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ABSTRACT

A possible explanation for quiet-time electron increases, increases in the intensity of 4-12 MeV interplanetary electrons that have been reported by Simnett, Cline, and McDonald, is discussed. It is argued that the electrons in quiet-time increases are galactic in origin, but that the observed increases are not the result of any variation in the modulation of these particles in the inner solar system. It is suggested instead that quiet-time increases may occur when more electrons than normal penetrate a modulating region that lies far beyond the orbit of earth. The number of electrons penetrating this region may increase when field lines that have experienced an unusually large random walk in the photosphere are carried by the solar wind out to the region. As evidence for this increased random walk, it is shown that five solar rotations before most of the quiet-time increases there is an extended period when the amplitude of the diurnal anisotropy, as is measured by the Deep River neutron monitor, is relatively low. Five rotations delay time implies that the proposed modulating region lies at $\sim$ 30 AU from the Sun, assuming that the average solar wind speed is constant over this distance at $\sim$ 400 km/sec. The implications for the correlation between periods of low amplitude diurnal anisotropy and quiet-time increases on interplanetary conditions out to $\sim$ 30 AU, and some possible models for the proposed modulating region are also considered.

I INTRODUCTION

In the companion paper to this one, Simnett, Cline and McDonald report observations of increases in the intensity of 4-12 MeV interplanetary electrons, which they have labeled "quiet-time electron increases". The electron intensity is observed to increase by a factor ~ 5 over the background level of galactic electrons, with a more or less symmetric time profile. The intensity can remain enhanced for of order five days to two weeks, and the events have the curious feature of occurring in anti-coincidence with increases in the low energy solar proton intensity.

In this paper we discuss a possible explanation for quiet-time electron increases. In Section II we argue that the electrons in quiet-time increases are galactic in origin, but that the observed increases are not the result of any variation in the modulation of these particles in the inner solar system. We propose instead that quiet-time increases occur when more electrons than normal penetrate a modulating region that lies far beyond the orbit of earth. In Section III we discuss some observational evidence that supports this explanation. In Section IV we interpret this evidence as indicating among other things, that the modulating region lies ~ 30 AU from the Sun and we consider some possible models for the modulating region. In Section V we suggest some additional observations that might be performed to confirm or contradict the conclusions of this paper.

II GENERAL INFORMATION AND A POSSIBLE EXPLANATION

In Figure 1 we have plotted the daily averages of the 4-12 MeV interplanetary electron intensity reported by Simnett, et al. (1971) for the years 1965 through 1968. The events that occur directly following detectable flare activity on the Sun are denoted in Figure 1 by the dark boxes. Simnett, et al. report that the remaining events that result in increases in the electron intensity can be divided into two general categories: recurrence events and quiet-time electron increases. One of the distinguishing features between these last two categories, each of which is characterized by a nearly symmetric time profile, is that recurrence events occur in coincidence with increases in the MeV proton intensity, whereas quiet-time increases occur in anti-coincidence (see Figure 11 in the paper by Simnett, et al. (1971)). Simnett, et al. conclude that the electrons in recurrence events are solar in origin. Recurrence events are detected one solar rotation following a flare-associated event, and the electrons and accompanying protons appear to be coming from the same active region that produced the original flare. We argue here, however, that the electrons in quiet-time increases are galactic in origin, these events representing localized increases in a general background flux of galactic electrons. Note in Figure 1 that during periods of limited solar activity there is present a relatively steady flux of electrons, which is of course real, detector background having been removed. This background flux is particularly evident, for example, during the periods October 1965 - May 1966 and March-October 1968. Although it is hardly a conclusive argument, the steadiness of the background flux is a good indication that we are observing here mainly galactic electrons. A flux of solar electrons should exhibit the high variability characteristic of solar activity. More direct evidence that the background flux is due to galactic electrons has been obtained recently by Webber and Lezniak (1971) who observe that its radial gradient lies somewhere in the range 0-30%/AU. The gradient of a steady flux of solar electrons would be negative and perhaps $\sim$ - 200%/AU. We can conclude that quiet-time increases are simply localized increases in this galactic background flux, because the spectral index for the intensity during a quiet -time increase is the same as it is for the background flux. Simnett, et al. (1971) report that this common spectral index is about -2, and thus it defines a flatter spectrum than is observed during flare-associated events (spectral index $\sim$ -3) or during recurrence events (spectral index $\sim$ -4 or 5). Of course, that the electrons in quiet-time increases are galactic in origin is not surprising in view of the anti-correlation between quiet-time increases and increases in the low energy solar proton intensity. It is difficult to imagine how the Sun, which is almost a quasi-continuous source of low energy protons (Kinsey, 1970), could accelerate electrons to relativistic energies without producing an accompanying proton increase. We will discuss this anti-correlation between quiet-time increases and increases in the solar proton flux in more detail in Section IV. In Figure 1 we have marked with brackets the quiet-time increases reported by Simnett, et al. (1971). The events marked with dashed brackets are less clear-cut than the others since here it is not as readily established that the electron increases anticorrelate with an increase in the MeV proton flux, and the increase over the local electron background is quite small. All of these events will be discussed in detail in Section III.

Probably the simplest explanation for quiet-time increases is to postulate that there is some process operative in the interplanetary medium that normally excludes some fraction of the galactic electrons from the inner solar system (defined arbitrarily to be the region lying within the first 5-10 AU of the Sun), and that this process is less effective during a quiet-time increase. The modulation mechanism that partially excludes galactic cosmic ray nuclei and high energy electrons (say, in the range 0.1-20 GeV) from the inner solar system is of course well known; as these particles propagate into the inner solar system they are scattered by irregularities in the magnetic fields carried outward by the solar wind (see a recent review by Jokipii, 1971). If 4-12 MeV electrons also experience this scattering, we might imagine that quiet-time increases occur when scattering conditions in the inner solar system are altered permitting more galactic electrons to enter. However, note in Figure 1 that the background flux of galactic electrons is relatively constant from 1965 through 1968. In fact, Simnett, et al. (1971) report that the background flux is reduced by a factor of $\sim$ 1.25 over this time span, which covers solar minimum conditions to near solar maximum conditions. This is about the same modulation experienced by relativistic protons and is quite small when contrasted with, for example, the reduction by a factor $\sim$ 10 in the intensity of 10-50 MeV galactic protons over the same time period. The evidence is, then, that 4-12 MeV galactic electrons are relatively insensitive to any changes in the scattering conditions in the inner solar system. We construe this to indicate that the electrons experience little scattering in the inner solar system, and consequently we can not alter these scattering conditions to account for the factor

~ 5 increases in the intensity that occur during quiet-time increases. Evidently the interplanetary magnetic field in the inner solar system is not irregular to any significant degree with a scale-size comparable with the gyro-radius of a 4-12 MeV electron (~ 7000 km in a 5 γ field). It should be noted that it is possible to construct models in which the electron intensity remains relatively time invariant, but there is still appreciable scattering (see Lezniak and Webber, 1971). However, in addition to being rather artificial, these models predict a radial gradient for the intensity larger than that observed. If we estimate the gradient predicted by such models, using, for example, the force-field approximation of Gleeson and Axford (1968a) (see Fisk and Axford, 1970), we find that it is $\sim 100\%$/AU, as compared with the observed gradient for ~ 10 MeV electrons of 0-30%/AU (Webber and Lezniak, 1971). Rather, the small magnitude of the observed gradient is consistent with our conclusion that 4-12 MeV electrons experience little scattering in the inner solar system.

The lack of significant scattering of 4-12 MeV electrons in the inner solar system is also evident during solar flare events. Of course, we should restrict ourselves to examining only flares that occur at $\sim 45^{\circ}$ west solar longitude since then we will minimize the influence that propagation near the Sun will have on the observed time profiles. In Figure 2 we have shown the behavior of the intensities of 4-12 MeV electrons, and protons of several different energies, as were observed by Cline and McDonald (1968) for the classic medium-sized flare which occurred at 48° west solar longitude on 7 July 1966. Note that the rise time of the electron event is quite rapid compared with the proton events, and that the electron event is essentially over in considerably less than a day. The time profile of the electron event is in fact similar to the time profiles of the relativistic proton events produced by some of the larger flares (e.g. the 15 November 1960 flare). Thus, despite vastly different rigidities, 4-12 MeV electrons and relativistic protons experience a similar amount of scattering in the inner solar system, which, considering the short duration of these flare events, must be quite limited. A diffusion coefficient $\sim 10^{22}$ cm^2/sec for diffusion along the field lines near the earth (or for diffusion in the heliocentric radial direction) would adequately produce the diffusive time profile for the electrons shown in Figure 2, and cause the anisotropy to decay. Actually, the 4-12 MeV electrons may experience less scattering in the inner solar system than is indicated by this diffusive time profile. Note that the electrons did not begin to arrive at earth until $\sim$ 30 minutes after the flare, despite the fact that the flare was located at the base of the interplanetary field lines leading to earth. This suggests that there was some trapping or diffusion of the electrons near the Sun, which could have produced some of the diffusive effects seen at earth (Cline and McDonald, 1968). Also, we note that Lin (1970) has observed that certain flares can emit bursts of $\sim$ 40 keV electrons that arrive at earth essentially unattenuated by scattering in the interplanetary medium. Wang, et al. (1971) have extended the observations of these events to include electrons with energies $\sim$ 1 MeV, and find that they also exhibit this 'scatter-free' behavior. Unless interplanetary conditions are significantly different during 'scatter-free' events than they are during flares with a normal diffusive time profile, the diffusive effects exhibited by normal flares must be mainly the result of diffusion near the Sun. The evidence from solar flares, then, is that a diffusion coefficient $\gtrsim 10^{22}$ cm^2/sec for, say, diffusion in the heliocentric radial direction is adequate for describing the behavior of 4-12 MeV electrons in the inner solar system near earth. If we assume that this diffusion coefficient holds throughout the inner solar system, we find that the intensity of galactic electrons in this energy range will vary on the average by a factor $\lesssim 1.8$ over the first 10 AU out from the Sun.

