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FRANK B. McDONALD
THOMAS L. CLINE
GEORGE M. SIMNETT

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GODDARD SPACE FLIGHT CENTER
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THE MULTIFARIOUS TEMPORAL VARIATIONS OF
LOW-ENERGY, RELATIVISTIC COSMIC-RAY ELECTRONS

F. B. McDonald and T. L. Cline
NASA-Goddard Space Flight Center
Greenbelt, Maryland 20771

G. M. Simnett
University of California
Riverside, California 92502

ABSTRACT

A detailed examination is made of the intensity variations of 3 - 12 meV interplanetary electrons. The data used are from the Goddard Cosmic Ray experiment flown on the IMP series of satellites and cover the period from just prior to the last solar minimum through to the onset of the present solar maximum (i.e., from December 1963 through August 1969). A morphology for the intensity changes is tentatively proposed which includes solar flare-associated events, solar co-rotating increases, Forbush decreases, and quiet-time increases, as well as the long term eleven-year variation. It is contended that the electron component observed both during quiescent times and during quiet-time increases are galactic in origin. The quiet-time increases represent a completely new phenomenon that appears to be unique to the low energy electron population. During a quiet-time increase the electron intensity is enhanced by a factor of 3 to 5 over a period of days, and, in general, these periods anti-correlate with low-energy solar particle events. Qualitatively, their amplitude diminishes with increasing solar activity. One possible explanation for the origin of quiet-time increases, which involves the augmented penetration of galactic electrons into the inner solar system, is suggested in the accompanying paper by Fisk and Van Hollebeke (1971). Because of the large short-term changes, the 11-year modulation of these low energy galactic electrons is not well defined. An upper limit of a factor of 2.3 is placed on the intensity change observed from solar minimum to solar maximum.

INTRODUCTION

The study of the low energy galactic cosmic-ray electron component is of fundamental importance in terms of the information it might yield on the origin and the transport of cosmic rays within the galaxy. At the present time, even with sophisticated detectors operating beyond the magnetosphere, it is possible to make observations only within the solar system, where solar activity both modulates the galactic electron intensity and provides a sporadic source of solar electrons. Therefore, it is not feasible to separate the galactic and solar components with limited observations. However, a detailed study of the temporal intensity variations over a major fraction of a solar cycle may not only provide a means of separating these components, but may also yield new information on the modulation of electrons in the MeV energy region. We present here the results of such an analysis of 3-12 MeV electrons from 1963 to 1969.

To place the low energy data in perspective, it is instructive to examine the nucleon and electron data over a large energy interval (Fig. 1). As previously observed by Pal (1970), the two spectra are surprisingly similar in broad detail. The proton energy spectrum passes from a power law of $E^{-2.65}$ at high energies through an extended maximum around 300 MeV. It exhibits a minimum at lower energies and eventually rises sharply at energies below 20 MeV. The electron spectrum changes from a power law of $\sim E^{-2.5}$ through a broad plateau region below 1 GeV and then increases rapidly below ~ 60 MeV. Using the non-thermal radio emission to deduce the interstellar electron spectra, and the complete diffusion-convection energy loss theory of

solar modulation, Goldstein, et al. (1970) find that the observations are consistent with power law spectra in the interstellar region down to energies of ~ 200 MeV. Thus, the structure observed in both the electron and proton spectra between ~ 200 MeV and 1 GeV is apparently produced by the modulation process.

However, the increases observed at low energies in both spectra cannot be explained in such a straightforward manner. The low energy turn-up in the proton spectrum (Fig. 1) was first observed by Fan et al. (1968a). Kinsey (1970), using the data from the Goddard Space Flight Center experiments on IMP 4, showed on the basis of 4-day averages that this turn-up was always present from June 1967 to May 1969, and that the solar contribution to the proton intensity was dominant in the 1 - 10 MeV region. However, the data to be presented here suggest that the electron intensity enhancement during undisturbed times has an origin quite different from the proton increases. We base this on a detailed examination of the temporal variations of the 3-12 MeV electron component. It is possible to group most of the changes into five categories.

(1) Flare-associated solar electron events: In general, these display the same characteristics as the accompanying solar protons, which include a diffusive particle propagation and association of the intensity increases with x-ray flares and microwave radio emission.

(2) Co-rotating solar electron increases: While these are an important feature of the MeV proton and keV electron component, they appear to occur infrequently in the MeV electron region.

(3) Forbush decreases: These are generally similar to those observed with high-latitude neutron monitors, except that the recovery phase for electrons has a different time profile.

(4) Quiet-Time Increases: These represent a new phenomenon and are unique to the electron population above 1 MeV. They last for periods from a few days to two weeks and can display a 27-day recurrence. At times the electron intensity may increase by as much as a factor of 5 above the minimum quiescent level at 1 A.U.. Qualitatively, the energy spectra of the increases above background are similar to that determined for the galactic component ($\sim E^{-2}$). These events are strikingly anti-correlated with low energy (< 10 MeV) proton events. It appears most probable that these increases are of galactic origin.

(5) The long-term modulation of low energy electrons: There appears to be a gradual change of the genuinely quiet-time electron intensity during the years of changing solar activity. However, the large short-term intensity variations make accurate measurements of the 11-year modulation particularly difficult.

The tentative classification scheme proposed above implies the existence of two solar components of the 3 - 12 MeV electrons observed at 1 A.U.: direct solar flare production and co-rotating solar electron streams. However, the quiet-time increases, the Forbush decreases and the 11-year modulation all imply that the galactic component probably dominates most of the time. Those electrons of galactic origin cannot necessarily be identified as to their mode of production, but are expected to be both interstellar "secondaries", i.e., beta-decay

electrons from excited nuclei, knock-on electrons, and meson-decay electrons from pion production; and cosmic-ray "primaries", i.e., those electrons which are accelerated with the nucleonic component of cosmic rays.

Experimental Technique

Observations of the interplanetary electron intensity in the energy range from 3 to 12 MeV have been made with identical detectors (Fig. 2) on board the eccentric earth-orbiting satellites IMP's - 1, 3, 4, and 5 for the following periods:

IMP - 1	November 27, 1963 - May 5, 1964
IMP - 3	May 30, 1965 - May 4, 1967
IMP - 4	May 24, 1967 - March, 1969
IMP - 5	June 21, 1969 - September 24, 1969

The apogees of these four satellites were 193,000 km, 250,000 km, 216,000 km and 182,000 km respectively. Data from IMP -1 and IMP -3 were excluded from our analysis for altitudes below 125,000 km, and data from IMP -4 and IMP -5 were excluded for altitudes below 100,000 km. The data retained are, therefore, not contaminated with electrons trapped in the earth's radiation belts.

The response of this instrument to electrons has been discussed in detail by Simnett and McDonald (1969). During non-flare times it is necessary to average over 24 hour periods to obtain statistically significant data. The techniques used here in compiling daily averages, applying the appropriate background corrections and intercomparing the electron data between the four satellites are discussed in Appendix A. In Fig. 3 a plot is shown of the electron counting rate in the

energy interval 3-12 MeV over the period covered by this analysis.

Background corrections have been applied to this data.

It is evident from Fig. 3 that the 3-12 MeV electron component shows many types of variations. The identification of a specific feature as an electron increase is somewhat subjective. It is not practical to select an intensity level and call all excursions above this "increases," as there will be times of low background when very distinct features may not qualify, and times of high background when every statistical fluctuation would be classed as an increase. Therefore, from practical necessity, some account must be taken of the contemporary electron background when assigning an increase to a specific time period. In addition, there are some intensity changes which alone would not be noteworthy, but become strikingly obvious when considered as part of a series of 27-day recurrent features. As a qualitative guide, a single increase should be around a factor of 2 above the contemporary background level to be considered as an event. Also, we have tended to exclude fluctuations lasting less than two or three consecutive days. Consequently a different observer may wish to include some additional quiet-time events. However, we feel that we have selected the majority of non-flare events, although we recognize the possibility of omissions.

Interpretation of Results

A tentative morphology for these events was outlined in the introductory section. Four types of short term (≤ 27 days) increases are defined, two of which are solar in origin: flare-associated increases and co-rotating events. The other two, Forbush decreases and quiet-time

increases, as well as the long term 11-year variation, appear to be modulations of a galactic component. In the following sections we seek to justify in detail this classification scheme.

Flare Associated Events

The sun is known to be a frequent source of electrons of energies ≥ 1 MeV. The existence of energetic solar electrons was first invoked by Boischot and Denisse (1957) to explain the enhanced continuum radio emission following some large solar flares. Relativistic solar electrons were first observed at balloon altitudes by Meyer and Vogt (1962) late in one of the July, 1962 events. However, it was not until the 7 July 1966 event (Cline and McDonald, 1968) that a complete time-history of the interplanetary MeV electron component was obtained.

These studies have been extended to higher energies by Koechlin et al. (1969) and Datlowe et al. (1969). Simnett (1971) has also given a complete description of the IMP -4 events.

These flare associated events generally display the following characteristics:

1. The event begins with an optical flare near a complex spot configuration in a large center of activity. There are simultaneous microwave and x-ray bursts followed by a long lived type-IV continuum. The correlation of flare-associated particle events with this sequence of developments on the sun is so strong that it is assumed impulsive events not associated with significant solar activity must occur on the non-visible portion of the sun.

2. In almost every case the flare-associated electrons are accompanied by a nuclear component extending above ~ 10 MeV.

3. As is seen in Fig. 4, the rise to maximum intensity requires typically 10 times the transit time. Velocity dispersion is generally observed in the arrival times of particles with different energies. The decay time is generally an order of magnitude greater than the rise time. The time histories are completely different from those observed for co-rotating events.

4. In the 3-12 MeV range, Simnett (1971) has found that the energy spectrum of the flare electrons is of the form E^{-3} and appears in most cases to be a constant of the flare process.

The data in Fig. 4 for the 7 July 1966 event illustrate a typical time history for an electron event. This "classical" event clearly fits the characteristics previously listed. The IMP 3 and IMP 4 flare-associated events have been discussed in detail by Cline and McDonald (1968b) and Simnett (1971) and the 7 July 1966 event is included here to illustrate the characteristic properties. From May 1967 to May 1969, a period of moderately high solar activity, some 26 flare-associated events (Simnett 1971) account for most of the intensity increases. During the 1964-65 solar minimum period there were only three observed solar electron events and the quiet-time increases are dominant.

