1up

X-661-72-76
PREPRINT

NASA TM X- 65887

THE CORONAL TRANSPORT OF THE FLARE-ASSOCIATED SCATTER-FREE ELECTRONS

J. R. WANG

MARCH 1972

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

(NASA-TM-X-65887) THE CORONAL TRANSPORT OF THE FLARE ASSOCIATED SCATTER FREE ELECTRONS J.R. Wang (NASA) Mar. 1972 22 p CSCL 03B
N72-25724
Unclas
G3/29 30373

X-661-72-76
PREPRINT

THE CORONAL TRANSPORT OF THE FLARE-ASSOCIATED SCATTER-FREE ELECTRONS

J. R. Wang
Goddard Space Flight Center

March 1972

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

PRECEDING PAGE BLANK NOT FILMED

ABSTRACT

A total of 11 scatter-free electron events from McMath plage region 8905 were observed by IMP 4 during the period from July 29 to August 3, 1967. The transit times and duration of these electron events in the energy channels of 22 to 45 keV and 170 to 1000 keV are examined in detail. We find that the duration of 170- to 1000-keV electrons shows a strong dependence upon the heliolongitude of the associated flare. Typical values of the duration full width at half maximum vary from ~4 min at ~50° W to ~12 min at ~10° and ~90° W heliolongitudes. In addition, the difference in times at which the maximum intensities of the 22- to 45-keV and 170- to 1000-keV electrons occur is observed to change from ~18 min near 50° W to ~13 min at ~10° and ~90° W heliolongitudes.

To explain these observations, we propose an idealized two-dimensional diffusion model for the transport of these electrons in the solar corona. In this model, the 22- to 45-keV electrons escape promptly from flare site to the feet of the interplanetary magnetic field lines, whereas the 170- to 1000-keV electrons suffer slight scattering. The diffusion coefficient for 170- to 1000-keV electrons is estimated to be ~3 X 10^{18} cm^2/s. Finally, a possible relation between the scatter-free and the classical diffusive-type electron events is discussed.

PRECEDING PAGE BLANK NOT FILMED

CONTENTS

THE CORONAL TRANSPORT OF THE FLARE-ASSOCIATED SCATTER-FREE ELECTRONS

J. R. Wang*
Goddard Space Flight Center

INTRODUCTION

Lin (1970*a, c*) was the first to report the observations of the scatter-free solar-flare electrons in the interplanetary medium. His observations suggest that these electrons belong to a new class of flare-associated events, which are quite different from the classical diffusive-type events reported rather extensively in the literature[1] (e.g., Anderson and Lin, 1966; Cline and McDonald, 1968; Datlowe, 1971; Lin, 1970*b*; Lin and Anderson, 1967; Meyer and Vogt, 1962; Simnett, 1971; Van Allen and Krimigis, 1965). To illustrate the unusual features displayed by these electrons, we have plotted in Figure 1 the intensity-time profiles for several energy channels of two events that occurred at ~1650 and ~2000 U.T. on July 30, 1967. Both of these events are associated with small optical flares from McMath plage region 8905. The most distinct nature of these events lies in the initial rapid rise and decay in electron population. The duration of these initial intensity peaks depends upon electron energies, but is $\lesssim$40 min in general. On the contrary, the classical diffusive-type electron events were observed to have a rise time of ~1 hr or greater, followed by an exponential (or power-law) decay of several hours or days. The scatter-free electrons discussed in this paper are those appearing in the initial peaks.

The main features of the scatter-free solar-electron events as observed and studied by Lin (1970*a, c*), and subsequently by Wang et al.[2] (1971), and Lin et al.[3] are the following:

(1) These electron events appear to occur in groups from a single active region. McMath plage region 8905 alone (central meridian passage July 29, 1967) produced 14 observed events.

(2) The heliolongitudinal range in which the scatter-free electrons were observed to occur was generally referred to as the open cone of propagation (Lin, 1970*c*). For region 8905, this open cone happens to be from ~10° to ~80° W. There is no strong heliolongitudinal dependence of the duration full width at half intensity maximum (FWHM) and transit time for low-energy scatter-free electrons of energies equal to or greater than 22 keV. This

*NAS-NRC Resident Research Associate.

[1] J. D. Sullivan: "Two Solar Flare Electron Components and Their Relationship to the Proton Component," *J. Geophys. Res.*, to be published.

[2] J. R. Wang, R. P. Lin, and L. A. Fisk: "The Flare-Associated Scatter-Free Electrons in the Energy Range of 20-1500 keV, in preparation.

[3] R. P. Lin, J. R. Wang, and L. A. Fisk: "Propagation of the Scatter-Free Electrons in the Interplanetary Medium," in preparation.

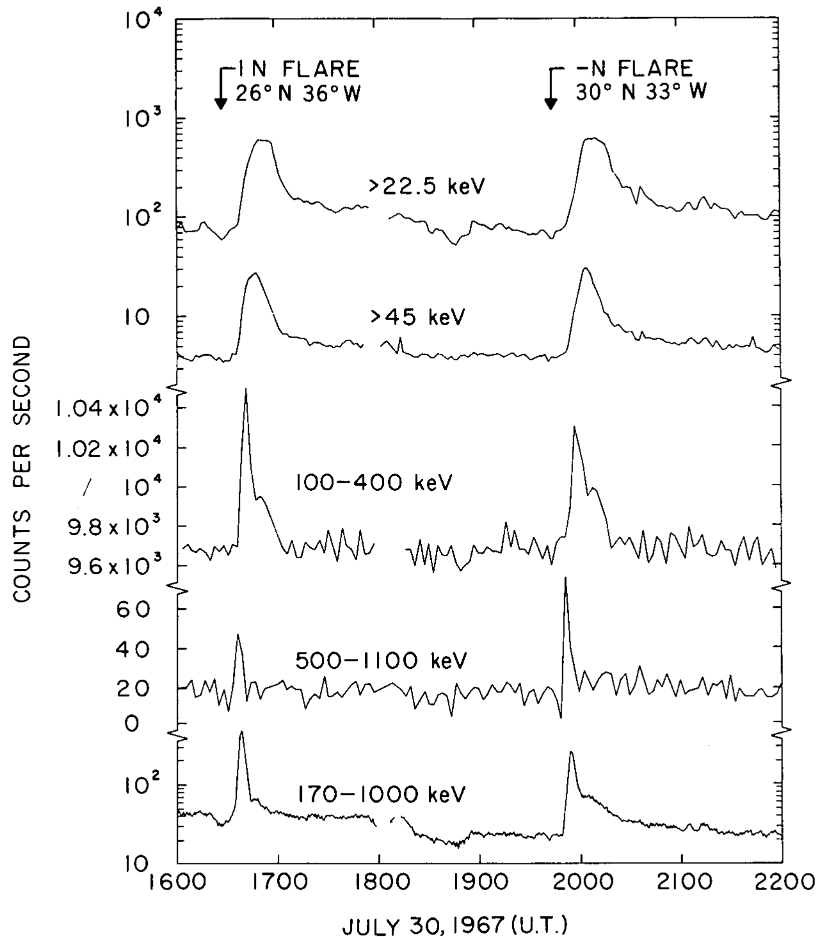

Figure 1—The intensity-time profile of two scatter-free electron events from McMath plage region 8905. The effect of velocity dispersion for different energy channels is obvious from this plot.