Although 4-12 MeV electrons do not appear to suffer appreciable modulation in the inner solar system, this does not mean necessarily that they suffer little modulation throughout the solar cavity. There could exist a modulating region remotely far beyond the orbit of earth that controls the emission of particles into the inner solar, permitting more electrons to enter during a quiet-time increase. Presumably, the interaction of the electrons with the magnetic fields in such a modulating region can be described by a diffusion process, with an appropriate diffusion coefficient parallel and perpendicular to the mean magnetic field direction. We are clearly not in a position to observe directly changes in the parallel diffusion coefficient that could result in quiet-time increases. Irregularities that are generated locally in the modulating region determine the rate at which particles diffuse along the field lines. However, we may be able to observe directly changes in the perpendicular diffusion coefficient. Jokipii and Parker (1969) have shown that particles are transported across the mean field direction principally as the result of the stocastic nature of the magnetic fields; the particles follow field lines that are random walking about the mean field direction. At the orbit of earth, most of the random walk of the interplanetary field lines appears to be produced by photospheric turbulence. The base of the field lines move randomly with the supergranulation motions in the photosphere, and then as the solar wind drags the field lines out from the Sun the entwinning which is evident at earth results (Leighton, 1964; Jokipii and Parker, 1969). Suppose that photospheric turbulence is the main source of the random walk beyond the orbit of earth, out to and including at least part of the proposed modulating region. Then, the rate at which field lines move in the photosphere will determine, at least in part, the rate at which particles will diffuse across the modulating region. When field lines that experienced an unusually large random walk in the photosphere are carried out by the solar wind to the modulating region, more 4-12 MeV electrons (and perhaps other particles) will diffuse across this region, gaining access to the inner solar system and producing a quiet-time increase at earth. Note that the mean field direction in the proposed modulating region will be, presumably, mainly azimuthal about the Sun, and hence the random walk of the field lines will be particularly important for diffusion in the heliocentric radial direction. Clearly, we can test the above hypothesis by seeing whether periods of unsually large random walk are observed before quiet-time increases, with a delay time which is then a measure of how long the solar wind takes to propagate from the orbit of earth to the modulating region.

III SUPPORTING OBSERVATIONAL EVIDENCE

In order to establish that there exists a correlation between the occurrence of quiet-time increases and of periods when the magnetic field lines experience an unusually large random walk, we obviously must have a reliable and sensitive measure of how much field line random walk is taking place. The only direct measure of the random walk is the power at zero frequency in the power spectrum of magnetic field fluctuations (Jokipii and Parker, 1969). However, the errors involved in determining the power at low frequencies are quite large. It would be difficult to distinguish between order of magnitude changes in the low frequency power on a short-term basis, much less the changes by a factor of 2 or so that we will require. Also, there is the practical difficulty that power spectra are not readily available for all the different time periods we will consider. We suggest instead that a useful measure of the random walk is the amplitude of the cosmic ray diurnal anisotropy, as is observed by neutron monitors. Clearly, the diurnal anisotropy does not have any of the practical difficulties associated with power spectra since neutron monitor data is readily available and the amplitude of the anisotropy can be determined to quite high accuracy ($\sim 0.1\%$). The formula for the amplitude of the diurnal anisotropy, ξ, during quiet periods, assuming that there is appreciable diffusion perpendicular to the mean field direction (due presumably to the field line random walk) is (Krimsky, 1965; Parker, 1967):

$$\xi = \frac{3CV_w}{v} \frac{(1 - \kappa_\perp/\kappa_\parallel)\tan\psi)}{(1 + \kappa_\perp/\kappa_\parallel)\tan^2\psi)} \tag{1}$$

Here, $\kappa_\parallel$ and $\kappa_\perp$ are the diffusion coefficients parallel and perpendicular to the mean field direction, respectively, and ψ defines the angle between the mean field direction and the heliocentric radial direction. The solar wind speed is given by V_{SW}, the particle speed by v, and C = $(2 + \mu)/3$ is the Compton-Getting factor with μ the spectral index (Gleeson and Axford, 1968b). During periods of unusually large random walk, $K_\perp$ will of course increase over its average value which we take to be $\kappa_\perp \simeq 2 \times 10^{21}\beta$ cm^2/sec. ($\beta = v/c$ with c the speed of light), in agreement with the findings of Jokipii and Parker (1969). Note that $\kappa_\perp$ for relativistic protons and electrons will be about the same since $\kappa_\perp$ depends only on β. However, some rigidity dependent corrections to $\kappa_\perp$ for protons may be necessary if the proton gyro-radius exceeds the correlation length of the magnetic field (Jokipii, 1967). Also, during periods of large random walk, $\kappa_\parallel$ for relativistic protons will be smaller than its typical value of $\sim 10^{22}$ cm^2/sec (for, say, 5-10 GeV protons (Jokipii and Coleman, 1968)) since it depends inversely on the power at low frequencies in the power spectra of field fluctuations (Jokipii, 1967). Thus, the ratio $\kappa_\perp/\kappa_\parallel$ will increase when the random walk increases, exceeding its average value for relativistic protons of $\kappa_\perp/\kappa_\parallel \sim 0.2$. This increase will result in a commensurate reduction in the amplitude of the diurnal anisotropy, which has an average value of $\sim 0.4\%$, suggesting that there should exist a direct correspondence between periods of low diurnal anisotropy and periods of large random walk of field lines.

Using a simple harmonic analysis, we have computed the amplitude of the diurnal anisotropy from the pressure-corrected hourly averages of the counting rate of the Deep River neutron monitor. We have performed this analysis using the data from the 24 hour period centered on every 12 hours from early 1965 through early 1968. The average amplitude of the diurnal anisotropy measured at Deep River was $\sim 0.4\%$ for the years 1966-68, and $\sim 0.35\%$ for 1965 (VanHollebeke, 1970). We will consider as small any amplitude less than 0.3% for 1966-68, and less than 0.25% for 1965. Although continuous data is available for these years, not all the computed anisotropies will be a reliable measure of the random walk.

For example, we cannot determine accurately the amplitude of the diurnal anisotropy when the counting rate of the neutron monitor is varying rapidly, as it does in a Forbush decrease. We have eliminated from consideration, then, any amplitudes that were determined when the daily average of the monitor rate varied from day to day by more than 1%. Also, it was assumed explicitly in deriving equation (1) that there is no significant component of the anisotropy in the heliocentric radial direction, with the result that the anisotropy points in the positive azimuthal direction (counter-clockwise about the Sun). It is also assumed that there are no significant gradients in the azimuthal or polar directions since, presumably, these could not be maintained when there is appreciable diffusion across the mean field direction. For the diurnal anisotropy to be a reliable measure of the random walk, we require, therefore, that it has a direction such that the maximum flux of cosmic rays is observed within $\pm$ 3 hours of the 18 hour direction UT (after proper corrections are made for the bending of the trajectories of the partides in the geomagnetic field). We note, however, that it is difficult to obtain a small amplitude diurnal anisotropy unless there is a large random walk of the field lines. It appears to us unlikely that, for example, azimuthal or polar gradients could substantially reduce the amplitude of the diurnal anisotropy. However, when the amplitude is small, such gradients or perhaps small time variations in the cosmic ray intensity could cause the observed maximum to occur in other than the 18 hour direction. We therefore accept as an indication of large random walk any anisotropy with an amplitude < 0.3% (0.25% in 1965), even when this anisotropy does not satisfy the direction criterium we impose on larger amplitude anisotropies.

In Figure 3 we have plotted the amplitudes of the diurnal anisotropy that are a reliable measure of the random walk during the period January 1967 through April 1968. The plot is divided into Bartels solar-rotation periods of 27 days. Shown also in the figure is the sector structure of the interplanetary magnetic field (Fairfield, private communication). Light shading indicates a sector with fields directed mainly away from the Sun; dark shading, mainly toward the Sun. The times when quiet-time increases occur are denoted by brackets which are identical to those shown in Figure 1. The horizontal dashed line in Figure 3 marks an amplitude of 0.3%. Any amplitude less than this is considered to indicate a large random walk of the field lines. Note in Figure 3 that some of the calculated amplitudes are greater than $\sim 0.6\%$, which is largest amplitude that can be obtained from equation (1) using the average values for $C = 1.5$, $V = 400$ km/sec., and $\psi = 45^{\circ}$. Periods of enhanced diurnal anisotropy can result when there are high-speed streams in the solar wind, significant deviations of the field from the spiral angle, or for several other reasons (see Venkatesan and Fisk, 1971; VanHollebeke, 1971). Irrespective of the cause of these large amplitudes, we consider that they imply little field line random walk. Note also in Figure 3 that quiet-time increases are well-correlated with sector structure in that they do not generally extend over more than one sector. There is one notable exception to this rule, the event of 28 August - 6 September 1967. The main conclusion to draw from Figure 3, however, is that quiet-time increases and periods of low amplitude diurnal anisotropy occur in a pattern. If we trace the sector containing a well-defined quiet-time increase back five solar rotations, then within the sector on the fifth rotation, there is an extended period of low amplitude diurnal anisotropy. We do not contend that this pattern is obvious, but rather it can be seen only after considerable study. Since a sector can be expected to undergo some evolution over five rotations, the relative positions of associated quiet-time increases and periods of low amplitude within the sector may change. Also, the period of low amplitude may be of different duration than that of the quiet-time increase, although it will be an extended period lasting, say, not less than five days. The eleven quiet-time increases shown in Figure 3 can be divided into three categories: (i) for seven of the events there is an extended period of low amplitude diurnal anisotropy five rotations earlier, (ii) two of the events are questionable quiet-time increases and have no associated, low amplitude period, and (iii) for two of the events we can not trace the sector containing the increase back five rotations. In Table 1 we have listed the events in category (i), together with their associated periods of low amplitude. Listed also for each of the periods of low amplitude are the ratio of the number of amplitudes < 0.3% to the number of amplitudes that are a reliable measure of the random walk, and the ratio of the number of reliable amplitudes to the total number of possible amplitudes (two per day for each day of the period). Only for the second event, 6-16 November 1967, is there insufficient data to establish convincingly that there is an associated period of low amplitude, although all the data available for this period have an amplitude < 0.3%. On averaging over the remaining six events, 82% of the reliable anisotropies have an amplitude < 0.3%. Compare this with the percentage of reliable amplitudes < 0.3%, computed using data from the entire period January 1967 through April 1968, of only 41%. The two quiet-time increases in category (ii), for which there are no associated periods of low amplitude, are the events of 3-11 January 1968 and 29 January - 5 February 1968. These are questionable quiet-time increases in that the increase over the local quiet-time flux is quite small (see Figure 1) and it cannot be established definitely that the events anticorrelate with increases in the MeV proton flux (see Figure 11 of the paper by Simnett, et al., 1971). If these events are in fact due to an increase in the flux of galactic electrons, as opposed to solar electrons, we suggest that they are only the remnants of the well-defined quiet-time increases that occurred in the same sector on the three previous solar rotations (see Figure 3). The two quiet-time increases in category (iii) are the events of 5-10 August 1967 and 28 August - 6 September 1967. Although the sector containing these increases cannot be traced back to determine whether there are associated periods of low amplitude diurnal anisotropy, there is evidence that the sector existed for the required five rotations, lying out of the ecliptic. Interplanetary magnetic fields can generally be related directly to the weak, background photospheric fields (Wilcox, 1968). Examination of solar magnetogram data for this period (see Solar Geophysical Data, Nos. 271-278) suggests that this sector existed at least as far back as solar rotation 1827 when it was associated with the magnetic fields of McMath plage No. 8687, which occurred at solar latitude ~ N22 (Schatten, private communication). We suggest that the sector at this point lies north of the ecliptic, although we cannot rule out the possibility that at least part of the positive sector seen in the ecliptic at the end of rotation 1827 (light-shading in Figure 3) also originates from this region. On successive solar rotations the sector appears to arise from McMath plages nos. 8719, 8760, 8798, which are the return passages of plage 8687, and then from 8831 or 8835, 8871, and so forth, which are a new series. Plages 8831 and 8835 develop in the same region wherein 8798 occurred, with presumably no break in the continuity of the interplanetary magnetic fields originating from this region. During solar rotation 1832, when the sector originates in plage 8871, it appears in the ecliptic and remains there for many solar rotations, particularly for rotations 1833 and 1834, where the two quiet-time increases in category (iii) occur.