Co-Rotating Solar Electron Events

Low energy co-rotating electron and proton streams are one of the dominant features of solar energetic particle emissions (Bryant et al., 1965; Fan et al., 1966; Fan et al., 1968b; Anderson, 1968; McDonald, 1971; Lin and Anderson, 1967). The term "co-rotating event" is employed as a generic description covering what various authors have called recurrent, delayed,

plage-associated and core-halo events. All of these imply a long-lived solar source. The characteristics of these events are markedly different from those of flare-associated increases. The co-rotating events may extend over a fourteen day period. They have steep energy spectra and display no velocity dispersion in the onset phase. Both the rise and decay times can be quite large (> 24 hours). The occurrence of MeV electrons in co-rotating events appears to be a relatively rare phenomenon; there are only some 4 occasions when this was observed during the 1964-1968 period. Co-rotating events differ from the quiet-time increases described later in that their electron energy spectra are steeper and they are accompanied by low energy protons as well as geomagnetic disturbances and frequently coincide with Forbush decreases.

The flare associated event of 7 July 1966 occurred in active region MP 8362 which had a central meridian passage of 3.4 July, 1966. This region returned as MP 8413 with a CMP on 31.9 July 1966. On 30 July there was an increase in the 3-12 MeV electron component as well as in protons > 18 MeV. In addition, the data of Anderson (1969) show a large increase in protons > 0.5 MeV and electrons > 0.045 . The time profile for all four components is quite different from that observed in the flare-associated events (Fig. 5). The appearance of the recurrence events just prior to the CMP of the active region in which the previous flare had occurred is similar to that previously reported for low energy co-rotating proton events by McDonald and Desai (1971). It is not known when the 3-12 MeV electrons of 30 July were accelerated, although it is doubtful that they could have been stored at the sun since the flare of 7 July 1966. It is interesting to note that there was a

class-2b flare in this region at 33°E on 28 July with strong X-ray and type-IV radio emission. This did not produce a prompt flare-associated event but could have enhanced the co-rotating particle stream.

The flare-associated event of 14 September 1966 at 90°W also produced possible recurrence events centered on the CMP of MP 8484 on 4.1 October 1966. There is also a small increase in early November. Both of these show a positive correlation with MeV protons. The solar association is somewhat puzzling since MP 8484 was a small, quite insignificant region during its October and November transit.

There are two additional co-rotating events, in October 1966 and November 1967. These occur adjacent to quiet-time increases and are discussed in a later section.

Forbush Decreases

We have examined the behavior of the 3-12 MeV electron component at times of large Forbush decreases that did not coincide with energetic solar electron events. As time progresses toward solar maximum the rate of occurrence of such Forbush decreases diminishes. Six events from IMP -3 and six events from IMP -4, which coincide with decreases in the Deep River neutron monitor rate of 3% and 2% respectively, are shown in Figure 6. Each set of six events is super-imposed on a daily basis, together with corresponding superimpositions of the neutron monitor results; the data were aligned at the commencement of the decreases in the neutron monitor rates. Eight quiet periods were selected at random for comparison, and superpositions of the electron and neutron monitor data and the coefficients resulting from cross-correlation analyses are also shown in the figure. There is no doubt that the electron density

is suppressed at the time of a large Forbush decrease. It is also apparent that the electron rate recovers faster than the neutron monitor rate at first, and further, that the recoveries of the 1966 decreases, at least, are followed by a second phase characterized by a very slow (2 month) post-recovery increase. Almost zero correlation is found for the quiet periods. The data used for all these analyses were taken during time periods which did not include solar particle events. It may be contended that Forbush decreases could occur regardless of the origin of the genuine quiet-time background interplanetary electrons, since the rapid decay of flare events does not appear to support the hypothesis that such particles might be stored for long periods in the interplanetary region. However, we contend that the positive correlation of the electron intensities with the neutron monitor rate during Forbush decreases indicates a galactic origin for the background electron intensity.

Quiet-Time Increases

The flare-associated and recurrence electron increases as well as the Forbush decreases represent extensions of previously known particle phenomena. However there are some 18-19 increases occurring during the approximately four-year observing period that appear to represent a new and completely unique phenomenon. These tend to occur during relatively undisturbed times, so we have labeled them "quiet-time increases".

They have the following properties:

- (1) They represent a factor of 2 - 5 increase in the 3-12 MeV electron intensity and last from 5 to 14 days. The time history is symmetrical and markedly different from that displayed by flare-associated events.

(2) The energy spectra of the increases in general are of the form $\sim E^{-2}$, which is close to the $E^{-1.75}$ obtained when the electron intensity was relatively constant over a period of several months. As will be discussed later, it is felt that the spectral measurements during these quiet different periods are very similar.

(3) There is a remarkable anti-correlation with low energy co-rotating proton events.

(4) The increases tend to occur during periods of rising neutron monitor counting rates.

(5) The data suggest there is a moderate dependence on solar activity and that the intensity as well as the number of events decreases with increasing solar activity.

(6) In general the increases are contained within a single inter-planetary magnetic section.

(7) The increases frequently occur in groups of three or more and sometimes display a 27 day-periodicity.

To confirm these properties and to determine the origin of these increases, we examine in detail the individual events and some of their correlations with other phenomena.

The first series of quiet-time increases was observed with IMP-1 in early 1964. Fig. 7 shows the electron data, the Deep River neutron monitor rates and the University of Chicago low energy proton data for this period. There are four electron increases at 27 ± 1 day intervals which are completely out of phase with the proton events. A superposition of the four quiet time increases along with the superimposed sector data (Wilcox and Ness 1965) and neutron monitor data indicates

the events last for some 6 - 9 days and peak near a sector boundary (Fig. 8).

The next series consists of three well defined events extending from mid-August through late September, 1965 (Fig. 9). Two of the events are spaced 27 days apart and the third is interspersed between them. Three low energy proton events were observed during this period by the University of Chicago IMP-3 cosmic ray detectors, on 16 August, 3 September, and 30 September 1965 (O'Gallagher and Simpson 1966). There was small flare-associated event on October 4, 1965. The co-rotating proton events are indicated by cross-hatched areas on Fig. 9 along with the Deep River neutron monitor data. Again, the anti-correlation between quiet-time electron events and the low energy proton increases is most striking.

The IMP 4 data was of greater statistical accuracy (by a factor of 2.5) than that of IMP 1 and 3 and this may partially explain why some nine quiet-time increases were detected between August 1967 and March 1968. These events, which are the most striking of all the quiet-time increases, are shown in Fig. 10.

The first two events are centered on 6 August and 2 September 1967 and are spaced approximately 27 days apart. The next event is centered on 16 October 1967 and lasts for some 12 days. From 5 to 16 November 1967 there is a fourth event. There was a moderate flare-associated event on 2 November but the electron intensity had returned to background by 4 November. This quiet-time event occurs some 24 days after the October increase. As in the other events in this series, the electron peak occurs at a minimum in the flux of low energy protons. However, there is a significant overlap between the declining phase of the

quiet-time electron increase and a low energy proton event, which will be discussed in a later paragraph. There was also a flare-associated event early in December followed by a well defined quiet-time increase. There are four small events during the first three months of 1968 which are also indicated in Fig. 10. There are two additional increases in early 1968 (January 3-11 and January 28-February 5) which are just above our threshold for defining quiet-time increases.

The electron, low energy proton, and Deep River neutron rates, and interplanetary sector structure from 1 June 1967 to 1 June 1968 are plotted in Fig. 10. The centroids for each of the nine quiet-time increases are indicated by arrows projecting into the low energy proton and Deep River neutron monitor data. In almost every case the centroid of the quiet-time increase coincides with a minimum in the MeV proton distribution.

The five quiet-time increases between August and November have been normalized in amplitude at the time of maximum and then superimposed. This procedure gives the average profile for the series, shown in Fig. 11, and insures that no one increase will be dominant. The neutron monitor data, superimposed without normalization, show an essentially monotonic increase throughout the electron increase, followed by decreases 8-9 days after the electron maximum. However, the form of the electron and neutron monitor increases is quite different. It is felt that the situation is more complex than a simple change in the modulation parameters.

Because of the improved statistical quality of the IMP-4 data it was possible to determine accurately the energy spectra of the larger quiet-time increases during 1967 by summing over the complete event.

The energy spectra for the 28 August to 6 September, 10-23 October, and 6-14 November 1967 periods are shown in Fig. 12. Above 4 MeV all four spectra are in strong agreement with a power law of E^{-2} . This is slightly steeper than the $E^{-1.75}$ reported by Simnett and McDonald (1969) for periods when the electron flux is relatively stable over a period of several months. However, their data covered the range 3-22 MeV. When examined in detail one observes a slight break at ~ 10 MeV, with the data from 3-10 MeV being closer to E^{-2} , and the $E^{-1.75}$ results fitting a single power law to the entire range. By contrast, the energy spectra of solar flare electrons are generally of the form E^{-3} (Simnett 1971; Datlowe 1971). It is expected that the co-rotating streams containing energetic electrons will display even steeper energy spectra.

The November, 1967 event shows a strong enhancement at lower energies and is inconsistent with an E^{-2} spectrum below 4 MeV. This appears to be due to the close overlap between the quiet-time increase and a solar co-rotating event which reached a maximum on 13 November 1967. Fig. 13 presents a comparison of the 3-12 MeV electrons with 0.3-0.9 MeV electrons, and it shows that their time histories are almost completely unrelated.

The turn-up in the spectrum is more distinctive in the 10-14 November period, as would be expected from the low energy data. Also shown for comparison is the 1 MeV proton component which tracked the lower energy electrons. It is interesting to note that even when the quiet-time electron event is distorted by a co-rotating solar particle event, the peak in the quiet-time increase occurs when the low energy proton intensity is at a minimum on 8 November.

