the duration of the periods when quiet-time increases were present. With the exception of the 1964 bar all of the periods fall close to or contain the predicted time of crossing Jupiter's field line. There does, however, appear to be a tendency for the field line crossing to occur near the beginning of these periods. Field line distortion will occur due to changes in solar wind speed. Speeds greater than 350 km/sec will produce straighter field lines which in turn will mean that the earth-crossing of Jupiter's field line will take place earlier in time. Such a mechanism is therefore incapable of explaining the tendency of increases to occur after the field line crossing. Field line co-rotation would tend to sweep particles around azimuthally in the co-rotation direction which in turn could permit electrons to be seen at the earth after the time that Jupiter's field line is crossed. This mechanism would, however, require long electron containment times ($\sim$7 days). In view of the short decay times of solar flare electrons ($\lesssim$ 1 day) such a mechanism is probably not possible.

The specific details of the quiet-time increases are also of interest. For example, the average duration of the individual increases at earth is generally on the order of 10 days, which is somewhat longer than the duration of the increases seen on Pioneer 10 near Jupiter.

The magnitude of the increases differs greatly between Pioneer 10 and the earth. At earth the increases are typically a factor of 2-5 over the background whereas on Pioneer 10 they are as much as a factor of 300 over background. Thus the increases near Jupiter are $\sim$50-150 times as large as the increases near earth. At this time we have not examined possible models for the propagation of these pulses; however the anti-correlation between quiet-time electron increases and low energy solar protons pointed out by McDonald et al. (1972), argues that turbulence or scattering effects are most important in this process.

Preliminary analysis of the upstream electron anisotropy in the 2-8 MeV interval on a daily basis shows that anisotropies, if they exist, are $\lesssim$10%. Further work can be expected to reduce this limit by at least a factor of 5. The existing limit does, however, show that a significant randomization of the particle motion has occurred over the $\lesssim$.5 AU distance between Pioneer 10 and Jupiter at the time of the measurements.

IV. INTERPRETATION OF RESULTS: CAN JUPITER BE THE SOURCE OF QUIET-TIME LOW-ENERGY COSMIC RAY ELECTRONS AS WELL?

The data presented in the preceding sections strongly support the conclusion that most, if not all, the quiet-time increases at 1 AU are of Jovian origin. We now address the question of whether some or all of the low-energy ambient electrons previously thought to be of galactic origin could possibly be coming from Jupiter. It was pointed out in the introduction that there were several puzzling features in the behavior of these particles, including their relatively small long-term modulation relative to higher energy protons and electrons. The spectra of only a few quiet-time increases during 1967 and 1969 have been reported (McDonald et al., 1972). The spectral form of E^{-2} during these events was consistent with the $E^{-1.75}$ spectrum reported by Simnett et al., (1969) for the ambient electrons over a broader energy range (3-20 MeV). Webber et al., (1972) showed that many of the 1968-69 increases maintained the same spectral form down to ~0.2 MeV. McDonald et al. used this as an agrument that the increases, as well as the nominal electron flux, were most probably of the same origin. The spectral index of the Pioneer 10 increases near Jupiter was ~1.5 (Trainor et al., 1974) with a probable uncertainty of a few tenths of a power. The Pioneer 10 spectrum is slightly flatter than the 1 AU spectra. Propagation effects, however, could produce a slight steepening of the electron spectrum as the particles travel inward from 5 to 1 AU.

Referring back to Fig. 5, it is apparent that near solar minimum (1965) the integrated flux during each 13-month interval of quiet-time increase electrons at 1 AU is of the same order as the integrated nominal flux of ambient electrons. During 1967 and 1968 the quiet-time increases were on the order of 25% of the nominal flux. From this point of view one can infer that Jupiter possesses the necessary source strength to supply these electrons.

Alternatively, one can calculate the source strength necessary to uniformly fill a sphere of radius 5 AU with .2-20 MeV electrons at an intensity of 5×10^{-2} electron/cm^2-sec-ster with a minimum lifetime of 2 hours which is of the order of the transit time. This gives a source strength of $\sim 10^{28}$ electrons/sec. If the source of these electrons was originally in the solar wind, then an acceleration efficiency of 10^{-2} is required (assuming an effective radius of the Jovian magnetosphere of 30 R_J). The ideal approach, of course, would be to calculate or determine the rate at which electrons are ejected from the Jovian magnetosphere. The energy input to the Jovian magnetosphere necessary for such a source strength is, however, significantly larger than the solar wind energy input and probably implies that some other energy source is required. One obvious candidate is Jupiter's rotational energy.

Finally, we turn to the question of the propagation of these electrons from Jupiter to the earth. If Jovian electrons are the source of the low-energy ambient cosmic-ray flux then they must somehow have been transported azimuthally over at least 180° in heliocentric longitude. Diffusion across field lines alone is probably insufficient to do this. Solar wind speed variations can probably only account for spreading the electrons out over 90° (3 mo. duration). Another possible mechanism is transport due to co-rotation of the interplanetary magnetic field lines that Jupiter encounters as it moves about the sun. For this to work at all, containment lifetimes comparable to a solar rotation (i.e., $\sim$15 days) are needed. The decay times of solar flare electron events are, however, generally $\lesssim$1 day. It is, therefore, difficult to understand how such long containment times could exist for electrons in the inner solar system.