We have repeated the above analysis for the quiet-time increase in 1966 and for the three in 1965. In Figure 4 we have plotted the amplitudes of the diurnal anisotropy that are a reliable measure of the random walk, and indicated the sector structure and times of quiet-time increases, for the period March through December 1966. The quiet-time increase shown in this figure is marked in part with a dashed bracket because the latter portion of this event coincides with an increase in the MeV proton flux in what is apparently a co-rotating region. If we trace the sector that contains this increase back five solar rotations there is an extended period of low amplitude diurnal anisotropy from 28 May 1966 through at least 4 June 1966. Note also in Figure 4 that the sector containing the quiet-time increase appears to develop from two separate sectors, which combine between solar rotations 1819 and 1820. It is reasonable that the period of low amplitude anisotropy occurs in the sector that evolves into roughly the first half of the combined sector. It is in this portion of the combined sector where the well-defined part of the quiet-time increase occurs. During the period of low amplitude anisotropy, 56% of the number of possible anisotropies (two per day for each day of the period) are a reliable measure of the random walk, and of these 90% have an amplitude < 0.3%. For the three quiet-time increases in 1965, however, the situation is less clear-cut. Note in Figure 5, where we have plotted the relevant information for these three increases, that the events of 20 August - 1 September 1965 and 17-28 September 1965 appear to extend across sector boundaries. As can be seen by comparing Figures 1 and 5, however, there are detectable decreases in the electron intensity at the sector boundaries, which suggests, perhaps, that each of these increases is actually two events occurring simultaneously in adjacent sectors. The decreases in the intensity at the sector boundaries are marked in Figures 1 and 5 by vertical dashed lines. For all the events shown in Figure 5, it is difficult to establish that there are associated periods of low amplitude anisotropy since we cannot follow with certainty the development of sectors from rotation to rotation. The stable sector pattern of four distinct sectors, which had existed during solar minimum conditions, (Wilcox, 1968) dissolved in 1965 into the continuously changing field configuration seen in Figure 5. For the quiet-time increase of 24 August - 1 September 1965, however, there is some evidence for an associated period of low amplitude anisotropy, five rotations before the event. As can be seen in Figure 5, the amplitude of the diurnal anisotropy during the period 9-15 April 1965 is consistently less than 0.25%, which, as we indicated above, is the upper limit on a low amplitude anisotropy during 1965. Note, however, that we are missing much of the magnetic field data during the period 9-15 April 1965. (We are missing magnetic field data during the periods which are unshaded in the plots in Figures 3-5). Thus, in addition to the above-mentioned difficulties in following the sector pattern during this period, the missing field data precludes our being certain that the period of low amplitude anisotropy and the quiet-time increase occur in the same sector. For the quiet-time increase of 25-28 September 1965, there is no extended period, five rotations before the event, when the amplitude is really low. However, from 6-10 May 1965, the amplitude is quite close to 0.25%. For the events of 20-23 August 1965 and 16-24 August 1965 there do not appear to be any associated periods of low amplitude anisotropy. This may indicate that these last events are not independent quiet-time increases, but rather that they occur in connection with the events of 24 August - 1 September 1965 and 25-28 September 1965, which appear in the adjacent sector. More probably it reflects our inability to trace accurately the sector containing these increases over the required five rotations. For the event of 5-13 September 1965 we were unable to trace the sector back more than two rotations.

IV INTERPRETATION AND POSSIBLE MODELS

The observations discussed in Section III support the contention made in Section II, viz., when field lines that have experienced an unusually large random walk in the photosphere are carried by the solar wind out to a modulating region lying beyond the orbit of earth, more 4-12 MeV electrons than normal will penetrate this region and propagate into the inner solar system, producing a quiet-time increase at earth. The transit time of the solar wind from the orbit of earth to the location of the modulating region accounts for most of the delay of five rotations between the occurrence of the low amplitude period (period of large random walk) and of the quiet-time increase. The modulating region, then, must lie at $\sim$ 30 AU from the

Sun assuming that the average solar wind speed is constant over this distance at ~ 400 km/sec. The transit time of the electrons in from the modulating region must be short compared with one solar rotation (~ 27 days), since within this time the electron intensity seen at earth appears to respond to changes in the modulating region. This can be seen by noting that there is a unique period of low amplitude anisotropy for each of the quiet-time increases (when the association can be made), with recurrent series of quiet-time increases and their associated low amplitude periods both occurring over an equal number of solar rotations. The 4-12 MeV electrons must experience little scattering when propagating in from ~ 30 AU; for example, if they propagate freely along fields that on the average execute the Archimedes spiral pattern, then the distance along the fields from ~ 30 AU is ~ 450 AU, and the transit time ~ 2.5 days. These observations imply, of course, that interplanetary magnetic field lines (at least those on which quiet-time increases occur) extend continuously to ~ 30 AU, e.g. out to this distance there is no significant field line recombination. Note also that the delay time of five solar rotations does not vary from year to year (although the best observations discussed in Section III cover only the period 1966-68), indicating that there is no apparent change in the location of the modulating region with solar cycle. In this section we consider what the observations discussed in Section III, and other observations, imply about interplanetary conditions out to ~ 30 AU, and we consider some possible models for a modulating region lying at ~ 30 AU. We assume that the average solar wind speed is constant out to at least ~ 30 AU and that the interplanetary magnetic field, on the average, executes the Archimedes spiral pattern. However, all the numbers and parameters calculated below can be adjusted to accomodate a solar wind that, for example, slows down due to charge exchange with neutral interstellar hydrogen (e.g. Semar, 1970) or passes through a shock transition before ~ 30 AU, or to accomodate a field that deviates from the spiral pattern.

Interplanetary conditions out to ~ 30 AU

Many of the sectors into which the interplanetary magnetic field is partitioned have a well-defined field polarity, toward or away from the Sun, and exist with few apparent changes for many solar rotations (Wilcox, 1968; Wilcox and Colburn, 1969, 1970). In some others, the choice of the dominant field polarity can be at times quite subjective. The reappearance of a fixed sector pattern, rotation after rotation, suggests that the random walk of field lines in the photosphere does not generally extend across sector boundaries mixing fields of opposite polarity. (Photospheric turbulence is assumed to be the main cause of the random walk in the inner solar system (Jokipii and Parker, 1969)). Based on observations of the interplanetary magnetic field and of photospheric turbulence, Jokipii and Parker (1969) conclude that field lines, at least within a given sector, will random walk $\sim \pm$ 0.07 AU across the mean field direction in the time it takes the solar wind to propagate from the Sun to earth (~ 4 days). (A random walk of this magnitude is consistent with the perpendicular diffusion coefficient, $K_{\perp} \sim 2 \times 10^{21}\beta$ cm^2/sec., quoted in Section III). This spread will increase as the square root of time, so that for a sector that exists for, say, only two solar rotations the spread at earth is $\sim \pm$ 0.24 AU. If field line random walk were to extend uninhibited across sector boundaires, then between adjacent sectors there should exist a region where the field has no dominant polarity. On using the above spread of $\pm$ 0.24 AU, such a region should take ~ 2 days to be convected pass earth with the solar wind. Contrast this with some of the well-defined sectors where the fields have a uniform polarity, and at the boundaries are observed to change direction by ~ 180° within a few minutes (Wilcox, 1968). Observations of 4-12 MeV electrons also indicate that the random walk is confined to occur within sector boundaries, as can be seen in Figure 6 for the quiet-time increase that occurred in October 1967. Sector structure is indicated at the top of the figure. The sharpness of the drop in the electron intensity at the sector boundaries suggests that there is no tendency for the electrons to diffuse across the boundaries with random walking field lines. Of course, there are some simple ways to confine the random walk due to photospheric turbulence, so that it occurs only within sectors. Some years ago, Davis (1965) noted that within ~ 10-20 solar radii of the Sun the magnetic field energy generally exceeds the solar wind energy. Consequently, the solar wind is expected to originate from the Sun only from those isolated regions, 'magnetic nozzles', where because of its energy or because of the field configuration, it is able to escape. We note here that magnetic field lines random walking in one 'nozzle' will not mix with those random walking in another. If each of the 'nozzles' gives rise to one sector, or part of a sector, then the random walk will not extend across sector boundaries.

