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THE MAGNETIC STRUCTURE OF INTERPLANETARY SPACE*

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Introduction

A study of the magnetized plasma in interplanetary space is of prime interest to many problems in Solar-Terrestrial Physics. We are concerned here primarily with presenting a brief summary and overview of our present understanding of the interplanetary magnetic field structure.

Direct measurements between 0.7 to 1.5 AU of the interplanetary medium since 1962 has demonstrated the existence of a continuous flux of plasma from the sun, essentially as theoretically predicted by E. N. Parker and termed by him "the solar wind". It is also known that a very weak magnetic field of solar origin threads through this plasma continuously while generally maintaining a direct connection to the sun.

Representative values measured at 1 AU are: interplanetary magnetic field magnitude ranges between 2 to 40 gamma (1 gamma = 10 μ Gauss) with an average magnitude of 6 gamma; a positive ion flux with values between 10^8 to 10^{10} ions/cm^2/sec with an average 3×10^8 ions/cm^2/sec; densities range between 0.4 to 80 ions/cm^3 with an average of approximately 5 ions/cm^3. The average energy of an individual ion ranges between 500 ev to 4 kev corresponding to velocities of 300 to 900 km/sec with an average of 400 km/sec.

The temperature of the solar wind, as measured by the random velocities of ions and electrons relative to the mean bulk velocity, is quite complex. The interplanetary plasma is not in thermodynamic equilibrium with the ions possessing a magnetic field aligned temperature anisotropy of approximately 1.5 with a most probable T_p of 5×10^4 °K, while the electrons have a temperature of approximately 1.5×10^5 °K. The chemical composition is at times highly variable, but appears on average to be principally hydrogen, 95%, with the fraction of helium nuclei ranging between 0 to 15% and an average value of 5%. The direction of plasma flow, as measured at 1 AU appears to be on average from 1.5° East of the sun in a sense which would be consistent with a direct physical co-rotation of the outer solar corona to several solar radii. However, the direction of plasma flow is also highly variable, ranging as far as $\pm 10°$-$15°$ from the mean direction.

Synoptic studies of the physical properties of the interplanetary medium and in particular the interplanetary magnetic field, have revealed a sectoring or ordering of the direction and correlated variations of plasma velocity, density, terrestrial magnetic activity, and long-lived streams of solar cosmic rays. Second order results indicate a rich fine scale filamentary structure of the interplanetary medium in which individual flux tubes appear to be directly connected to the sun.

From these detailed satellite studies and long term observations, it is now possible to view the interplanetary medium as being structured on three characteristic time scales:

1. Micro Structure, < 1 hour, which includes shock waves and plasma magnetic field discontinuities on the kinetic scale;
2. Meso Structure, 1 to 100 hours, which includes filaments, kinks or loops in the interplanetary magnetic field; and
3. Macro Structure, > 100 hours, which refers to the sectoring of the interplanetary medium, the length of the interplanetary magnetic field filaments and large scale plasma streams.

These time scales may be converted to length scales by multiplication by the average solar wind velocity of 400 km/sec yielding:

1. $L_{micro} < 10^6$ km $\approx .01$ AU
2. $L_{meso} = 10^{6-8}$ km $\approx .1$ AU
3. $L_{macro} > 10^8$ km $= 1$ AU.

Recent reviews published presenting more detailed discussions of topics relevant to this paper are: Dessler (1967) summarizing theories of the solar wind and the interplanetary magnetic field; Hundhausen (1969), discussing primarily the interplanetary plasma; Parker (1965), summarizing and updating principally his theoretical model of the solar wind phenomena; Vasyliunas (1969), discussing experimental techniques for measurement of the interplanetary plasma;

and Wilcox (1968) presenting a synoptic review of solar and interplanetary magnetic fields. An attempt will be made in this paper to include references to current and original papers relevant to specific topics discussed in order to guide interested readers in this rapidly developing field.

One of the fundamental problems related to the large scale interplanetary magnetic field structure is that of the cosmic ray Forbush decrease. Two models proposed to explain this phenomenon are illustrated in Figure 1. Gold (1959) suggested that a tongue of plasma and magnetic field is ejected from the sun and responsible for the sweeping out of cosmic ray particles in the solar system leading to a classic Forbush decrease.

An alternative model proposed by Parker (1961) is that of a blast wave propagating into interplanetary space leading to a sharp field increase and a corresponding sweeping action. Sufficient evidence has been obtained by recent satellite experiments (Rao, McCracken and Bukata, 1967) to conclude that the model of Parker more readily explains the temporal variation of the characteristics of particle flux variations and changing anisotropies during and following a Forbush decrease.

These two models were proposed well in advance of direct in situ observations of the interplanetary medium. The model of Gold assumed a vacuum in interplanetary space while that of Parker considered the significant effects of an existing magnetized plasma in interplanetary space in studying the propagation of transient events of solar origin. An essential feature of the distinction between them is the presence in one of them of a steady-state solar coronal expansion and the resultant interplanetary magnetic field configuration.

The expansion of the solar corona into interplanetary space convectively extends the solar magnetic field with it since the plasma is highly conducting. Because the sun rotates it leads to a twisting of the solar magnetic field into a classical Archimedean spiral. The geometry of the interplanetary magnetic field is shown in Figure 2 as a function of solar wind velocity. Near 1 AU, the variation in direction is not a sensitive function of velocity. The definition of + or - polarity, to distinguish the directional sense of the magnetic field, is used in studying the periodic variations of the interplanetary field direction. Significant variations of the direction from the average spiral are also observed. This intrinsic spiral geometry is of fundamental importance in a study of the magnetic structure of interplanetary space.

Early Observations and Interpretations of Co-rotating Macrostructure

The earliest exploratory measurements of the solar plasma were probably those conducted by the USSR in 1959 on the moon probe Luna 1 (Gringauz, et al. 1960). Subsequently in 1961, the USA Explorer 10 satellite measured the solar plasma in the boundary layer formed by the interaction of the solar wind with the geomagnetic field, the magnetosheath (Bonetti, 1963). However, it was not until the US Mariner 2 space probe to Venus in 1966 that extended direct measurements of the solar plasma were performed.

Presented in successive 27 day intervals in Figure 3 are the velocity and plasma density measurements obtained by Mariner 2 for solar rotations 1767 to 1771. From these data it is clearly evident that specific regions of high velocity and lower density plasma persist for several solar rotations at relatively fixed heliographic longitudes. See for example the recurrent broad peak in velocities on September 2, October 1, 27, November 23 and December 20. A determination of the heliocentric radial gradient of the plasma flux and number density was detected from 1.0 to 0.7 AU. No variation was detected in the average plasma velocity with distance although a definite variation with relative heliographic longitude was observed. These long-lived high velocity plasma streams represent part of the macrostructure of the interplanetary medium.

In addition, interplanetary magnetic field measurements were performed on Mariner 2 but uncertainties associated with the contribution of the spacecraft magnetic field precluded a comprehensive survey with high accuracy. The results (Smith, 1964) were shown to be consistent with the Archimedean spiral geometry. Earlier exploratory studies of the interplanetary magnetic field by Pioneer 5 in 1959 (Greenstadt, 1966) had indicated the probable existence of a weak magnetic field, on the order of a few gamma, threading through interplanetary space.

Extended measurements of the interplanetary plasma on earth orbiting satellites was first accomplished by the IMP 1 or Explorer 18 satellite beginning in late-1963 (Bridge et al., 1965; Wolfe et al., 1966; Olbert, 1969). Accurate measurements of the interplanetary magnetic field were also obtained (Ness et al., 1964). The magnitude distribution of the instantaneous magnetic field measured over three solar rotations is presented in Figure 4. Note that the magnetic field is only very rarely less than 0.5 gamma and has a mean of 6.0 gamma. This indicates that the interplanetary medium is essentially thoroughly permeated by a magnetic field with an average magnitude of 6 gamma. Recent measurements by Explorer 34 in 1967 are shown for comparison and reveal no significant increase in the mean value of 6.2 gammas as solar activity has increased.

In the measurement of the direction of the interplanetary field, a coordinate system referred to as solar ecliptic was introduced.

The azimuthal direction, φ, is measured in a plane parallel to the ecliptic Eastward with respect to a radius vector connecting the point of observation to the sun. Satellite and space probe measurements have all been performed at very small distances from the ecliptic, when compared with the heliocentric radial distance. Thus these measurements are obtained essentially in the ecliptic plane and therefore limit the interpretation of the magnetic fields of interplanetary space to two dimensional structures.

The latitude, θ, is measured relative to the ecliptic plane and defined positive northward. The solar equatorial plane is inclined only 7° to the ecliptic but this may be important in future work.

Studies of the directional properties of the interplanetary magnetic field for IMP 1 showed that, in the ecliptic, the field was directed approximately equally along the Archimedean spiral directions of 135° or 315°. Normal to the ecliptic a small average southward component was measured, the magnitude of which was less than 1 gamma. The variation of the component transverse to the ecliptic is an essential feature in the analysis of the net transport of magnetic flux from the sun and has been discussed by Dessler (1967). More recently Rosenberg and Coleman (1969), in reviewing the variations of this component, have correlated its direction with heliographic latitude of the observation point.

A remarkable tendency for the periodic variation of direction of the interplanetary magnetic field was observed on IMP 1. Presented in Figure 5 is the interplanetary sector structure revealed from the IMP 1 directional data. The polarity of the direction is seen to repeat itself in a period of 27 days in a remarkable coherent fashion. The distortion of the pattern noted during orbits 1 and 2 of IMP 1 (orbital period 3.9 days), is due to a magnetic storm which occurred on December 2, 1963.

During these three solar rotations, 1784-1786, three of the interplanetary sectors, or regions in which the interplanetary magnetic field generally preserves a fixed polarity, extend over a time interval corresponding to 2/7 of the solar rotation period. Some uncertainty exists in the position of sector boundaries where rapid field reversals occur due to the periodic emersion of the IMP 1 spacecraft in the earth's magnetosphere and magnetosheath, precluding measurements of the interplanetary magnetic field.

These observations were made during a period in the solar cycle when activity was at its minimum. As solar activity has increased, however, the sector pattern has been found to evolve considerably although the existence of extended periods of time when fixed interplanetary magnetic field polarity directions exist has not changed. The ordering of the interplanetary magnetic field direction by sectors is an important feature of the macrostructure.

A study of the origin of the interplanetary magnetic field was accomplished by cross-correlating the direction of measurement by IMP 1 at 1 AU with photospheric magnetic field measurements.

On the surface of the sun the photospheric field was quantized into 10° latitudinal swaths with longitudinal increments of 5.7°, which correspond to time intervals of 12 hours. Figure 6 presents the cross-correlation coefficient between the directions of the interplanetary and photospheric magnetic fields at three different latitudes. A well-defined peak occurs at a lag of $4.5 \pm .5$ days which corresponds well with that which would be predicted on the basis of the direct measurement of average plasma velocity of 378 km/sec by Wolfe et al. (1966), and 360 km/sec by Olbert (1969) on the same satellite. Thus these studies of the recurrence character of the field direction and the cross-correlation with the photospheric field lead to the conclusion that the interplanetary magnetic field is definitely of solar origin (Ness and Wilcox, 1964).

An additional important result of the synoptic study of the interplanetary medium from the IMP 1 data was the detection of structure within each sector. The interplanetary magnetic field was found to increase to a maximum approximately 2 days after passage of a sector boundary and to decrease in magnitude thereafter to the next sector boundary. Also, the density of the plasma increased rapidly after a sector boundary passed and decreased but not in phase with the magnetic field magnitude variations (Wilcox and Ness, 1965).

Particularly interesting was the correlation of the interplanetary sector structure with persistent streams of cosmic rays observed on the same satellite by an experiment measuring protons with energies greater than 10 mev (Fan et al. 1966). Earlier observations of persistent streams of solar cosmic rays were conducted on Explorer 12 in 1961 by Bryant et al. (1965) but could not be related to the interplanetary magnetic field due to the lack of simultaneous measurements.

Observations by the IMP 2 satellite (Fairfield and Ness, 1967) in late 1964 revealed the continued existence of the quasi-stationary four sector macrostructure observed earlier by IMP 1. A breakup of this classical quasi-stationary pattern was detected in 1965 by Mariner 4 (Coleman et al. 1966, 1967) and IMP 3 (Ness and Wilcox, 1967). The changing sector pattern in 1965 led to an apparent lengthening of the recurrence period from 27 to 28 days. The differential rotation of the sun would then imply that the source of solar plasma had moved from the approximately 10° to 15° N latitudes observed for IMP 1 (Wilcox and Ness, 1967) to the higher latitude of approximately 20° to 25°.

The experimental evidence for the persistence of a quasi-stationary pattern in the direction of the interplanetary magnetic field suggests that the interplanetary medium must be viewed in a framework of <u>co-rotation</u> of structural features. It should be noted that this co-rotation is not a rigid rotation of the interplanetary medium with the sun but rather an apparent co-rotation deduced from the recurrent variations of physical properties measured in interplanetary space and associated with long-lived sources of solar plasma and magnetic field distributed in longitude on the surface of the sun.

Simultaneous measurements by satellites have revealed and confirmed further aspects of this co-rotation concept. A correlation of co-rotating meso structural details of the interplanetary magnetic field has been accomplished over distances up to 0.01 AU (Ness, 1966). Comparison of IMP 3 measurements at 1 AU with those by Mariner 4 (Coleman et al. 1967) indicate that out to a heliocentric distance of 1.5 AU the polarity pattern appears to co-rotate in a coherent and orderly fashion. Complimentary studies of recurrence periods of streaming protons by O'Gallagher and Simpson (1966) also confirm the general features of the co-rotating structure in the interplanetary medium.

Recent Measurements of the Interplanetary Macro Structure

Detailed continuous studies of the interplanetary medium have been conducted with high data rate satellites providing new results on the magnetic structure of interplanetary space. The deep space probe Pioneer 6 was launched December 16, 1965 and the next satellite in this series, Pioneer 7, was launched on August 17, 1966. The trajectories for these two satellites is shown in Figure 7. Unfortunately, the amount of simultaneous data obtained by these two space probes was not sufficient to permit a comprehensive investigation of co-rotating structures. However, they have provided important results relative to the micro structure of the interplanetary medium and the evolution of its macro structure during 1966.

The directional distribution functions of the interplanetary magnetic field for Pioneer 6 and 7 observations is shown in Figure 8. In the plane of the ecliptic it is seen that the magnetic field is approximately along the Archimedean spiral direction. A small but significant difference is detected in the directional properties between the two data sets which can be associated with a variation of heliocentric distance from the sun. The Pioneer 6 distribution, measured between 0.7-1.0 AU, peaks at $140^\circ \pm 10^\circ$ (and $320^\circ \pm 10^\circ$). The Pioneer 7 distribution peaks at $120^\circ \pm 10^\circ$ (and $300^\circ \pm 10^\circ$) for observations between 1.0-1.1 AU. This approximately $20^\circ \pm 10^\circ$ decrease in spiral angle is close to the expected value of 10° for an ideal spiral assuming a velocity of 400 km/sec. The average velocity of the solar plasma during these periods is not yet available to incorporate the effects of any variability in velocity on the geometry of the spiral.

The change in distribution for positive and negative polarities between Pioneer 6 and Pioneer 7 is also noteworthy. The change from approximate equality in polarity on Pioneer 6 to almost a 2/1 ratio favoring negative polarity occurs on a relatively rapid time scale compared to the solar cycle. A sample of interplanetary magnetic field measurements during two solar rotations from these space probes is shown in Figures 9 and 10. The data in Figure 9, for solar rotation 1814, show the existence of essentially two sectors with the positive polarity sector predominating. The short interval on March 12-13 of negative polarity is associated with a significant transient event, a Forbush decrease following the expulsion of high velocity plasma from the sun.

In this case the magnitude of the magnetic field is greater than 7.5 gammas for more than 1 day. Only two other significant events in the magnetic field magnitude are detected during this solar rotation, on February 19 and 22. The obvious difference in the sector structure observed here, compared to that previously shown in Figure 5, is that there are only two sectors and that the small negative polarity sector exists for only five days while a positive polarity sector exists for 22 days.