suggests that magnetic field structures near the Sun play a dominant role in the propagation of these electrons.

(3) The velocity dispersion of the scatter-free electrons is very clean. For the two events shown in Figure 1 these electrons were observed to have equal distance of travel regardless of their energies (i.e., the electron speed is inversely proportional to the transit time). The derived electron release times near the Sun coincide with times of type III radio bursts. The distance of travel from the Sun to the Earth is ~1.3 AU.

(4) The duration times of the two events of Figure 1 could be almost entirely accounted for by velocity dispersion caused by finite energy windows of the detectors. There is a possible continuous near-Sun electron emission of up to ~3 min.

(5) The energy spectrum of the scatter-free electrons over the energy range of 20 to 1600 keV is best represented by $\propto e^{-E/E_0}$. There is no strong dependence of E_0 upon the position of the associated flare. E_0 is found to be ~70 ± 20 keV.

(6) The anisotropy averaged over the duration of the scatter-free electrons for the events in Figure 1 is found to be $\lesssim 50$ percent. On the other hand, if these electrons are scatter free in their interplanetary propagation, a highly anisotropic pitch-angle distribution is expected. During the period of observation, however, the distance of the Earth bow shock was unusually far away (> 20 Earth radii (Fairfield, 1971)). It was suggested that upstream waves such as those observed by Fairfield (1969) could have been responsible for the small anisotropy in the pitch-angle distribution.

(7) Immediately following the scatter-free peak in a given event, there are electrons that experience a fair amount of scattering in the interplanetary medium. Even for the two most ideal events shown in Figure 1, the scattered electrons are clearly present.

(8) The mean free path of interplanetary scattering for the scattered electrons is found to decrease with increasing energy. Typical mean free paths are $\sim 3 \times 10^{13}$ and $\sim 10^{13}$ cm for 22- to 45- and 500- to 1100-keV electrons, respectively. These mean free paths do not appear to differ appreciably for all the events occurring within the open cone of propagation.

In this paper we point out that the coronal transport of the scatter-free electrons of energies equal to or greater than 200 keV appears to be different from that of the low-energy electrons (22 to 45 keV). We show that there is a time delay of the 200- to 1000-keV electrons with respect to the 22- to 45-keV electrons for flare events originating from locations other than ~50° W heliolongitude (which presumably is the foot of the interplanetary magnetic field line leading to Earth). Furthermore, the duration of 200- to 1000-keV scatter-free electrons is observed to depend on the heliolongitude of the associated flare, being longer the further away the position of the associated flare is from ~50° W. We suggest that the electrons of energy equal to or greater than 200 keV may experience some scattering in the solar corona on their way out to the interplanetary medium. A simple two-dimensional equation (Axford, 1965; Reid, 1964) is applied to fit the observed heliolongitudinal dependence of both time delay and duration excess (which cannot be accounted for by the velocity dispersion in transit from the Sun to the Earth) of 200- to 1000-keV electrons. Finally, we discuss the results obtained from diffusion theory and their possible relation to the earlier release of 20- to 200-keV flare-associated electrons observed in some of the diffusive-type events[4] (Lin, 1970*b*; Lin and Anderson, 1967).

The electron responses of the detector systems have already been discussed in detail elsewhere[5] (Lin, 1970*b*).

OBSERVATIONAL RESULTS

Scatter-Free Electron Events From McMath Plage Region 8905

Lin (1971*c*) has studied this active region rather extensively. He found that, in addition to impulsive electron and proton events associated with solar flares, there was a general enhancement in the low-energy electron population near the Earth during the period from July 21 to August 8 when the region was within ~90° E and ~140° W of central meridian. There were three flare-associated proton

[4]See Footnote 1, page 1.
[5]See Footnotes 1 and 2, page 1.

events, and the enhancement in proton intensity during the period from July 24 to August 8 was also observed.[6] The general feature of the particle phenomena associated with this active region is similar to those reported by Fan et al. (1968) and by Anderson (1969).

A total of 16 electron events associated with this plage region was observed by Lin (1970*c*) from both IMP 4 and AIMP 2. Two of these events occurred outside the open cone of propagation and, therefore, had no associated scatter-free electron peaks. Three other events occurred when IMP 4 was near perigee and so were observed only by AIMP 2. Only the remaining 11 scatter-free electron events, which were seen by detectors on IMP 4, will be discussed. Table 1 summarizes some information on those events and the associated solar parameters. We note that there is a close association between the electron events and the type III bursts except for events 1 and 11 where information on radio waves is not available. This close relationship between electron emission and type III burst has already been reported by Lin (1970*b*) and was expected from the theory on the excitation of plasma waves in the solar corona (Wild et al., 1963).

Not all the observed scatter-free electron events were as ideal as the two shown in Figure 1, however. For example, the 170- to 1000-keV scatter-free electron intensity from event 3 listed in Table 1 was observed to fluctuate so that the time of maximum intensity could only be approximately determined. This intensity fluctuation was also observed in 22- to 45-keV electrons for event 1. (See Lin, 1970*c*, Figure 6a.) The time of maximum electron intensity and the duration FWHM in these cases would have to be estimated.

Times of Electron Onset and Maximum Intensity

For convenience of presentation, we shall define the following terms:

transit time = the difference in times of the maximum intensity in 10-cm radio burst and the electron onset.

Δt_{onset} = the time difference in the 22- to 45-keV and 170- to 1000-keV electron onsets.

Δt_{max} = the difference in times at which the 22- to 45-keV and 170- to 1000-keV electron maximum intensities occur.