The confinement of quiet-time increases to occur in the same sector as their associated low amplitude period, which was discussed in Section III, places a constraint on the mixing that can take place out to ~ 30 AU between fields of adjacent sectors. This mixing, which is due to interplanetary turbulence, is apparently not sufficient to cause electrons propagating in from the modulating region to diffuse out of the sector wherein occurs the large field line random walk that is reponsible for their penetration into the inner solar system. It is difficult to determine, however, whether these observations imply that little random walk of the field lines takes place across sector boundaries, in which case sector structure is essentially preserved out to $\sim$ 30 AU, or whether they imply that the mixing of fields between adjacent sectors is simply not very thorough. The electron gyro-radius is quite small compared with any reasonable scale-length for the turbulent mixing, e.g. the gyro-radius of an $\sim$ 10 MeV electron is $\sim 7\times10^3$km near earth (a field strength $\sim 5\ \gamma$), while the scale-size for interplanetary turbulence could be $\sim 10^6$km, consistent with the correlation length for density fluctuations reported by Intriligator and Wolfe (1970). Mixing on this scale may not bring enough of the fields of two adjacent sectors into sufficiently close contact (presumably within one electron gyro-radius) to allow a significant fraction of the electrons to pass from one sector to another. (The quiet-time increase of 28 August - 6 September 1967, the one notable exception to the rule that increases occur in one sector only, may be an example where the electrons, propagating in from $\sim$ 30 AU, follow random walking field lines across a sector boundary). It is, however, possible to obtain another measure of how well sector structure is preserved out to $\sim$ 30 AU. The observations discussed in Section III indicate that the number of electrons penetrating a modulating region at $\sim$ 30 AU is sensitive to the extent of the field line random walk occurring in the photosphere. Thus, out to $\sim$ 30 AU the random walk due to photospheric turbulence must be the most important random walk, always exceeding the random walk due to interplanetary turbulence. Between the Sun and earth, where the mean field direction is essentially radial, the average linear displacement perpendicular to the mean field direction that photospheric turbulence causes in field lines as they carried outward with the solar wind increases as $r^{3/2}$, where r is heliocentric radial distance. A factor $r^{1/2}$ enters because the displacement increases as the square root of the transit time (or radial distance) of the solar wind out from the Sun, and a factor r because the displacement perpendicular to the mean field will be amplified by the spherically diverging wind. Beyond the orbit of earth, where the mean field direction is essentially azimuthal, the displacement perpendicular to the mean field will increase only as $r^{1/2}$ in the ecliptic plane, while still increasing as $r^{3/2}$ in the polar direction (Parker, 1968; Jokipii and Parker, 1969). Hence, if the average displacement of field lines by the time they reach earth is $\sim$ 0.07 AU (Jokipii and Parker, 1969), then by $\sim$ 30 AU the average displacement in the ecliptic will have increased to $\sim$ 0.38 AU. If the interplanetary medium is turbulent out to $\sim$ 30 AU, the average, total displacement of field lines produced by such turbulence from the Sun to $\sim$ 30 AU must therefore be $\leqslant$ 0.38 AU. At $\sim$ 30 AU, a typical sector width in the ecliptic is $\sim$ 2 AU (some of the sectors containing quiet-time increases are observed for over half a solar rotation (see Figure 3)) so that interplanetary turbulence out to $\sim$ 30 AU does not appear to be sufficient to destroy the general sector pattern. In fact, interplanetary turbulence may actually cause only a small random walk of the field lines. Jokipii and Davis (1969) argue that much of the turbulence present in the inner solar system is the result of the interaction of low velocity streams in the solar wind with long-lived high velocity streams. Supposedly, this turbulence will effectively end at a heliocentric radius of some 5-10 AU to be followed by an essentially non-turbulent region. Consider, for example, that the characteristic velocity of this turbulence is $V_t \sim 50$ km/sec and the scale length if $\ell \sim 10^6$ km (Intriligator and Wolfe, 1970). Then, the displacement of field lines caused by this turbulence will be $\sim (V_t \ \ell \ \Delta \ t)^{\frac{1}{2}}$ = 0.09 AU, where Δ t= 3.75 x 10^6sec is the transit time of the solar wind out to 10 AU at a speed of 400 km/sec. This displacement, which is less than the $\sim$ 0.2 AU displacement due to photospheric turbulence over the same 10 AU distance, will be the total displacement caused by interplanetary turbulence out to $\sim$ 30 AU, and will cause only a minor perturbation on the overall sector pattern.

Possible models for the modulating region

Let us now consider some possible models for a modulating region lying at $\sim$ 30 AU. Suppose that at $\sim$ 30 AU turbulence develops in the solar wind that will cause a significant random walk of the interplanetary field lines, ultimately destroying the sector pattern. It is conceivable that turbulence could develop at $\sim$ 30 AU as the result of the considerable perturbing force that cosmic rays particles may exert on the solar wind. At $\sim$ 30 AU, the energy density due to all cosmic ray particles may be comparable with the wind's kinetic energy density. Using the demodulated spectra obtained by Goldstein et al. (1970a), which allow for modulation in the inner solar system, we find that the energy density in protons and alpha particles with energies $\gtrsim$ 100 MeV/nucleon is $\sim 10^{-12}$ ergs/cm^3. This is roughly 20% of the kinetic energy density of the solar wind at

$\sim$ 30 AU, and roughly 50% at $\sim$ 40 AU, assuming that the wind energy falls off as r^{-2}. Energy loss in the inner solar system prevents us from determining demodulated spectra and hence the energy density below $\sim$ 100 MeV/nucleon based on observations made near earth (Goldstein et al., 1970a; Gleeson and Urch, 1971). Particle spectra could turn up significantly below $\sim$ 100 MeV/nucleon (with no observable effects at earth), in which case the particle and wind energy densities may be comparable at 30-40 AU. Note also that the viscosity of the solar wind may be considerably smaller at $\sim$ 30 AU than it is at earth, making it possible for turbulence to develop in the presence of even small shears in the wind. Suppose that the viscosity of the solar wind varies as $T^{5/2}$ (where T is proton temperature), which assumes that the viscosity behaves according to the simple formula appropriate for fully ionized hydrogen in the absence of magnetic fields (Chapman, 1954; Parker, 1963). If the solar wind is cooled adiabatically beyond the orbit of earth, T will decrease as $r^{-4/3}$ and the viscosity as $r^{-10/3}$. However, the viscosity probably does not decrease this rapidly since the actual mean free path for interactions among solar wind particles may be smaller and vary more slowly with r than the Coulomb interaction length used in deriving the above simple formula. Note also that the Barnes' mechanism (Barnes, 1966), which appears to damp effectively hydromagnetic waves in the inner solar system (Jokipii and Davis, 1969) is probably not operative at $\sim$ 30 AU. In order that the waves are damped, the Barnes' mechanism requires that $\beta \equiv 8 \pi P/B^2 \gtrsim 0.5$, where P is solar wind plasma pressure and B is the intensity of the interplanetary magnetic field. The magnetic energy density, $B^2/8\pi$, decreases as r^{-2} beyond the orbit of earth, while at least in a simple model in which the solar wind cools adiabatically beyond earth, P varies as $r^{-10/3}$. Consequently, β, which is of order unity near earth (Hundhausen, 1970) is only ~ 0.01 at ~ 30 AU. It is also possible that turbulence at ~ 30 AU is associated with a standing shock transition in the solar wind, required, presumably, so that supersonic solar wind can merge with the local interstellar medium. However, most estimates for the location of this shock (e.g. Axford, et al., 1963) place it at distances greater than ~ 30 AU, although a large energy density of cosmic ray particles could conceivably bring it in closer.

As an illustration of some of the effects of significant interplanetary turbulence at ~ 30 AU, consider the following model which we have constructed to agree with the above conclusions about interplanetary conditions out to ~ 30 AU, and to predict the observed intensity increases that occur during quiet-time increases. Suppose that the characteristic velocity of the turbulence, V_t increases linearly with distance beyond 30 AU, i.e. $V_t = w\Delta r$, where w is a constant which we take equal to 20 km/sec/AU, and $\Delta r = r-30$ with r any heliocentric radial distance ≥ 30 AU, in units of AU. Suppose also that the scale-length for the turbulence is $\ell \sim 3\text{x}10^7$km(=0.2 AU), which is the radial projection to 30 AU of the scale-length of $\sim 10^6$km for turbulence seen near earth (Intriligator and Wolfe, 1970). This turbulence will cause interplanetary field lines to random walk about the mean field direction. For a given Δr, the average linear displacement, Δx, of the field lines perpendicular to the mean field direction is given by:

$$\Delta x \sim (\ell\ V_t \Delta t)^{\frac{1}{2}} = 0.1\ \Delta r \text{ (in units of AU)}$$

where Δt is the transit time of the solar wind over the distance Δr at a speed of 400 km/sec. Note that by the time the solar wind has propagated for one solar rotation beyond 30 AU (a distance of $\sim$ 6 AU), the turbulence will have produced a displacement $\Delta x \sim 0.6$ AU that should seriously disrupt the sector pattern. Of ccurse, at some point beyond 30 AU our description of the turbulence can not be valid since V_t can not increase indefinitely ($V_t \propto \Delta r$). The field line random walk due to this interplanetary turbulence (i.t.) will cause cosmic ray particles to diffuse across the mean field direction at a rate determined by a diffusion coefficient $K_\perp(\text{i.t.}) \sim (\Delta x)^2/t'$, where t' is the transit time along the mean magnetic field of the particles, which are assumed to be propagating freely (Parker, 1968; Jokipii and Parker, 1969). At large radial distances from the Sun ($r >> 1$ AU), where the fields are essentially azimuthal,

