ELECTRONS IN QUIET-TIME INCREASES, SAMPLERS OF CONDITIONS IN THE OUTER SOLAR SYSTEM

L. A. Fisk and M. VanHollebeke*
NASA/Goddard Space Flight Center
Greenbelt, Maryland, USA. 20771

Abstract

An explanation for quiet-time electron increases is proposed which predicts the existence of a modulating region for cosmic ray particles lying at ~ 30 AU from the Sun.

1. Introduction

In the companion paper to this one, McDonald, Cline and Simnett 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 intensity 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 2 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 3 we discuss some observational evidence that supports this explanation, and in Section 4 we interpret this evidence as indicating, among other things, that the modulating region lies at ~ 30 AU from the Sun.

2. 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 McDonald et al. (1971) for the years 1967 through 1968. The quiet-time increases are marked in this figure with brackets. The events marked with dashed brackets are less clear-cut than the others since here it is not as readily established that the electron increase anti-correlates with an increase in the MeV proton intensity, and the increase over the local electron background is quite small.

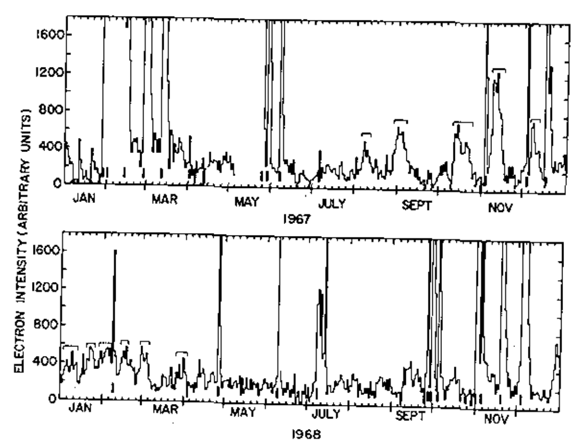

FIG. 1

*ESRO Postdoctoral Research Associate

We argue 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. Although it is hardly a conclusive argument, the steadiness of this 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 for the galactic origin for the background flux has been obtained recently by Webber and Lezniak (1971) who observe that the radial gradient of the background electron intensity lies somewhere in the range 0-30%/AU. The gradient of a steady flux of solar electrons would be negative and perhaps ~ -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. McDonald, et al. (1971) report that this common spectral index is about -2, and thus it defines a flatter spectrum than is observed during flare events (a spectral index ~ -3) or during recurrence events (a spectral index ~ -4 or 5).

We argue also that quiet-time increases are not the result of any variation in the modulation, or scattering conditions, experienced by 4-12 MeV electrons in the inner solar system. Note in Figure 1 that the background flux of galactic electrons is relatively constant from year to year. McDonald et al. (1971) report that the background flux is reduced by a factor < 1.25 from 1965 to 1968, which covers solar minimum conditions to near solar maximum conditions. The evidence is, then, that 4-12 MeV electrons are relatively insensitive to 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 cannot alter these scattering conditions to account for the factor ~ 5 increases observed during quiet-time increases. Evidently, the interplanetary magnetic field 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 5γ field). It should be noted that it is possible to construct models in which the electron intensity remains time invarient, but there is still appreciable scattering (see Lezniak and Webber, 1971). However, these models cannot account for the small magnitude of the observed gradient, 0-30%/AU (Webber and Lezniak, 1971) which is consistent with little scattering in the inner solar system.

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 to the inner solar system, permitting more electrons to enter during a quiet-time increase. Presumably, the behavior of the electrons in such a modulating region can be described by a diffusion process with an appropriate diffusion coefficient parallel and perpendicular to the mean field direction. We are clearly not in a position to observe directly changes in the parallel diffusion coefficient that could result in a quiet-time increase since this parameter is determined by irregularities generated locally in the modulating region. 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 a result of the stocastic nature of the 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 interplanetary field lines appears to be produced by photospheric turbulence (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, when field lines that have experienced an unusually large random walk in the photosphere are carried 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 since the mean field direction in the modulating region is presumably mainly azimuthal about the Sun, field line random walk will be particularly important for diffusion in the heliocentric radial direction. Clearly we can test the above hypothesis by seeing whether periods of usually large random walk are observed before quiet-time increase, with a delay which is then a measure of the transit time of the solar wind out to the modulating region.