The transit times of electrons of energy greater than 22 keV for all 16 events from region 8905 were examined in detail by Lin (1970*c*). He found that within the open cone of propagation there was no strong dependence of transit time upon the position of the solar flare. To see whether there is any difference in the propagation of the higher energy electrons with respect to the lower energy ones, we plot in Figure 2 both Δt_{onset} and Δt_{max} as functions of the heliolongitude of the associated flare. It is clear that there is no strong dependence of Δt_{onset} and, therefore, the transit time of 170- to 1000-keV electrons on the position of the associated flare. On the other hand, Δt_{max} shows a clear dependence on the flare position, although the uncertainty in Δt_{max} for each data point is not small. A typical value of Δt_{max} is ~18 min near ~50° W and ~13 min at ~10° and ~90° W heliolongitudes. This variation of Δt_{max} with flare position is shown in the appendix not to be the result of the

[6] F. B. McDonald, M. Van Hollebeke, and J. R. Wang, private communication.

Table 1—Scatter-free electron events from McMath plage region 8905.

Event	Date	Electron Observations				Associated Flare[a]					Type III Bursts[b]	
		22 to 45 keV		170 to 1000 keV		IMP	Onset (U.T.)	Maximum (U.T.)	Location		Start Time (U.T.)	End Time (U.T.)
		Onset (U.T.)	Maximum (U.T.)	Onset (U.T.)	Maximum (U.T.)				°N	°W		
1	July 29	0836	0840 to 0855	0826	0830 to 0836	1B	0820	0827	25	12	not available	
2	July 29	1546	1600	1536	1542	1N	1500	1520	25	16	1515	1532
3	July 29	1945	1954	1934	1942 to 1955	-F	1913	1916	31	04	1926	1935
4	July 29	2006	2015	1958	2003	1B	1939	1948	20	20	1942	2003
5	July 30	0222	0230	0213	0220	-N	0151	0156	24	18	0203	0213
6	July 30	0526	0534	0516	0521	1B	0510	0517	24	27	0509	0516
7	July 30	1644	1655	1634	1638	1N	1615	1636	26	36	1623	1639
8	July 30	2002	2014	1950	1954	-N	1945	1955	30	33	1937	1955
9	July 31	2138	2149	2128	2131	1B	2047	2115	19	50	2121	2128
10	August 2	1752	1802	1740	1746	1N	1726	1732	26	74	1729	1732
11	August 3	0943	0948 to 1000	0933	0942	1B	0915	0925	27	85	not available	

[a]Obtained from ESSA monthly reports on solar-geophysical data.
[b]Classification according to *Quarterly Bulletin of Solar Activity*.

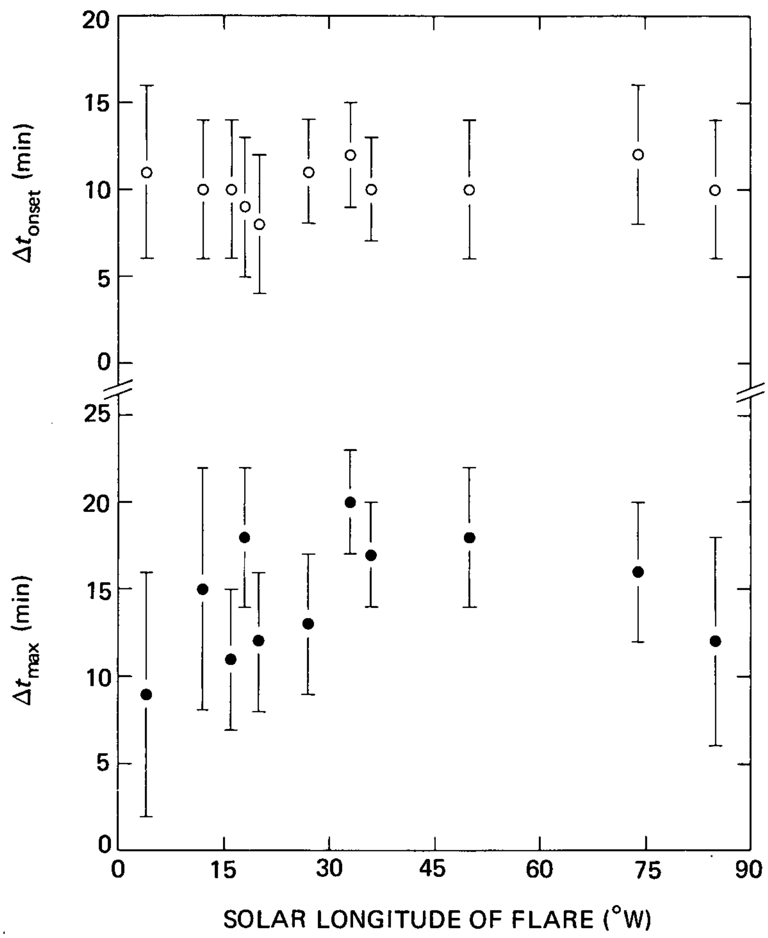

Figure 2—The differences in times of both electron intensity onsets Δt_{onset} and maxima Δt_{max} at energy channels of 22 to 45 keV and 170 to 1000 keV are plotted as functions of the heliolongitude of the associated flare. Although there is no strong dependence of Δt_{onset} upon flare position, Δt_{max} shows a systematic variation with the heliolongitude of the flare.

possible changes in the electron energy spectrum with flare longitude and, therefore, in the energy responses of the detectors.

The Duration of the Scatter-Free Electrons

Δt_{max} is not the only parameter that depends upon the heliolongitude of the associated flare. The observed duration of 170- to 1000-keV scatter-free electrons also shows the same effect. In Figure 3 we show the duration FWHM of the 170- to 1000-keV electron intensity plotted against the flare position. The variation of FWHM with the heliolongitude of the associated flare is quite obvious from the figure. Near 50° W, FWHM is typically ~4 min, while at ~10° or ~90° W, it increases to