The 1967-68 period is of particular interest, since the duration of the period when increases were present was the longest ($\sim$8 mo.) and the azimuthal propagation apparently most effective. This period corresponded to rather unusual interplanetary conditions where the dominant sector structure consisted of only two sectors. If, in fact, sector boundaries are obstacles to particle propagation, as is indicated by the confinement of quiet-time increases within sectors (McDonald, et al., 1972), then the presence of only two sectors in 1967-68 could indicate that propagation conditions were particularly favorable.

So far, then, we have been unable to come up with a satisfactory transport mechanism to fill the inner solar system with Jovian electrons. On the other hand, there are also difficulties with the assumption that this low-energy electron spectrum is due mainly to galactic knock-on electrons. This galactic knock-on contribution can be accurately calculated (Abraham et al., 1966) and has essentially the same spectral shape and is a factor $\sim$5 larger than the ambient electron spectrum. Generally it is expected that the modulation of the low-energy electrons is larger than this, and the large gradients of Jovian electrons between 1 and 5 AU also support the idea of a small diffusion coefficient κ and consequently a large modulation in the equatorial plane. If this is correct, then if interstellar knock-on electrons are the dominant component, they most probably will have had to enter over the solar poles where κ is presumably larger.

It is possible that there will be similar bursts of Jovian protons and alpha particles. The pre-encounter period contains a great deal of low-energy ($\sim$1 MeV) solar proton activity, and it is, therefore, difficult to identify any Jovian proton events. Moreover, these nuclei are one to two orders lower in intensity in the outer Jovian magnetosphere than electrons of the same energy and have a much steeper energy spectrum (E^{-4}). They are, therefore, not expected to be an important contribution in the inner solar system.

V. SUMMARY AND CONCLUSIONS

The principal conclusions of this paper are summarized as follows:

1. Jupiter is a strong source of MeV electrons as evidenced by the dramatic increase in electron activity as pioneer 10 approached the planet.
2. The escape of these electrons is an energy-independent process. One possibility is convective transport out of the Jovian magnetosphere.
3. The quiet-time increases at 1 AU have a distinct 13 month periodicity implying that most of them are of Jovian origin. There is a tendency for most increases to occur during a 1-3 month period after the earth crosses Jupiter's nominal field line.
4. The source strength required to populate the inner solar system with Jovian electrons is not unreasonable. However no satisfactory mechanism capable of transporting Jovian electrons over 360° in longitude is known to us at present.

FIGURE CAPTIONS

1. Pioneer 10 and 11 trajectories are shown in a non-rotating heliocentric coordinate system. Superimposed are idealized spiral magnetic field lines assuming a constant solar wind speed of 400 km/sec. The marks on the 1 AU circle indicate the position of the earth once each quarter.

2. The daily average counting rates for 6.2-8 MeV electrons on Pioneers 10(a) and 11(b). The black rectangles indicate the larger solar cosmic ray events. Most of these are of the low-energy co-rotating type.

3. Six hour counting rate averages are plotted for three electron energy intervals (2.1-3.7 MeV, 3.7-6.2 MeV and 6.2-8 MeV. The cross-hatched rectangles are the same solar proton events of Fig. 2. Note that in the Nov. 5 event data points from the two highest energy channels are intermixed with their nearest neighbors.

4. Electron energy spectra for a large interplanetary electron increase and in the outer Jovian magnetosphere. The data between .1 and 2 MeV is from the LET-II telescope (Trainor et al., 1974). This has a geometric factor of .015 cm^2-ster so meaningful measurements are possible only during the largest electron increases.

5. 3-12 MeV data from IMP's III and IV (McDonald and Simnett, 1972) and IMP V (Van Hollebeke, private communication) plotted in 13 month epochs. The dashed line is a convenience for identifying the electron increases. There still may be major solar contributions in some periods such as 28 July-10 August 1966 and 20 September-10 October 1966. The 13 month periodicity is clearly defined and the amplitude decreases over solar maximum (~1969).

A background subtraction has not been made for the data after July 1969.

6. The vertical bars give the duration of the periods when quiet-time increases were present during the various epochs shown in Figure 5. Arrows indicate when the length of the bar is uncertain due to a data gap. The diagonal line represents the time of the year that an idealized spiral interplanetary magnetic field line would connect the earth and Jupiter assuming a constant plasma velocity of 350 km/sec.