There are two additional periods - October, 1966 and December, 1968 - February 1969 - in which quiet-time increases may have occurred. The electron increase occurring from 15 October to 27 October, 1966 appears to be essentially identical to the November 1967 event discussed in the preceding paragraph. On 19-20 October, a maximum in the electron data occurs during a minimum in the low energy proton data. Some 5 days later, on 24 October there is a larger electron peak that coincides with an increase in the flux of low energy protons as well as a large Forbush decrease. The second period of interest is the interval from late December, 1968 - February, 1969 (Fig. 14). There is a small flare associated event on December 27. This is followed by an electron increase extending from 7 - 15 January. The electron energy spectra for this event (Fig. 15) is of the E^{-2} form, consistent with labeling this as a quiet-time increase. Starting on 5 February there is a small but steady increase, with some superimposed structure, that builds up to the large event of 25 February 1969. The energy spectrum and the fact that it follows some 27 days after the January event, suggest that the 7 February 1969 peak is a quiet-time increase, although the intensity is below our identification threshold, as are those for the small peaks on 14 and 20 February. The spectral data suggest that the small intensity increase may be mostly of solar origin. However, this increase above 3 MeV is less than 200 electrons $(m^2 \text{sec-sr-MeV})^{-1}$, and the spectral data are not conclusive. The Bell Telephone Lab. IMP-4 data of L. Lanzerotti (Private communication, 1971) and the Deep River neutron monitor rates for this period are also shown in Fig. 14. The anti-correlation between the quiet-time increases and the low energy protons is not well defined

in this period. This is partially due to a low energy event occurring in the middle of the January electron increase. The correlation with increasing neutron monitor rates during this time period is, however, quite good.

The E^{-2} energy spectrum, the anticorrelation with co-rotating proton increases, and the positive correlation with the neutron monitor data suggest very strongly that the quiet-time electron increases are not of solar origin and must indeed represent the inflow of galactic electrons.

The Long Term Variation in Electron Intensity

The question of a long term variation in the interplanetary electron intensity now becomes a rather difficult one to answer. The daily data plotted in Fig. 3 are never constant for long periods of time, and what is defined as the quiescent level is linked critically with our definition of a quiet-time increase. We adopt here the working hypothesis that gradual changes in intensity, over periods exceeding about ten days, do not constitute the beginning or the end of a quiet-time increase. Other changes which are more rapid and appear to fall outside a statistical fluctuation in the data are considered to be well defined increases and have been discussed above. Solar flare events are, of course, automatically excluded.

There are other period such as November 1966 - January 1967, when the electron intensity appears to undergo large and rapid changes; however, these variations were sufficiently ill-defined that they were excluded from the present analysis. The interval June 4 - July 31, 1965 is taken as representative of solar minimum. There are large gradual

changes during this period and it is just prior to the large quiet-time increases in August - September 1965. The period 10 October 1965 to 30 April 1966 is still very close to solar minimum and is included despite an apparent three-month periodicity in the data. The interval 1 May to 24 September, 1968 is selected as representative of the 1968 level. (The solar active periods from 6 - 11 June and 5 - 15 July are excluded. Outside these two periods the solar flares appear to have no influence on the background intensity.) Finally the period from 21 June to 2 September, 1969, after which time the data were contaminated with solar flare electrons, is chosen as also being representative of solar maximum conditions. The results are summarized in Table I along with the Deep River neutron rates averaged over the same periods.

It is apparent that the magnitude of the long-term variation is critically dependent on the choice of quiescent periods. In particular, between the June - July 1965 and the October 1965 - April 1966 periods the electron intensity levels decrease by 40% while the Deep River neutron monitor rates increase by 0.15%. The magnitude of the total electron intensity change between solar maximum and solar minimum is a factor of ~ 2.3 . The difference in the two 1965 measurements emphasizes the difficulty of defining the long term modulation. Nevertheless, the trend in the data is consistent with a modulation of the electron intensity in the same sense as that of the galactic proton intensity, rather than the inverse sense.

This solar cycle modulation of the low energy component was first noted by Simnett et al. (1970), and has been confirmed by several other investigators. Using balloon data, J. Luhmann (1971) finds that the

3-60 MeV electrons were modulated by a factor of 1.8 between 1965 and 1970. These results are consistent with the low upper limits on the electron modulation at energies < 30 MeV obtained by L'Heureux et al.(1968) and Beedle (1970).

For comparison, Lezniak and Webber (1970) find that 80 MeV protons vary by some 300% between 1965 and 1968, and Rygg and Earl (1971) find a 500% variation in the 30-300 MeV interval between 1965 and 1970. Thus, the low energy modulation of electrons appears less than that observed for the medium energy (< 300 MeV) nucleon component.

Discussion:

The low energy electron data suggest that processes of two entirely different time scales may be occurring in the modulation of galactic particles. The quiet-time increases suggest a sudden increase that takes place on the order of several days, having a time scale not too different from that of Forbush decreases; the 11-year modulation, of course, extends over a far greater time scale. A complication is that there are no corresponding large increases in the low energy (20-80 MeV) galactic cosmic rays, and only a positive trend is evident in the neutron monitor during the quiet-time increases. One possible resolution of this problem has been suggested by Fisk and Van Hollebeke (1972) who argue that quiet-time increases are not the result of any variation in the electron modulation in the inner solar system, but rather represent an increase in the number of electrons penetrating a modulating region that lies far beyond the orbit of earth. They postulate that the intensity of electrons penetrating this region will be increased when field lines that have experienced an unusually large random walk

in the photosphere are carried by the solar wind out to the region. They find observational evidence that supports this contention and indicates that the proposed modulating region lies ~ 30 AU from the Sun. One would expect a reduction in peak intensity of quiet-time increases as solar activity increases if such a two-step process is involved, and this is qualitatively what is observed: There is a decrease in the peak amplitudes as one goes from 1965 to 1967 to 1968 and preliminary examination of IMP-5 data from June, 1969 to August, 1970, reveals no cases comparable to those in 1964, 1965 or 1967, (J. Wang, M. Van Hollebeke, private communication, 1971). It appears most probable that the observed anticorrelation between low energy co-rotating solar proton events and quiet-time electron increases is also the result of solar modulation. The close relationship between the proton events and both Forbush decreases and geomagnetic disturbances is well established (Fan et al., 1968b; McDonald and Desai, 1971). These events appear to originate over active centers which are also associated with enhanced solar plasma streams.

Finally, given the hypothesis that the observed interplanetary electrons are of interstellar origin, the question arises as to whether the observed electrons are interstellar "secondaries" produced by cosmic rays in the "knock-on" and $\pi \rightarrow \mu \rightarrow e$ processes, or whether they are "cosmic-ray primary" electrons. The flux of galactic secondary electrons can be accurately calculated, reasonably independent of exact knowledge of the low-energy unmodulated proton spectrum (Abraham et al., 1966; Perola and Scarsi, 1966; Beedle, 1970). The solar minimum quiescent

electron intensity is essentially in agreement with the total calculated secondary interstellar intensity from the predominant knock-on process. However, during the 1965 quiet-time increases, the observed peak intensity at 3 MeV was five times the calculated value. This suggests either one must also have galactic "primary electrons" present in the MeV interplanetary electron component or that the nuclear intensity in the 5-10 GeV range has been underestimated by a factor of 5. The latter hypothesis does not appear plausible.

At the high energies, ≥ 1 GeV, the positron to electron ratio is sufficiently low (see, e.g. Meyer, 1969) compared with that expected from pion production as to indicate that the bulk of those electrons are of primary origin. In the ≈ 3 -30 MeV region, the positron to electron ratio is also quite low (Cline and Porreca, 1970; Beuermann et al., 1970) and does not appear to rise as sharply as the electron spectrum does in this energy region (Fig. 1). This low abundance of 3 to 30 MeV positrons is consistent either with a secondary electron origin from the knock-on process, or with a primary origin, but is inconsistent with a pion-decay source process, as happens to be the case at the high energies. In the distinct, very low-energy region, characteristic of beta processes (< 1 MeV), measurements indicate the possibility of another positron component (Cline and Hones, 1970), but here the positron to electron ratio as a function of energy must yet be determined before any specific sources can be ruled out. Thus, to solve the question as to the predominance of galactic primary electrons in the few-MeV interplanetary population and to confirm the origin of the quiet-time increases, additional studies may be necessary. Measurements of the

temporal changes in the ≈ 0.1 -50 MeV positron intensity should yield independent clues. Finally, gradient observations of the interplanetary electrons can provide confirmation of the galactic origin of quiet-time electrons.

APPENDIX A

The dE/dx versus E detector (Fig. 2) consists of a CsI (Tl) crystal 0.1 cm thick by 5.08 cm in diameter, which serves as a energy loss, or dE/dx detector, operated in coincidence with another CsI (Tl) crystal 2 cm thick by 5.08 cm in diameter which serves as a total energy or $E - dE/dx$ detector for stopping particles. A plastic scintillator anti-coincidence guard counter surrounds the sides and base of the total energy detector.

The problem of normalizing the data from four different satellites over lengthy periods of time with no overlap is straightforward. The primary corrections are for gain and background changes. The dE/dx and $E - dE/dx$ channels are defined completely in energy space by determining the end point of the stopping proton distribution; this is a well defined quantity that can be measured accurately. For each orbit the dE/dx gain factor was measured by two methods: one used the minimum ionization line defined by stopping electrons and one used the end point of the stopping proton distribution. In the electron region a histogram was made by summing the lowest 15 - 20 channels in $E - dE/dx$. A sample histogram is shown in insert (a) in Fig. 16. This electron peak defines the minimum ionizing line. The end point of the stopping proton distribution provides an independent method for measuring the dE/dx gain changes. The results of the two methods were in agreement within 3%. The $E - dE/dx$ gain factor was then adjusted so that a histogram of matrix counts close to the proton line plotted versus the perpendicular distance in channel space from

the line peaked at zero. A sample histogram is shown in insert (b) in Fig. 16. Gain changes up to 30% were observed over the lifetime of IMP's 1 and 3. IMP 4 was stable by comparison, and the gain changes were negligible ($< 3\%$) over the 23-month lifetime of the satellite. Only the first three months' data from IMP-5 were used; during this time there were no significant gain changes.