To illustrate the rapid evolution of sector structure, data obtained by Pioneer 7 during solar rotation 1822, eight solar rotations later, is shown in Figure 10. A small positive polarity sector of seven days length corresponds in heliographic longitude to the negative sector observed during SR 1814. Also the large negative polarity sector of the two sector pattern in SR 1822 corresponds to the positive polarity sector observed in SR 1814. Hence the entire polarity pattern has been inverted.

The dynamic nature of the interplanetary sector structure is revealed from the separate Pioneer 6 and 7 measurements by studying the recurrence tendency of the interplanetary sectors. The autocorrelation coefficients for the interplanetary magnetic field directions as observed by Pioneer 6 and 7 is shown in Figure 11. A distinct recurrence tendency at a period of 29 days is observed in data averaged over both 3 and 12 hour intervals for Pioneer 6. However, in the case of Pioneer 7 the recurrence period is only 27.3 days. Taking into account the differential motion of Pioneer 6 and 7 with respect to the earth leads to an adjustment of these recurrence periods to approximately 28 days which could be consistent with a quasi-stationary sector pattern, if such existed.

A summary of the polarity measurements obtained in 1966 by other satellites in earth orbit is shown in Figure 11. Throughout the year, a continuous evolution consisting of the birth and death of various sector structures is readily evidenced in the data. In order to properly interpret other solar terrestrial events related to the macro structural feature of sectors in the interplanetary medium, it is essential that direct measurements of the interplanetary magnetic field polarity be utilized. The ability to predict sector structures forward in time is valid only approximately during periods other than at solar minimum.

Other features of the macro structure are the general tendency for interplanetary magnetic field events, where the magnitude is larger than 7.5 gammas, to persist for 1-2 days. Some of these events are noticable for their very sharp rise and decay time while others are noted only by the large magnitude of the magnetic field.

A theoretical model has been developed for the quantitative comparison of the direction of the interplanetary magnetic field and the solar magnetic field (Schatten, 1969). The basis for the model is summarized schematically in Figure 13. Measurements of the photospheric magnetic field on Surface 1 are extended through Region 2 by potential theory and lead to closed field lines and complex loops of magnetic field structure. The currents flowing near the source surface are assumed to eliminate the transverse components of the magnetic field at Surface 2 and from this region on, the solar wind extends the resultant magnetic field into interplanetary space. Reasonable agreement has been obtained by Schatten (1969) and Schatten, Wilcox and Ness (1969) in this method of extrapolating the interplanetary magnetic field into interplanetary space. This method will be valuable for those studies of the interplanetary magnetic field structure when direct satellite observations were not available but the necessary photospheric measurements were.

A study of the large scale magnetic structure, as modified by transient events due to solar flares, is possible only with simultaneous measurements from several satellites and space probes widely separated in interplanetary space. One such event occurred during July 1966 and will be discussed briefly here. This event has been studied in detail by numerous authors in a joint effort, the Solar Proton Flare program, and results of other studies related to this event are available in the Annals of the IQSY publications.

The interplanetary magnetic field data associated with this event is shown in Figure 14. The solar flare on July 7 at 0027 led to a significant interplanetary magnetic field event and a sudden commencement geomagnetic storm on July 8 at 2102. Associated with the sudden commencement storm was the existence of an interplanetary shock wave in interplanetary space, whose dramatic particle deflection effects were observed by experiments on Explorer 33 by Van Allen and Ness (1967).

An interpretation of the macro structure of the interplanetary medium at the time of this event is shown in Figure 15. The possible interpretation of the shock and distorted sector structure following the event is also shown. The limited measurements available on the Pioneer 6 spacecraft, with which measurements were compared, does not permit a unique identification of the interplanetary shock on that space probe.

The large scale geometry of the interplanetary magnetic field constructed assuming a stationary structure is shown in Figure 16. The data obtained at 1 AU are extrapolated between 0.4 and 1.2 AU by a method developed by Schatten, Wilcox and Ness (1969) and Schatten (1969). During this transient event obviously this assumption is severely violated as evidenced in the shock wave interpretation as proposed in Figure 15. However, the method faithfully reveals the increased field strength as the sector boundary is distorted. Under more favorable circumstances, this method has permitted a study of the development of a solar active region producing a loop in the magnetic field structure and thus giving birth to a new sector (Schatten, Ness and Wilcox, 1968).

Microstructure

Detailed fluctuations of the interplanetary magnetic field have been studied from various points of view. Early studies of the power spectra of fluctuations by Coleman (1966) were directed to the effects that such irregularities carried outward by the solar wind would have on the deflection of galactic cosmic rays. A review of cosmic ray modulation theories has recently been presented by Webber (1967). One interesting problem is whether or not peaks in the spectra occur at characteristic frequencies associated either with the sun or the intrinsic plasma instabilities of the interplanetary medium. No evidence has been found in the data for the persistence of a spectral peak such as might be expected from the 300 second periodicity in the supergranulation pattern on the sun (Leighton et al. 1962; Michael, 1967). The results indicate a spectral energy density function which decreases rapidly with increasing frequency. Important questions are the cause of these fluctuations and their variation with frequency and solar activity.

Samples of recent measurements of the interplanetary magnetic field and its fluctuations over two limited 12 hour periods are shown in Figure 17. The interplanetary magnetic field direction changes rapidly and quite frequently as indicated by the dotted lines. The magnitude of the magnetic field in interplanetary space is much less variable. This qualitative view is substantiated by numerous statistical and quantitative mathematical studies of the fluctuations in interplanetary space.

The dotted lines in Figure 17 identify discontinuities (Landau and Lifshitz, 1960; Colburn and Sonett, 1966) in the interplanetary magnetic field structure. These phenomena have been interpreted in terms of classical magnetohydrodynamic surfaces separating regions of differing plasma properties which are in equilibrium with each other and are being convected outward from the sun by the solar wind (Burlaga and Ness, 1968, 1969; Burlaga, 1968, 1969a, b; Siscoe et al. 1968).

The source of these discontinuities is not yet known and the distance to which these discontinuities persist is both unknown and not predicted. Examples of these discontinuities on a finer time scale is shown in Figure 18. They are observed to be sudden changes principally in the direction although the examples selected here show changes in the magnitude also. These discontinuities occur with a frequency of approximately 1 every 10^4 second for directional changes of 30° or more. A copious number of such discontinuities is always present in the interplanetary medium and their identification and interpretation has been one of the more significant recent advances in studying the micro scale structure of the interplanetary magnetic field.

A model of a tangential discontinuity is shown in Figure 19. The surfaces of these discontinuities are assumed to be locally plane and the conclusion that they are being convectively transported from the sun requires simultaneous measurements by satellites separated in space. This has been shown to be true by Burlaga and Ness (1969).

From observations of the anisotropy of solar cosmic rays correlated with the interplanetary magnetic field, McCracken and Ness (1966) have deduced that the interplanetary medium is in fact structured into a bundle of separate flux tubes, at first called filaments, which directly connect to the sun.

The proper identification of the specific type of magneto-hydromagnetic discontinuity requires a complimentary set of accurate plasma and magnetic field data. Most prominant are those directional discontinuities for which there is no magnitude change; Burlaga (1968) has concluded that such flux tubes are in motion relative to each other as they are being convected outwardly from the sun. This relative motion is due to the interaction of plasma streams of different velocities.

This introduces the concept of a <u>glide plane</u>, as a description of the surface separating these flux tubes. Statistical studies of the distribution of glide plane normals indicate that the interplanetary flux tubes are more topologically similar to "flat noodles lying on a plate".

The power spectra of the interplanetary magnetic field fluctuations have been studied from several deep space probes (Coleman, 1966; Siscoe et al., 1968; Sari and Ness, 1969). The results indicate a spectral density decreasing rapidly with increasing frequency. Spectral results generally show an inverse dependence on frequency $P \propto f^{-\alpha}$ and $\alpha = 1\text{-}2$.

Samples of power spectra computed from 30 second averages over 12 hour periods is shown in Figure 20. The three orthogonal components and the magnitude of the field are presented in a solar ecliptic coordinate system. It is noted that the spectral density of the magnitude fluctuations is substantially less than that of any of the individual components. This substantiates the previous qualitative statement based upon visual inspection of the data that regardless of the source of fluctuations in the interplanetary magnetic field, the magnitude tends to be much more constant and uniform than the direction of the field. This indicates either transverse wave modes or tangential discontinuities.

The analyses of the spectral slopes shown in Figure 20 yield a coefficient $\alpha = 2$. This is independent of the level of magnetic activity. The possibility that discontinuities can contribute significantly to the power spectra results has been considered by Sari and Ness (1969). In fact it appears that depending upon the number of discontinuities present in the data, they may contribute the major portion of energy of the spectra in certain portions of the frequency spectrum. A summary of results obtained studying power spectra is shown in Figure 21. The variation in the spectral shape which is shown is probably not directly interpretable in terms of a change of the fluctuation spectra. Rather it is more probably related to a secular change in the frequency of occurrence of discontinuities.

Finally, a brief discussion of the least frequently occurring events in interplanetary space, interplanetary shock waves. Direct observational evidence for such features has been reported only on Mariner 2 (Sonett et al. 1966), Explorer 33 (Van Allen and Ness, 1967), Explorer 34 (Burlaga and Ogilvie, 1969) and Vela 3 (Gosling et al. 1967). The abrupt increase in the interplanetary magnetic field strength accompanying the propagating shock wave has been shown to be directly correlated with the deflection of galactic cosmic rays from the solar system. These observations support the theoretical model proposed by Parker (1961) and Wentzel (1964) who studied the effects of a shock front due to an interplanetary blast wave.

Recently, evidence for the existence of very low frequency but large amplitude Alfvén waves in the interplanetary medium has been reported from correlated magnetic field and plasma measurements on the Mariner 5 spacecraft (Belcher, Davis and Smith, 1969). One problem in the unique identification of waves propagating in the interplanetary medium is that the solar wind bulk velocity doppler shifts the frequency spectrum significantly because the phase velocity of these waves is only 10-20% of the solar wind speed.

The unique interpretation of fluctuations as waves requires two observing points so that the convective transport of spatial irregularities can be separated from the convective transport of propagating waves by detecting the necessary time differentials associated with the wave propagation. Time variations which are observed are given by:

$$\frac{d\vec{B}}{dt} = \frac{\partial \vec{B}}{\partial t} + (\vec{V}.\nabla)\vec{B}$$

In interplanetary space the 2nd term on the right hand side is larger than the first by about a factor of 5-10. However, the evidence for the waves from the joint $\vec{V}$, $\vec{B}$ data is statistically significant although the waveforms are not simple quasi-sinusoidal temporal variations. The possibility exists that the correlated fluctuations may represent an ensemble of spatially convected MHD discontinuities.

Summary and Future Studies

A quasi-stationary sectoring of the interplanetary magnetic field direction and ordering of the magnetic field magnitude, solar wind velocity, density and associated terrestrial magnetic activity has been observed in satellite studies conducted since 1962. The sectoring of the interplanetary magnetic field is consistent with a model of the interplanetary magnetic field direction suggested by Ahluwahlia and Dessler (1962) in which the large unipolar magnetic regions on the sun give rise to a preferred orientation or fixed polarity for the interplanetary magnetic field.

An alternative explanation for the sector structure has been proposed by Davis (1965) in which a very limited region on the surface of the sun is responsible for the solar wind flux. These regions are postulated to be the persistent solar streams first identified in the Mariner 2 data and subsequently readily identifiable in later long term observations. The major question to be answered, then, is whether or not the large scale magnetic field observed in interplanetary space representing the macro structure is in fact related to the large scale structure observed on the surface of the sun or only indirectly. Wilcox (1968) has referred to these two alternatives as the mapping and nozzle hypotheses. Detailed features of satellite observations reveal a highly structured interplanetary medium with numerous micro structural features such as MHD discontinuities and interplanetary shock waves. The possibility of unraveling the complex meso-structure topology of the interplanetary magnetic field microstructure exists with simultaneous measurements of cosmic ray anisotropies and magnetic field measurements. A sample of such data is shown in Figure 22. The model proposed to explain these simultaneous reversals of the azimuth of the magnetic field and cosmic ray anisotropy is shown at the right. A very complex loop structure in the interplanetary medium is required.

The detection of tangential discontinuities suggest the existence of a numerous quasi-planer surfaces separating regions of magnetized plasma which are in equilibrium with each other and are being convectively transported from the sun. The interaction of plasma streams of different properties has been studied in the framework of the effects on co-rotation of large scale structures in the interplanetary medium and the East-West asymmetry of solar wind flow (Siscoe, Goldstein and Lazarus, 1969). A schematic diagram of the two possibilities are shown in Figure 23. The interaction between plasma streams with different directions and/or different speeds may generate both shock waves and discontinuity surfaces. As yet, there is no other suggestion for the origin of the discontinuities and thus their true nature has yet to be established.

The significance of the copious number of such discontinuity surfaces in the interplanetary medium with respect to cosmic ray propagation processes has yet to be fully determined. Depending upon the rigidity of cosmic rays, they may be highly collimated in their propagation down each flux tube from their source point or alternatively very frequently scattered by the irregularities in the magnetic field between the separate flux tubes.

At the present time only a small portion of available satellite experimental data has been thoroughly digested with respect to analysis and interpretation. Essentially simultaneous and continuous observations of the interplanetary medium began in 1965 and continues through the present time. As these data are analyzed, processed and published we can anticipate a substantial increase in our understanding of the structure of the interplanetary medium.

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FIGURE CAPTIONS

Figure 1 The Gold and Parker models of the interplanetary magnetic field proposed to explain cosmic ray Forbush decreases. The possible location of satellite measured Energetic Storm Particle populations relative to these hypothetical configurations is shown (Rao, McCracken and Bukata, 1967).

Figure 2 Theoretical Archimedean spiral angle of interplanetary magnetic field based upon uniform radial expansion of coronal plasma into interplanetary space according to solar wind model of Parker (1963). The polarity of the field direction, + and -, is indicated and is consistent with the convention for photospheric magnetic field observations.

Figure 3 Three hour average values of solar wind plasma velocity, V, and proton number density n_p (logarithmic scale) as observed by Mariner 2 in 1962 (Neugebauer and Snyder, 1966).

Figure 4 Magnitude histograms of the interplanetary magnetic field observed by IMP 1 in 1963-1964 and Explorer 34 in 1967 (Ness, 1968; Fairfield, 1969).

Figure 5 Circular superposed epoch chart of polarity of interplanetary magnetic field during successive three hour intervals as measured by the IMP 1 satellite during November 1963 to February 1964. A quasi-stationary co-rotating sector structure in the polarity of the magnetic field is evidenced by the ordering of the direction into four time intervals during which the polarity is constant and recurrent with a 27.3 day period (Ness and Wilcox, 1965).

Figure 6 Cross-correlation between IMP 1 magnetic field direction and the photospheric field direction for three latitudes on the sun. The positive peak at about $4\frac{1}{2}$ days corresponds to a uniform radial solar wind velocity of 385 km/sec. The negative peaks at $-3\frac{1}{2}$ days and +13 days can be understood in terms of the quasi-stationary sector structure (Ness and Wilcox, 1964).

Figure 7 Interplanetary trajectories of Pioneer 6 and 7 space probes in heliocentric coordinates relative to the earth-sun line. The time differentials, relative to time of observation at earth, for co-rotation of structures in the interplanetary medium is indicated along each trajectory.

Figure 8 Directional histograms of interplanetary magnetic field parallel and perpendicular to the ecliptic for Pioneers 6 and 7 (Burlaga and Ness, 1968).

Figure 9 Measurements of the interplanetary magnetic field by Pioneer 6 during solar rotation 1814 in 1966. Polarity of sector indicated by + or - and position of sector boundaries by short vertical line at bottom of figure.

Figure 10 Measurements of the interplanetary magnetic field by Pioneer 7 during solar rotation 1822 in 1966.

Figure 11 Autocorrelation of Pioneer 6 and 7 polarities in 1966.

Figure 12 A summary of measurements of the polarity of the interplanetary magnetic field in 1966 as measured by the earth orbiting satellites Explorers 18, 28 and 33.

Figure 13 Schematic representation of the theoretical model developed by Schatten (1969) for studying the extension of the photospheric magnetic field into interplanetary space.