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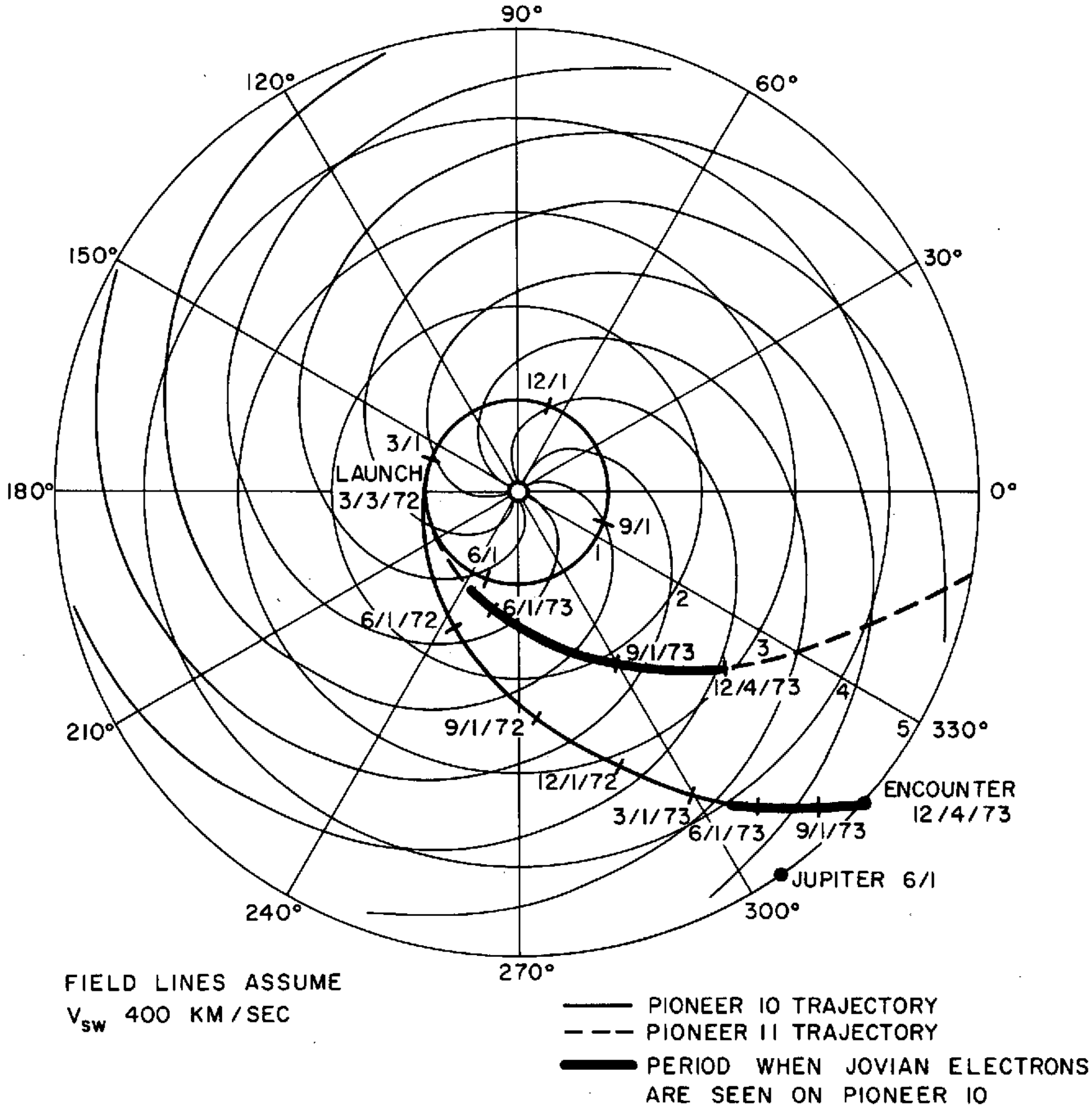