The second important effect which is not identical for the different detectors is the background contamination in the electron region. The energy spectrum for nine orbits of IMP 3 from June 4, 1965 to July 20, 1965 was determined by subtracting the background contamination, using a method previously described (Simnett and McDonald, 1969), and this spectrum was compared with the IMP 4 spectrum obtained in the same way. This permits a normalization between these time periods on IMP 3 and IMP 4.

In order to compute a daily average of the electron flux a rectangular region of the dE/dx versus $E - dE/dx$ matrix was selected from the IMP 4 data such that threshold areas were specifically excluded but the majority of electrons were included. This is shown in Fig. 16 as the electron "box" and the number of counts per day in this region, as a function of time, is defined as $E(t)$. From a consideration of the absolute calibrations on IMP 3 and IMP 4, this was translated into an equivalent region on the IMP 3 matrix. A background box, defined in a similar way, is also shown in Fig. 16. The number of electrons contributing to the count in this box is negligible and the count per day is defined as $B(t)$. The relation between the

electron intensity $I_e(t)$ and the number of counts in the electron and background boxes, $E(t)$ and $B(t)$ can be defined by the equation:

$$I_e(t) = \left[\frac{E(t) - K B(t)}{M(t)} \right] \cdot \frac{\bar{R}(t)}{G} \quad (1)$$

where $\bar{R}(t)$ is the mean rate of particles which satisfy the logic requirements for matrix analysis, averaged over a day; G is a factor computed from the detector geometrical factor and electron detection efficiency; $M(t)$ is the daily total number of counts in the matrix; and K is a constant. $\bar{R}(t)$ depends on the interplanetary charged particle intensity. The factor in square brackets is the fraction of the total analyzed events that is identified as electrons, with $K B(t)$ as the background correction. The constant K was determined from the time period for which the detailed spectral analysis had been made, since for that time period $I_e(t)$ was known. A check on the validity of this method was made by performing a spectral analysis on further time periods for IMP's-3 and 4 and comparing the results with those obtained using equation (1). The constant K is somewhat spacecraft dependent, and a different constant was computed for the IMP-3 data. The change in the absolute counting rate in the background box between April 1967 (IMP-3) and June 1967 (IMP-4) was -16%. This change is probably due to the different mass distributions around the detectors on the two satellites. A similar procedure was used for the IMP-1 data for which the time periods chosen for detailed background analysis were super-imposed in phase with the 27-day pattern discussed by Cline and McDonald (1968-a).

The IMP-4 and IMP-5 satellites carried an additional solid state dE/dx versus E detector, with a plastic scintillator anticoincidence guard. The dE/dx element of this telescope is used to obtain daily averages of the 1 MeV proton component.

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TABLE I

Time Period	Electron Intensity ($\text{m}^{-2}\text{sec}^{-1}\text{ster}^{-1}$)*	Deep River Neutron Monitor Rate Averaged Over The Appropriate Time Period
1. June 4 - July 31, 1965	$109. \pm 7.5$	7042
2. October 10, 1965 - April 30, 1966	$76. \pm 4.5$	7050
3. May 1 - September 24, 1968 (Excluding June 6 to 11, July 5 to 15)	$60. \pm 5.5$	6461
4. June 21 - September 24, 1969	46.5 ± 5.0	6283

*calculated on the basis of a spectrum $dJ/dE \propto E^{-1.75}$

FIGURE CAPTIONS

Fig. 1 The electron, positron, proton and helium differential energy spectra in interplanetary space at 1 A.U. near solar minimum.

The shaded portion of the low energy proton spectrum reflects the great variability in this region. These data represent the work of many investigators and is intended to place the low energy electrons and protons in perspective [See G. Gloeckler and R. Jokipii (1966) and P. Meyer, (1969)].

Fig. 2 Schematic cross section of the E vs dE/dx detector system.

Fig. 3 Daily averages of the 3-12 MeV electron intensity in interplanetary space. Appropriate background corrections have been applied. Times of occurrence of solar flares which produce electrons of energy > 3 MeV are shown by the rectangular boxes. For an $E^{-1.75}$ spectrum 100 arbitrary flux units are equal to 30.0 ± 0.6 electrons/ m^2 -sec-sr.

Fig. 4 The time history of the 3-12 MeV electron component for a "classical" flare-associated event on 7 July 1966. Also shown for comparison as a dashed line is the 19-80 MeV proton component. There is a well defined velocity dispersion at the onset of this event.

Fig. 5 The 19-38 MeV proton intensity time history covering two solar rotations from June - August 1966. The 3-12 MeV electron intensity is plotted for the second rotation. Data from Anderson (1969) show in detail the low energy co-rotating particle streams for protons > 500 keV and electrons > 45 keV. There are increases in

both the electron and proton intensity coincident with the CMP of MP 8413, which had produced the 7 July flare on its previous rotation.

Fig. 6 Superposition of 6 Forbush decreases for both IMP III and IMP IV. The events selected were the larger decreases (as defined by the Deep River neutron monitor) which were free of MeV solar electrons. Shown for comparison are the Deep River neutron monitor averaged over the same set of events.

Fig. 7 The series of recurrent quiet-time electron increases observed in 1964 by IMP 1. The positions of the four well-defined increases are marked by the double arrows projecting toward the Deep River neutron monitor data and the low energy proton data. The dashed arrows in January 1967 indicate a possible fifth event. The proton data is from the University of Chicago cosmic ray detector on IMP 1 (Fan et al., 1966) and represents the proton flux > 0.9 MeV. The MeV electron events and the co-rotating solar proton events are clearly out of phase. The shaded area represents the contribution from a flare-associated event on 16 March 1964.

Fig. 8 A 27-day superposition of the four quiet-time increases from February to 5 May 1964. Also shown are the locations of the interplanetary magnetic sectors and the superposition of the Deep River neutron monitor. The electron maximum is near the sector boundary. There is no strong correlation of the electron intensity with the neutron monitor data.

Fig. 9 The series of quiet-time increases observed by IMP III during August and September 1965. There were three very small low-energy proton events observed by the University of Chicago on IMP-3 and Pioneer 6 (O'Gallagher and Simpson, 1966) which are indicated by the hatched region. Also plotted are the Deep River neutron data for the period. The arrows represent the centroids of the three quiet-time increases. The increase on 4 October 1965 is a flare-associated event.

Fig. 10 Composite plot of 3-12 MeV electrons, 1 MeV proton and Deep River neutron monitor rates for 9 quiet-time increases between August, 1967 and April, 1968. The arrows represent the centroids of the electron increases. The upper portions of the flare associated electron increases are cross-hatched. The sector data are indicated along the top with the solid portions representing positive sections.

Fig. 11 Superposition of five quiet-time increases and Deep River neutron monitor rates for August - December 1967. Electron increases have been normalized in amplitude at the times of maximum.

Fig. 12 Energy spectra for four quiet-time increases during the last half of 1967. The solid line, representing an E^{-2} spectrum, is in excellent agreement with the data, except for the 3 MeV points in November, 1967.

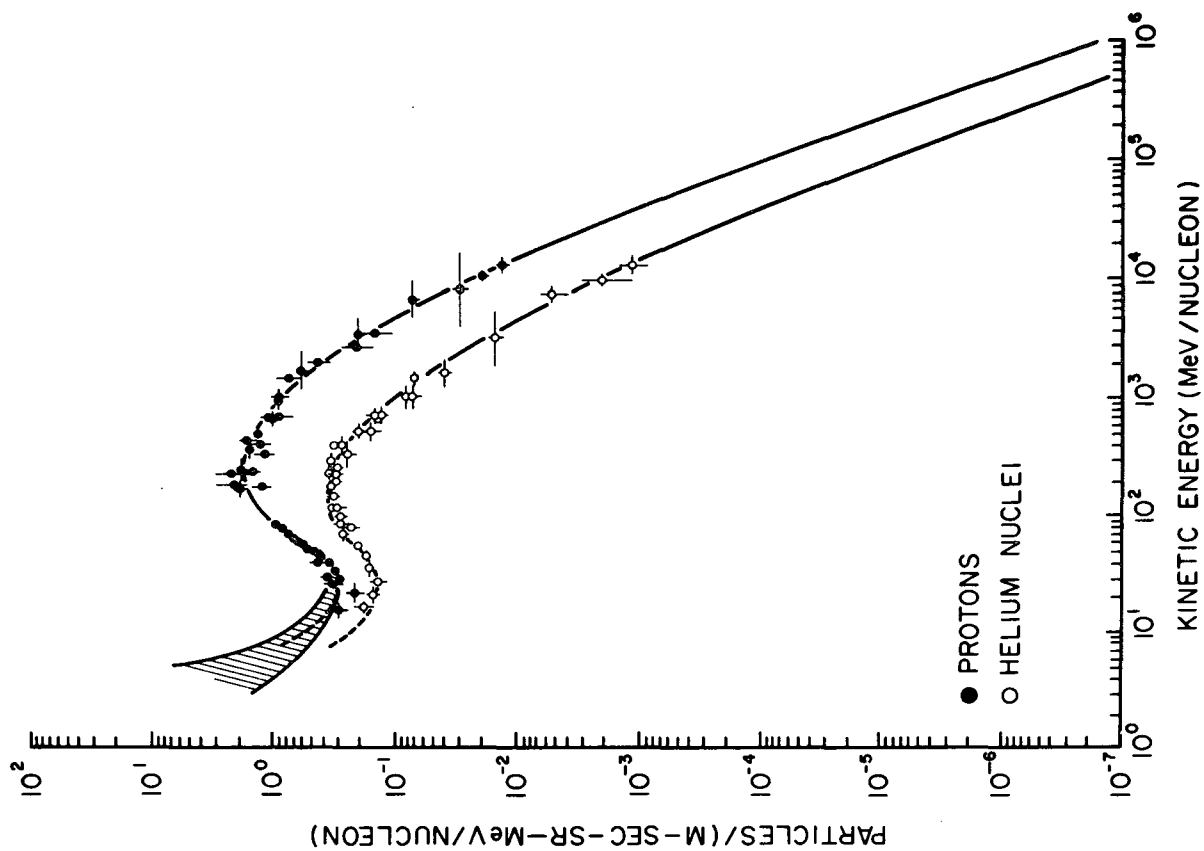
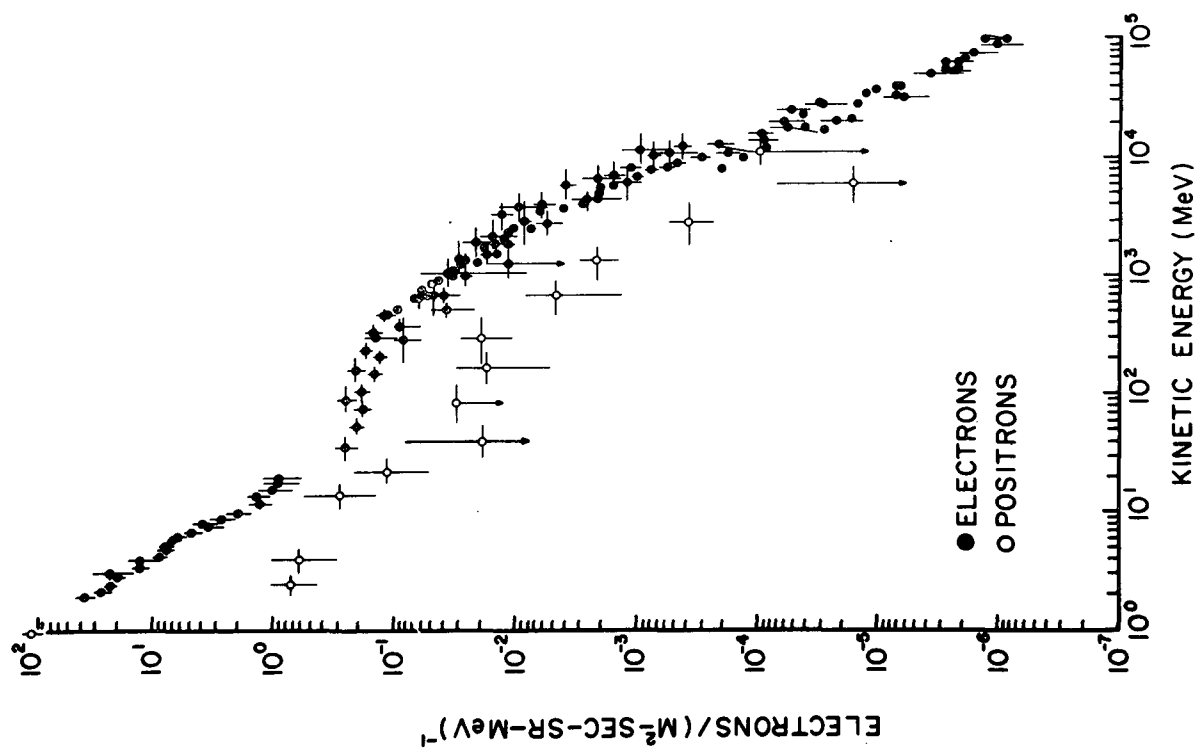
Fig. 13 Time history for the 1-19 November, 1967 period for 0.5-1.0 MeV and 3-12 MeV electrons and 1 MeV protons showing close