Figure 14 Geocentric solar ecliptic hourly averages of the interplanetary magnetic field as measured by Explorer 33 during the interval 5-12 July 1966. Dotted portions represent measurements obtained in the magnetosheath. The planetary magnetic activity index Kp is plotted at the top (Ness and Taylor, 1968).

Figure 15 The interplanetary sector structure at the time of the July 7 flare as deduced from the preceding 27 days of IMP 3 measurements (left panel). The longitude of the source flare on the sun is marked by an arrow. The sector boundary is shown distorted in the way one might expect following a sudden increase in a localized area of solar wind flux, both density and velocity (Ness and Taylor, 1968).

Figure 16 Extrapolated ecliptic magnetic field measurements, obtained by Explorer 33 during the July 1966 solar proton event, utilizing method of Schatten (1969) to predict the field between 0.4 and 1.2 AU from measurements at 1 AU. Compare topology of interplanetary sector structure deduced by this technique with that shown in Figure 15.

Figure 17 Measurements of interplanetary magnetic field by Pioneer 6 on 2 days in 1965 expressed in spherical spacecraft-centric solar ecliptic coordinates. Dotted lines indicate discontinuities (Sari and Ness, 1969).

Figure 18 An example of cascaded tangential discontinuities in the interplanetary medium as identified by correlated interplanetary magnetic field and plasma parameters obtained Pioneer 6 (left panel). U represents bulk velocity and V_T represents thermal velocity (Burlaga, 1968). A D-sheet tangential discontinuity interpreted by Burlaga (1968) as a transition region with annihilation of the magnetic field (right panel).

Figure 19 Model of tangential discontinuity separating interplanetary magnetic field flux tubes with different orientations (Burlaga, 1968).

Figure 20 Power spectra of the interplanetary magnetic field components and magnitudes for two 12 hour periods in December 1965. Dotted lines indicate an inverse square frequency dependence. The planetary magnetic activity index Kp for each period is included (Sari and Ness, 1969)

These measurements were obtained when the satellite was 10^6 km from the earth at a sun-earth angle of 89^o (Sari and Ness, 1969).

Figure 21 Summary of computations of spectra of interplanetary magnetic field fluctuations indicating ranges and frequency dependencies (Sari and Ness, 1969).

Figure 22 Simultaneous measurements (McCracken, Rao and Ness, 1968) of the temporal variation of cosmic ray proton flux (7.5-45 mev), azimuth of the interplanetary magnetic field and the cosmic ray anisotropy during passage of a magnetic sector boundary past the Pioneer 6 spacecraft in 1966 (left panel). A model proposed to explain these simultaneous reversals of the magnetic field direction and cosmic ray anisotropy (right panel).

Figure 23 Schematic representation of the interactions between fast and slow moving solar wind plasma streams. The left panel (a), indicates a slow stream preceding while in the right panel, (b), a fast stream is shown preceding (Siscoe, Goldstein and Lazarus; 1968).

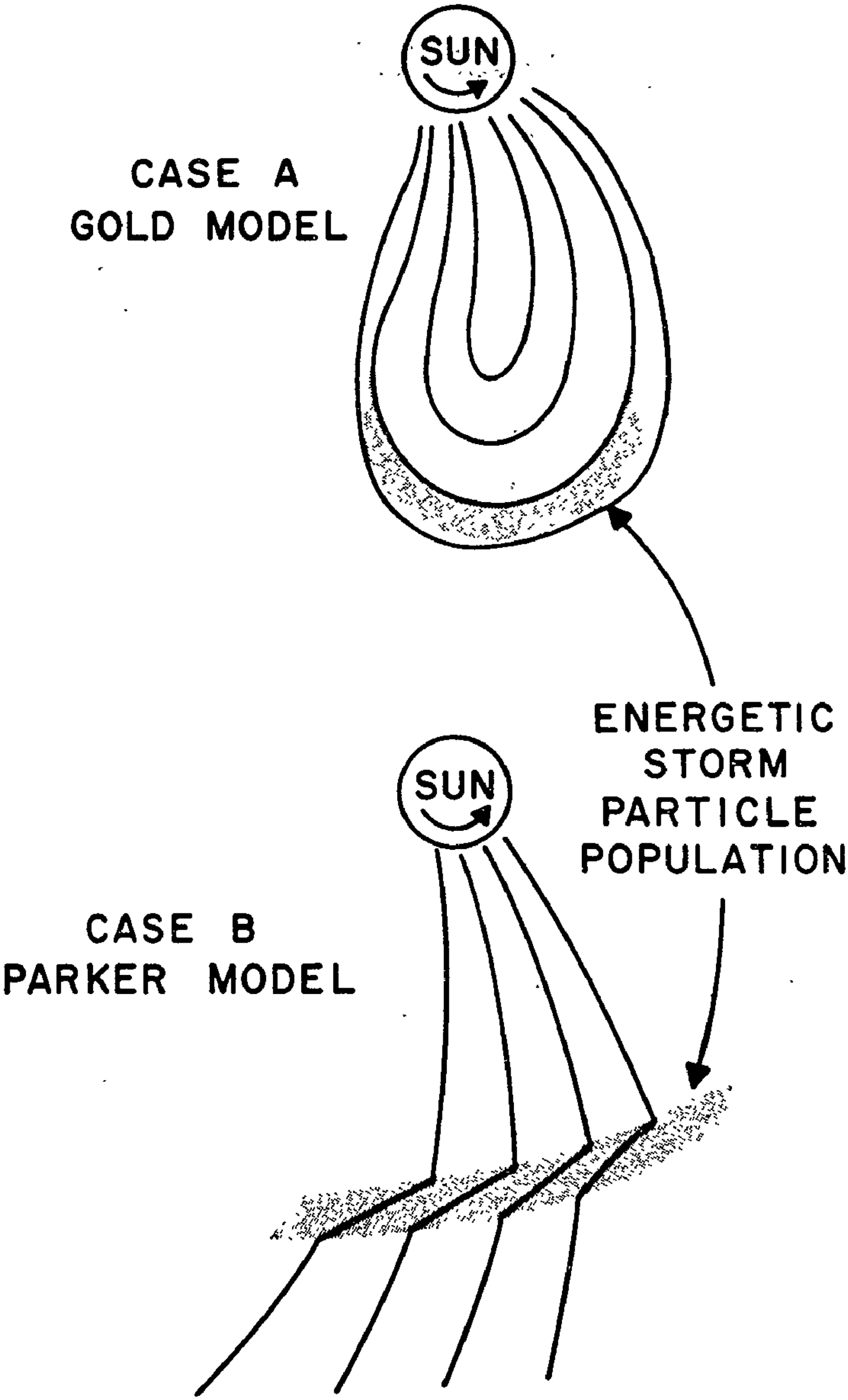

SUN
CASE A
GOLD MODEL
ENERGETIC
STORM
PARTICLE
POPULATION
SUN
CASE B
PARKER MODEL

Figure 1

THEORETICAL INTERPLANETARY MAGNETIC FIELD STREAMING ANGLE

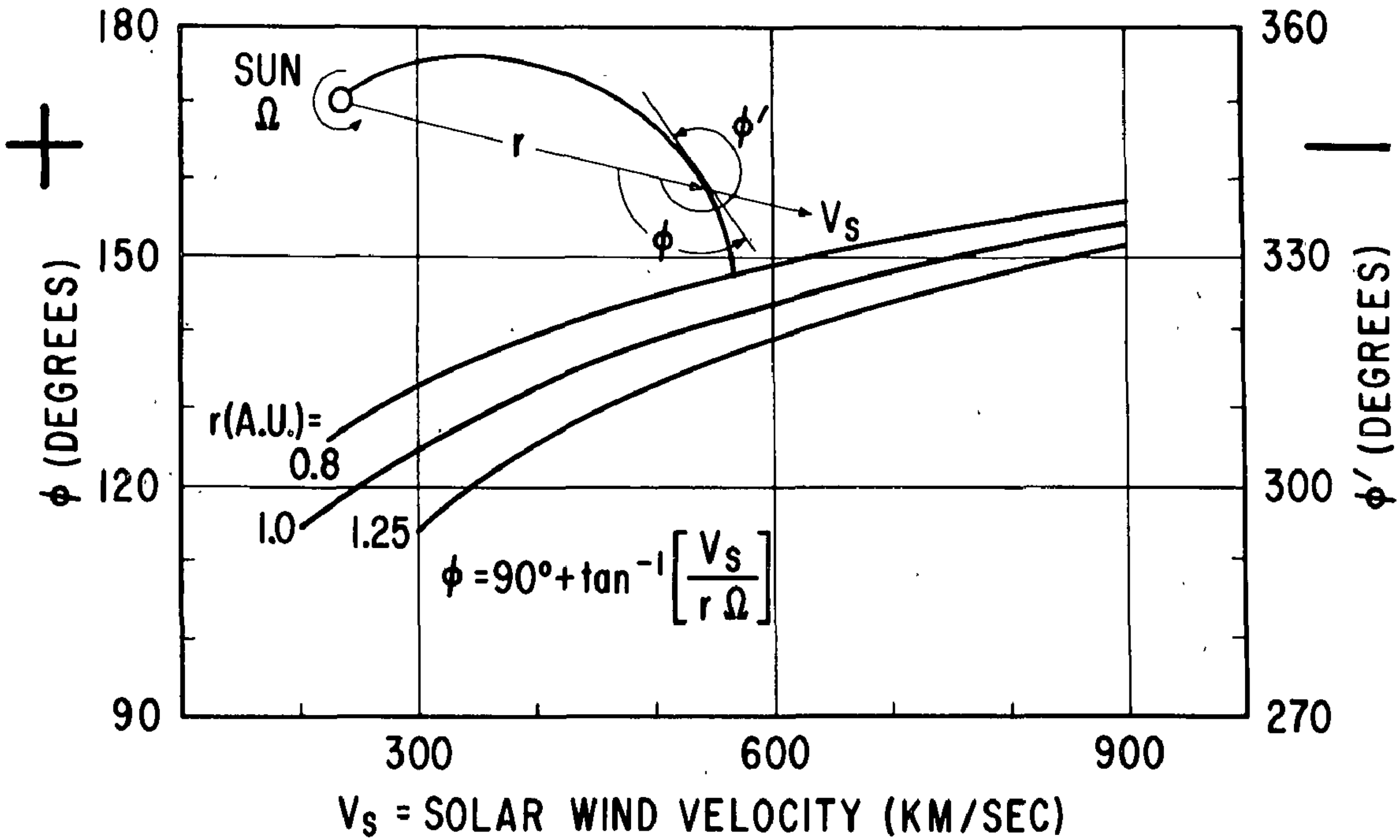


Figure 2

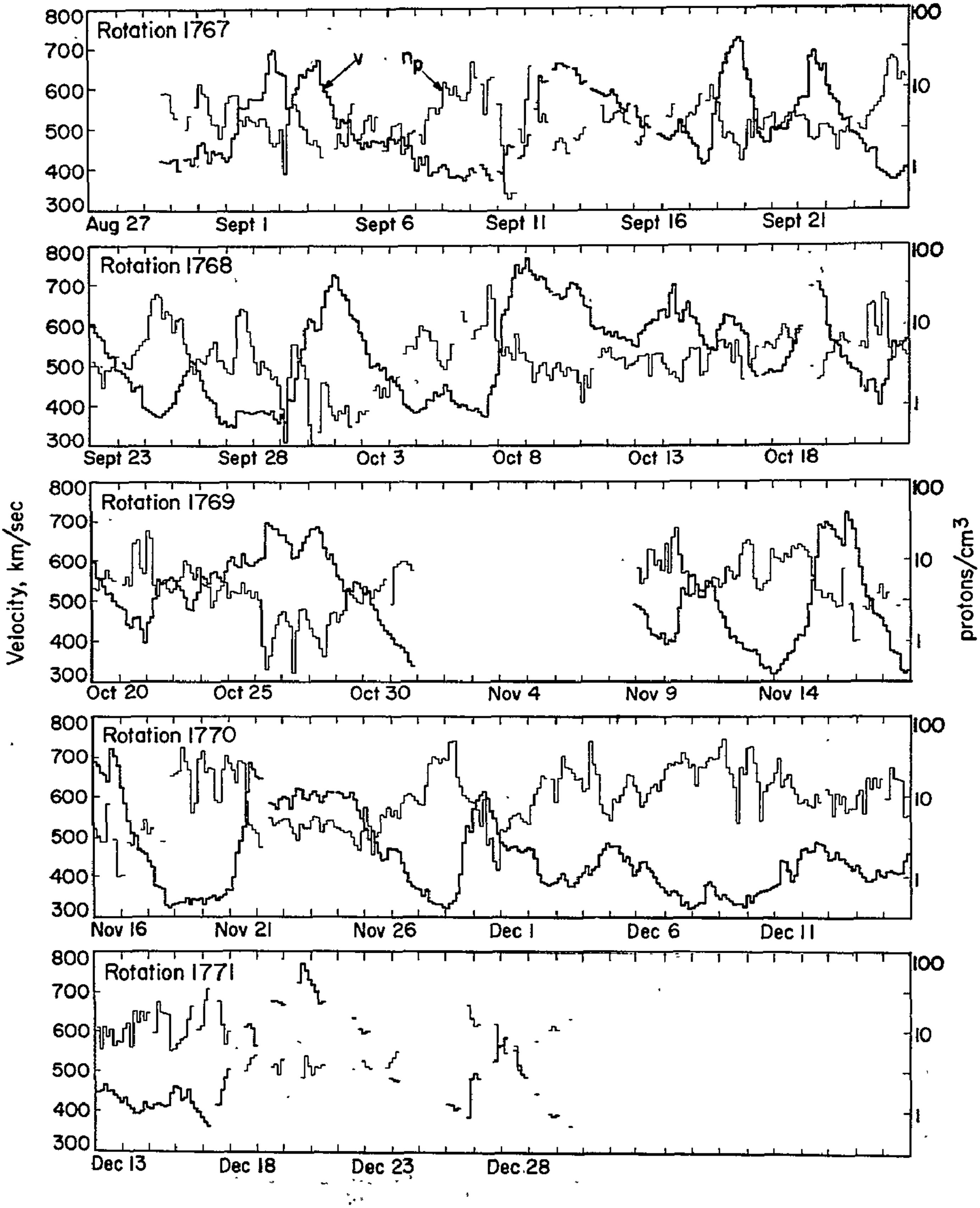

Rotation 1767
Rotation 1768
Rotation 1769
Rotation 1770
Rotation 1771
v
n_p
Velocity, km/sec
protons/cm^3
800
700
600
500
400
300
100
10
1
Aug 27
Sept 1
Sept 6
Sept 11
Sept 16
Sept 21
Sept 23
Sept 28
Oct 3
Oct 8
Oct 13
Oct 18
Oct 20
Oct 25
Oct 30
Nov 4
Nov 9
Nov 14
Nov 16
Nov 21
Nov 26
Dec 1
Dec 6
Dec 11
Dec 13
Dec 18
Dec 23
Dec 28