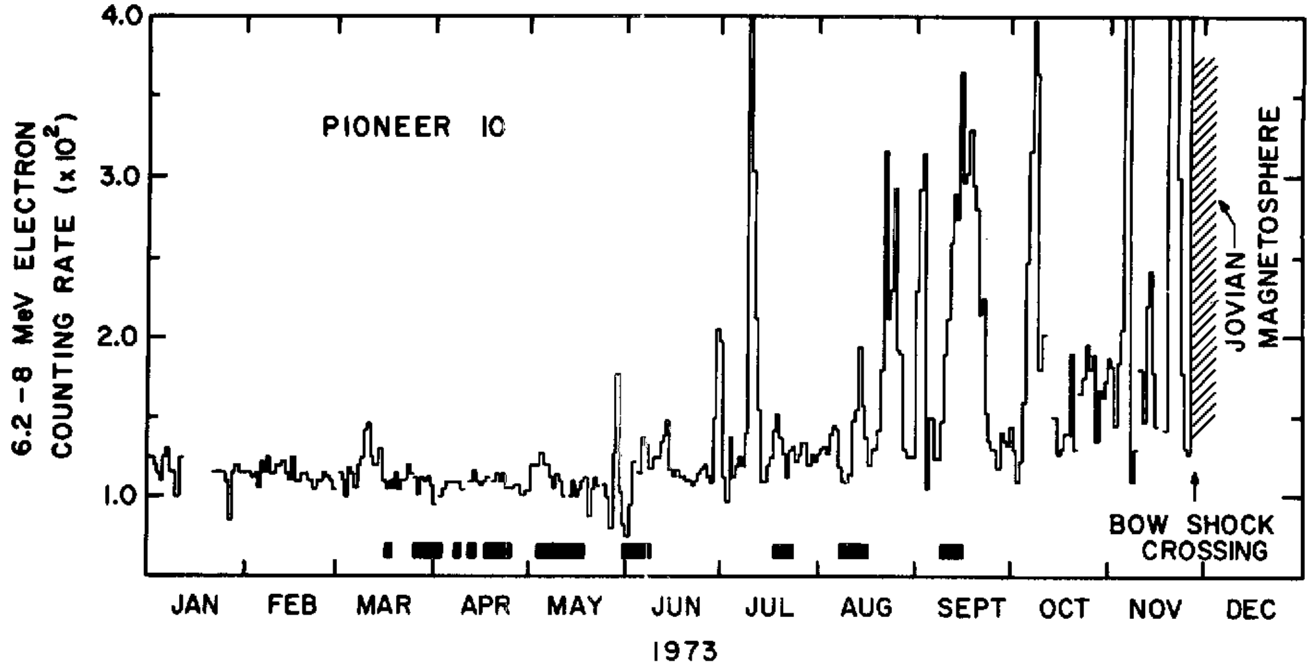
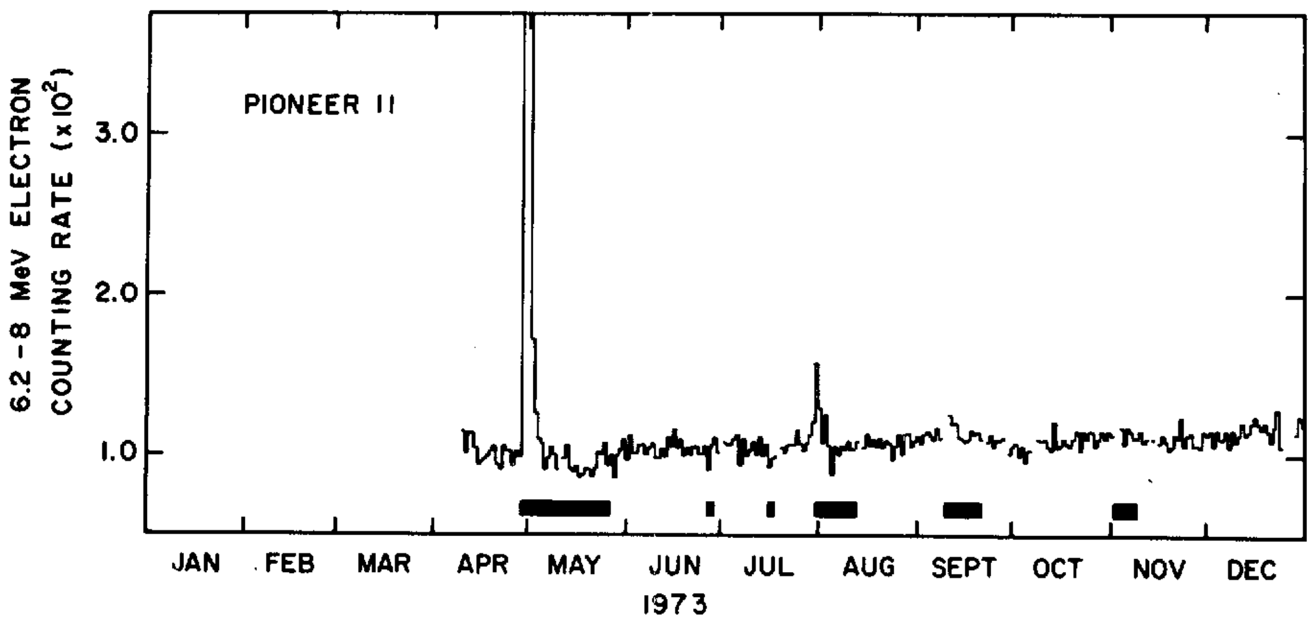