3. Supporting Observational Evidence

In order to establish that there exists a correlation between the occurrence of quiet-time increases and of periods of large field line random walk, we obviously must have a reliable and sensitive measure of how much 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 and there is the practical difficulty that power spectra are not available for all the time periods we consider. We suggest instead that a useful measure of the random walk is the amplitude of the diurnal anisotropy, as is observed by neutron monitors. The formula for this amplitude, ξ, during quiet-periods, assuming that there is appreciable diffusion perpendicular to the mean field direction is (Krimsky, 1965; Parker, 1967):

$$\xi = \frac{3CV_{SW}}{v}\,\frac{(1 - \kappa_\perp/\kappa_\parallel)\tan\Psi}{(1 + \kappa_\perp/\kappa_\parallel\tan^2\Psi)} \qquad (1)$$

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 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, 1968). During periods of large random walk, the ratio $\kappa_\perp/\kappa_\parallel$ increases over its average value ~ 0.2 (Jokipii and Parker, 1969). $\kappa_\perp$ depends directly, while $\kappa_\parallel$ inversely, on the power at low frequencies in the power spectra of field fluctuations. Thus, there should exist a direct correspondence between periods of low diurnal anisotropy and periods of large field line random walk.

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 during 1967-1968. The average amplitude during this period was $\sim 0.4\%$ (VanHollebeke, 1971). We consider as low any amplitude $< 0.3\%$. Although continuous data is available for these years, not all the computed anisotropies are a reliable measure of the random walk. We have eliminated from consideration any amplitude computed when the daily average of the monitor rate varied from day to day by more than 1%, or whose direction was inconsistent with the lack of significant radial streaming assumed in deriving (1).

In Figure 2 we have plotted the amplitudes of the diurnal anisotropy (in %) 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 this interplanetary magnetic field (Fairfield, private communication). Light-shading indicates a sector with fields directed mainly away from the Sun; dark shading, mainly toward. The times when quiet-time increases occur are marked with brackets identical to those shown in Figure 1. The horizontal dashed line markes an amplitude of 0.3%. Any amplitude less than this is considered to indicate a large field line random walk. Note in Figure 2 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 2, however, is that quiet-time increases and periods of low amplitude 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 considerably study. The eleven quiet-time increases shown in Figure 2 can be divided into categories: (i) for seven of the events there is an extended period of low amplitude 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 cannot trace the sector back five rotations. In Table 1 we have listed the events in category (i), together with their associated low amplitude periods. Listed also for each of the low amplitude periods 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 number of reliable amplitudes to the total possible amplitudes (2/day for each day of the period).