Figure 3

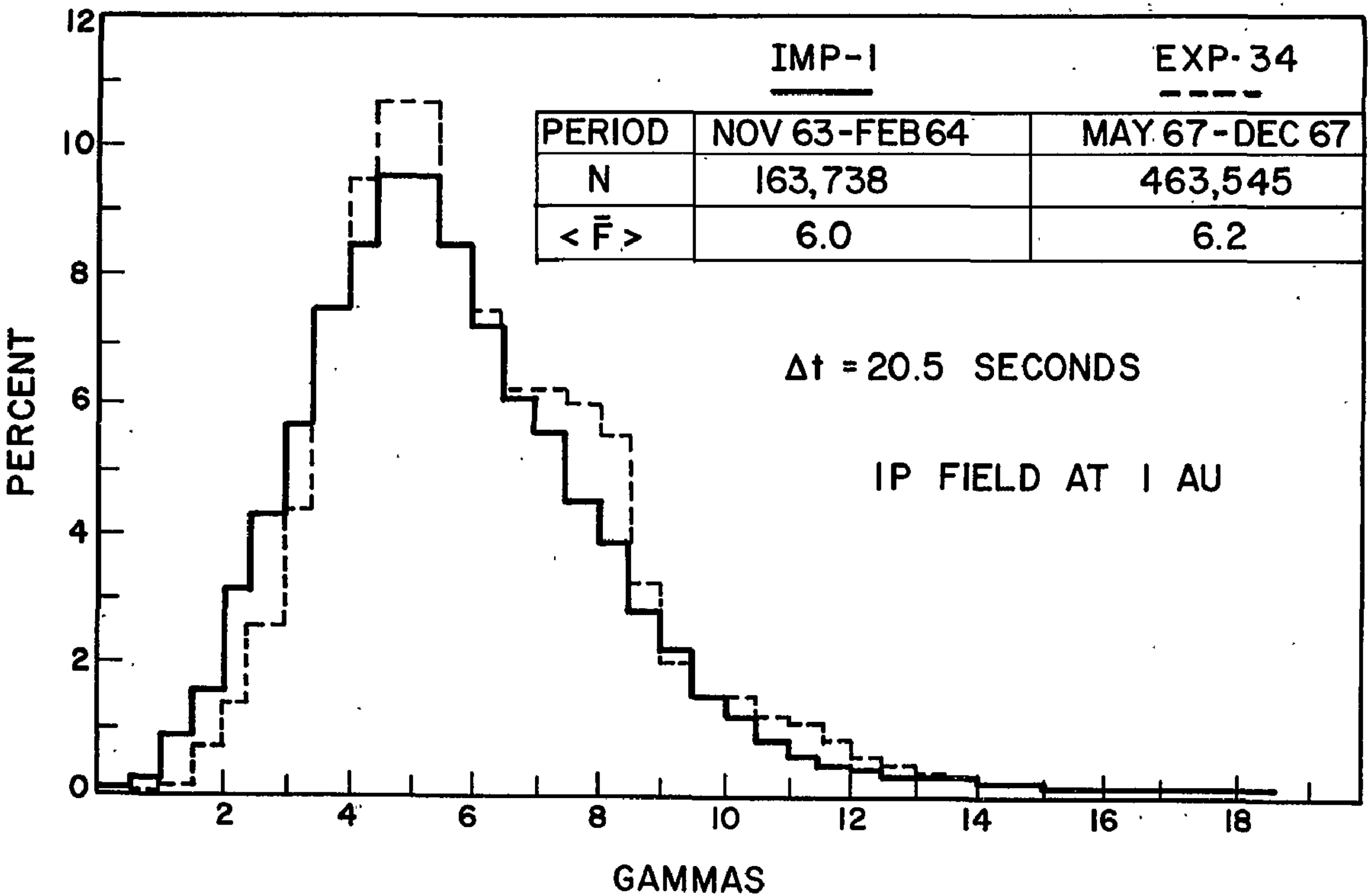

IMP-1
EXP-34
PERIOD
NOV 63-FEB 64
MAY 67-DEC 67
N
163,738
463,545
< F̄ >
6.0
6.2
Δt = 20.5 SECONDS
IP FIELD AT 1 AU
PERCENT
GAMMAS
0
2
4
6
8
10
12
14
16
18

Figure 4

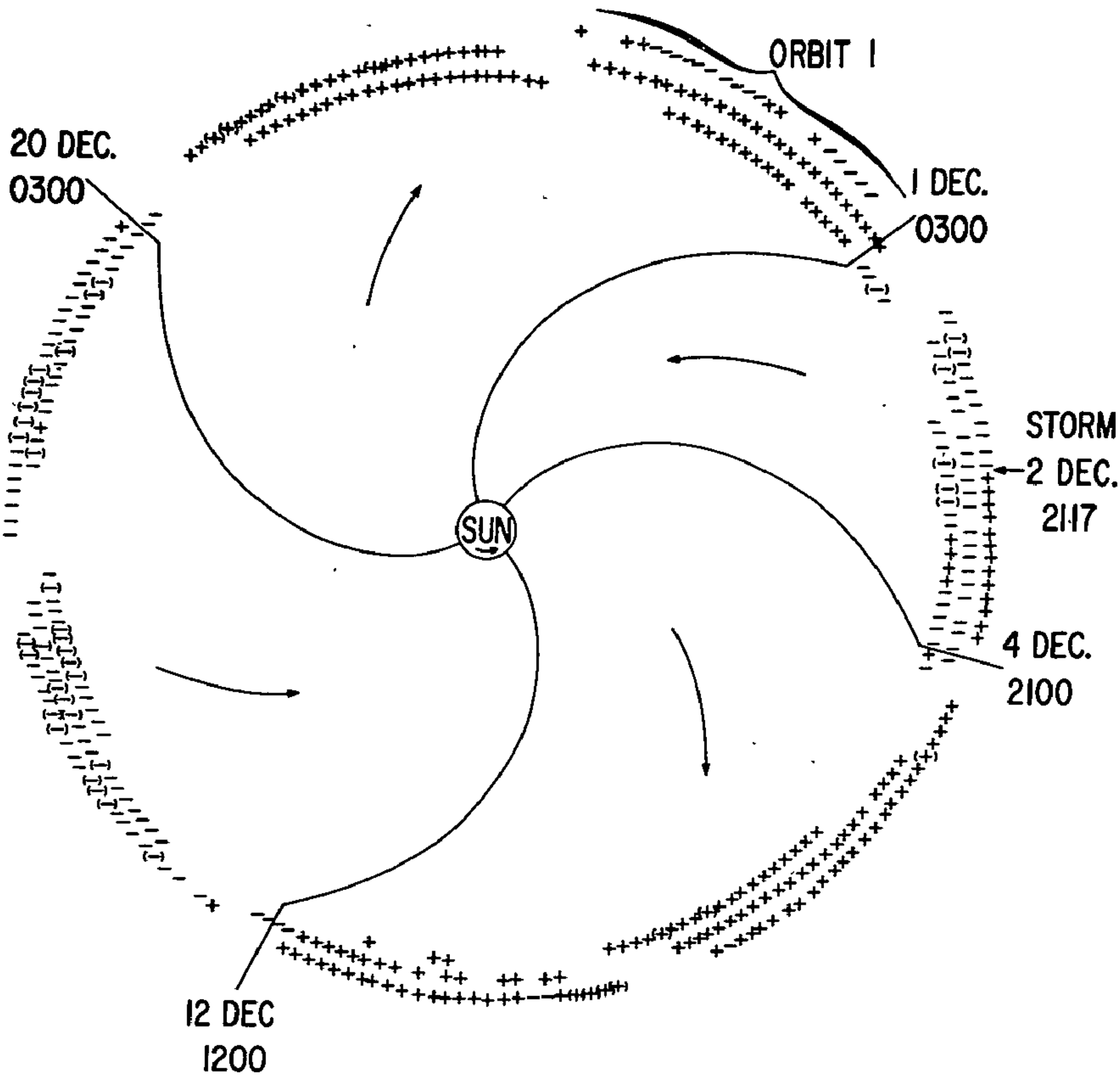
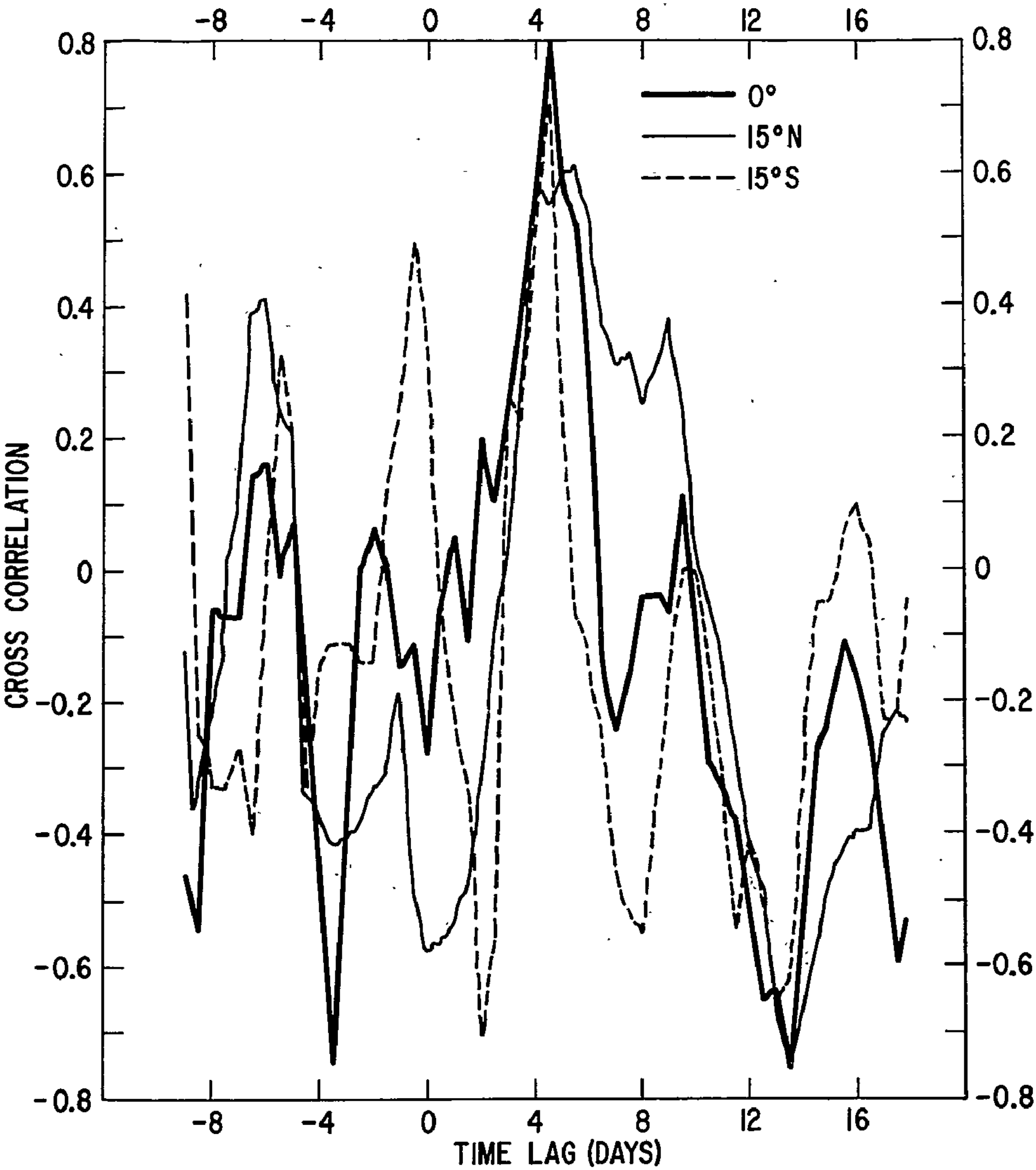
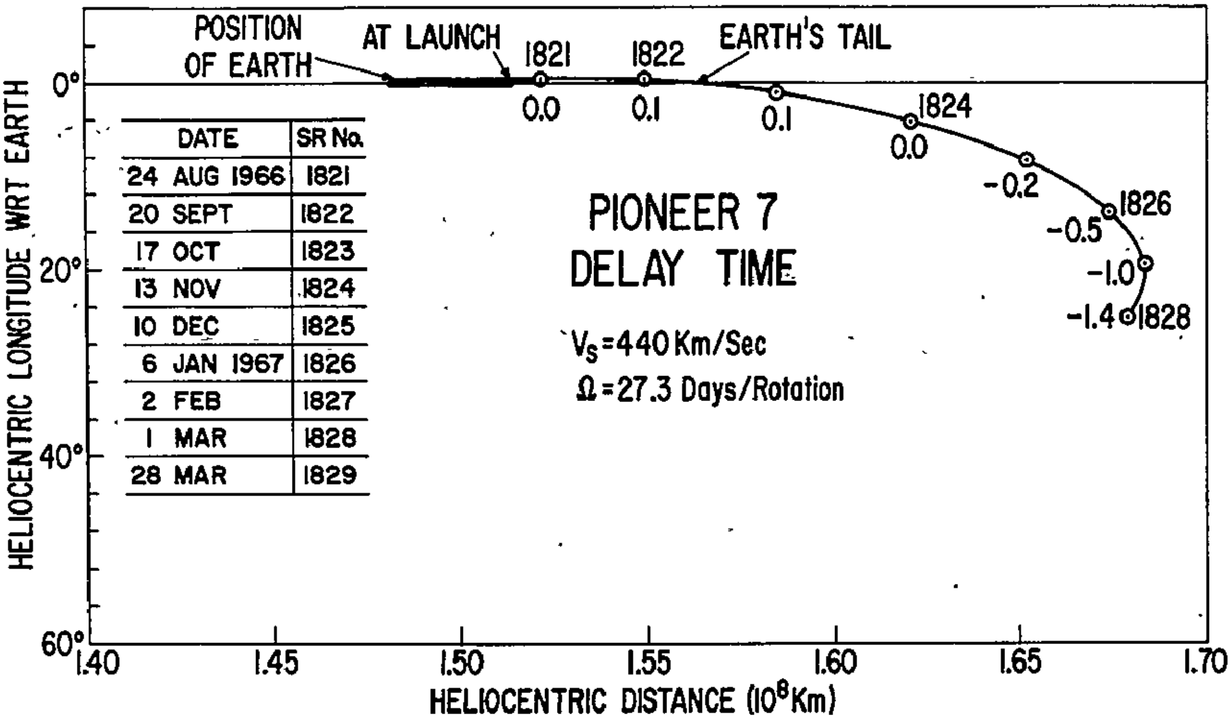

ORBIT I
20 DEC.
0300
I DEC.
0300
STORM
2 DEC.
2117
SUN
4 DEC.
2100
12 DEC
1200

Figure 5

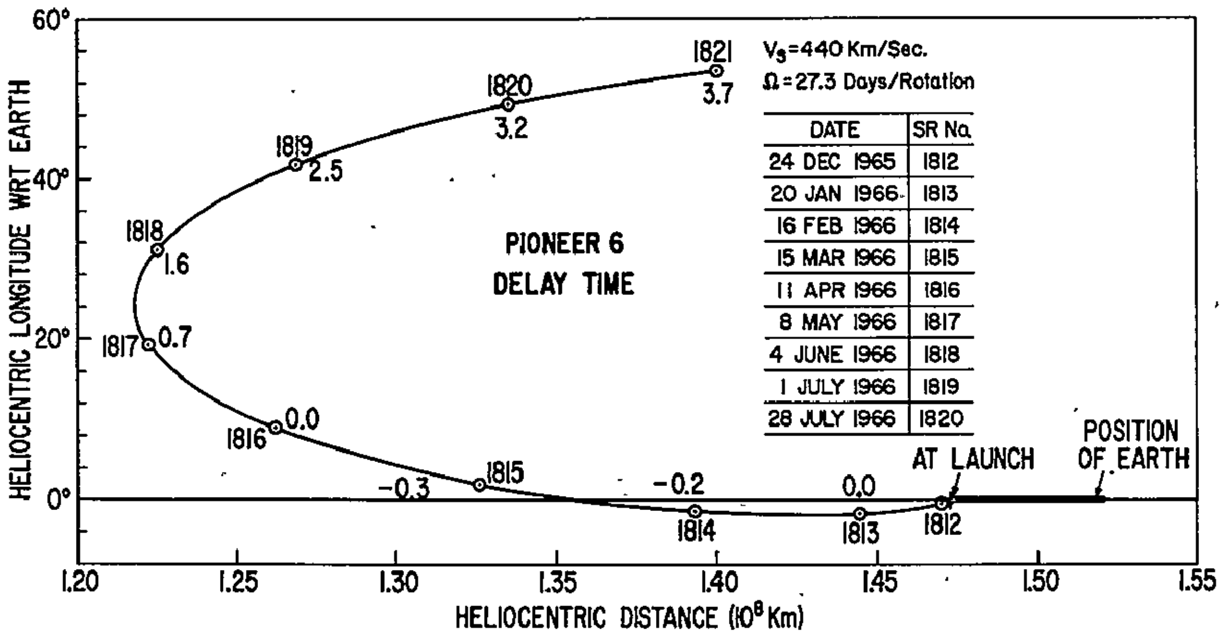


-8
-4
0
4
8
12
16
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
0°
15°N
15°S
CROSS CORRELATION
TIME LAG (DAYS)