90°
60°
30°
0°
330°
300°
270°
240°
210°
180°
150°
120°
12/1
3/1
LAUNCH
3/3/72
9/1
1
6/1
2
6/1/73
3
9/1/73
12/4/73
4
5
6/1/72
9/1/72
12/1/72
3/1/73
6/1/73
9/1/73
ENCOUNTER
12/4/73
JUPITER 6/1
FIELD LINES ASSUME
V_{SW} 400 KM / SEC
PIONEER 10 TRAJECTORY
PIONEER 11 TRAJECTORY
PERIOD WHEN JOVIAN ELECTRONS
ARE SEEN ON PIONEER 10

Fig. 1



PIONEER 10
6.2 - 8 MeV ELECTRON COUNTING RATE (x 10^2)
4.0
3.0
2.0
1.0
JOVIAN MAGNETOSPHERE
BOW SHOCK CROSSING
JAN FEB MAR APR MAY JUN JUL AUG SEPT OCT NOV DEC
1973



PIONEER 11
6.2 - 8 MeV ELECTRON COUNTING RATE (x 10^2)
3.0
2.0
1.0
JAN FEB MAR APR MAY JUN JUL AUG SEPT OCT NOV DEC
1973

Fig. 2

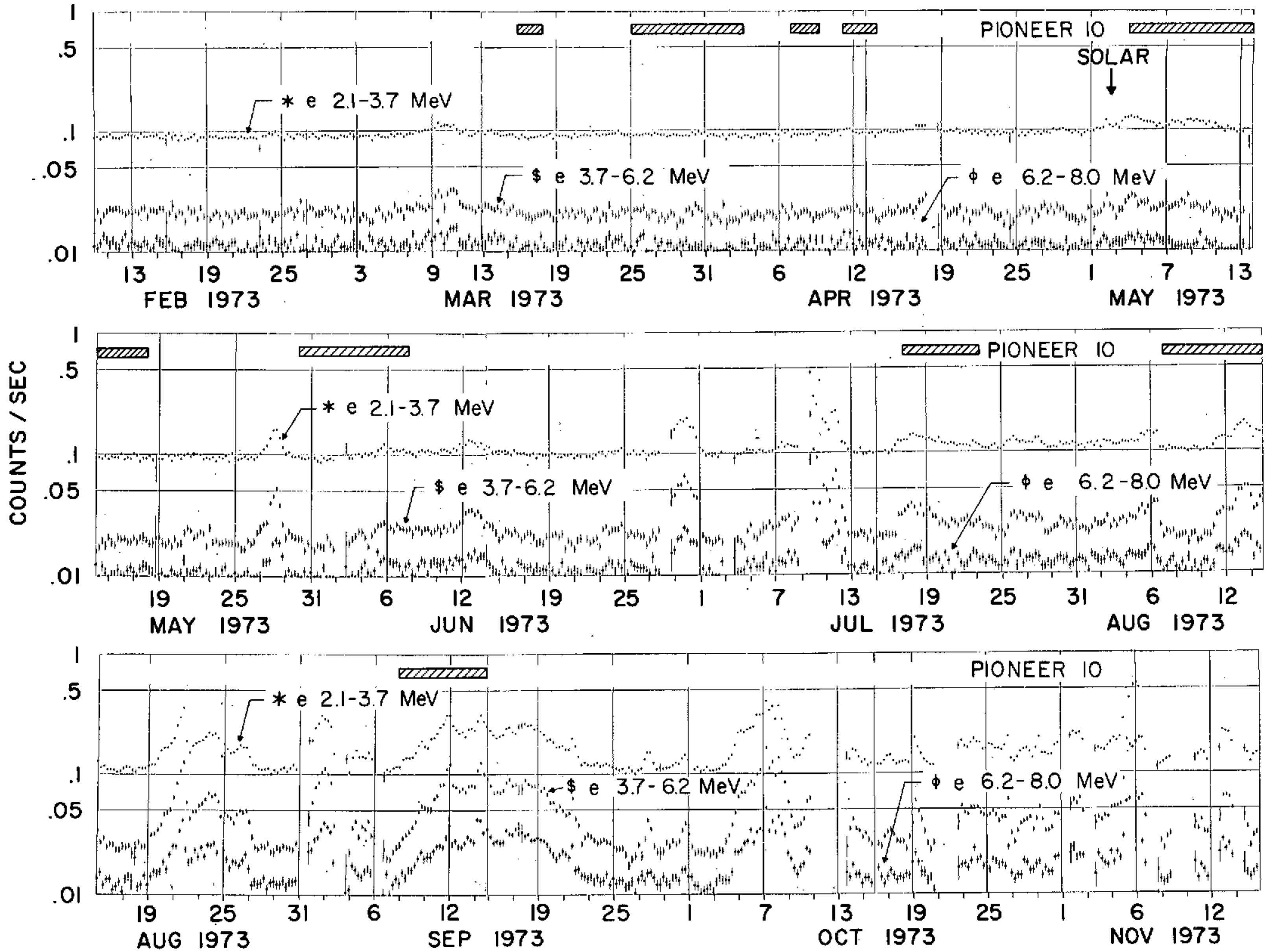
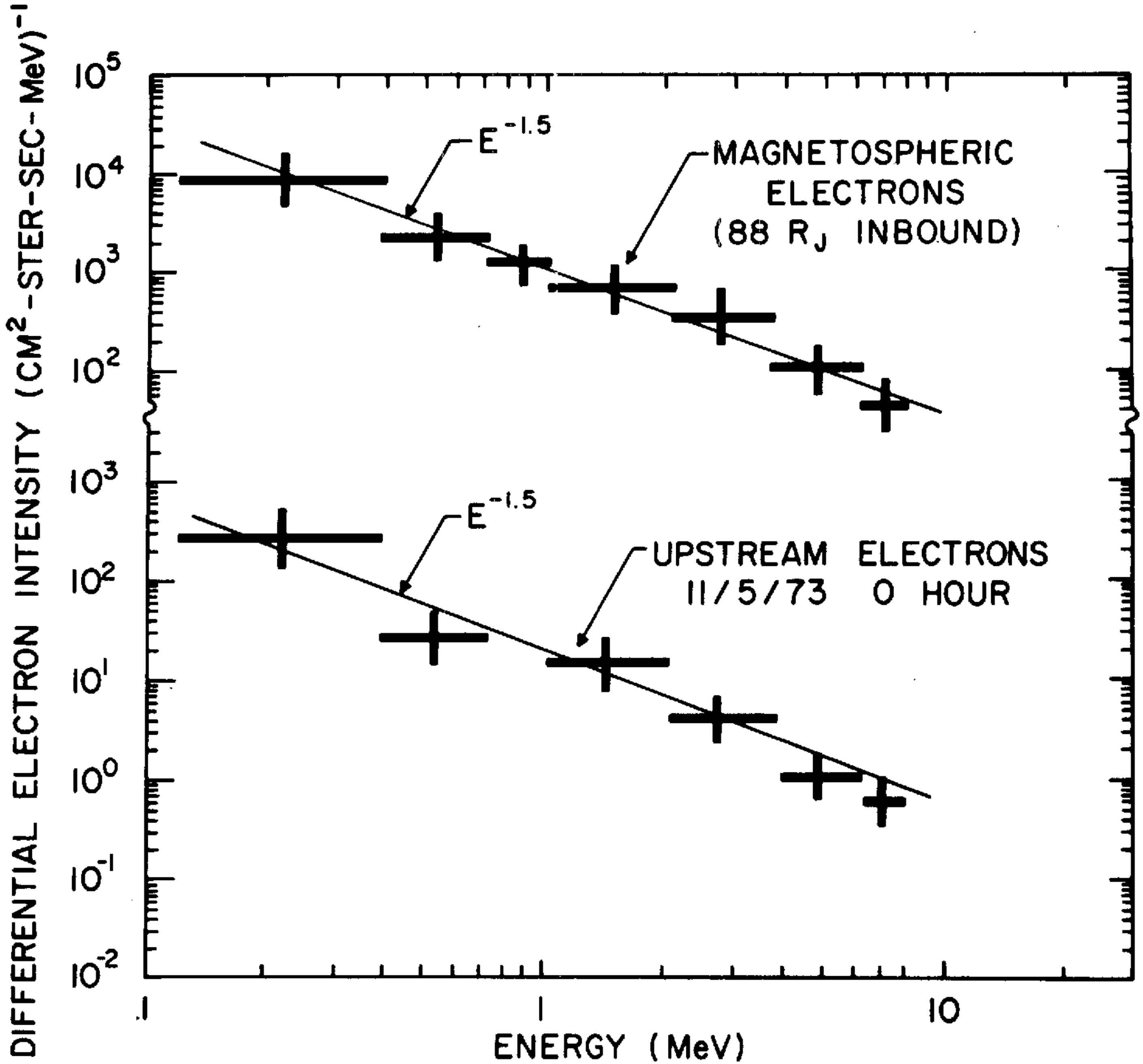