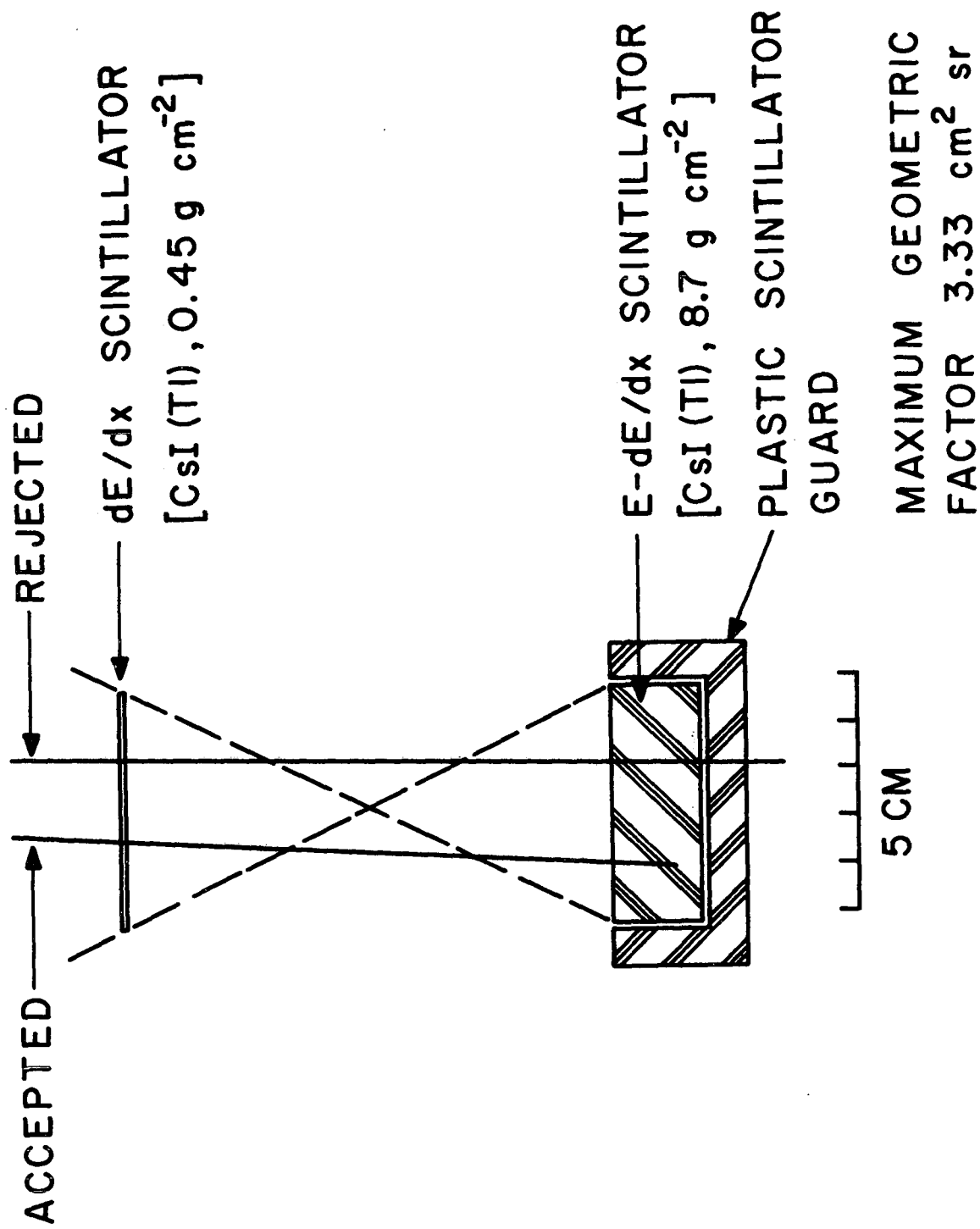
juxtaposition of a quiet-time increase and a co-rotating solar event. In particular, the 0.5-1.0 MeV electrons follow the MeV proton increase and are probably predominantly solar in origin.