$$t' \sim \frac{\Omega r \Delta r}{V_{sw} c\beta}$$

where Ω is the angular speed of rotation of the Sun ($\sim 2\pi/24$ days), V_{sw} is the solar wind speed ($\sim$ 400 km/sec), and $c\beta$ is particle speed. Hence $K_\perp(\text{i.t.}) \sim 1.5 \times 10^{20}\ \beta\ \Delta r\ \text{cm}^2/\text{sec}$, where we have set $r = 30$ AU, and, again, Δr is in units of AU. When Δr is small (a distance close to 30 AU), diffusion perpendicular to the mean field due to interplanetary turbulence will be relatively unimportant compared with the diffusion resulting from field line random walk in the photosphere. We saw above that beyond the orbit of earth the linear displacement perpendicular to the mean field direction, due to photospheric turbulence, increases as $r^{1/2}$ in the ecliptic (or any r-$\emptyset$ plane near the ecliptic) and as $r^{3/2}$ in the polar direction. The distance along the mean field, and consequently the transit time of the particles, increases beyond earth as $r^2/2$. Hence, at an average perpendicular diffusion coefficient resulting from photospheric turbulence (p.t.) is $\kappa_\perp$(p.t.) $\sim 2\times10^{21}\ \beta\ cm^2$/sec. near earth (Jokipii and Parker, 1969), then at ~ 30 AU it is $\kappa_\perp$(p.t.) $\sim 1.3\times10^{20}\beta\ cm^2$/sec. in the ecliptic, and $\kappa_\perp$(p.t.) $\sim 1.2\times10^{23}\beta\ cm^2$/sec. for diffusion in the polar direction. The diffusion coefficient in the ecliptic may be larger than this since any interplanetary turbulence will tend to bring some of the random walk of the field lines in the polar direction into the ecliptic plane. We assume here that $\kappa_\perp$(p.t.) in the ecliptic is $\sim 3\times10^{20}\beta\ cm^2$/sec. at ~ 30 AU. With this choice, and our choices for the various other parameters, $\kappa_\perp$(p.t.) in the ecliptic and $\kappa_\perp$(i.t.) are about equal when Δr = 2 AU, which is a typical width, in the ecliptic, for a sector at ~ 30 AU. Note that sectors at ~ 30 AU lie with their boundaries in essentially the azimuthal direction. Consider also that the interplanetary turbulence at ~ 30 AU produces small-scale irregularities in the magnetic field capable of scattering 4-12 MeV electrons to the extent that the electrons are transported across the turbulent region, in the heliocentric radial direction, principally as a result of the field line random walk. A mean free path $\lambda \sim 1$ AU is sufficient for this purpose since particles must propagate along the mean field in essentially the azimuthal direction. With this choice for the mean free path, our assumption that particles propagate freely while following random walking field lines (needed in deriving the various values of $\kappa_\perp$ above) still holds approximately, since $\lambda \sim 1$ AU is much greater than the scale-length for the various random walks (e.g. the scale-length for the random walk due to interplanetary turbulence is ~ 0.2 AU). We have then the following model. For $\Delta r \geqslant 2$ AU, the electrons are transported across the turbulent region principally as a result of the random walk due to interplanetary turbulence. This diffusion will carry the electrons across sector boundaries, in particular, into a sector lying at $\Delta r \leqslant 2$ AU. The electrons diffuse across this sector as a result of the random walk due to photospheric turbulence until they come to where the interplanetary turbulence ceases or equivalently where there is no more scattering along field lines. Then they propagate freely along the fields of the sector, into the inner solar system. Clearly, any variation in $K\perp$(p.t.) will alter the number of electrons entering the inner solar system. With the average value for $K\perp$(p.t.) at ~ 30 AU of 3×10^{20} cm^2/sec., the electron intensity drops across the $\Delta r \sim 2$ AU sector width, in the turbulent region, by a factor $\sim \exp(-V_{sw}\Delta r/K\perp(\mathrm{p.t.})) = 55$ on assuming a simple convection-diffusion modulation and taking $V_{sw} = 400$ km/sec. Doubling $K\perp$(p.t.), which is consistent with observed reduction in the amplitude of the diurnal anisotropy five solar rotations before quiet-time increases (see Section III), will increase the intensity of electrons entering the inner solar system by a factor ~ 7, in agreement with the increase by a factor ~ 5 observed during quiet-time increases.

We can also consider a model for a modulating region lying at ~ 30 AU, in which the field lines of adjacent sectors recombine, forming closed loops. The number of electrons penetrating such a modulating region may be quite sensitive to the extent of the field line random walk, since diffusion by this means may be the only way in which electrons can move between loops. However, in this model we would have to explain why quiet-time increases occur in one sector only, since now the fields of adjacent sectors are connected at ~ 30 AU. We could also consider a model in which some of the fields of adjacent sectors annihilate each other at ~ 30 AU, accelerating lower energy electrons to 4-12 MeV with an accompanying intensity increase that is seen as a quiet-time increase at earth. However, in this model there are some difficulties in accounting for the energy required in quiet-time increases. The energy density of 4-12 MeV electrons during quiet-time increases (calculated from the intensities reported by Simnett, et al. (1971)) is found to be $\sim 3.6\text{x}10^{-16}$ ergs/cm^3. Presumably, this energy density is essentially constant over the volume occupied by the quiet-time increase since we assume that the electrons propagate freely along the fields. Some quiet-time increases are observed for almost one half a solar rotation, so it is not unreasonable to assume that a quiet-time increase can occur over a volume, say, one tenth the volume of the interplanetary medium out to ~ 30 AU, $\sim 3.8\text{x}10^{43}$ cm^3. The energy involved in a quiet-time increase is then $\sim 1.4\text{x}10^{28}$ ergs. The magnetic field energy density at ~ 30 AU, however, is $\sim 10^{-13}$ ergs/cm^3. Consequently, to account for the energy in a quiet-time increase we must completely annihilate the fields at ~ 30 AU over a volume $\sim 1.4\text{x}10^{41}$ cm^3 (= 41(AU)^3), or partially annihilate them over a larger volume. Although large volumes are available, such wholesale annihilation of the fields appears to us unlikely.

The reduction in the intensity of 4-12 MeV electrons in our proposed modulating region may be considerable, so that we observe a substantially lower intensity in the inner solar system than exists in the interstellar medium. For example, in the model with a turbulent modulating region, discussed above, we estimated that the average intensity could be reduced by a factor of ~ 50 in just a region of width ~ 2 AU, around ~ 30 AU. Of course, we have no way of estimating the overall extent of the modulation, since, among other things, we do not know the size of the modulating region. A reduction in the intensity by a factor of ~ 100 or so, however, would not be inconsistent with an interstellar electron spectrum that is a simple extrapolation to lower energies of the power law spectrum which can be calculated above $\sim$ 200 MeV from the observed non-thermal radio noise (Goldstein, et al., 1970b). The spectral index of this interstellar spectrum is $\sim$ 1.8, in good agreement with the observed spectral index for 4-12 MeV galactic electrons of $\sim$ -2 (Simnett, et al., 1971). In our model with a turbulent modulating region, where particles are transported across this region principally as a result of the random walk, the modulation of 4-12 MeV electrons is energy independent ($\beta \simeq 1$), and thus leaves the spectral index unchanged.

We should also consider the possibility that the intensities of other particles, cosmic ray nuclei and higher energy electrons, are reduced in the proposed modulating region at $\sim$ 30 AU. The extent of the modulation will depend in part on how much scattering these particles experience. However, we do not expect to see well-defined increases in the intensities of these particles at times of large field line random walk, the counterparts of quiet-time electron increases. With their larger gyro-radii, protons, for example, will find it easier than 4-12 MeV electrons to diffuse across sector boundaries while propagating in from $\sim$ 30 AU. Also nuclei with energies up to $\sim$ 20 GeV/nucleon and electrons in the range, say, 0.1-20 GeV experience scattering in the inner solar system so that an increase in the intensities of these particles will be reduced and spread over a longer time than a comparable increase in the intensity of 4-12 MeV electrons. It is interesting to note, however, that Simnett, et al., (1971) report that the counting rate of neutron monitors generally increases at times of quiet-time increases.

Further Comments

It should be noted that Parker (1968) was the first to suggest that the random walk of field lines in the photosphere provides a means whereby low energy cosmic rays can gain access to the inner solar system. In Parker's model, the diffusion resulting from this random walk takes place throughout the solar cavity, allowing low energy particles to penetrate from the interstellar medium to the inner solar system irrespective of the smallness of their gyro-radius. However, we have argued in this paper that the random walk due to photospheric turbulence does not generally extend across sector boundaries, the sector pattern existing out to $\sim$ 30 AU. At least as regards 4-12 MeV electrons, then, this random walk will not influence the transport of particles into the inner solar system out to $\sim$ 30 AU, but rather will effect particle entry only in a narrow region around $\sim$ 30 AU. Beyond $\sim$ 30 AU, field line random walk may also be important in particle transport, but then, in for example our model with a turbulent modulating region, the random walk is caused by interplanetary turbulence.

Finally, let us consider the observed anti-correlation between quiet-time increases and increases in the MeV solar proton flux (Simnett, et al., 1971). We have argued in this paper that quiet-time increases occur as a result of conditions that exist on the Sun (a large field line random walk in the photosphere) five solar rotations preceding the observed event. Consequently, these events should occur independently of any variations in the intensity of solar protons in the interplanetary medium, which depends on concurrent solar conditions. However, an increase in the electron intensity is unlikely to occur coincident with a proton increase even if, by chance, concurrence is required by the various conditions that are responsible for these events. An increase in the solar proton flux is generally accompanied by disturbances in the interplanetary magnetic field, or by new field structures being dragged out from the Sun. Electrons propagating in from ~ 30 AU may thus be excluded from connecting onto the field lines where proton increases occur. In Figure 7 we have plotted 3-hour averages of the direction of the interplanetary magnetic field during the large proton increases in late 1967 that occurred near but anti-correlated with quiet-time increases (see Figure 11 in the paper by Simnett, et al., (1971)). As can be seen in this figure, during proton increases the field is disturbed, deviating significantly from the Archimedes spiral angle or exhibiting high variability. With a little imagination, one can also see evidence for loop structures in the field.

V CONCLUDING REMARKS

Although we believe the ideas presented in this paper are plausible and consistent with available data, they are nevertheless quite speculative. It is perhaps useful, then, to suggest future observations that might be performed to confirm or contradict our conclusions. It would be useful to determine, for example, whether the intensity of 4-12 MeV positrons also increases at the time of a quiet-time electron increases. Positrons at these energies should be galactic in origin (Ramaty, et al., 1970), and thus the observation of such an increase would confirm the galactic origin for the electrons in quiet-time increases. It would be useful to measure the radial gradient of the electron intensity during quiet-time increases, since this measurement could also be used to confirm the galactic origin of the electrons, and, in addition, to estimate the extent of the modulation experienced by these particles in the inner solar system. Of course, measurements made from space probes flown into the outer solar system will provide a direct test for our conclusions.

In conclusion, we have proposed in this paper an explanation for quiet-time electron increases that predicts the existence of a modulating region for cosmic ray particles, lying at $\sim$ 30 AU from the Sun.

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TABLE 1. Evidence of a correlation between the occurrence of periods of low amplitude diurnal anisotropy and of quiet-time electron increases.

Times of quiet-time electron increases	Associated low amplitude periods	Amplitudes < 0.3% / Reliable amplitudes	Reliable Amplitudes / Total possible amplitudes
10-23 October 1967	31 May-9 June 1967	71 (%)	70(%)
6-16 November 1967	26 June-7 July 1967	100	30
5-12 December 1967	23 July-3 Aug. 1967	100	54
19-25 January 1968	30 Aug.-4 Sept. 1967	83	100
13-18 February 1968	28 Sept.-3 Oct. 1967	91	91
28 Feb.-5 March 1968	10-17 October 1967	71	87
26 March-2 April 1968	10-20 November 1967	73	68

Figure 7. A plot of 3-hour averages of the direction of the interplanetary magnetic field during the large increases in the low energy solar proton intensity in late 1967. The arrows indicate the direction of the field in the ecliptic, with V marking 3-hour periods when the field was too variable to be averaged meaningfully. Magnetic fields directed more than 30° out of ecliptic are also indicated.

FIGURE CAPTIONS

Figure 1. Plot of the daily averages of the 4-12 MeV interplanetary electron intensity from 1965 through 1968 (after Simnett, et al., 1971). Solar flares are dencted by dark boxes, and quiet-time increases by brackets.