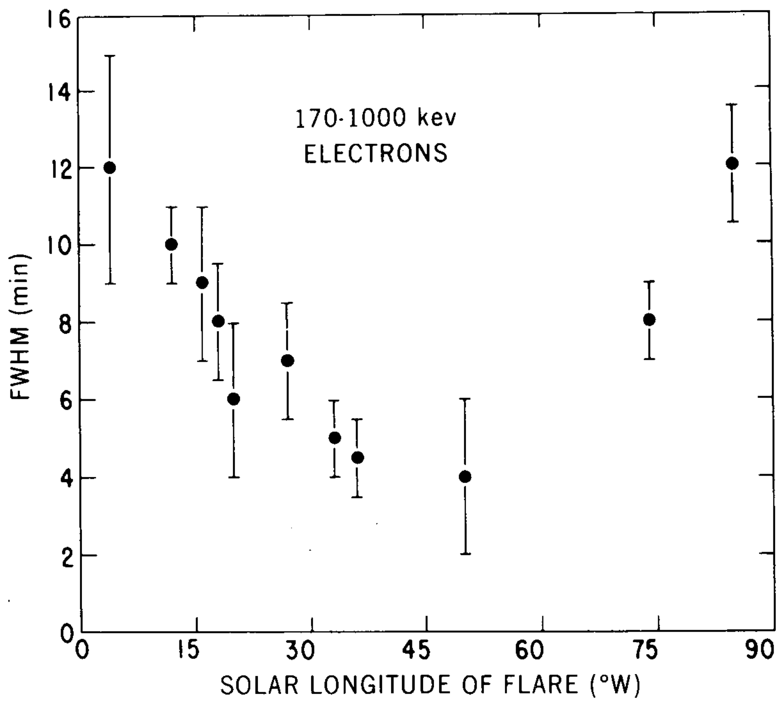

Figure 3—The duration FWHM of the 170- to 1000-keV scatter-free electrons is plotted as a function of the heliolongitude of the associated flare. There is a clear dependence of the event duration upon the flare position.

~12 min. This strong dependence of FWHM on flare longitude does not appear to be shared by electrons of energy greater than 22 keV within the open cone of propagation which, for this active region, covers a heliolongitude range from ~10° to ~80° W (Lin, 1970*c*).

The FWHM as well as the times of electron onset and maximum intensity in the energy channels of 100 to 400 keV and 500 to 1100 keV are not analyzed here because of detector sensitivity. Of the 11 scatter-free electron events listed in Table 1, only 5 of them were observed to show distinct electron intensity increase above the background of detection in these two energy channels.[7] However, a detailed analysis, for the energy range of 500 to 1100 keV, on both scatter-free and scattered electrons from those five events, implies a dependence of FWHM upon the flare position[8] similar to that shown in Figure 2. This further enhances the unique features of scatter-free electrons of energy greater than 200 keV.

The observed systematic variations of both Δt_{max} and FWHM with flare longitude strongly suggest that the origin of these electrons is relatively close to the flare site and that the electrons of energy greater than 200 keV and the 22- to 45-keV electrons propagate rather differently in the solar corona. First, we note that the 22- to 45-keV electrons from solar flare located far from ~50° W are not likely

[7]See Footnotes 2 and 3, page 1.
[8]See Footnote 3, page 1.

to be released earlier than those from flare near ~50° W. It is perhaps reasonable to regard the observed decrease in Δt_{max} as the result of retardation of 170- to 1000-keV electrons with respect to 22- to 45-keV electrons. Second, the FWHM of 170- to 1000-keV electrons originating from solar flares near 50° W heliolongitude could mostly be accounted for by velocity dispersion.[9] A reasonable model of coronal transport for these scatter-free electrons has to be able to interpret the observed pattern in the time delay and the excess of FWHM (other than that caused by velocity dispersion) displayed by 170- to 1000-keV electrons. In the following two sections, we shall propose such a model and discuss its consequences.

CORONAL TRANSPORT OF THE SCATTER-FREE ELECTRONS

There is evidence, both observational and theoretical, that the diffusion coefficient perpendicular to the prevailing interplanetary magnetic field lines is small for low-rigidity particles (Anderson, 1969; Jokipii, 1967; Krimigis et al., 1971; Lanzerotti, 1969; O'Gallagher, 1970; O'Gallagher and Simpson, 1966). Because the gyroradius of electrons of energy less than or approximately equal to 1 MeV is only $\lesssim$ 350 km for a magnetic field strength of 5γ, we do not expect these electrons to diffuse easily across the magnetic field lines, especially when they are scatter free. Therefore, it is reasonable to assume that the scatter-free electrons discussed in the previous section, after being accelerated near the flare site, have direct access to the location around the foot of the interplanetary magnetic field line extending to Earth. Then, they simply follow the field lines and propagate outward from the Sun.

It is likely that the conditions in both solar corona and the interplanetary medium must be right in order to have scatter-free electrons. However, the observed variations of both Δt_{max} and FWHM with the flare position shown in Figures 2 and 3 could most easily be interpreted in terms of a reasonable model of coronal transport. On the basis of the known features and results summarized previously, we shall assume the following highly idealized model for the coronal transport of the scatter-free electrons (see Figure 4):

(1) There is an open magnetic field line configuration of ~80° in longitude range, with ~40° on each side of plage region 8905, similar to Figure 11 of Fan et al. (1968). The longitude range the energetic electrons have access to may be wider to account for the observed enhancement of low-energy electron population in interplanetary space during the period from July 21 to August 8 (Lin, 1970*c*), but beyond ~40° on either side of the active region, the model of coronal diffusion such as that suggested by Anderson (1969) could be satisfactory. The possible loop structures in the coronal magnetic field[10] are neglected.

(2) Immediately after being accelerated, the 22- to 45-keV electrons escape from the lower solar atmosphere along the magnetic field lines. The electrons of energy approximately equal to or greater than 200 keV would follow the same paths but, in addition, are scattered by the magnetic field irregularities on the way out. The scattering is assumed to be frequent enough so that the problem could be treated by simple diffusion theory.

(3) The region of the solar atmosphere through which the electrons escape or diffuse is thin compared to the dimensions of the Sun; therefore, a two-dimensional diffusion equation

[9]See Footnote 2, page 1.
[10]K. H. Schatten: "Current Sheet Magnetic Model for the Solar Corona," *Cosmic Electrodyn.*, to be published.