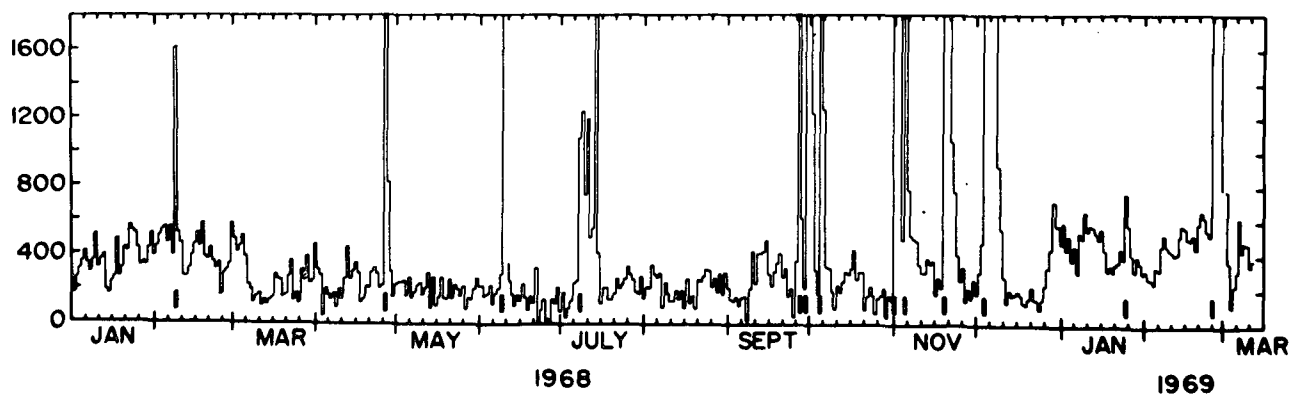
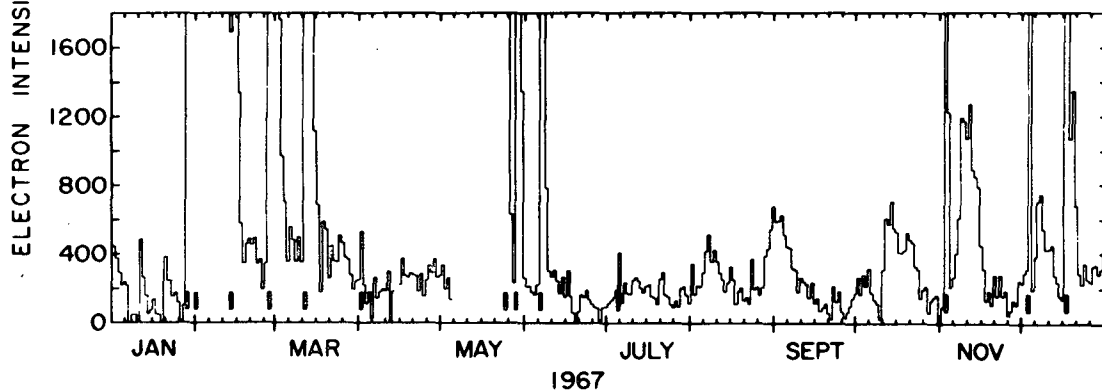
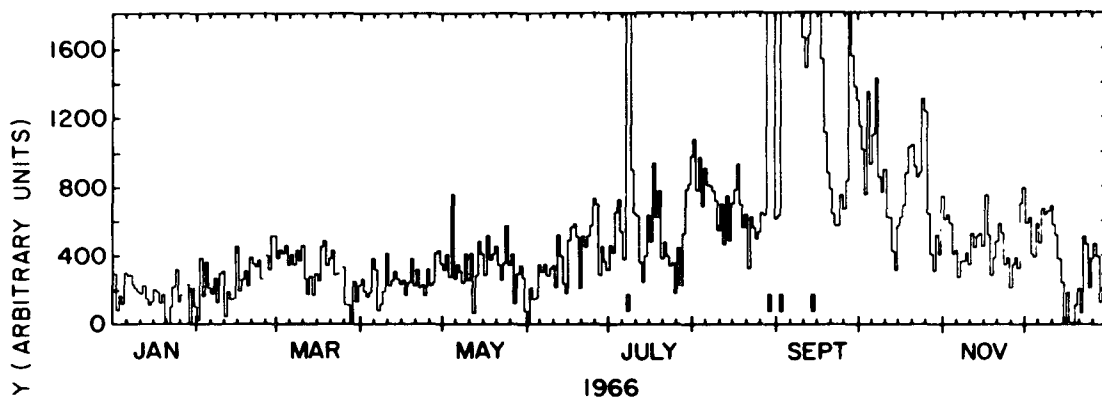
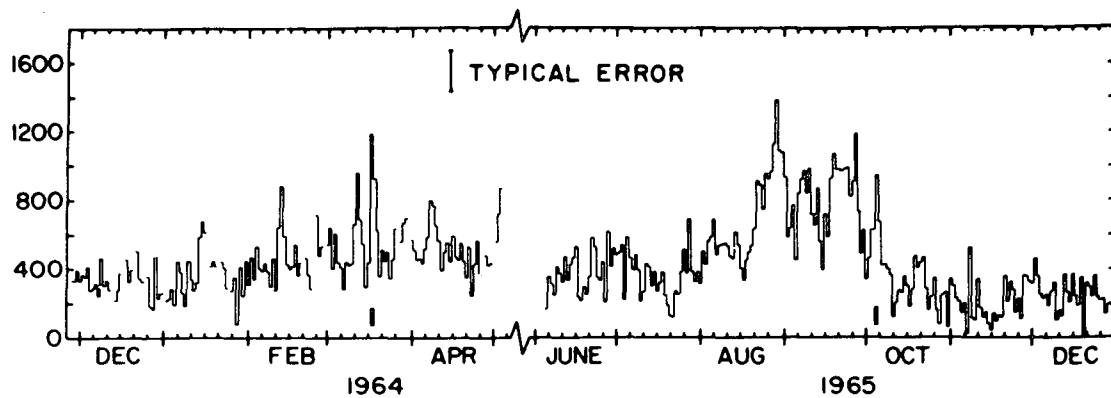
Fig. 14 Time history of 3-12 MeV electrons, MeV protons and the Deep River neutron monitor for the period December 1968 - February 1969. The proton data from the Bell Telephone Labs. experiment on IMP -4 (Lanzerotti, Private communication, 1971). The first electron increase in late December is a flare associated increase. It is felt that the increases occurring in the periods 7-16 January, 5-10 February and 11-24 February are consistent with their being quiet-time increases. The anti-correlation with low energy solar protons is not as marked as in previous cases. The gradual increase starting in early February probably represents the superposition of a low intensity solar component.

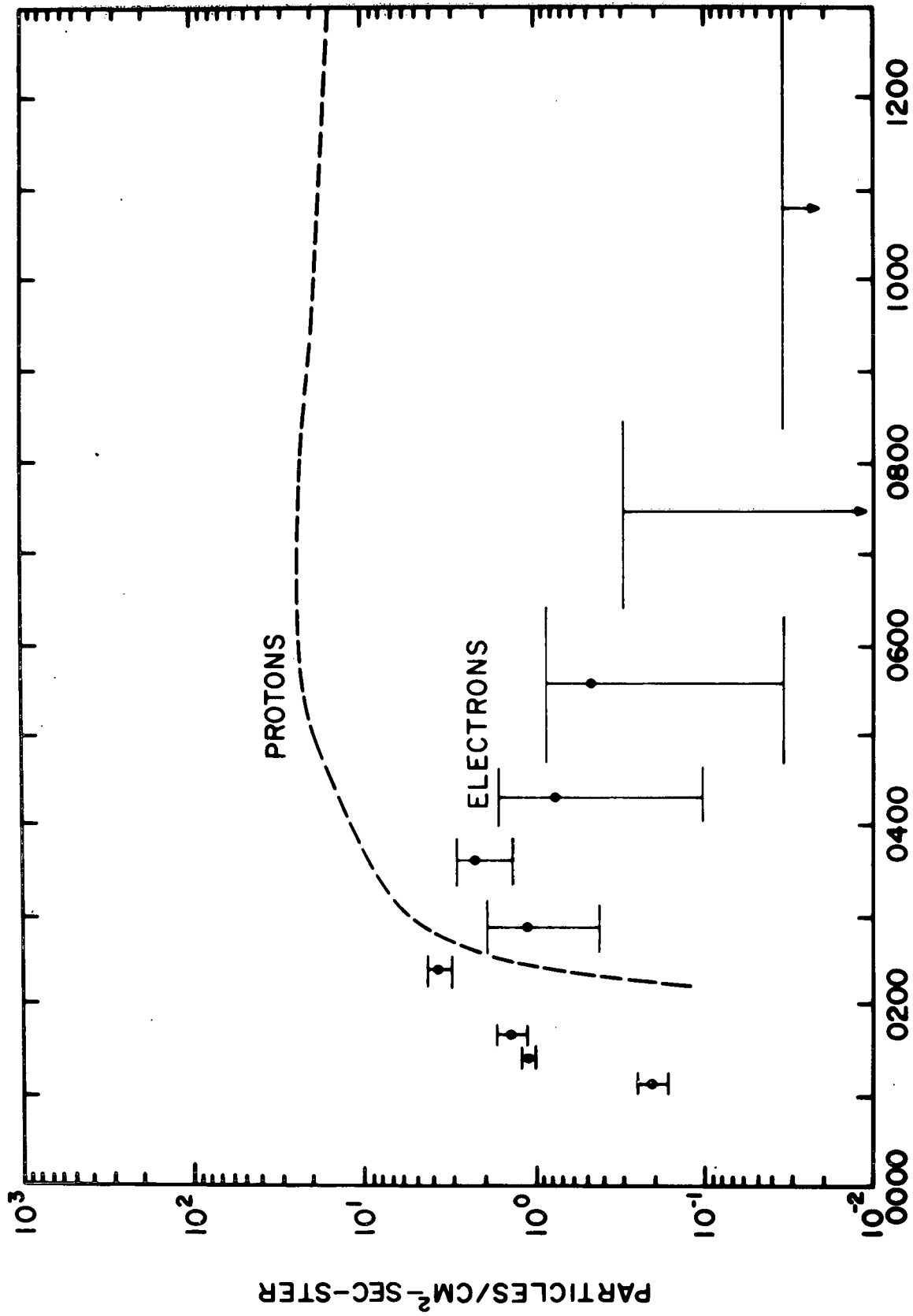
Fig. 15 Energy spectra for three possible quiet-time increases in the January - February 1969 period. All spectra are consistent with a E^{-2} spectrum (solid line).

Fig. 16 Schematic representation of the dE/dx versus $E-dE/dx$ matrix showing the measured electron and proton lines and the location of both the electron and background boxes. Insert A shows histogram taken by summation perpendicular to the proton line near the end point. Insert B shows a histogram across the minimum ionizing electron line defined by stopping particles.



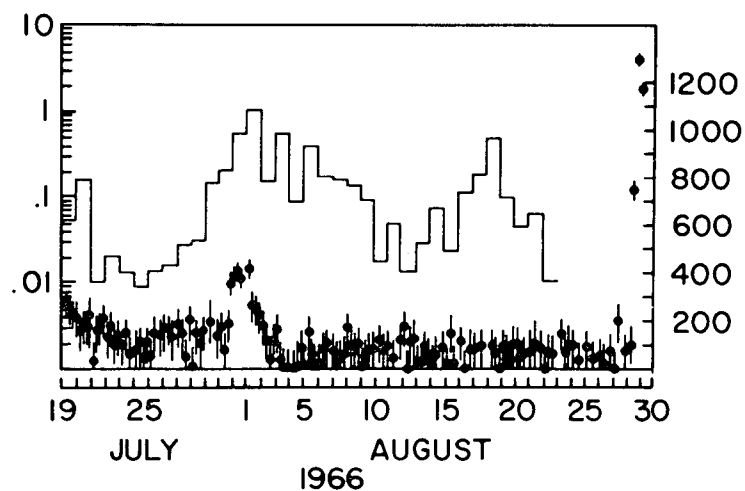
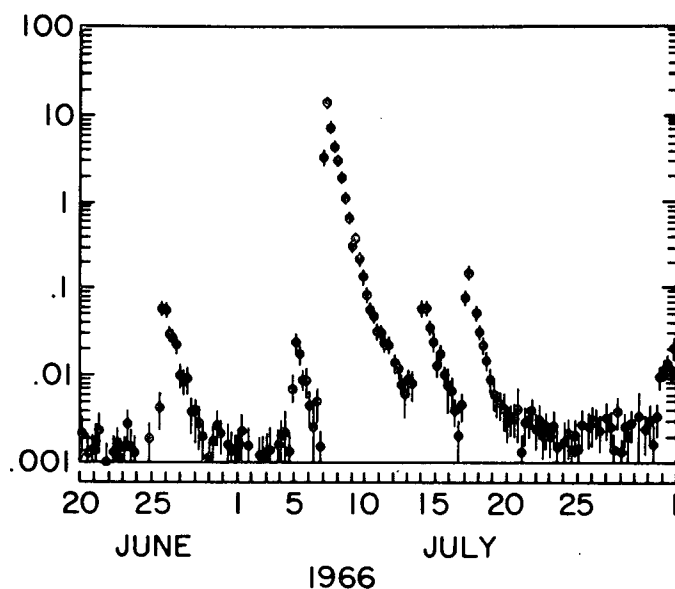