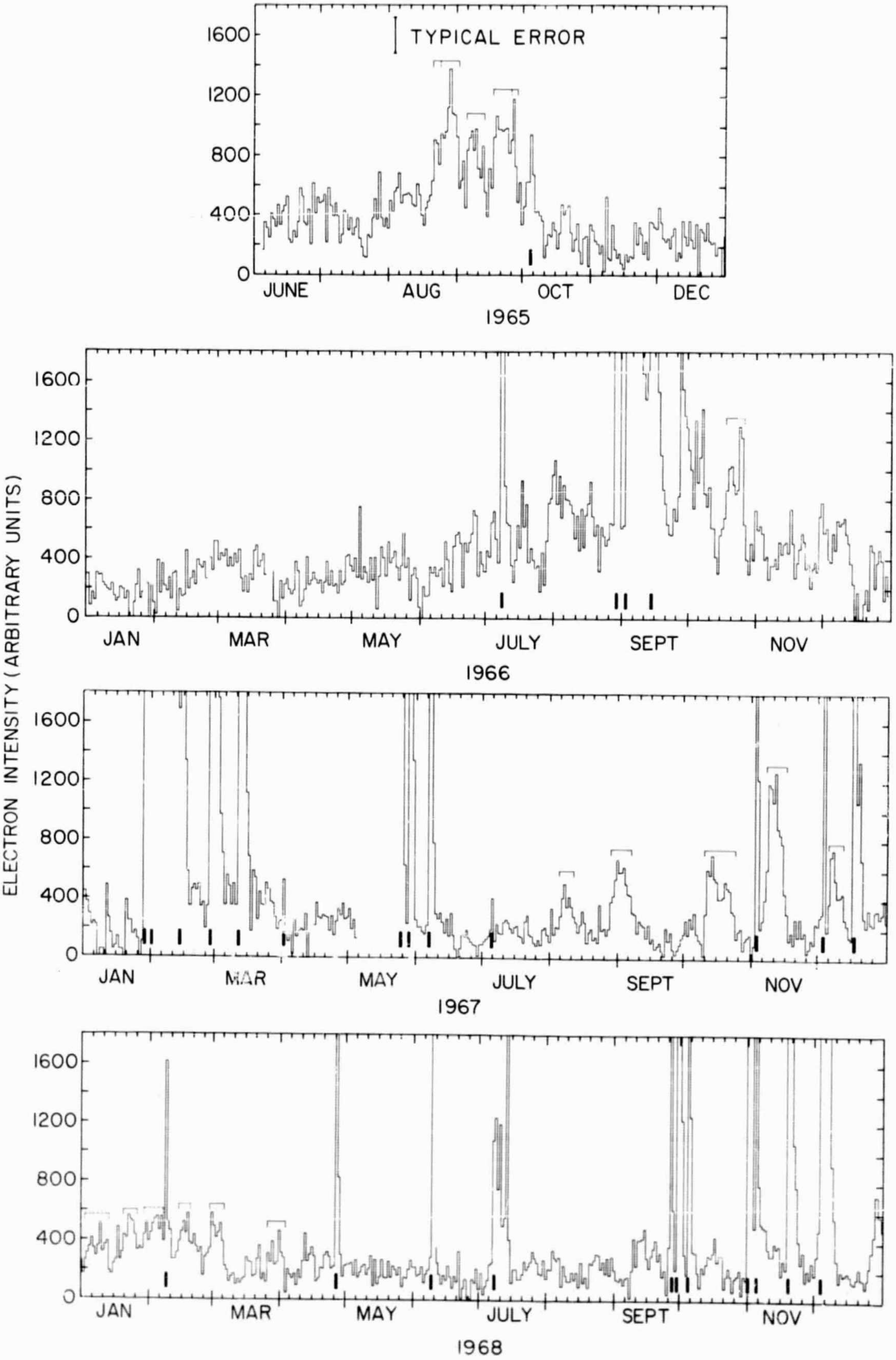
Figure 2. Time profiles of the intensity of 4-12 MeV electrons and various energy protons, following the flare of 7 July 1966 (after Cline and McDonald, 1968). The particles were assumed to be accelerated in this flare coincident with the maximum emission of energetic x-rays.

Figure 3. Plot of the amplitudes of the diurnal anisotropy that are a reliable measure of the random walk (plotted in %), interplanetary sector structure, and times of quiet-time increases for the period January 1967 through April 1968. The plot is divided into Bartels solar rotation periods of 27 days. Light shading indicates a sector with fields directed predominantly away from the Sun; dark shading, predominantly toward the Sun. Magnetic field data is unavailable during unshaded periods (Fairfield, private communication). The brackets marking quiet-time increases are identical to those shown in Figure 1.

Figure 4. Same as Figure 3 for the period March through December 1966.

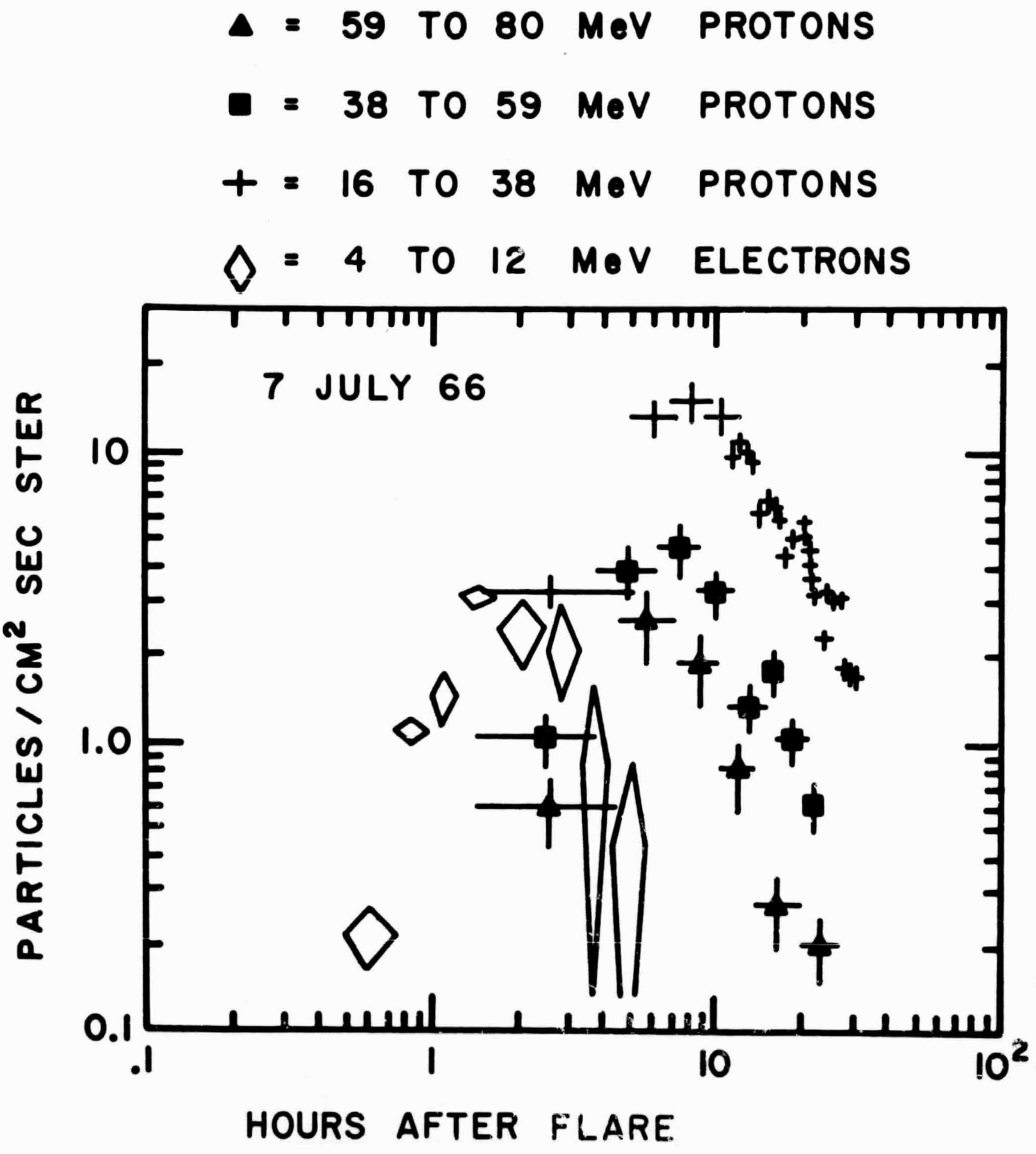
Figure 5. Same as Figure 3 for the period February through March 1965. Magnetic field data, in this case, is from Wilcox and Colburn, (1969).

Figure 6. Plot of the intensity of 4-12 MeV electrons and the sector structure during the quiet-time increase of 10-24 October 1967. The sector structure is indicated at the top of the figure. Light-shading denotes fields directed predominantly away from the Sun, dark-shading predominantly toward the Sun.



TYPICAL ERROR
1600
1200
800
400
0
JUNE
AUG
OCT
DEC
1965
ELECTRON INTENSITY (ARBITRARY UNITS)
JAN
MAR
MAY
JULY
SEPT
NOV
1966
1967
1968

FIGURE 1



▲ = 59 TO 80 MeV PROTONS
■ = 38 TO 59 MeV PROTONS
+ = 16 TO 38 MeV PROTONS
◇ = 4 TO 12 MeV ELECTRONS
7 JULY 66
PARTICLES / CM² SEC STER
10
1.0
0.1
.1
1
10
10²
HOURS AFTER FLARE