Figure 6

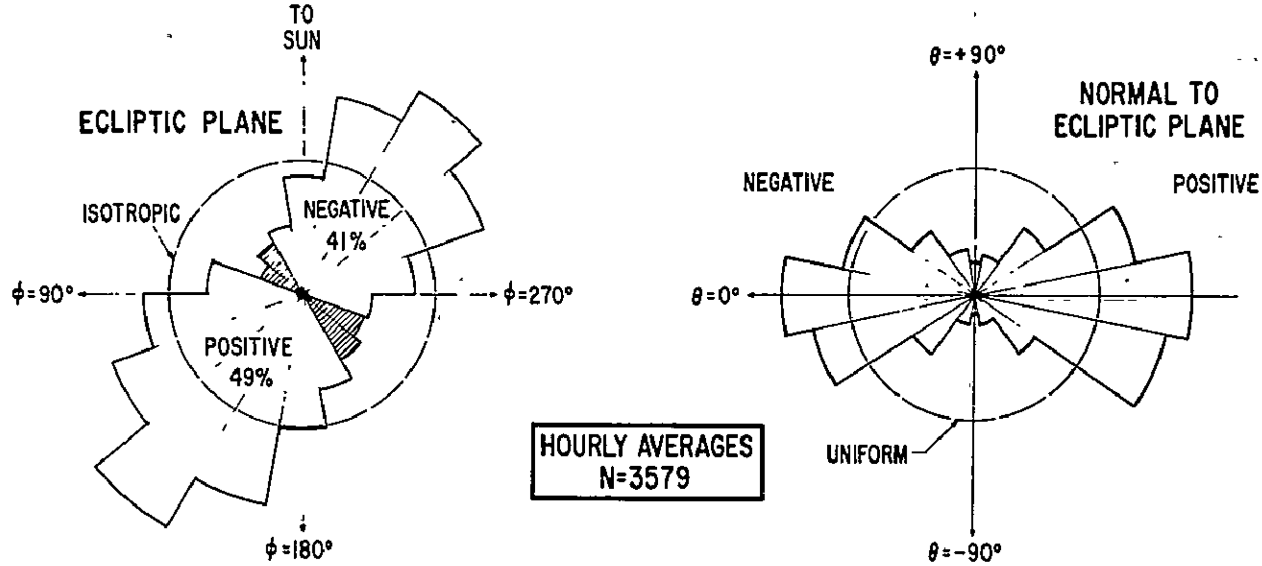


POSITION OF EARTH
AT LAUNCH
EARTH'S TAIL
PIONEER 7
DELAY TIME
V_S=440 Km/Sec
Ω=27.3 Days/Rotation
DATE | SR No.
24 AUG 1966 | 1821
20 SEPT | 1822
17 OCT | 1823
13 NOV | 1824
10 DEC | 1825
6 JAN 1967 | 1826
2 FEB | 1827
1 MAR | 1828
28 MAR | 1829
HELIOCENTRIC LONGITUDE WRT EARTH
HELIOCENTRIC DISTANCE (10^8 Km)

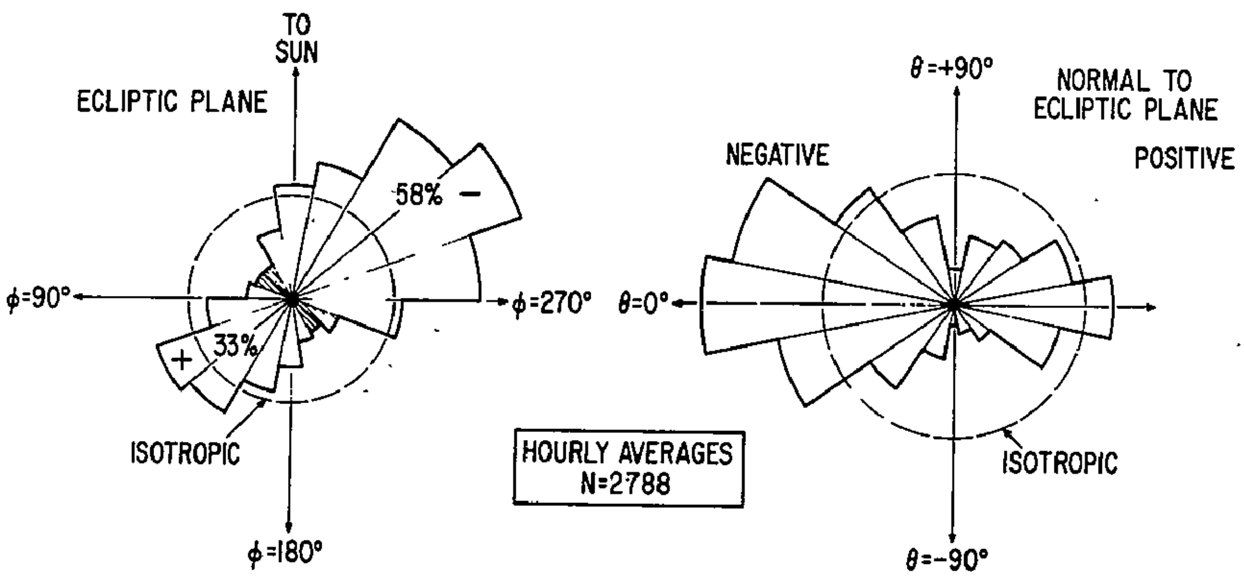


V_S=440 Km/Sec.
Ω=27.3 Days/Rotation
PIONEER 6
DELAY TIME
DATE | SR No.
24 DEC 1965 | 1812
20 JAN 1966 | 1813
16 FEB 1966 | 1814
15 MAR 1966 | 1815
11 APR 1966 | 1816
8 MAY 1966 | 1817
4 JUNE 1966 | 1818
1 JULY 1966 | 1819
28 JULY 1966 | 1820
AT LAUNCH
POSITION OF EARTH
HELIOCENTRIC LONGITUDE WRT EARTH
HELIOCENTRIC DISTANCE (10^8 Km)

Figure 7



PIONEER 6, 16 DEC '65-29 SEPT '66



PIONEER 7, 18 AUG 1966-7 FEB 1967

Figure 8

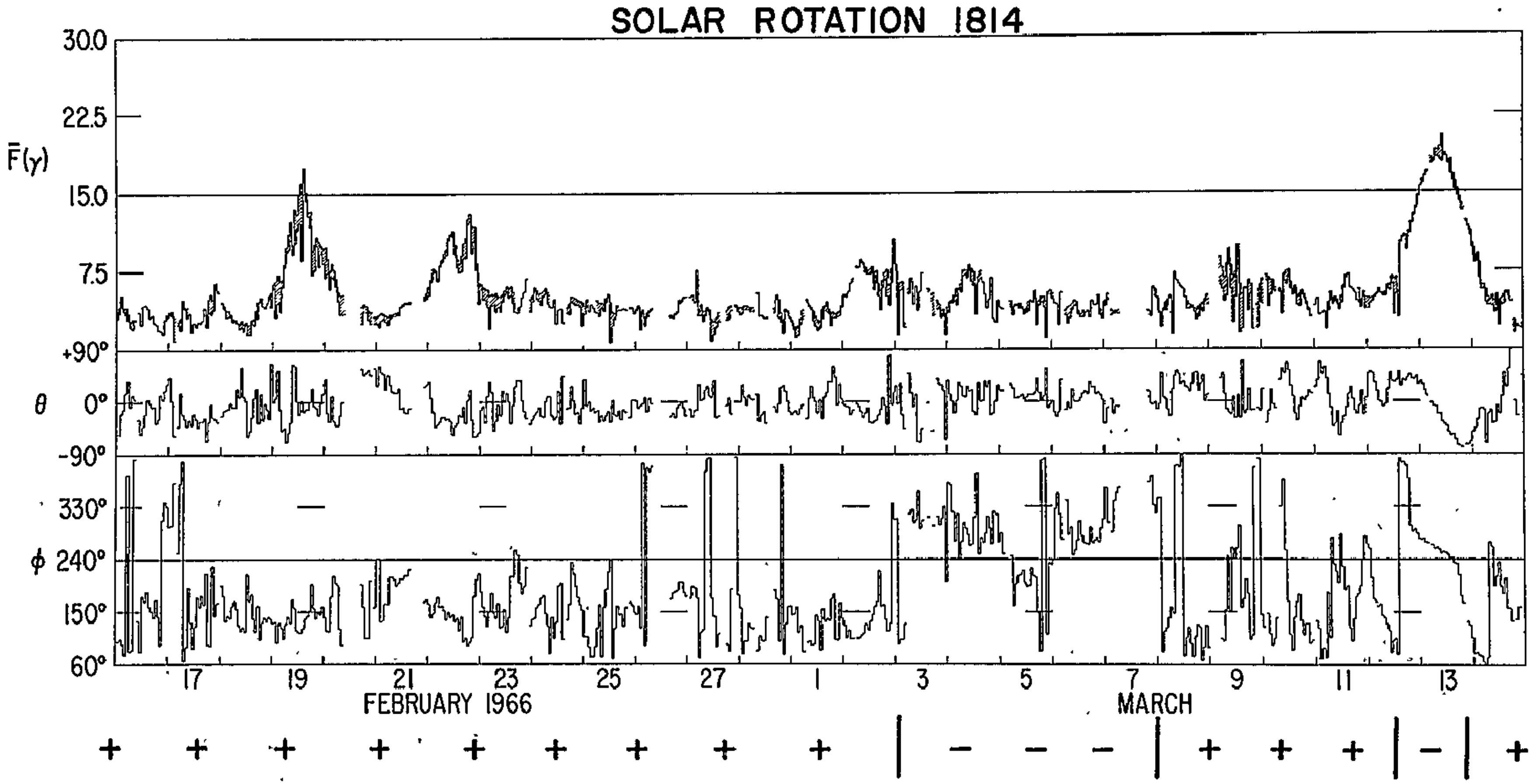

SOLAR ROTATION 1814
30.0
22.5
F̄(γ)
15.0
7.5
+90°
θ
0°
-90°
330°
φ 240°
150°
60°
17
19
21
23
25
27
1
3
5
7
9
11
13
FEBRUARY 1966
MARCH
+ + + + + + + + + | − − − | + + + | − | +

Figure 9

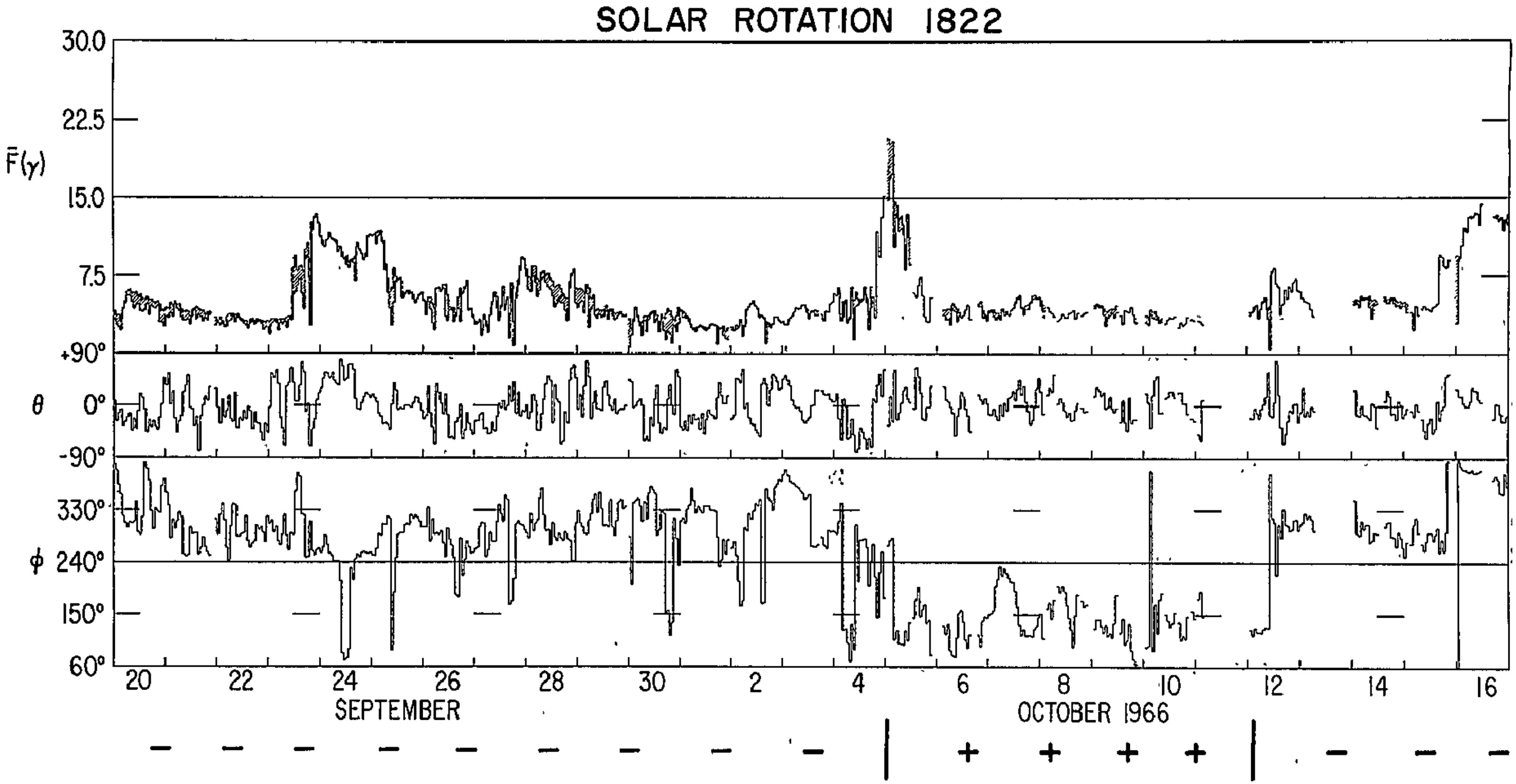

SOLAR ROTATION 1822
30.0
22.5
F̄(γ)
15.0
7.5
+90°
θ
0°
-90°
330°
φ 240°
150°
60°
20
22
24
26
28
30
2
4
6
8
10
12
14
16
SEPTEMBER
OCTOBER 1966