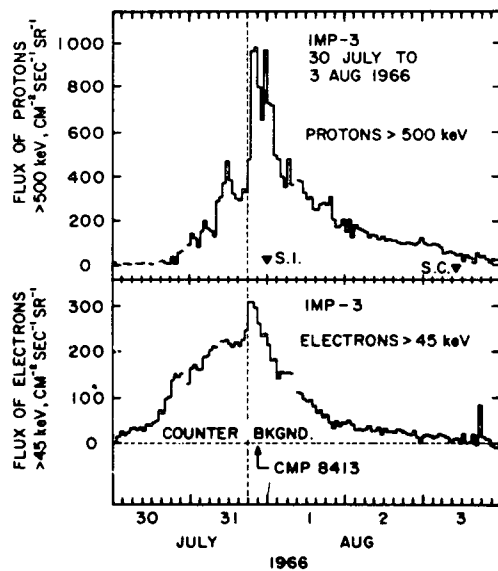


U.T., 7 JULY 1966

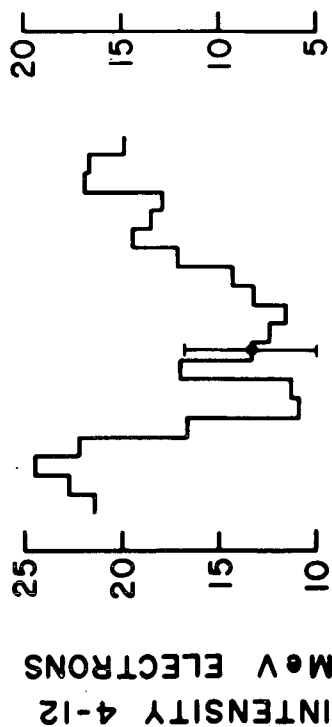
16-38 MeV PROTONS/CM²-SEC-STER



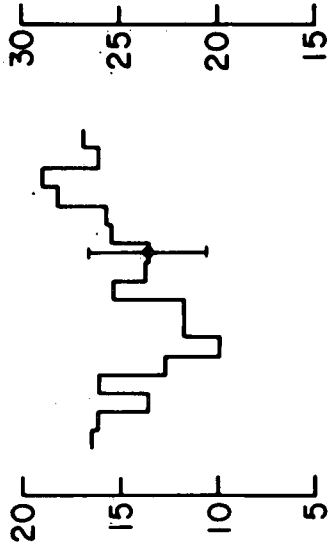
4-12 MeV ELECTRONS



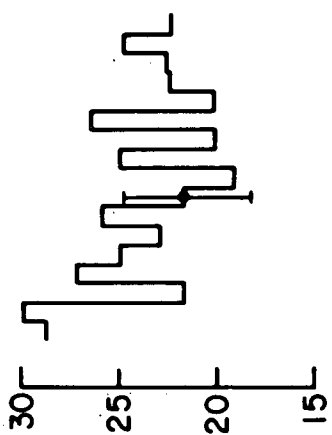
6 EVENTS IMP - III



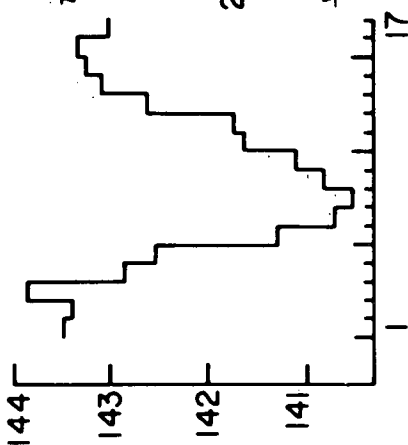
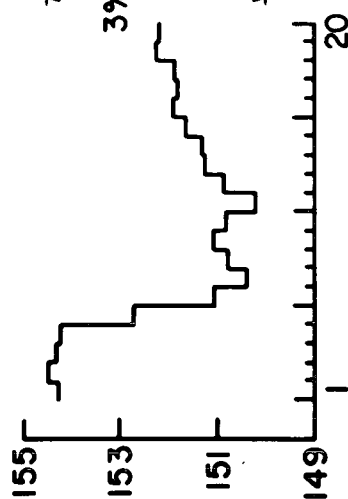
6 EVENTS IMP - IV