FIGURE 2

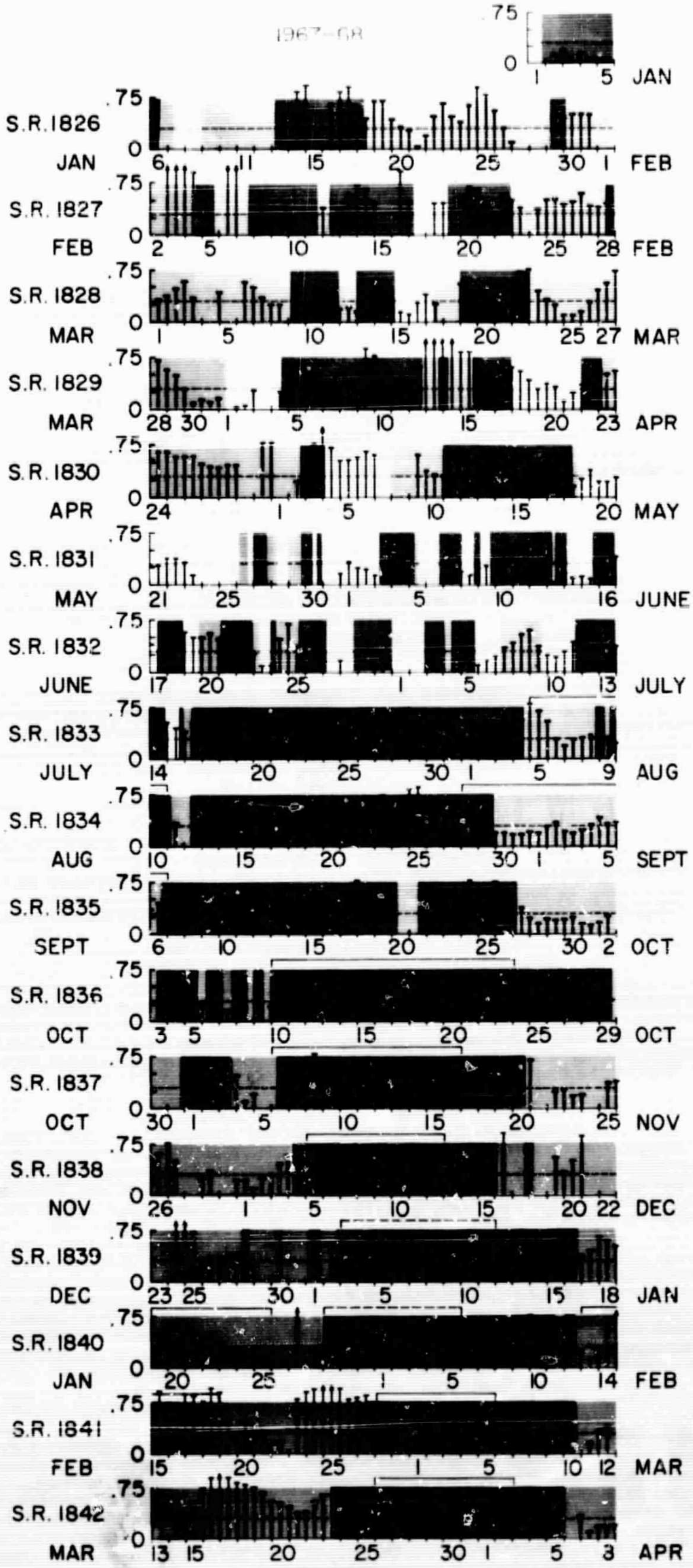

S.R. 1826
S.R. 1827
S.R. 1828
S.R. 1829
S.R. 1830
S.R. 1831
S.R. 1832
S.R. 1833
S.R. 1834
S.R. 1835
S.R. 1836
S.R. 1837
S.R. 1838
S.R. 1839
S.R. 1840
S.R. 1841
S.R. 1842
JAN
FEB
MAR
APR
MAY
JUNE
JULY
AUG
SEPT
OCT
NOV
DEC
.75
0

FIGURE 3

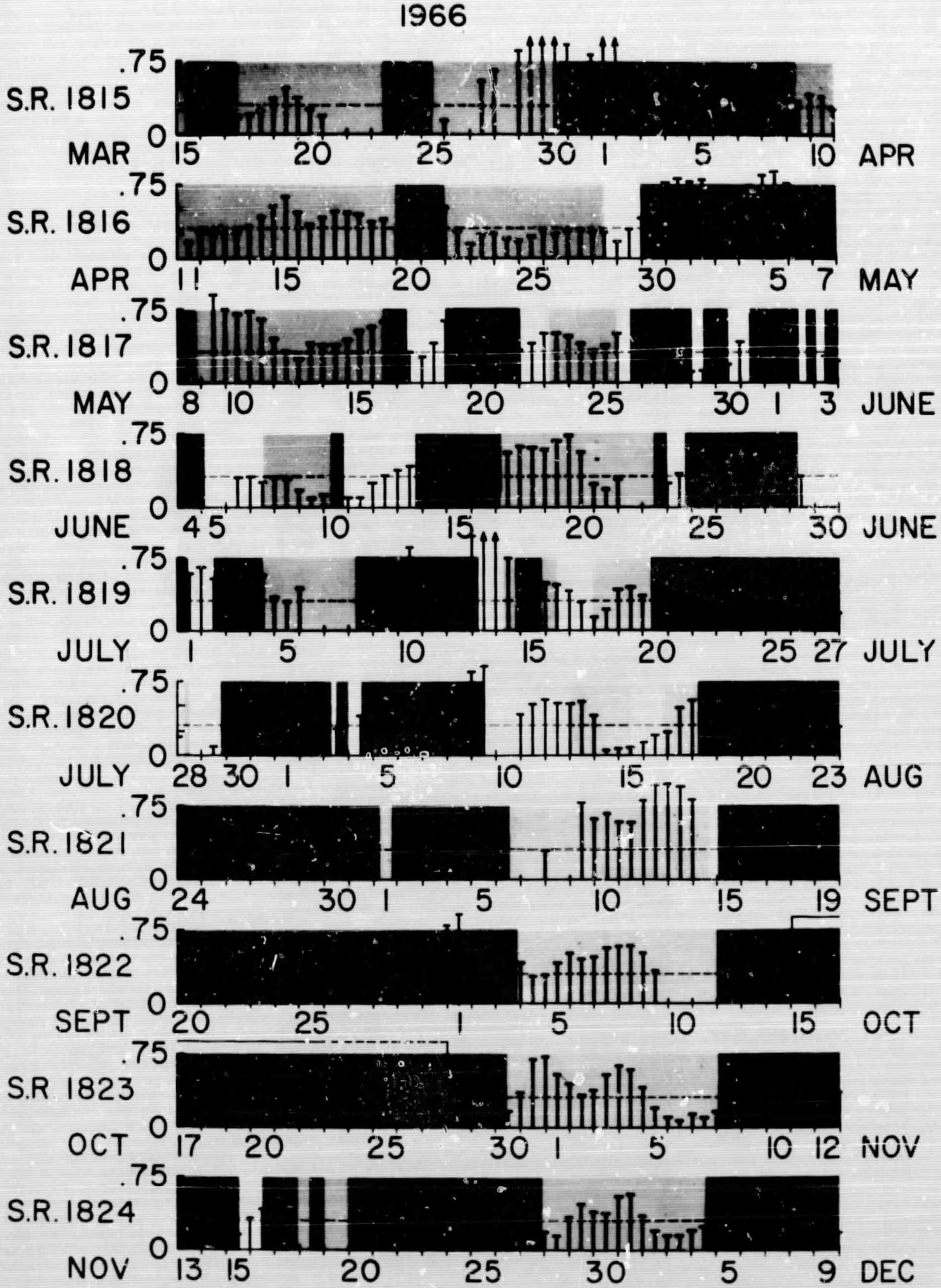
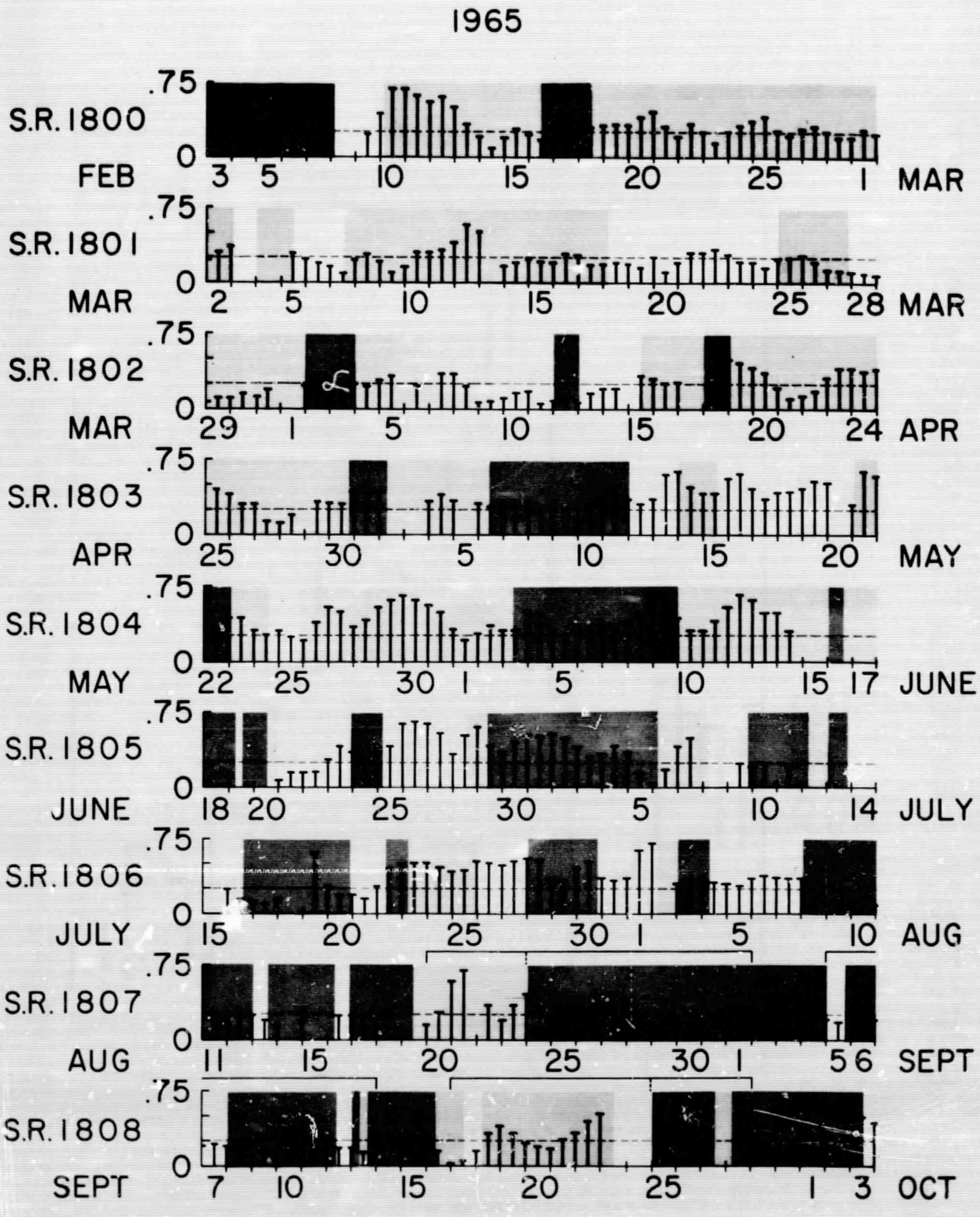