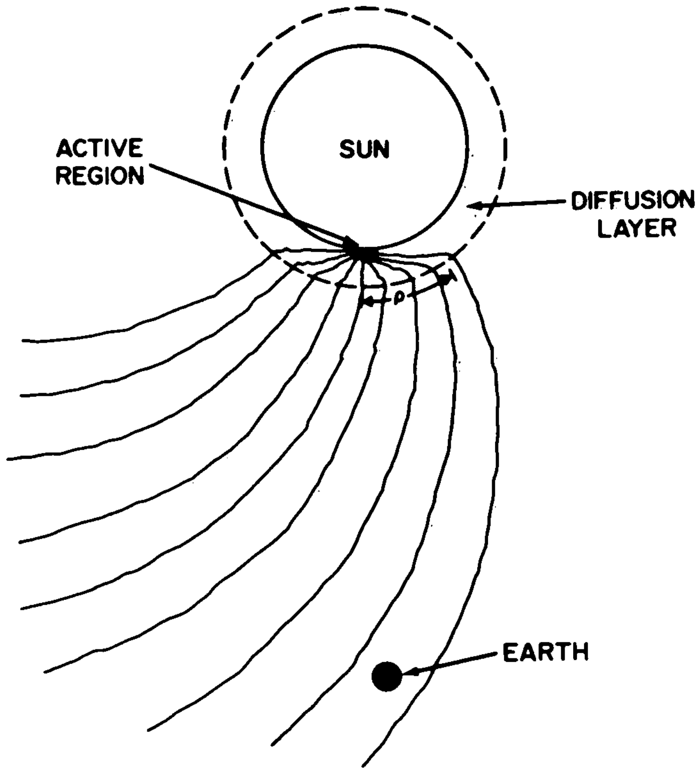

Figure 4—A proposed model of the magnetic field configuration of the active region that gives rise to the scatter-free electron events discussed in the text. The dashed circle concentric with the Sun defines the boundary of the diffusion layer.

could be applied (Axford, 1965; Reid, 1964). The effect caused by curvature of the diffusion layer is neglected.

(4) The intensity of the 170- to 1000-keV electrons observed near the Earth, when extrapolated back to the Sun after the velocity dispersion caused by interplanetary propagation is taken into account, is assumed to be proportional to surface density $U(\rho, t)$, ρ being the distance from the flare site to location near 50° W heliolongitude.

With this model of coronal transport, and neglecting the loss of electrons along the path (which is irrelevant to the following discussion), the solution of the two-dimensional diffusion equation (Axford, 1965; Reid, 1964), with an impulsive source at $\rho = 0$ and $t = 0$, is

$$U(\rho, t) = \frac{A}{t} \exp\left(-\frac{\rho^2}{4\kappa t}\right) \tag{1}$$

Here κ is the isotropic diffusion coefficient for 170- to 1000-keV electrons, which is assumed to be constant over the region of interest, and A is a parameter related to the initial number of electrons released at the origin of the flare.

For illustrative purposes, we have plotted in Figure 5 both the calculated FWHM and the time t_{max} at which maximum surface density $U(\rho, t_{max})$ occurs as functions of κ. Two values of ρ have been used in the plot; they are 3×10^{10} and 5×10^{10} cm, which correspond to the heliolongitudinal range of ~25° and ~41°, respectively. The calculated FWHM is to be compared with the excess of the observed FWHM for events originating from locations other than ~50° W. In this case, t_{max} may be regarded as equivalent to Δt_{max} in our idealized model because the direct transit time of 22- to 45-keV electrons from flare site to ~50° W is negligible. By comparing Figures 2, 3, and 5, the value of κ could readily be estimated. For example, from Figures 2 and 3 the observed changes in Δt_{max} and FWHM are, respectively, ~5 min and ~9 min over a longitudinal range of ~41°. These changes in Δt_{max} and FWHM immediately place the value of κ in the range from 2×10^{18} to 5×10^{18} cm²/s.

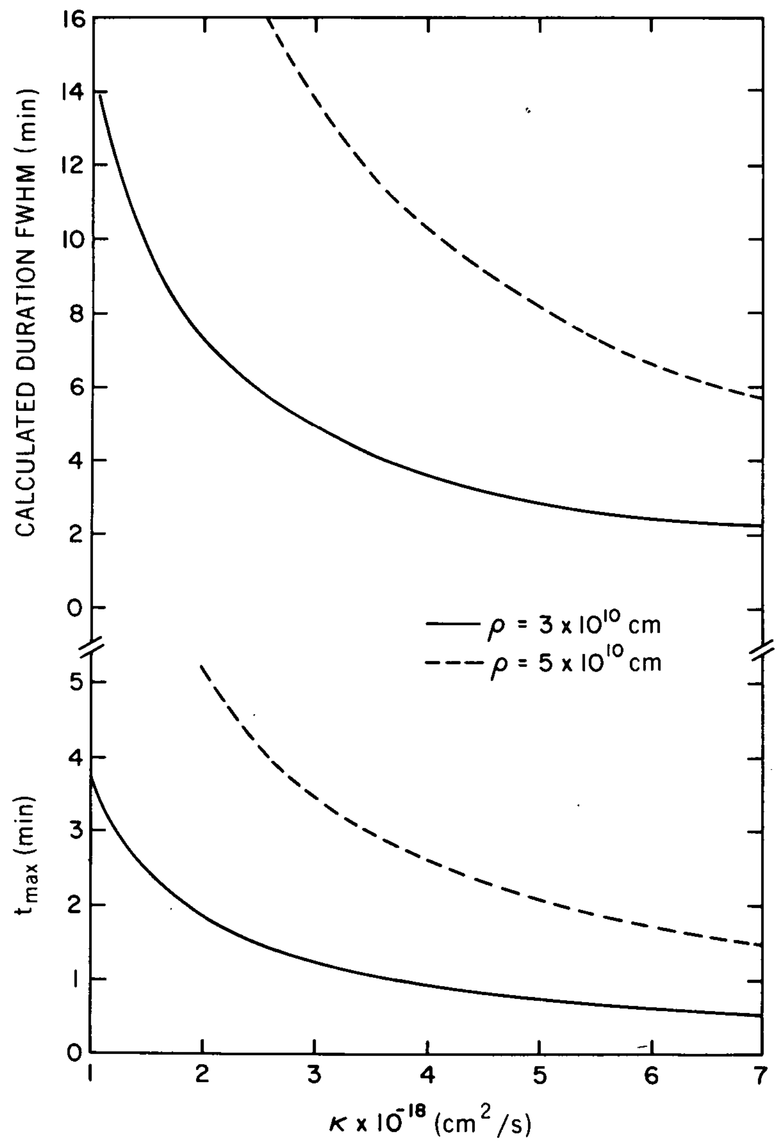

Figure 5—The duration FWHM and t_{max} as calculated from Equation 1 are shown here as a function of the diffusion coefficient κ. Two values of ρ are used in the plot.