Figure 10

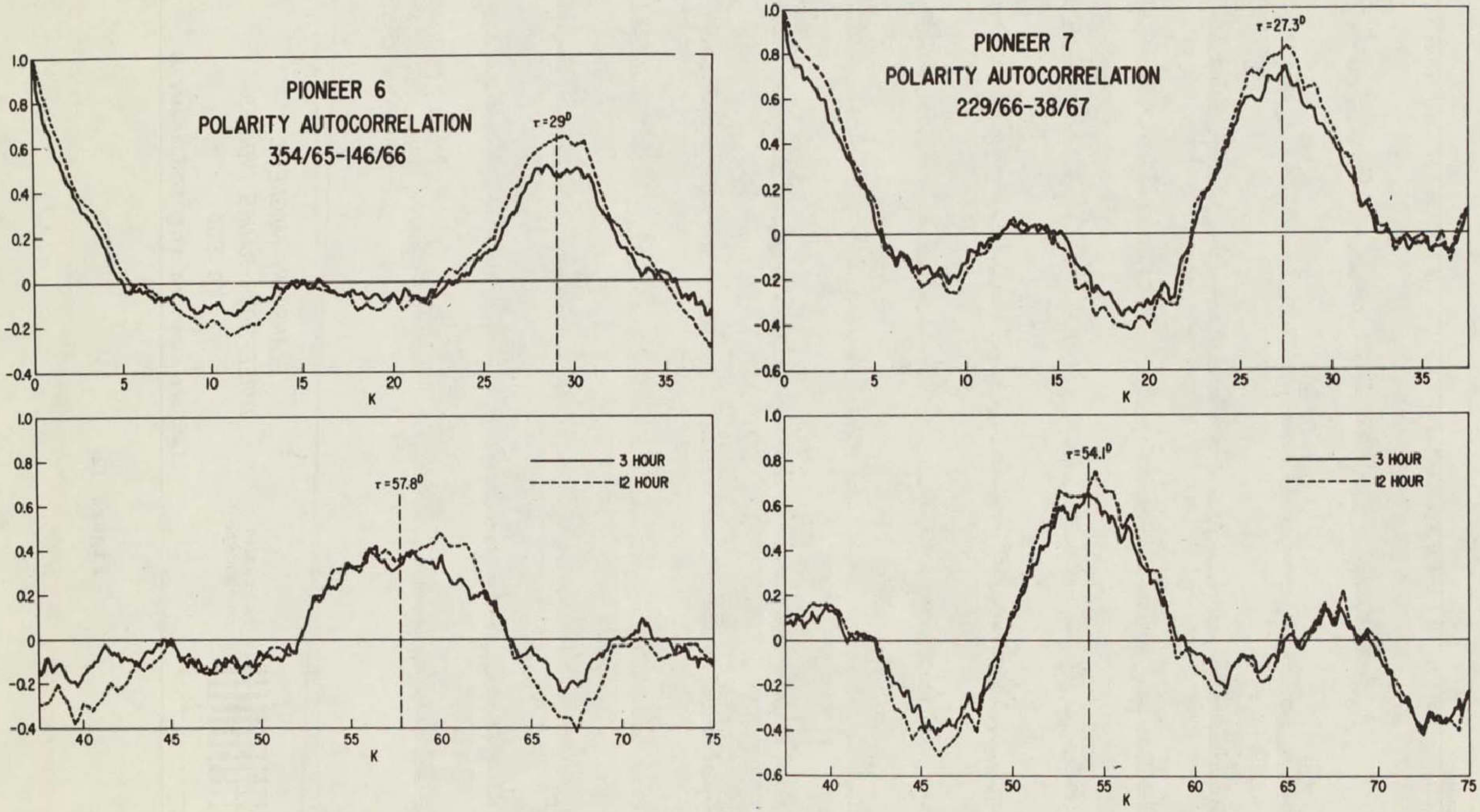
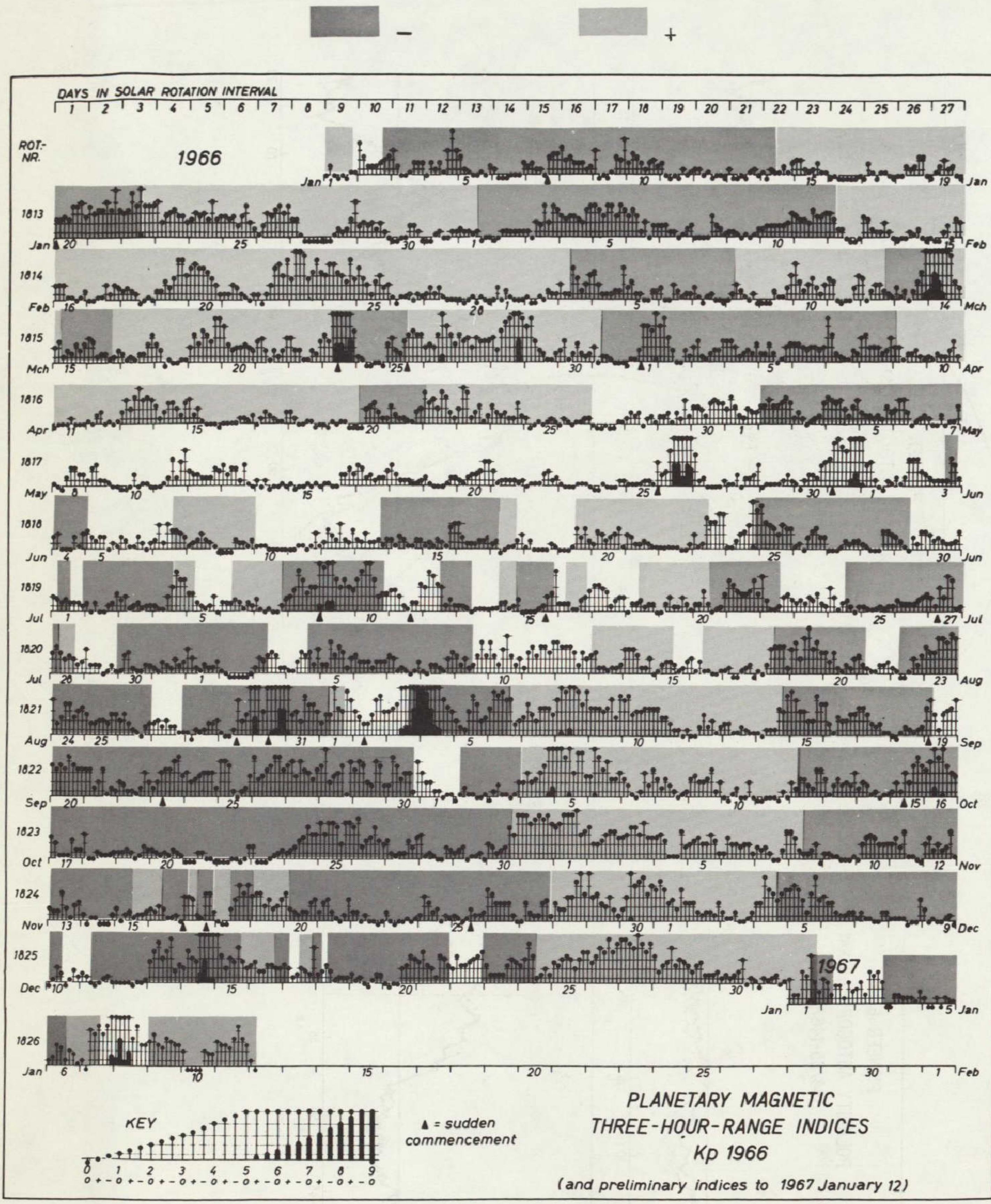

PIONEER 6
POLARITY AUTOCORRELATION
354/65-146/66
τ=29^D
τ=57.8^D
PIONEER 7
POLARITY AUTOCORRELATION
229/66-38/67
τ=27.3^D
τ=54.1^D
K
3 HOUR
12 HOUR

Figure 11



-
+
DAYS IN SOLAR ROTATION INTERVAL
ROT.-NR.
1966
1813
1814
1815
1816
1817
1818
1819
1820
1821
1822
1823
1824
1825
1967
1826
KEY
▲ = sudden commencement
PLANETARY MAGNETIC
THREE-HOUR-RANGE INDICES
Kp 1966
(and preliminary indices to 1967 January 12)

Figure 12

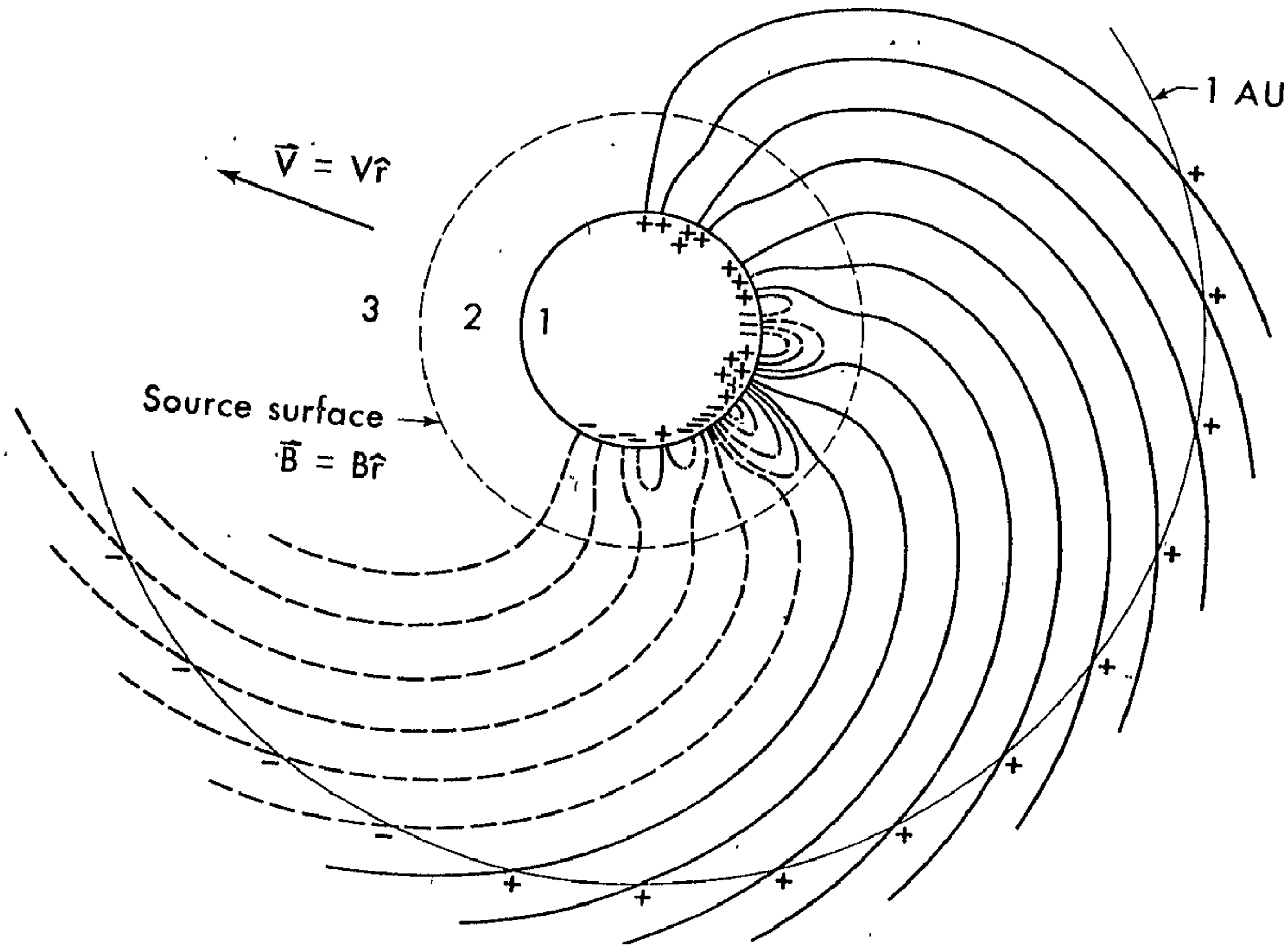


Figure 13

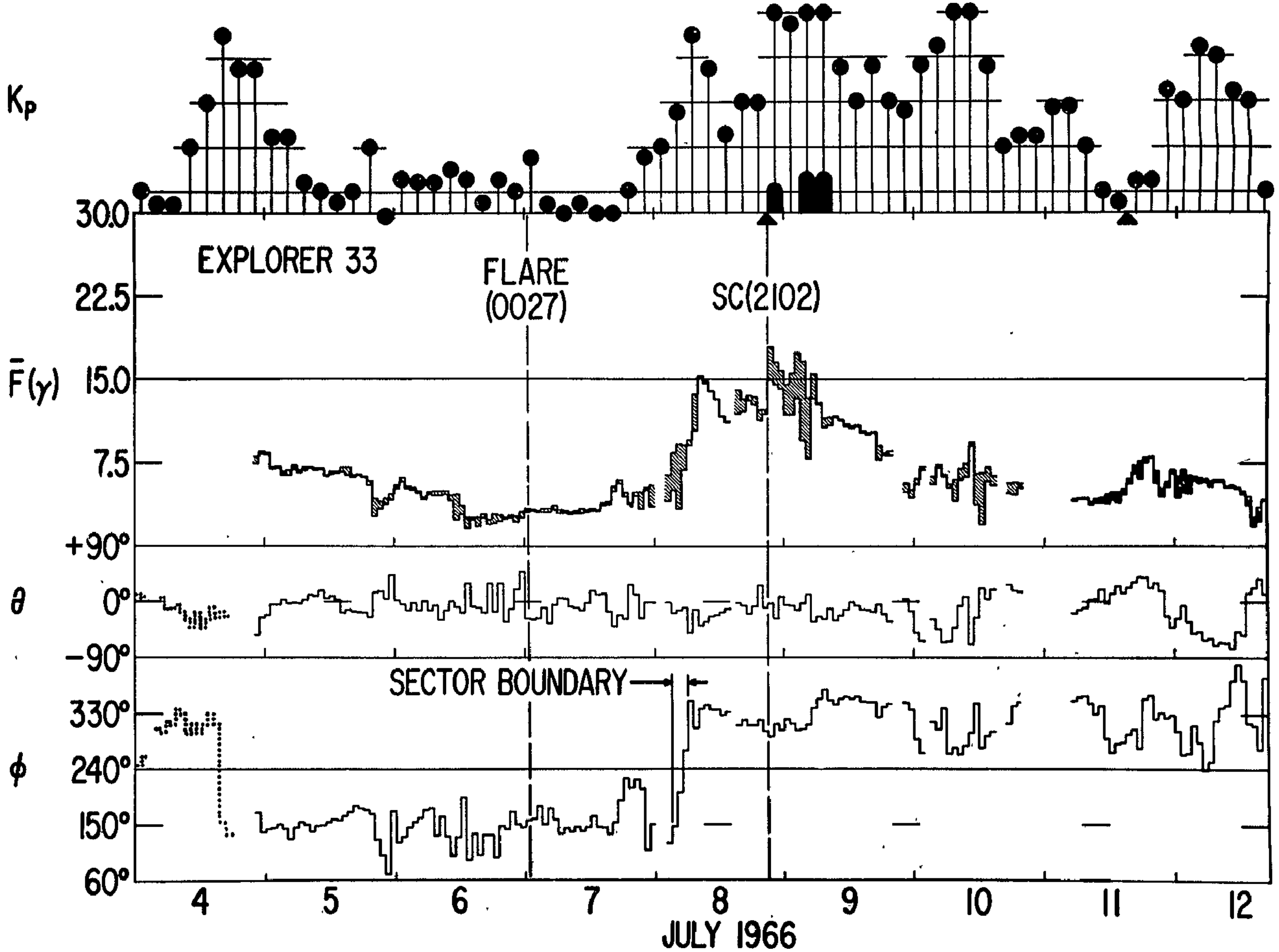

Kp
30.0
22.5
15.0
7.5
F̄(γ)
EXPLORER 33
FLARE
(0027)
SC(2102)
+90°
θ
0°
-90°
SECTOR BOUNDARY
330°
φ
240°
150°
60°
4
5
6
7
8
9
10
11
12
JULY 1966