COUNTS / SEC
PIONEER 10
SOLAR
* e 2.1-3.7 MeV
$ e 3.7-6.2 MeV
ϕ e 6.2-8.0 MeV
FEB 1973
MAR 1973
APR 1973
MAY 1973
JUN 1973
JUL 1973
AUG 1973
SEP 1973
OCT 1973
NOV 1973

Fig. 3



DIFFERENTIAL ELECTRON INTENSITY (CM^2-STER-SEC-MeV)$^{-1}$
$E^{-1.5}$
MAGNETOSPHERIC ELECTRONS (88 R_J INBOUND)
$E^{-1.5}$
UPSTREAM ELECTRONS 11/5/73 0 HOUR
ENERGY (MeV)

Fig. 4

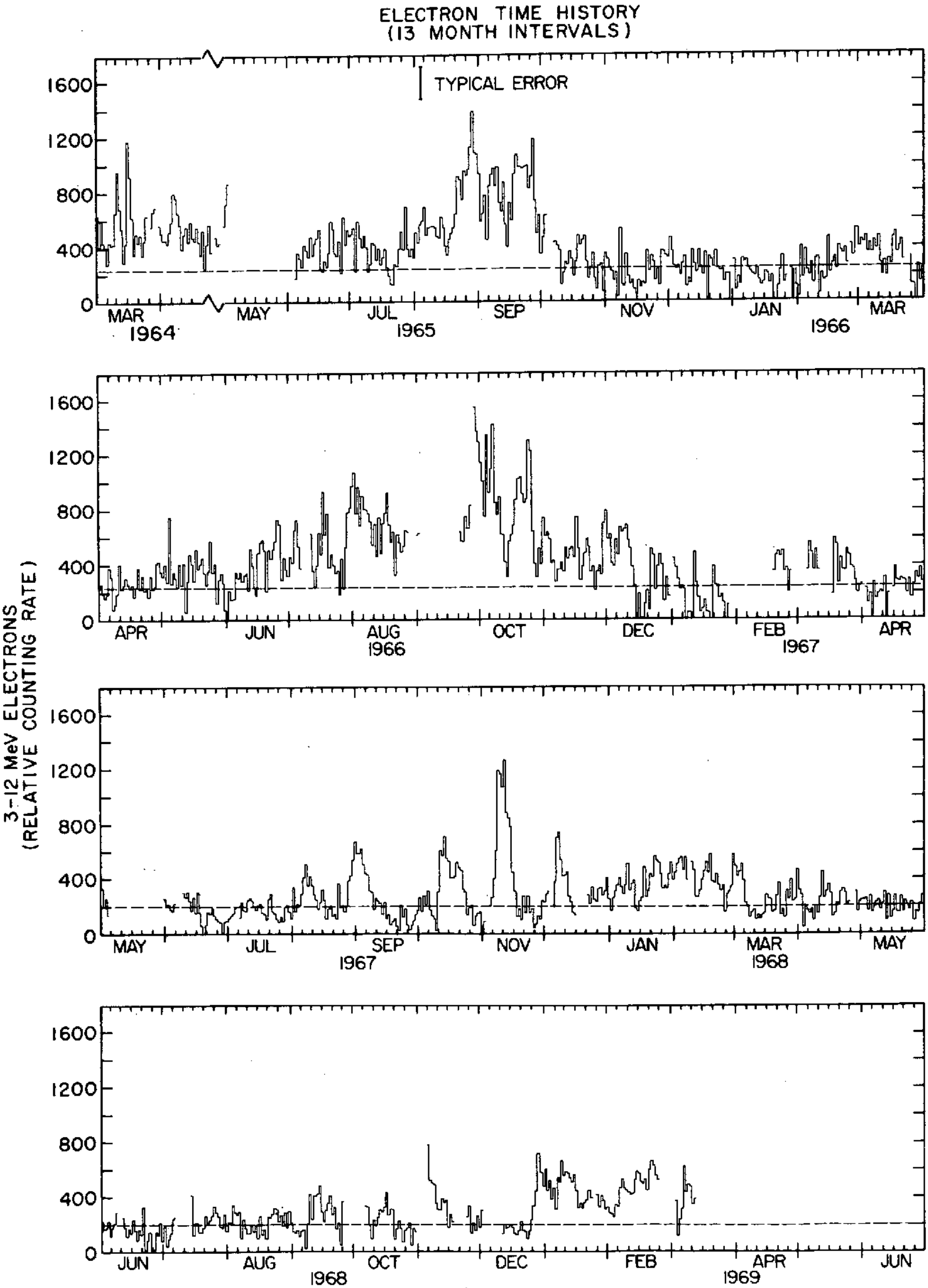
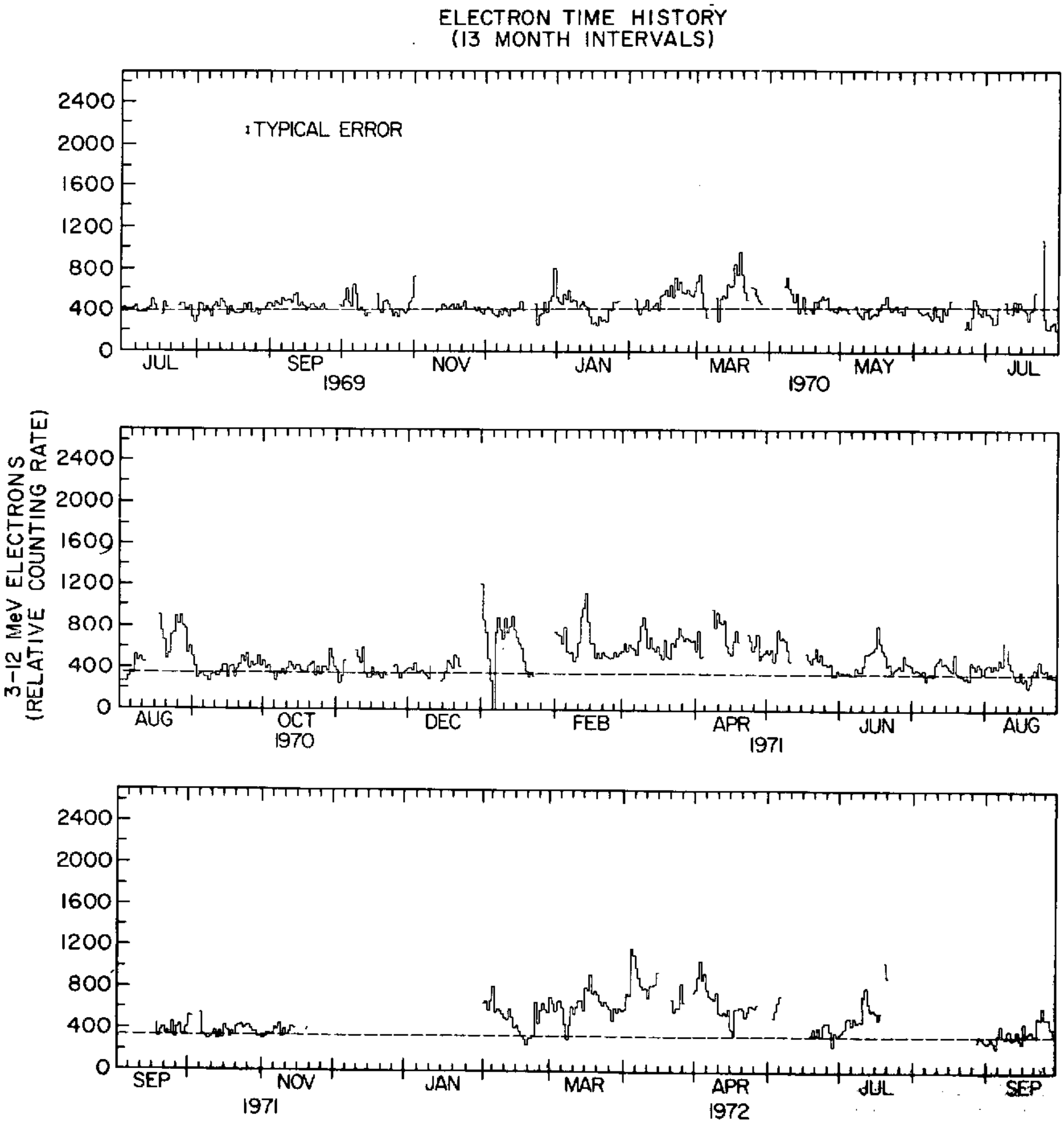