A comparison of the variations of the calculated and observed FWHM and Δt_{max} is shown in Figure 6. The observed FWHM and Δt_{max} in this plot were the same as those in Figures 2 and 3. The two smooth curves were derived from Equation 1 with $\kappa = 3 \times 10^{18}$ cm^2/s. It is clear that the agreement between the calculated and the observed FWHM and Δt_{max} is reasonably good, although a stronger dependence of Δt_{max} upon heliolongitude of flare is implied from the observed data points.

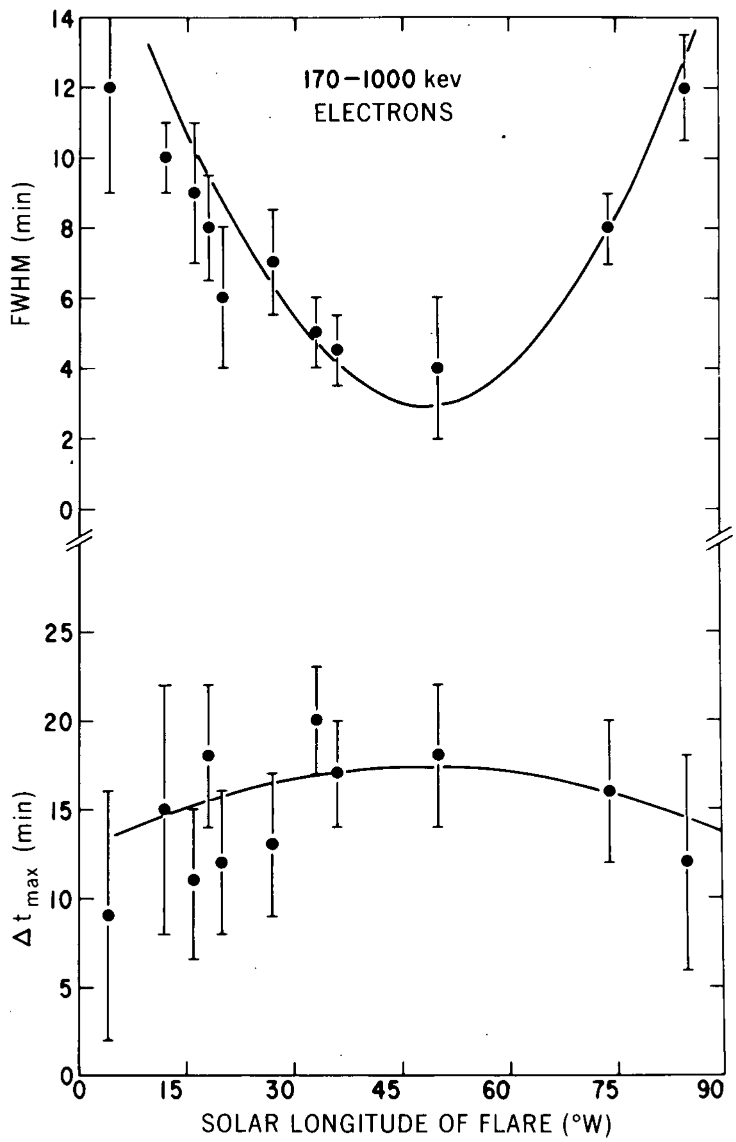

Figure 6—The measured duration FWHM (170 to 1000 keV) and Δt_{max} of the scatter-free electrons as a function of flare longitude are replotted here for comparison with the results derived from two-dimensional diffusion theory. The two solid lines show the expected variations of duration FWHM and Δt_{max} with flare position if the diffusion coefficient is 3×10^{18} cm^2/s.

Equation 1 also implies a weak dependence of Δt_{onset} upon the longitude of the associated flare. This is to be illustrated in the following example. For 9 out of 11 events in Table 1, the maximum intensity of the 170- to 1000-keV scatter-free electrons is at least 10 times higher than the intensity level at onset. Assuming an extreme case with $\kappa = 2 \times 10^{18}$ cm^2/s and $\rho = 5 \times 10^{10}$ cm, Equation 1 gives a time t_1 of ~1 min at which the density $U(\rho, t_1)$ is 0.1 times the maximum density $U(\rho, t_{max})$; t_1 could be regarded as a close estimate on the expected change of Δt_{onset} for events at ~10° or ~90° W with respect to ~50° W heliolongitude. A 1-min change in Δt_{onset} over the longitudinal range of ~40° is clearly consistent with the data shown in Figure 2. Thus, our model of coronal transport appears to be able to explain the observed features of the scatter-free electron events.

DISCUSSION

Scattering Mean Free Path for 200- to 1000-keV Electrons in the Solar Corona

We feel that direct field line connections between the flare site and the location near ~50° W are necessary to have rapid transit of the scatter-free electrons that are subsequently observed near the Earth. In addition, we require the existence of the magnetic field irregularities with scale sizes comparable to the gyroradius of electrons of energy greater than 200 keV along the field lines so that these electrons are scattered slightly on their way out to the interplanetary medium. As a result of this scattering, the bulk electron propagation (as reflected by peak intensity) slows down and FWHM increases. It is likely that, in contrast to our idealized model of coronal transport, the 22- to 45-keV electrons also suffer some scattering in the solar corona. However, in view of the observed pattern of Δt_{max} shown in Figure 2 and the lack of strong dependence of FWHM upon flare position within the open cone of propagation (Lin, 1970*c*), κ of 22- to 45-keV electrons may be considerably greater than that of 200- to 1000-keV electrons.

The diffusion coefficient for 200- to 1000-keV electrons derived from the previous section is ~3×10^{18} cm^2/s. Because $\kappa = \frac{1}{3} v\lambda$ from diffusion theory (v = electron speed), the mean free path λ for these electrons is ~3.5×10^8 cm. The collision time τ is then on the order of 10^{-2} s. For a solar flare occurring at a distance greater than $\rho \sim 10^{10}$ cm (equivalent to a heliolongitude range of ~8°), the time delay of the bulk electrons is on the order of 10 s or more. This is much longer than τ and the direct transit time ($= \rho/v \sim 0.4$ s for $\rho = 10^{10}$ cm). Thus, the treatment by the diffusion theory in the previous section is approximately valid (Fisk and Axford, 1969).