Figure 14

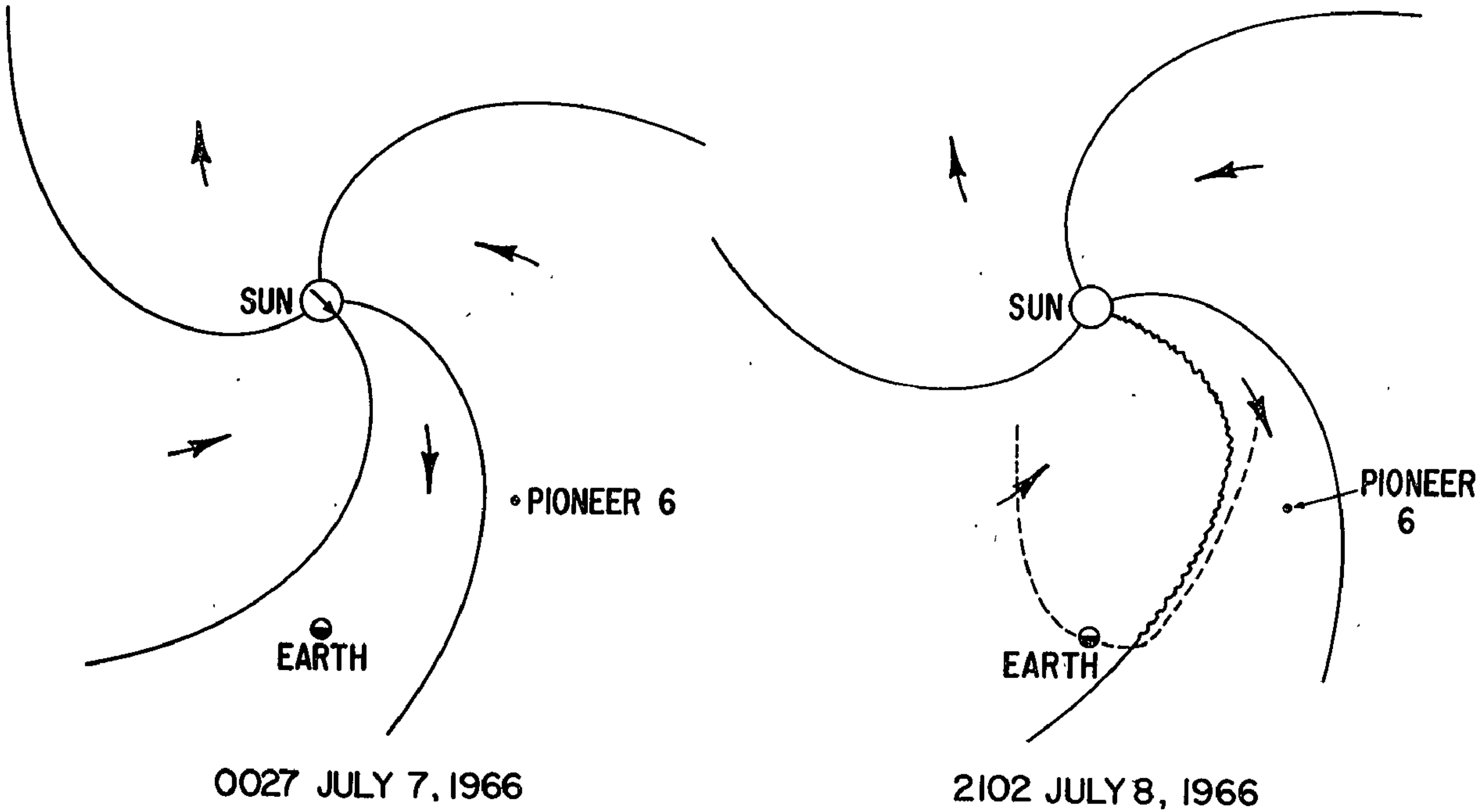
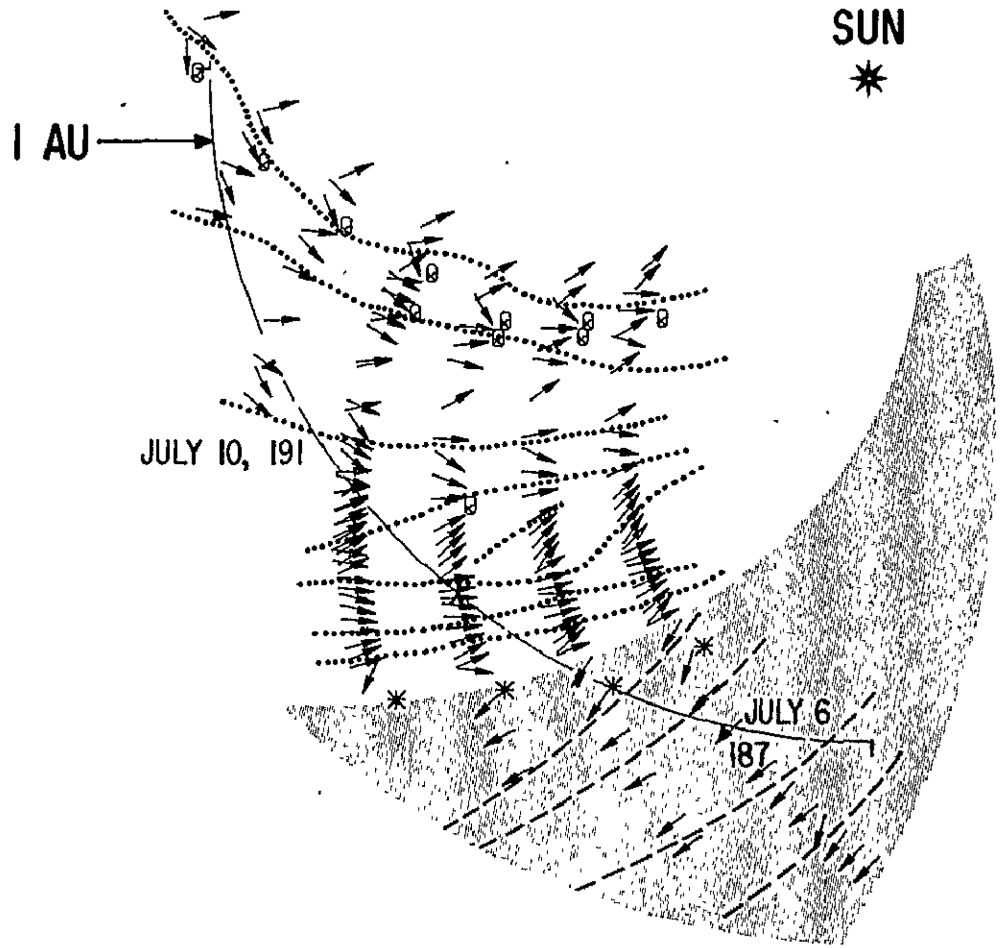

SUN
PIONEER 6
EARTH
0027 JULY 7, 1966
SUN
PIONEER 6
EARTH
2102 JULY 8, 1966

Figure 15



IMP-D ECLIPTIC MAGNETIC FIELD
187/66-194/66
JULY 6, 1966-JULY 13, 1966

Figure 16

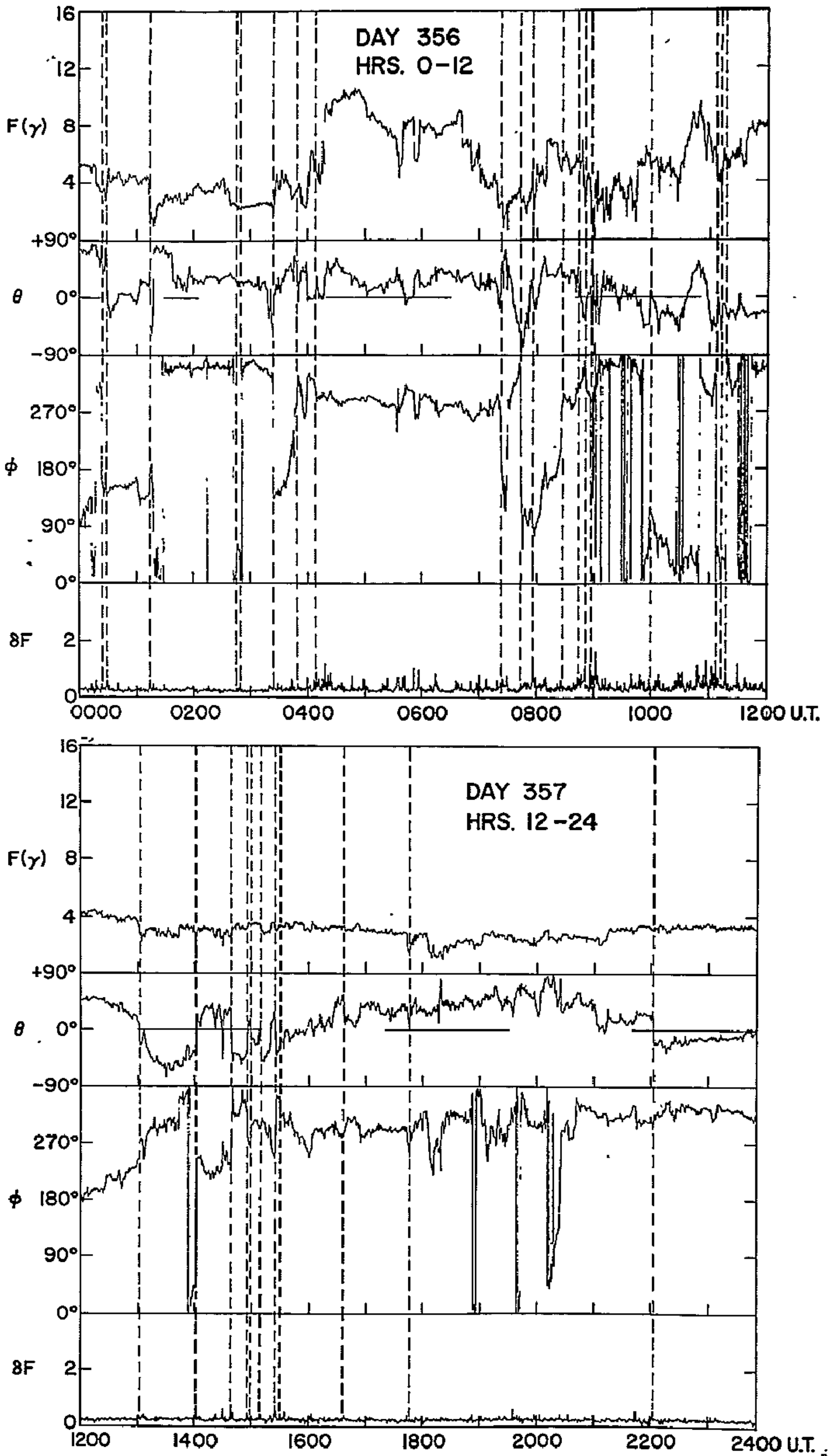
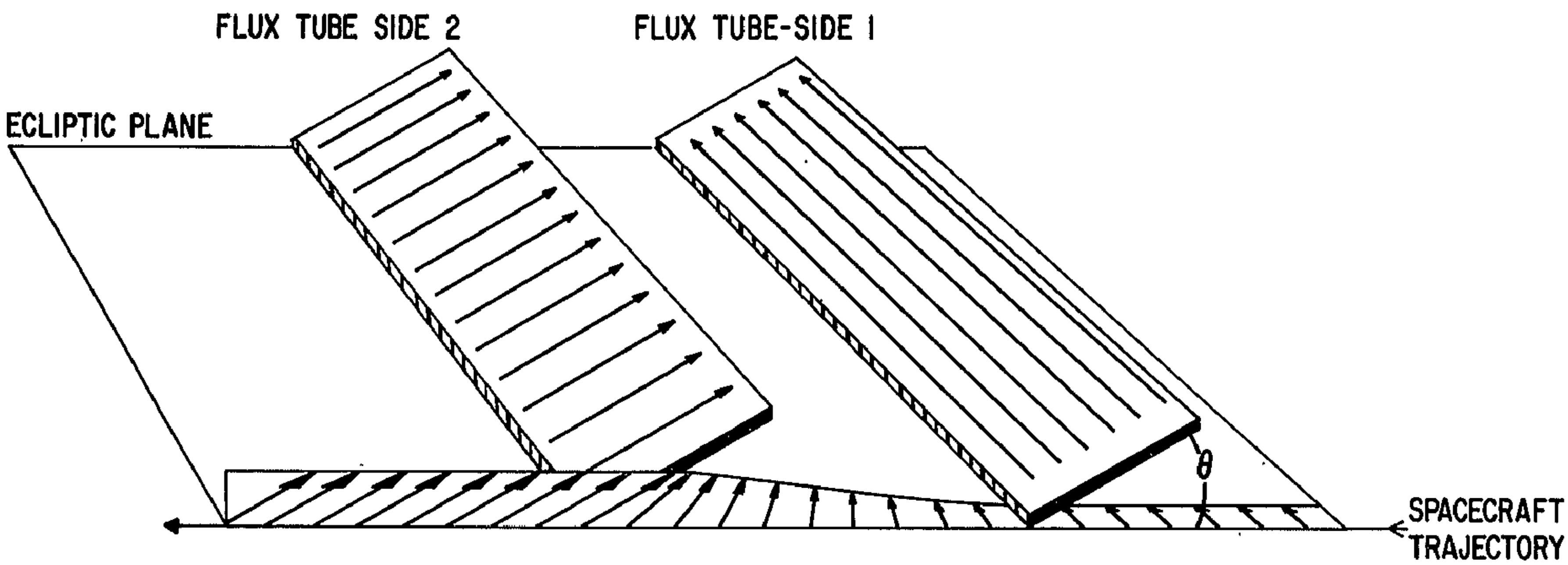
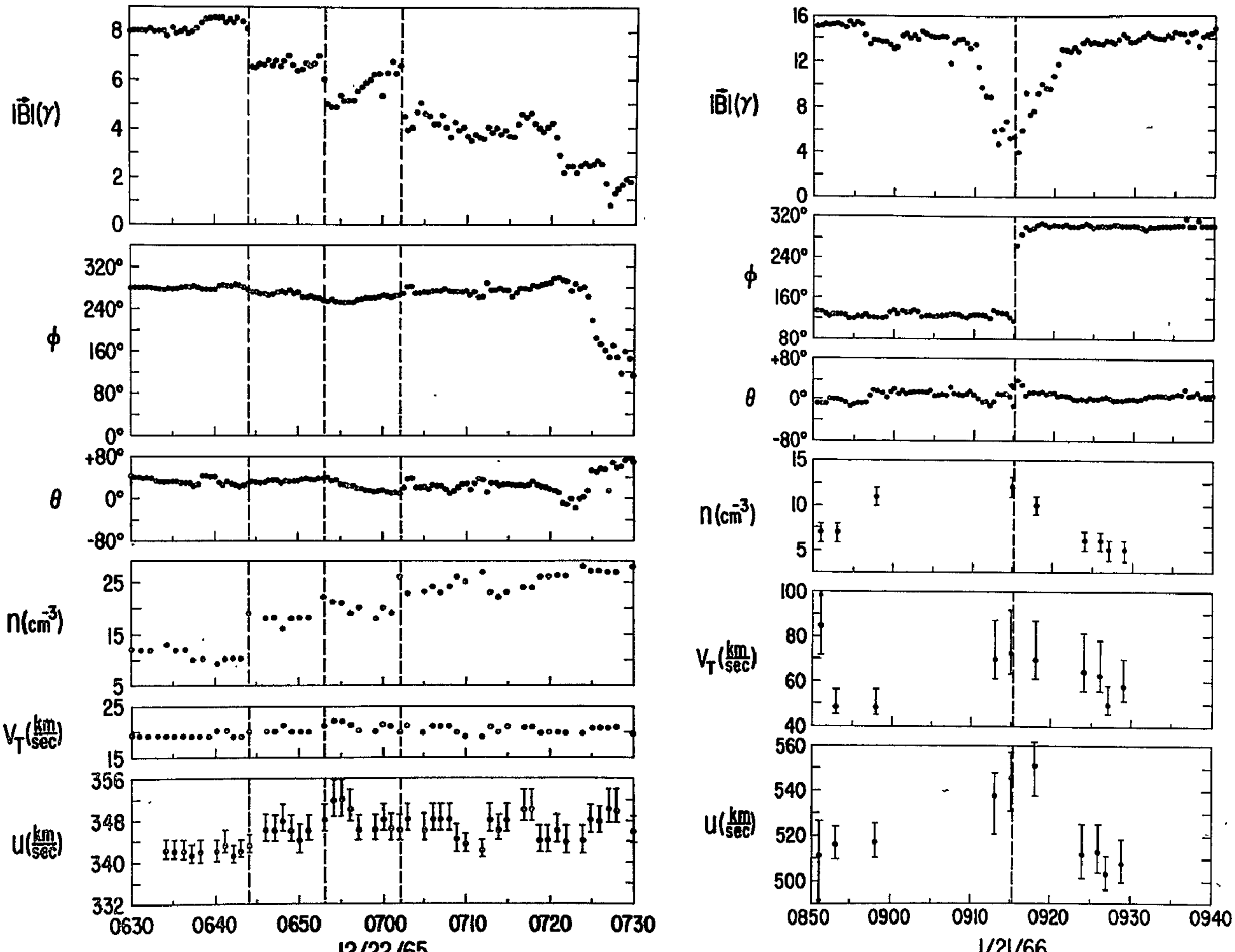

DAY 356
HRS. 0-12
F(γ)
θ
φ
δF
0000
0200
0400
0600
0800
1000
1200 U.T.
DAY 357
HRS. 12-24
1200
1400
1600
1800
2000
2200
2400 U.T.