1966
S.R. 1815
.75
0
MAR 15 20 25 30 1 5 10 APR
S.R. 1816
.75
0
APR 11 15 20 25 30 5 7 MAY
S.R. 1817
.75
0
MAY 8 10 15 20 25 30 1 3 JUNE
S.R. 1818
.75
0
JUNE 4 5 10 15 20 25 30 JUNE
S.R. 1819
.75
0
JULY 1 5 10 15 20 25 27 JULY
S.R. 1820
.75
0
JULY 28 30 1 5 10 15 20 23 AUG
S.R. 1821
.75
0
AUG 24 30 1 5 10 15 19 SEPT
S.R. 1822
.75
0
SEPT 20 25 1 5 10 15 OCT
S.R 1823
.75
0
OCT 17 20 25 30 1 5 10 12 NOV
S.R. 1824
.75
0
NOV 13 15 20 25 30 5 9 DEC

FIGURE 4



1965
S.R. 1800
.75
0
FEB
3 5 10 15 20 25 1
MAR
S.R. 1801
MAR
2 5 10 15 20 25 28
MAR
S.R. 1802
MAR
29 1 5 10 15 20 24
APR
S.R. 1803
APR
25 30 5 10 15 20
MAY
S.R. 1804
MAY
22 25 30 1 5 10 15 17
JUNE
S.R. 1805
JUNE
18 20 25 30 5 10 14
JULY
S.R. 1806
JULY
15 20 25 30 1 5 10
AUG
S.R. 1807
AUG
11 15 20 25 30 1 5 6
SEPT
S.R. 1808
SEPT
7 10 15 20 25 1 3
OCT

FIGURE 5

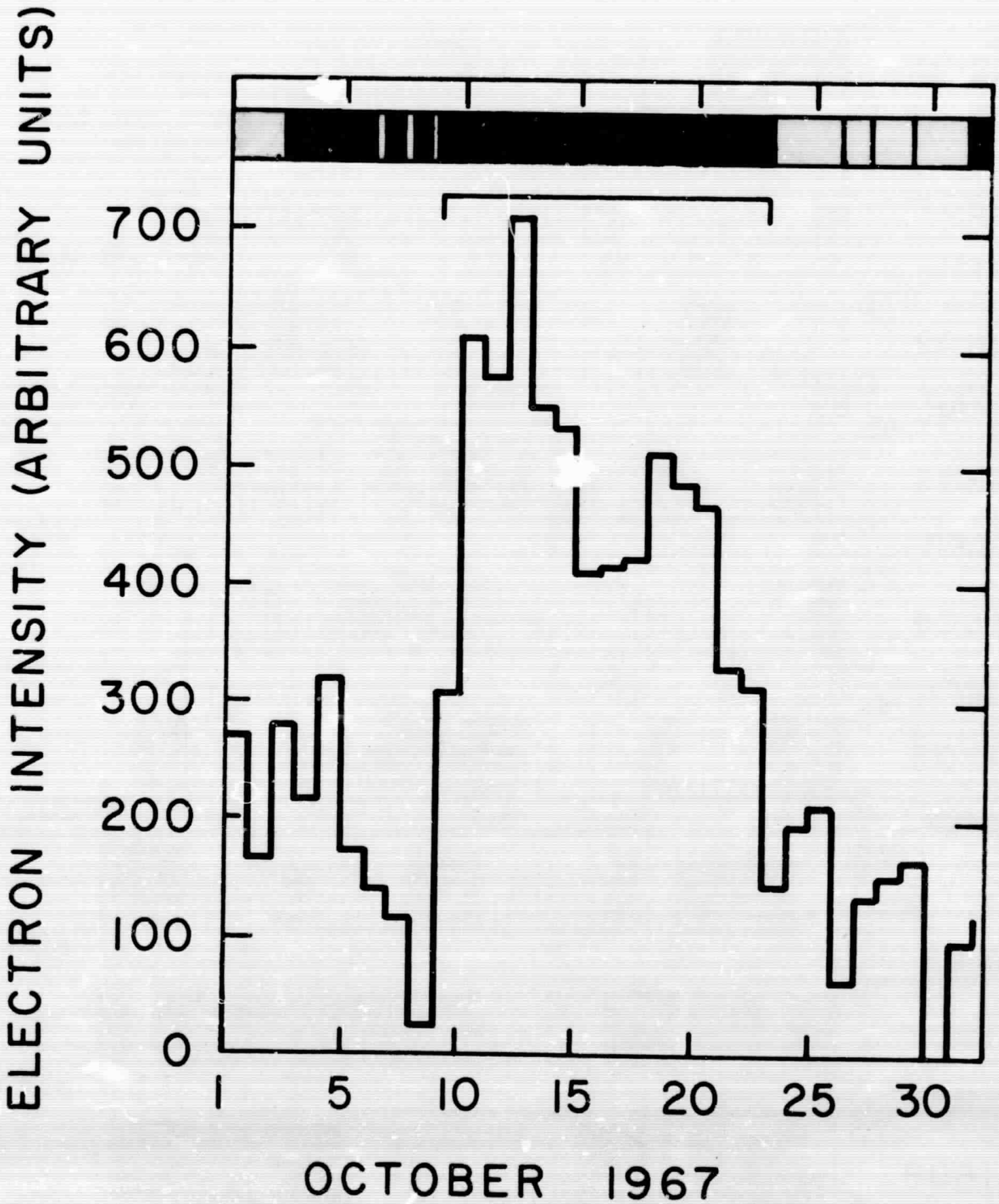

ELECTRON INTENSITY (ARBITRARY UNITS)
700
600
500
400
300
200
100
0
1
5
10
15
20
25
30
OCTOBER 1967

FIGURE 6

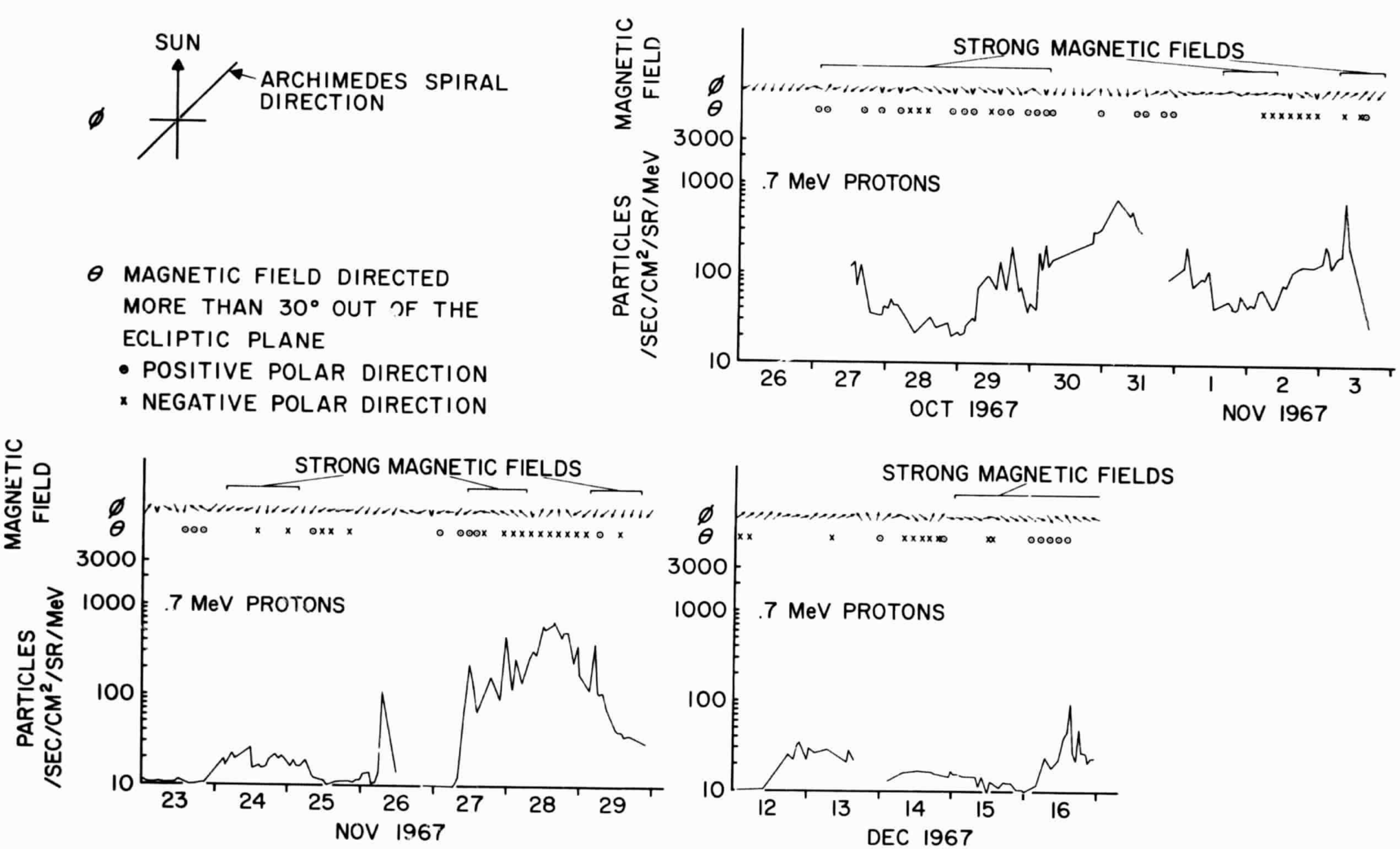

SUN
ARCHIMEDES SPIRAL DIRECTION
Ø
θ MAGNETIC FIELD DIRECTED MORE THAN 30° OUT OF THE ECLIPTIC PLANE
• POSITIVE POLAR DIRECTION
x NEGATIVE POLAR DIRECTION
MAGNETIC FIELD
STRONG MAGNETIC FIELDS
Ø
θ
3000
1000
100
10
.7 MeV PROTONS
PARTICLES /SEC/CM²/SR/MeV
26 27 28 29 30 31 1 2 3
OCT 1967
NOV 1967
MAGNETIC FIELD
STRONG MAGNETIC FIELDS
Ø
θ
3000
1000
100
10
.7 MeV PROTONS
PARTICLES /SEC/CM²/SR/MeV
23 24 25 26 27 28 29
NOV 1967
STRONG MAGNETIC FIELDS
Ø
θ
3000
1000
100
10
.7 MeV PROTONS
12 13 14 15 16
DEC 1967

FIGURE 7