As previously mentioned, the 170- to 1000-keV electrons are scattered by the magnetic field irregularities in the solar corona. This is perhaps a reasonable presumption because the electron-electron or electron-proton collision is not an efficient scattering process even for a plasma density as high as ~10^9 electrons (or protons)/cm^3. For example, to deflect the fast-moving electrons by 90° or more, the deflection time (Spitzer, 1962) would have to be

$$t_D = \frac{v^3 m^2}{8\pi e^4 n \ln \Lambda[\phi(lv) - G(lv)]} \tag{2}$$

where m and e are respectively the mass and charge of electrons and n is the ambient plasma density. Both $\ln \Lambda$ and $\phi(lv) - G(lv)$ were tabulated by Spitzer (1962). For $n = 10^9$ electrons/cm^3, coronal temperature = 10^6 K, and electron speed $v \cong 2 \times 10^{10}$ cm/s, ln $\Lambda = 19.3$ and $\phi(lv) - G(lv) \cong 1$. Putting these values into Equation 2 yields $t_D \cong 300$ s, which is much too long to be considered in our model. Furthermore, t_D increases rapidly with v, which, in contradiction with observations, suggests a larger κ for higher energy electrons.

Comparison With Other Related Studies

Recently, Fisk and Schatten[11] discussed an efficient mechanism on the transport of cosmic rays in the solar corona. They argued that streams of energetic particles may drift at nearly their propagation speed along the current sheets separating discontinuous field structures in the corona. Whereas this mechanism may provide an efficient way to transport relativistic electrons or protons of energies greater than 1 MeV in the lower corona, it is perhaps not rapid enough to be responsible for the transport of scatter-free electrons of energies equal to or less than 1 MeV discussed in the previous sections. For example, the gyroradius for a 30-keV electron in a 10^{-4}-T (1-G) field is only ~600 cm; the characteristic thickness of the current sheets would have to be $\lesssim 600$ cm, which is unlikely, in order to have the process of "current-sheet diffusion" operating efficiently. Furthermore, it is difficult to interpret in terms of this process the observed time delay of the 200- to 1000-keV electrons with respect to the 22- to 45-keV electrons when they originate from locations other than ~50° W heliolongitude.

A recent report by Simnett (1971) suggested that the scatter-free electrons discussed previously were not directly associated with the solar flares listed in Table 1, but were previously accelerated and trapped in the upper corona. The release of these electrons was then triggered by the flare. Whereas the storage of energetic particles in the corona is perhaps possible and is a useful model in the interpretation of delayed and/or recurrent particle events (Anderson, 1969; McDonald and Desai, 1971; Simnett, 1971; Simnett and Holt, 1971), it does not give a satisfactory explanation to certain observed features of scatter-free electron events. For if the electrons were indeed trapped in the upper corona, the release of more than 170 keV relative to 22- to 45-keV electrons should not depend upon the flare location, and the systematic pattern of Δt_{max} and FWHM shown in Figures 2 and 3 should not be observed. We feel that it is more natural and satisfactory to explain the observed features in terms of our model.

The observed time delay of higher energy electrons with respect to the lower energy ones discussed in the previous sections is not necessarily restricted to events that are scatter free. In fact, Lin and Anderson (1967), Lin (1970*b*), and Sullivan[12] have reported evidences of an earlier, near-Sun release of low-energy electrons in some flare-associated diffusive-type particle events. It is very likely that there may be some relation between these scatter-free and diffusive-type electron events. For example, if we assume that the diffusive-type electron events are simply the extension of the scatter-free electron events, differing only in the extent of direct field-line connections between the flare site and the feet of the interplanetary magnetic field lines, then the observed delay in the release of higher energy electrons with respect to the lower energy ones reported by Lin and Anderson (1967), Lin (1970*b*), and Sullivan[13] follows naturally from our model. The magnetic field structures are perhaps very entangled

[11] L. A. Fisk and K. H. Schatten: "Transport of Cosmic Rays in the Solar Corona," *Solar Phys.*, to be published.

[12] See Footnote 1, page 1.

[13] See Footnote 1, page 1.

for those diffusive-type events and the accelerated energetic electrons are expected to suffer extensive scattering in the solar corona. As a result of this extensive scattering and the increasing diffusion coefficient with decreasing energy (for electrons of energy approximately equal to or less than 1 MeV) implied by the analysis of the previous sections, the higher energy electrons may show a time delay with respect to the lower energy ones even at the onset of a given event. An immediate consequence from this process is that the particle release near the Sun may be continuous over a time interval of up to several tens of minutes.

It has been suggested[14] that, for diffusive-type events, earlier injection of low-energy electrons might imply a two-step or a single, evolutionary process for electron acceleration. There is also evidence (Lin, 1970*b*) that acceleration of low-energy electrons may be quite different from high-energy ones. Although any one of these acceleration processes may very well occur, we feel that the effect of electron transport on the solar corona should not be neglected. It is also likely that both the acceleration processes and the coronal diffusion have contributed to the observed phenomenon.

SUMMARY

The difference in times at which the observed maximum intensity for 22- to 45-keV and 170- to 1000-keV scatter-free electrons occurs is shown to vary with the longitude of the associated flare. It is the largest (~18 min) for events near 50° W heliolongitude and gradually decreases for events occurring on either side of ~50° W.

The duration FWHM obtained from the intensity-time profile of 170- to 1000-keV scatter-free electrons shows a strong dependence on the position of the associated flare. Typical FWHM is ~4 min for events near 50° W and ~13 min for events near 10° and 90° W.

As a result of the preceding data, we propose a two-dimensional diffusion model in the solar corona to account for the observed features of 170- to 1000-keV electrons. The diffusion coefficient for these electrons is estimated to be $\sim 3 \times 10^{18}$ cm^2/s.

The results of our present study, when extended to the case of diffusive-type solar-electron events, could also explain the delayed release of higher energy electrons with respect to the lower energy ones, which has been observed and reported in the literature.

ACKNOWLEDGMENTS

The author is grateful to Dr. F. B. McDonald for his cooperation in the use of laboratory facilities at Goddard Space Flight Center. The author thanks Dr. J. A. Simpson, Dr. K. A. Anderson, and Dr. R. P. Lin for supplying data used in this analysis and Dr. R. P. Lin and Dr. L. A. Fisk for their critical review of this manuscript. Dr. K. C. Hsieh and Dr. J. D. Sullivan provided detailed information on the electron response of the University of Chicago cosmic-ray telescope in the energy range of 170 to 1000 keV.

[14]See Footnote 1, page 1.