Figure 17



TANGENTIAL DISCONTINUITY

Figure 18



|B|(γ)
φ
θ
n(cm⁻³)
V_T(km/sec)
u(km/sec)
0630
0640
0650
0700
0710
0720
0730
12/22/65
0850
0900
0910
0920
0930
0940
1/21/66

Figure 19

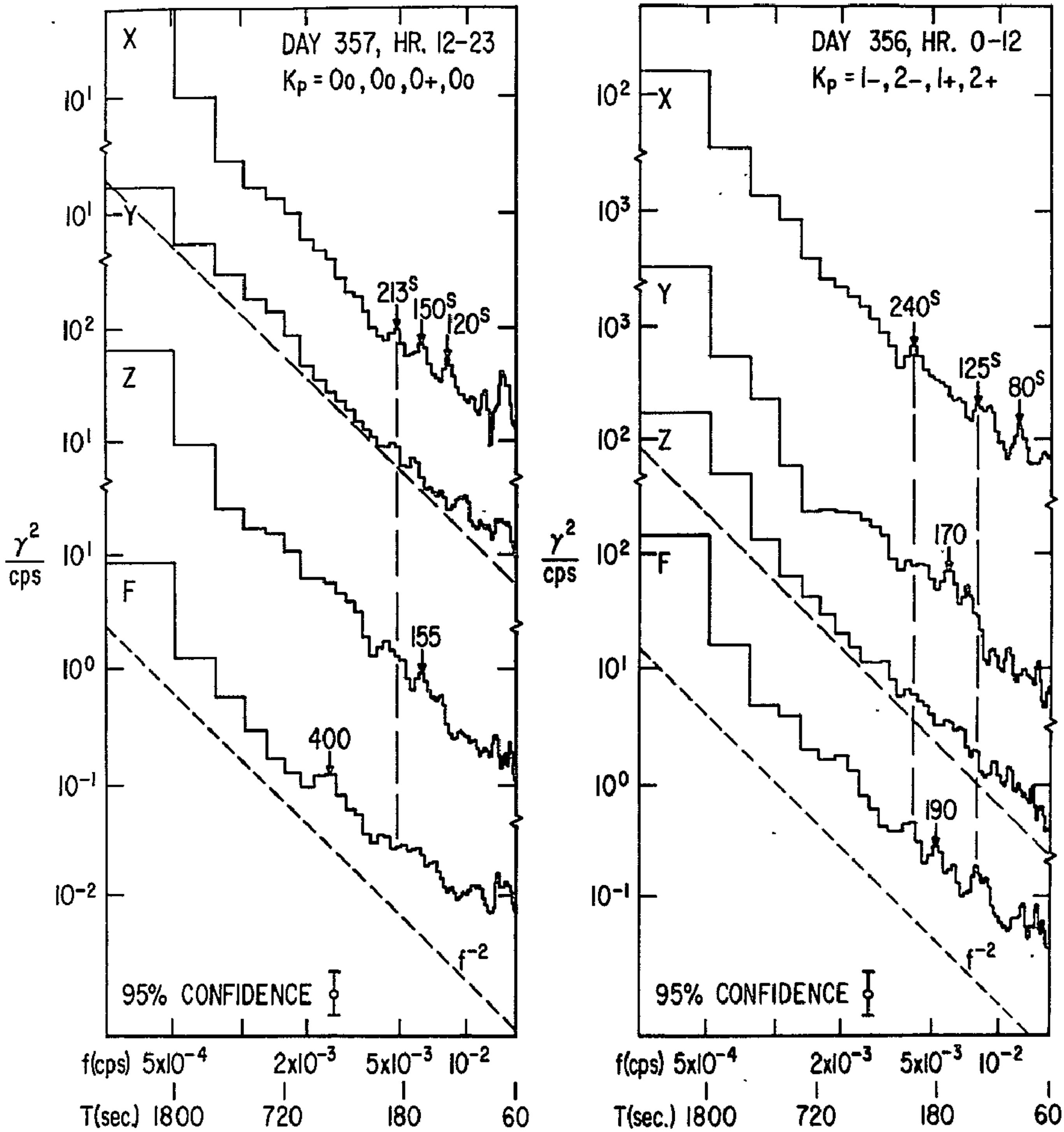
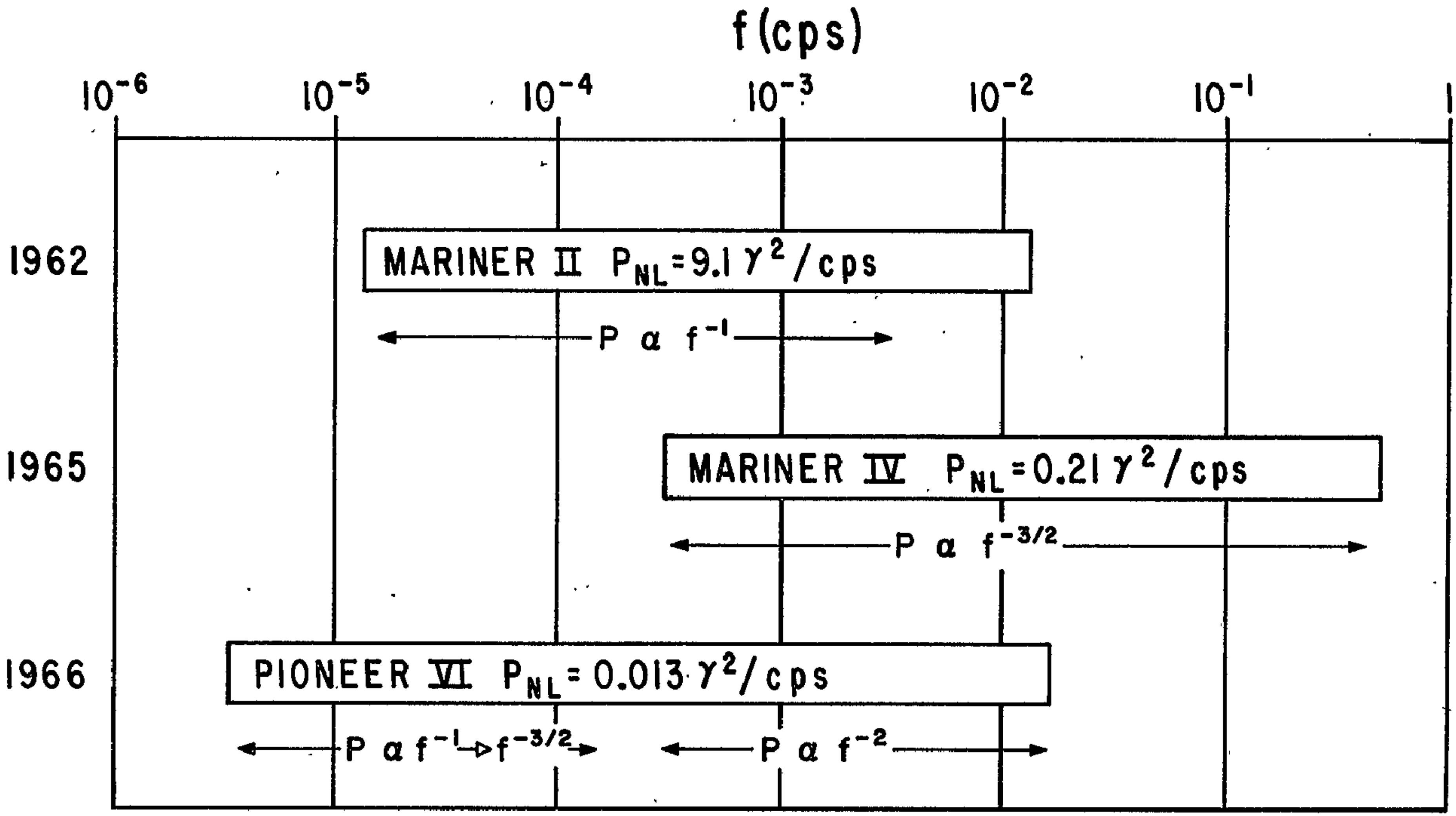
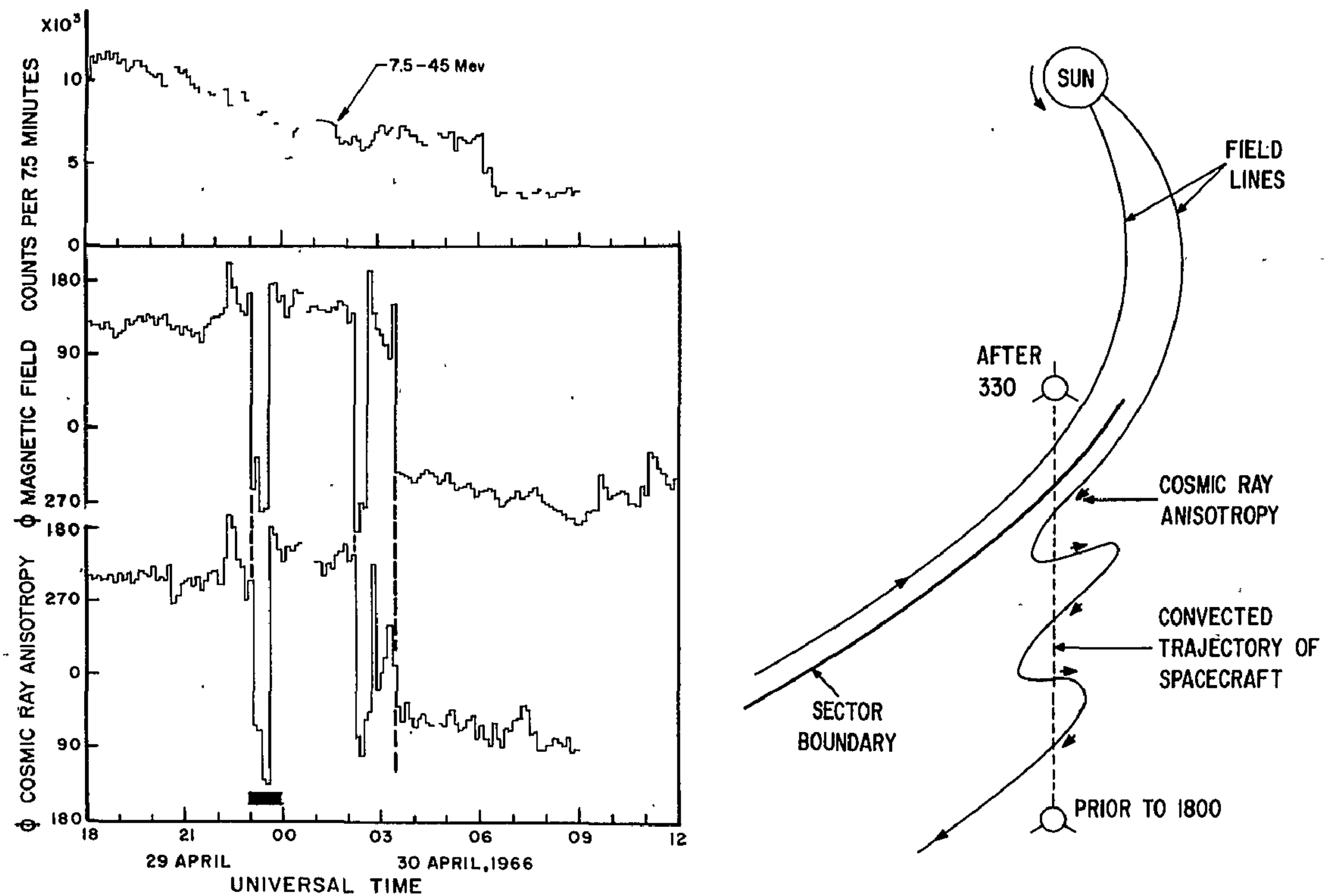

DAY 357, HR. 12-23
Kp = 0o, 0o, 0+, 0o
X
Y
Z
F
213s
150s
120s
155
400
f-2
95% CONFIDENCE
γ²/cps
f(cps) 5x10-4 2x10-3 5x10-3 10-2
T(sec) 1800 720 180 60
DAY 356, HR. 0-12
Kp = 1-, 2-, 1+, 2+
240s
125s
80s
170
190

Figure 20



f(cps)
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
1
1962
MARINER II P_NL=9.1 γ²/cps
P α f^-1
1965
MARINER IV P_NL=0.21 γ²/cps
P α f^-3/2
1966
PIONEER VI P_NL= 0.013 γ²/cps
P α f^-1 → f^-3/2
P α f^-2

Figure 21



X10³
COUNTS PER 7.5 MINUTES
7.5–45 Mev
10
5
0
φ MAGNETIC FIELD
180
90
0
270
φ COSMIC RAY ANISOTROPY
180
270
0
90
180
18
21
00
03
06
09
12
29 APRIL
30 APRIL, 1966
UNIVERSAL TIME
SUN
FIELD LINES
AFTER 330
COSMIC RAY ANISOTROPY
CONVECTED TRAJECTORY OF SPACECRAFT
SECTOR BOUNDARY
PRIOR TO 1800

Figure 22

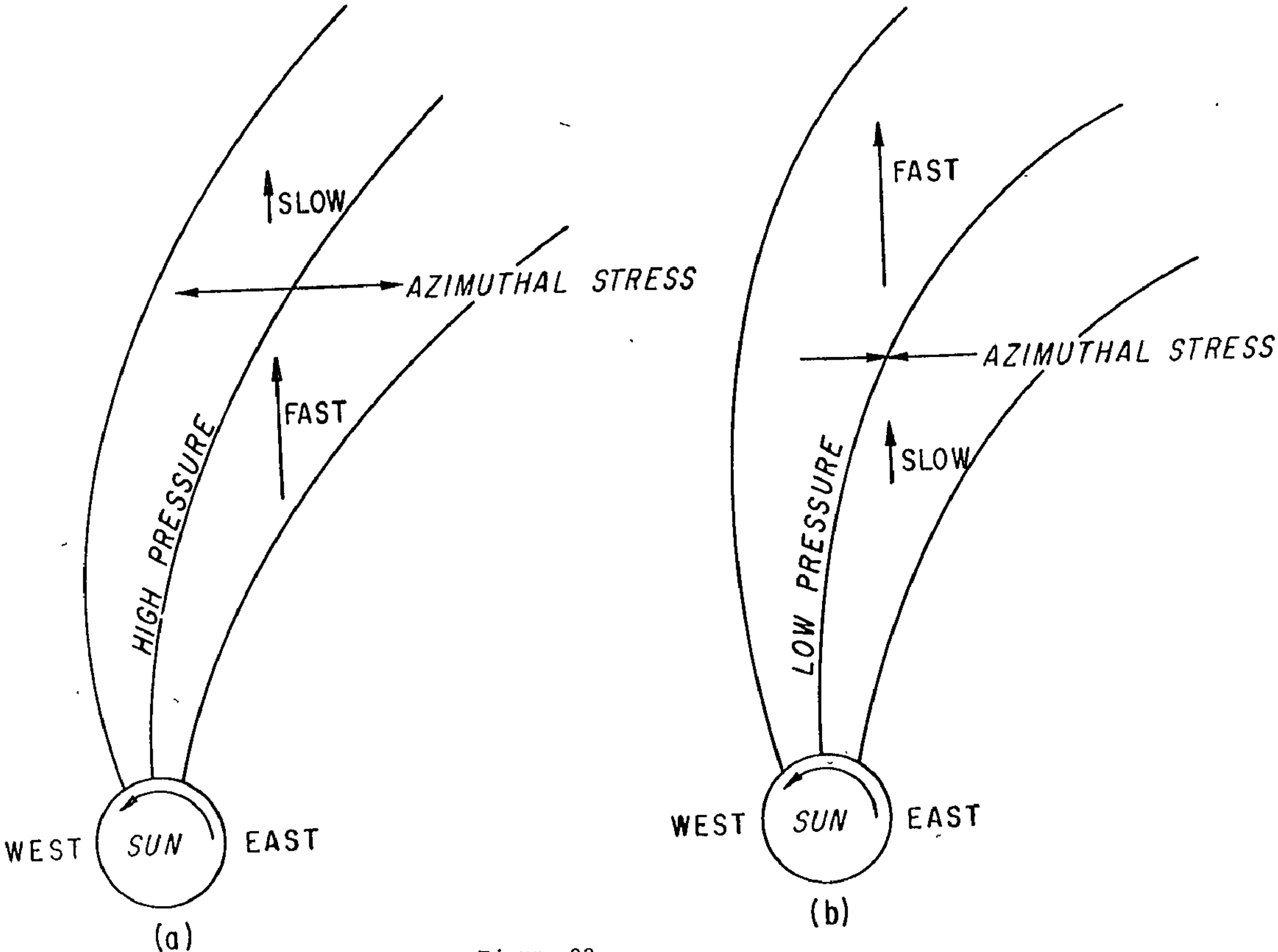

SLOW
AZIMUTHAL STRESS
FAST
HIGH PRESSURE
WEST
SUN
EAST
(a)
FAST
AZIMUTHAL STRESS
SLOW
LOW PRESSURE
WEST
SUN
EAST
(b)

Figure 23