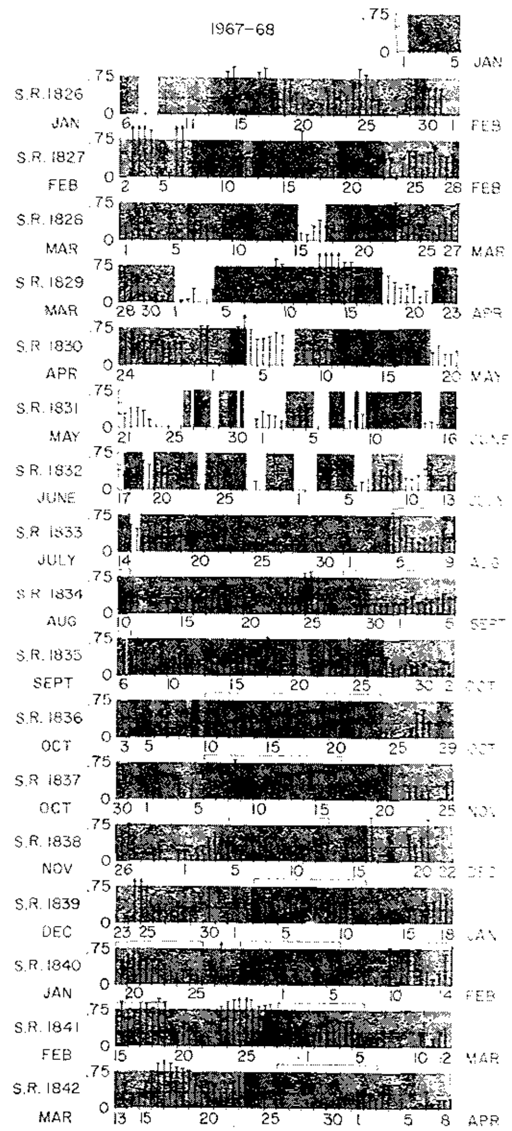

FIG. 2

TABLE 1

Quiet Time Increases	Low Amplitude Periods	Ampl <0.3% / Reliable Ampl.	Reliable Ampl. / Total Ampl.
10-23 Oct. 1967	31 May-9 June 1967	71(%)	70(%)
6-16 Nov. 1967	26 June-7 July 1967	100	30
5-12 Dec. 1967	23 July-3 Aug. 1967	100	54
19-25 Jan. 1968	30 Aug.-4 Sept. 1967	83	100
13-18 Feb. 1968	28 Sept.-3 Oct. 1967	91	91
28 Feb.-5 March 1968	10-17 Oct. 1967	71	87
26 March-2 April 1968	10-20 Nov. 1967	73	68

Only for the second event is there insufficient data to establish convincingly that there is an associated low amplitude period, although all the data available for the period have an amplitude < 0.3%. On averaging over the remaining six events, 82% of the reliable amplitudes are < 0.3%. Compare this with the percentage of reliable amplitudes < 0.3%, computed using the data from the entire period January 1967-April 1968, of only 41%. The two events in category (ii) are 3-11 January 1968 and 29 January-5 February 1968. 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 increases that occurred in the same sector on the three previous rotations. The two events in category (iii) are 5-10 August 1967 and 28 August-6 September 1967. Although the sector containing these increases cannot be traced back to locate the associated low amplitude period, we can establish, by examining solar magnetogram data, that the sector probably existed for the required five rotations, lying out of the ecliptic.

4. Interpretation

These observations support the contention made in Section 2, 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 beyond the orbit of earth, more 4-12 MeV electrons 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 and of the quiet-time increase. The modulating region, then, must lie at ~ 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 ~ 30 AU must be short compared with one solar rotation, since within this time the electron intensity seen at earth appears to respond to changes in the modulating region. These observations imply, of course, that interplanetary field lines (at least those on which quiet-time increases occur) are continuous out to ~ 30 AU. They can also be used to show that sector structure is essentially preserved out to ~ 30 AU. The limit we can place on the random walk of field lines due to interplanetary turbulence, by noting that this random walk must always be less than that due to photospheric turbulence, suggests that interplanetary turbulence is not sufficient out to ~ 30 AU to destroy the overall sector pattern.

Finally, consider the observed anti-correlation between quiet-time increases and increases in the low energy solar proton intensity (McDonald et al., 1971). The electron increases should occur independently of any proton increase. A quiet-time increase depends on solar conditions five solar rotations preceding the observed event, whereas an increase in the proton flux depends on concurrent solar conditions. However, the interplanetary magnetic field during the large proton increases in late 1967, the period when the anti-correlation is most evident (see McDonald et al., 1971) are quite disturbed and show evidence for loop structures. Thus, electrons propagating in from ~ 30 AU may be excluded from connecting onto the field lines where the proton increases occur.

5. References

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