Appendix

The electron response of a given detector is not very sensitive to the change in the electron energy spectrum. To illustrate this point, we shall define the effective energy response $\bar{E}$ of a given detector as

$$\bar{E} = \frac{\int_{E_{\min}}^{E_{\max}} J(E)\, E\, \mathrm{Eff}(E)\, dE}{\int_{E_{\min}}^{E_{\max}} J(E)\, \mathrm{Eff}(E)\, dE} \tag{A-1}$$

where $J(E)$ and $\mathrm{Eff}(E)$ are, respectively, the electron differential energy spectrum and the electron efficiency of the detector. $E_{\min}$ and $E_{\max}$ refer, respectively, to the lower and upper energy cutoffs of the detector response. Assuming $J(E) = Ae^{-E/E_0}$ and with $\mathrm{Eff}(E)$ known from detector calibration,[15] $\bar{E}$ and, therefore, effective particle speed $\bar{v}$ and transit time t can be derived. Because $dt \propto d\bar{v}/\bar{v}^2$ for a fixed distance of travel (~1.3 AU from the Sun to the Earth), it would be sufficient to examine this effect only for the 22- to 45-keV electrons. We find that a change of the characteristic energy E_0 from 70 keV to 300 keV is required to produce a corresponding change in t for 0.5 min. From the spectral measurements of all available events listed in Table 1, there is no evidence of drastic change in the energy spectrum with flare position ($E_0 \cong 70 \pm 20$ keV and is approximately independent of flare position.[16]) Therefore the observed variation in $\Delta t_{\max}$ with flare longitude shown in Figure 2 must be caused by factors other than the change in E_0.

[15]See Footnote 2, page 1.
[16]See Footnote 3, page 1.

PRECEDING PAGE BLANK NOT FILMED

REFERENCES

Anderson, K. A. 1969, "Electrons and Protons in Long-Lived Streams of Energetic Solar Particles." *Solar Phys.* **6**:111.

Anderson, K. A.; and Lin, R. P. 1966, "Observations on the Propagation of Solar-Flare Electrons in Interplanetary Space." *Phys. Rev. Lett.* **16**:1121.

Axford, W. I. 1965, "Anisotropic Diffusion of Solar Cosmic Rays." *Planet. Space Sci.* **13**:1301.

Cline, T. L.; and McDonald, F. B. 1968, "Relativistic Electrons From Solar Flares." *Solar Phys.* **5**:507.

Datlowe, D. 1971, "Relativistic Electrons in Solar Particle Events." *Solar Phys.* **17**:436.

Fairfield, D. H. 1969, "Bow Shock Associated Waves Observed in the Far Upstream Interplanetary Medium." *J. Geophys. Res.* **74**:3541.

Fairfield, D. H. 1971, "Average and Unusual Locations of the Earth's Magnetopause and Bow Shock." *J. Geophys. Res.* **76**:6700.

Fan, C. Y.; Pick, M.; Pyle, R.; Simpson, J. A.; and Smith, D. R. 1968, "Protons Associated With Centers of Solar Activity and Their Propagation in Interplanetary Magnetic Field Regions Co-rotating With the Sun." *J. Geophys. Res.* **73**:1555.

Fisk, L. A.; and Axford, W. I. 1969, "Anisotropies of Solar Cosmic Rays." *Solar Phys.* **7**:486.

Jokipii, J. R. 1967, "Cosmic Ray Propagation," Pt. 2, "Diffusion in the Interplanetary Magnetic Field." *Astrophys. J.* **149**:405.

Krimigis, S. M.; Roelof, E. C.; Armstrong, T. P.; and Van Allen, J. A. 1971, "Low Energy ($\geqslant$0.3 MeV) Solar Particle Observations at Widely Separated Points ($>$0.1 a.u.) During 1967." *J. Geophys. Res.* **76**:5921.

Lanzerotti, L. J. 1969, "Low-Energy Solar Protons and Alphas as Probes of the Interplanetary Medium: The May 28, 1967, Solar Event." *J. Geophys. Res.* **74**:2851.

Lin, R. P. 1970*a*, "Observations of Scatter-Free Propagation of ~40 keV Solar Electrons in the Interplanetary Medium." *J. Geophys. Res.* **75**:2583.

Lin, R. P. 1970*b*, "The Emission and Propagation of ~40 keV Solar Flare Electrons," Pt. 1, "The Relationship of ~40 keV Electrons to Energetic Proton and Relativistic Electron Emission by the Sun." *Solar Phys.* **12**:266.

Lin, R. P. 1970*c*, "The Emission and Propagation of ~40 keV Solar Flare Electrons," Pt. 2, "The Electron Emission Structure of Large Active Regions." *Solar Phys.* **15**:453.

Lin, R. P.; and Anderson, K. A. 1967, "Electrons > 40 keV and Protons > 500 keV of Solar Origin." *Solar Phys.* **1**:446.

McDonald, F. B.; and Desai, U. D. 1971, "Recurrent Solar Cosmic Ray Events and Solar M Regions." *J. Geophys. Res.* **76**:808.

Meyer, P.; and Vogt, R. 1962, "High-Energy Electrons of Solar Origin." *Phys. Rev. Lett.* **8**:387.

O'Gallagher, J. J. 1970, "The Heliocentric Longitude Intensity Profile of 15-MeV Protons From February 5, 1965, Solar Flare." *J. Geophys. Res.* **75**:1163.

O'Gallagher, J. J.; and Simpson, J. A. 1966, "Anisotropic Propagation of Solar Protons Deduced From Simultaneous Observations by Earth Satellites and the Mariner 4 Space Probe." *Phys. Rev. Lett.* **16**:1212.

Reid, G. C. 1964, "A Diffusive Model for the Initial Phase of a Solar Proton Event." *J. Geophys. Res.* **69**:2659.

Simnett, G. M. 1971, "The Release of Energetic Particles From the Sun." *Solar Phys.* **20**:448.

Simnett, G. M.; and Holt, S. S. 1971, "Long Term Storage of Relativistic Particles in the Solar Corona." *Solar Phys.* **16**:208.

Spitzer, L. 1962, *Physics of Fully Ionized Gases,* Interscience Pub.

Van Allen, J. A.; and Krimigis, S. M. 1965, "Impulsive Emission of ~40 keV Electrons From the Sun." *J. Geophys. Res.* **70**:5737.

Wang, J. R.; Fisk, L. A.; and Lin, R. P. 1971, "Observations of the Scatter-Free Solar-Flare Electrons in the Energy Range of 20-1000 keV." *Proc. 12th Inter. Conf. Cosmic Rays* **2**:438.

Wild, J. P.; Smerd, S. F.; and Weiss, A. A. 1963, "Solar Bursts." *Annu. Rev. Astron. Astrophys.* **1**:291.