ELECTRON TIME HISTORY
(13 MONTH INTERVALS)
TYPICAL ERROR
3-12 MeV ELECTRONS
(RELATIVE COUNTING RATE)
0
400
800
1200
1600
MAR
1964
MAY
JUL
1965
SEP
NOV
JAN
1966
MAR
APR
JUN
AUG
1966
OCT
DEC
FEB
1967
APR
MAY
JUL
SEP
1967
NOV
JAN
MAR
1968
MAY
JUN
AUG
1968
OCT
DEC
FEB
APR
1969
JUN

Fig. 5a



ELECTRON TIME HISTORY
(13 MONTH INTERVALS)
TYPICAL ERROR
3-12 MeV ELECTRONS
(RELATIVE COUNTING RATE)
2400
2000
1600
1200
800
400
0
JUL
SEP
NOV
JAN
MAR
MAY
JUL
1969
1970
AUG
OCT
DEC
FEB
APR
JUN
AUG
1970
1971
SEP
NOV
JAN
MAR
APR
JUL
SEP
1971
1972

Fig. 5b

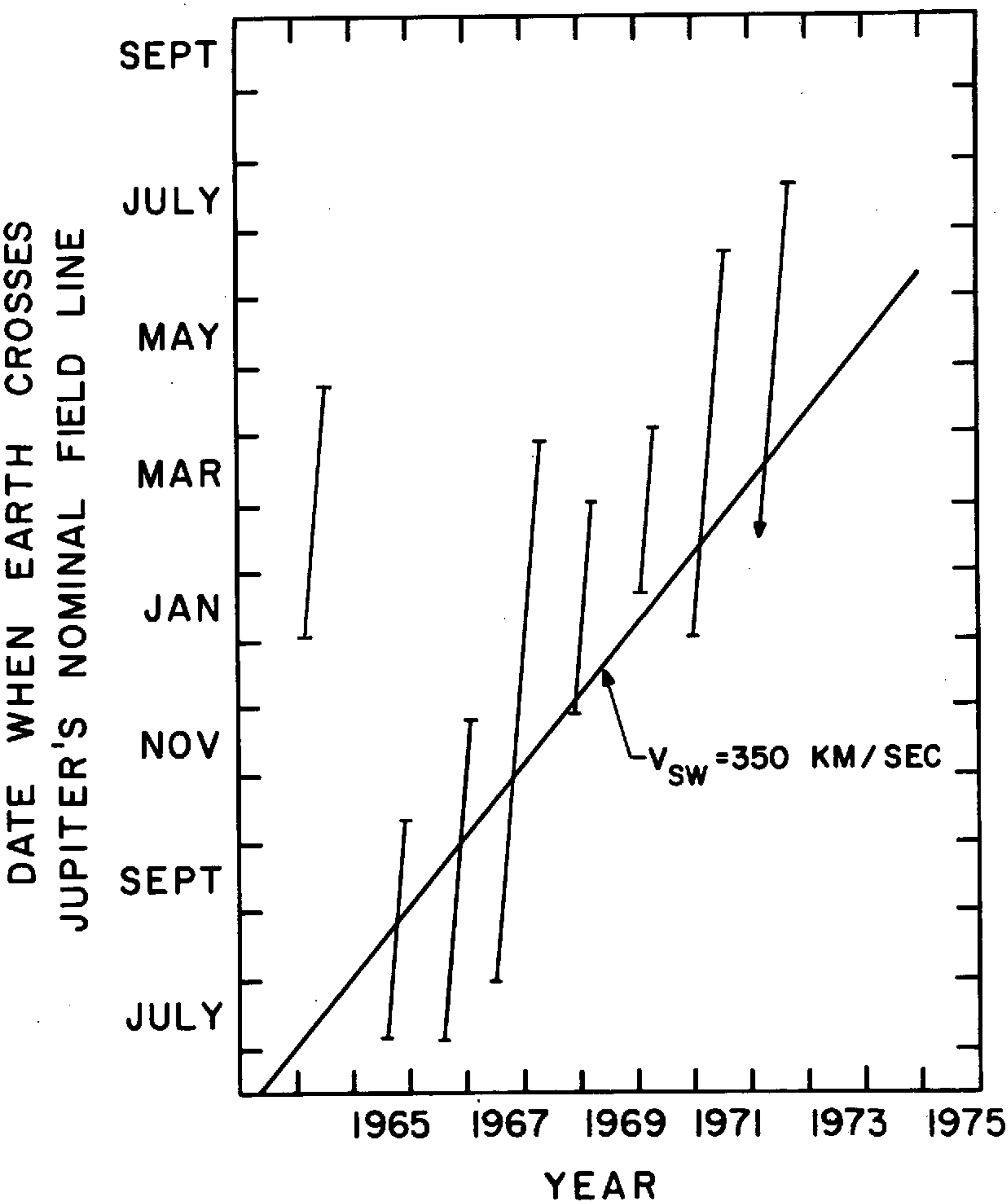

DATE WHEN EARTH CROSSES
JUPITER'S NOMINAL FIELD LINE
SEPT
JULY
MAY
MAR
JAN
NOV
SEPT
JULY
V_{SW} =350 KM/SEC
1965
1967
1969
1971
1973
1975
YEAR

Fig. 6