8 QUIET PERIODS



DEEP RIVER NEUTRONS

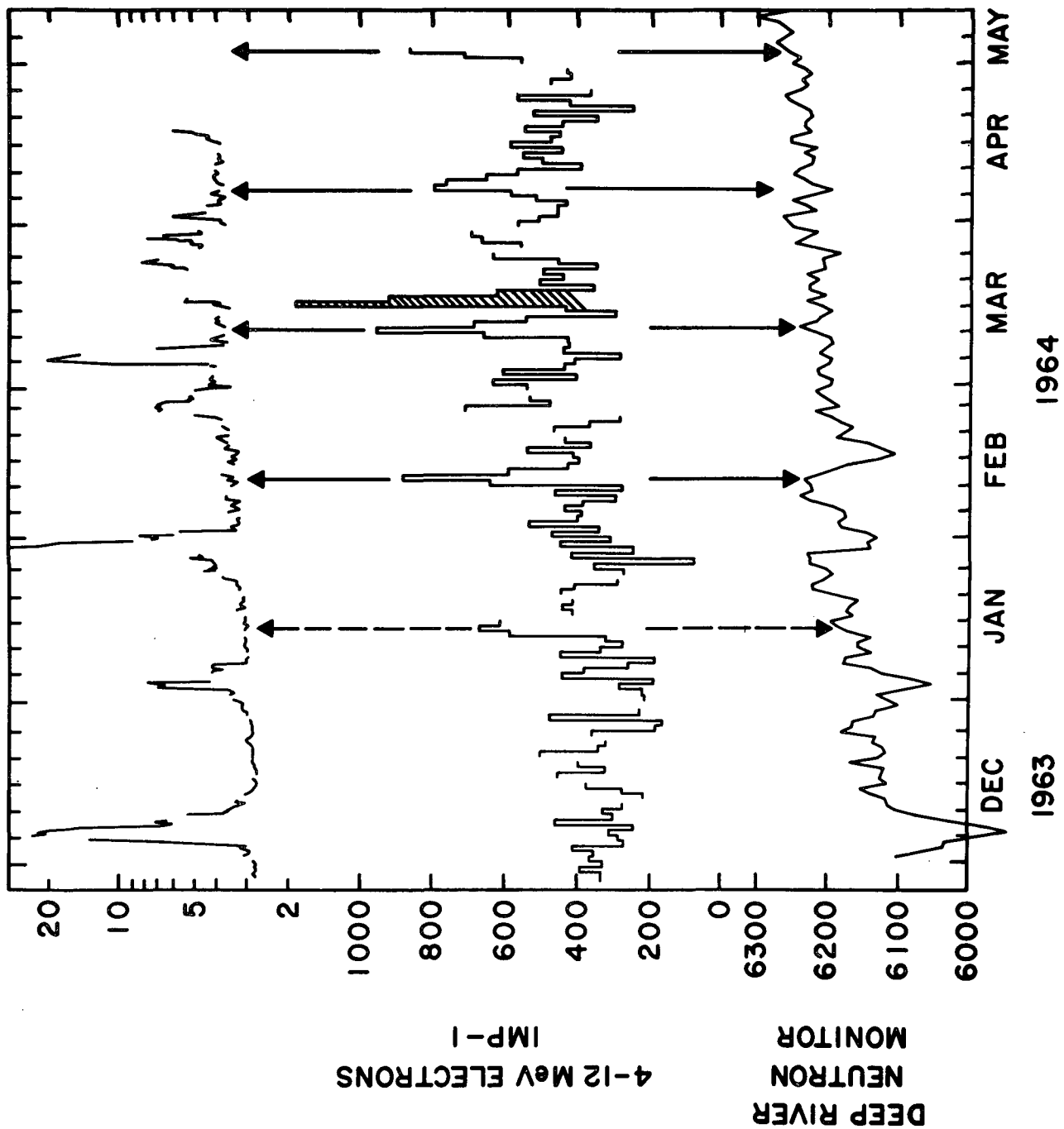


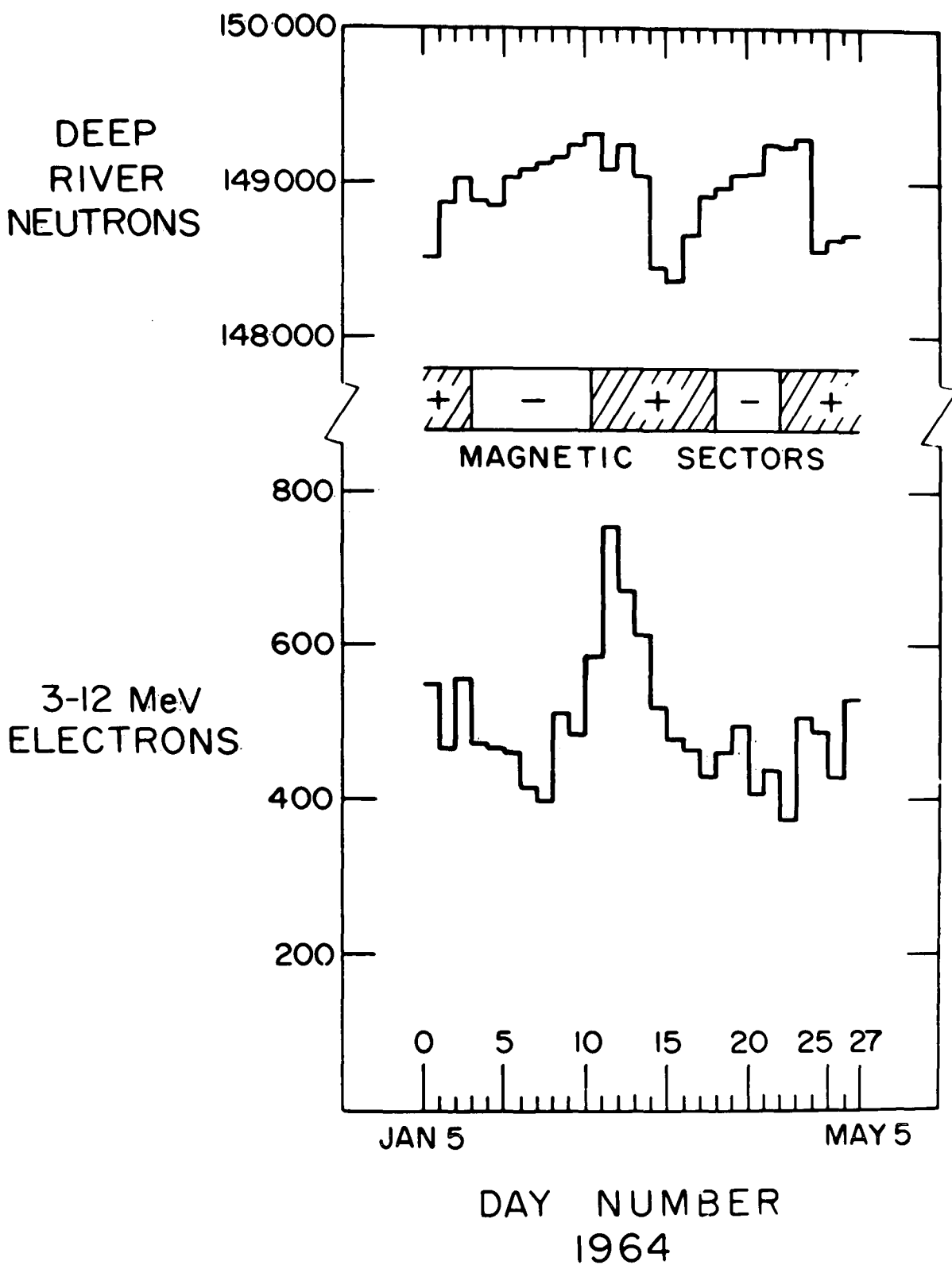
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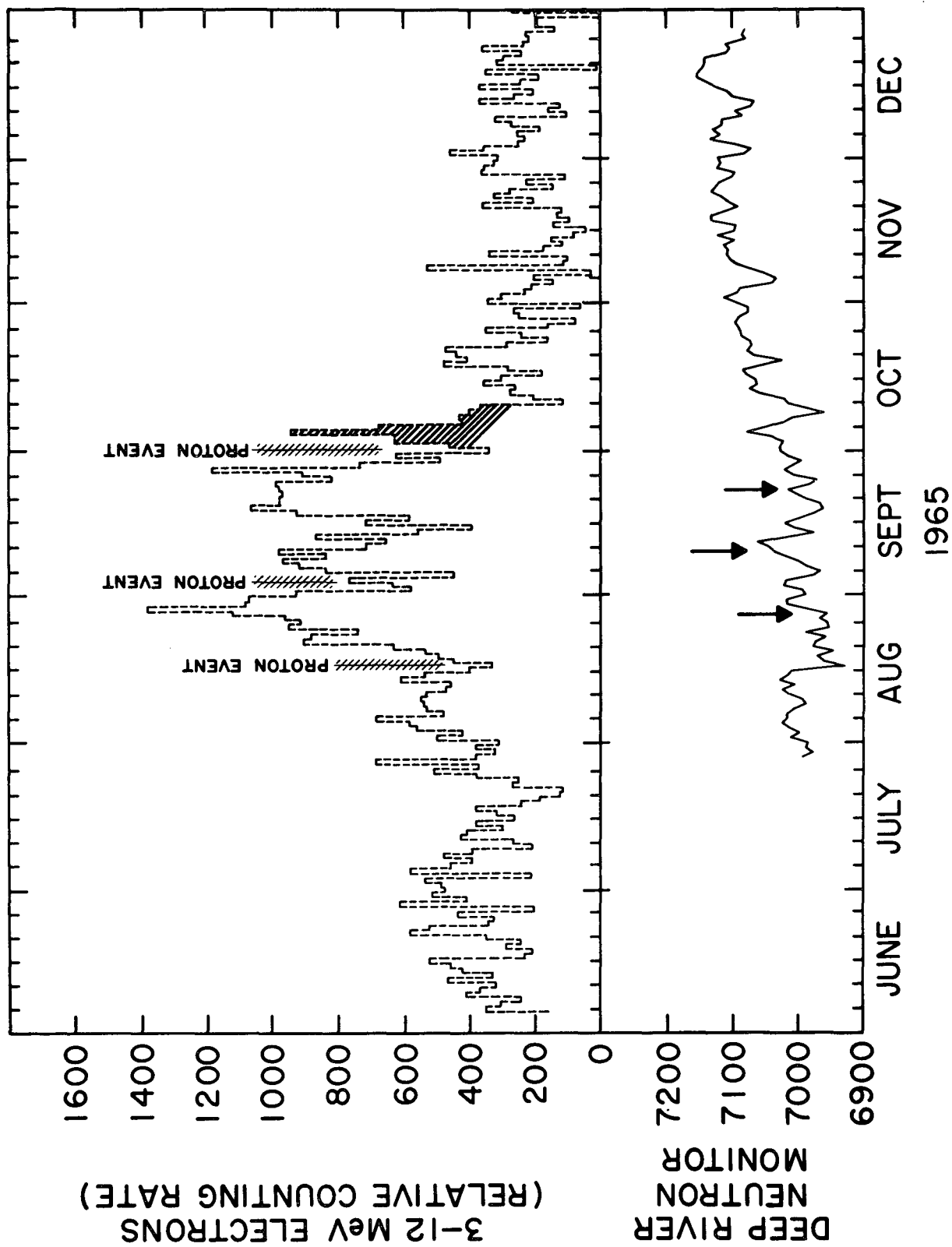
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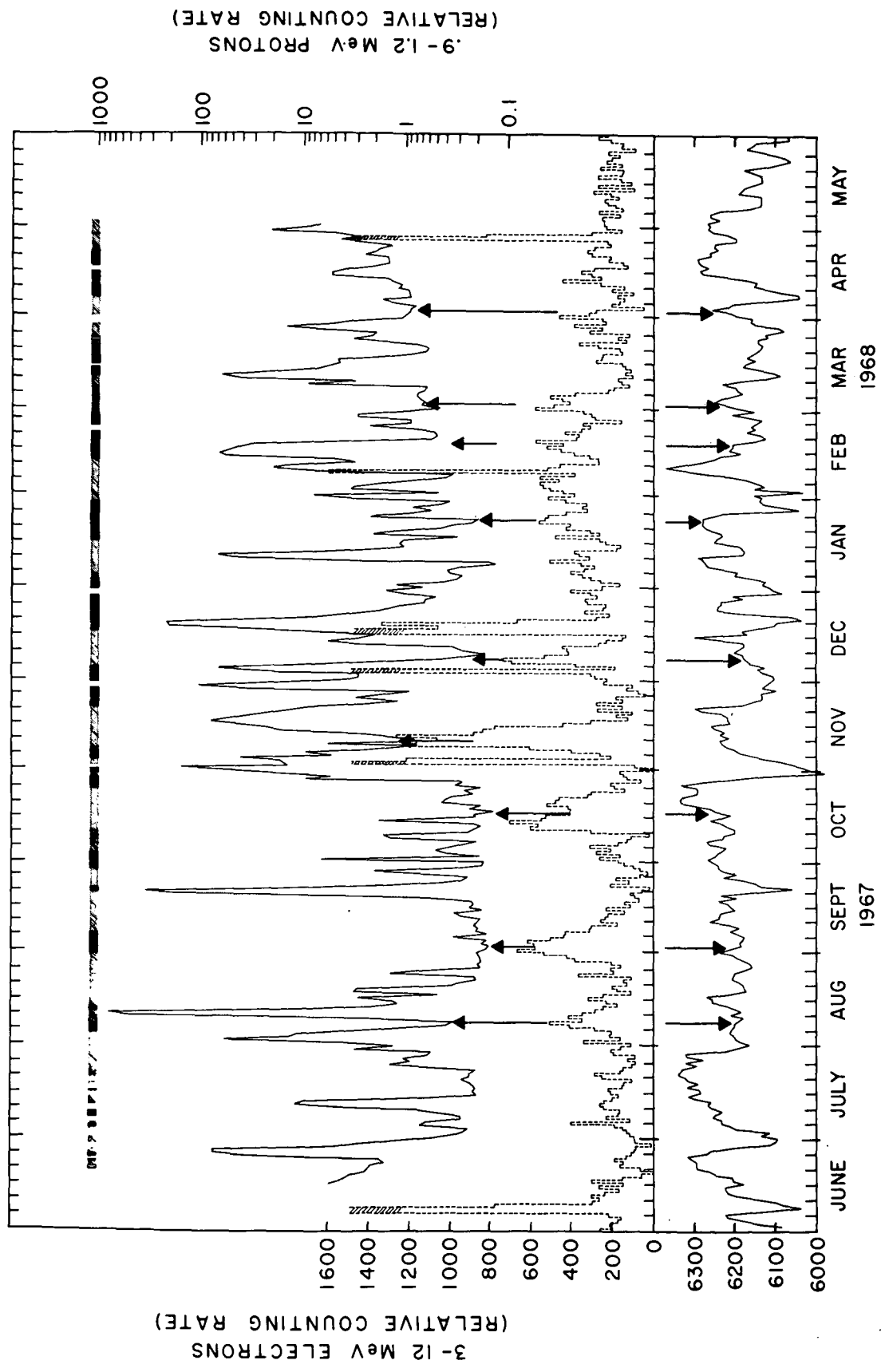
DAY NUMBER

CORRELATION COEFF. $0.83^{+0.03}_{-0.10}$ CORRELATION COEFF. $0.65^{+0.06}_{-0.25}$ CORRELATION COEFF. -0.01 ± 0.17









DEEP RIVER NEUTRONS
(DAILY AVERAGES)

