SOLAR FLARE PARTICLE RADIATION

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I. INTRODUCTION

The sun is a source of copious fluxes of charged particles which escape into interplanetary space. These particles range in energy from the few keV solar wind particles to the several hundreds of MeV particles produced by the larger solar flares. There is even growing evidence that the sun may be a nearly continual emitter of low energy (several tens of keV) protons. This review is limited in that it concerns itself essentially entirely with the characteristics of the solar particles accelerated by solar flares and subsequently observed near the orbit of the earth.

The number of solar flares and the fluxes of energetic ($\gtrsim$ 20 MeV) solar particles observed at the earth varies in a manner similar to that of the sunspot number during the eleven-year solar cycle. This is illustrated by the data of Fig. 1 where the smoothed sunspot numbers for cycles 19 and 20 are plotted as a function of time. Also shown are histograms of the yearly integrated proton intensities for protons $\gtrsim$ 30 MeV for both solar cycles (A. J. Masley, private communication). These particle fluxes are obtained from riometer measurements of solar proton-produced PCA events in the polar-cap regions. The solar particle fluxes peaked in total intensity a year or more after the sunspot maximum during cycle 19. It remains to be seen if this same phenomenon holds during the current cycle.

This review discusses in order solar particle intensity-time profiles, the composition and spectra of solar flare events, and the propagation of solar particles in interplanetary space. The last section, dealing with the effects of solar particles at the earth, discusses riometer observations of polar cap cosmic noise absorption events and the production of solar cell damage at synchronous altitudes by solar protons.

II. INTENSITY-TIME PROFILES

Detectability Limits

The first observations of energetic particles due to solar production were the sea-level measurements of Lange and Forbush (1942), and Forbush (1946). Using shielded ionization chambers built to observe galactic cosmic rays, large enhancements in the chamber counting rates on 28 February 1942 (~1 day prior to a large magnetic storm), on 7 March 1942, and 25 August 1946 were observed. The development of the cosmic ray neutron monitor in the late 1940's and the super neutron monitor in the late 1950's and early 1960's have enabled many more solar particle increases to be observed on the ground. The neutron multiplicity monitor (Nobles et al., 1967) enables particle spectral information to be obtained from a single station.

Other pre-spacecraft observations of solar cosmic rays were made during the IGY period by polar cap radio absorption techniques (Bailey, 1957) and by balloon measurements. The balloon observations of Anderson (1958) provided the first direct identification of solar protons.

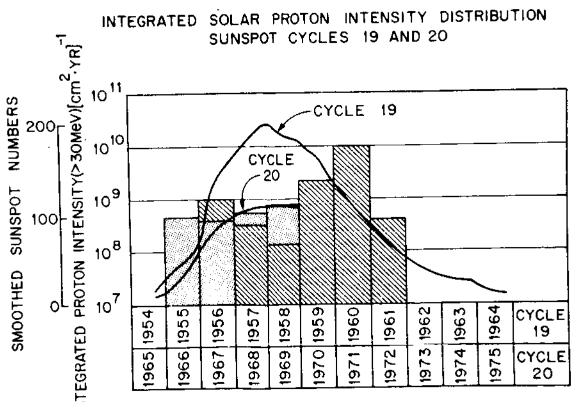

Fig. 1 Plot of the smoothed sunspot numbers for solar cycles 19 and 20 and histograms of the annual fluxes of solar protons (E > 30 MeV) for solar cycle 19 (shaded bars) and cycle 20 (dotted bars). Figure courtesy of A. J. Masley.

The neutron monitor has continued to be a valuable tool for the detection of energetic solar particles. The world-wide deployment of stations provide data for studying both the direction of incidence of the primary particles as well as their energy. An example of the difference in response to an event by super neutron monitors at two different energy (or rigidity) cut-off latitudes is shown in Fig. 2 for data measured during the 28 January 1967 solar event (Bukata et al., 1969). The vertical cut-off rigidity for the Churchill station is 1.0 GV (determined essentially entirely by the atmospheric cut-off) while that of Dallas, at mid-latitudes geomagnetically, is 4.35 GV.

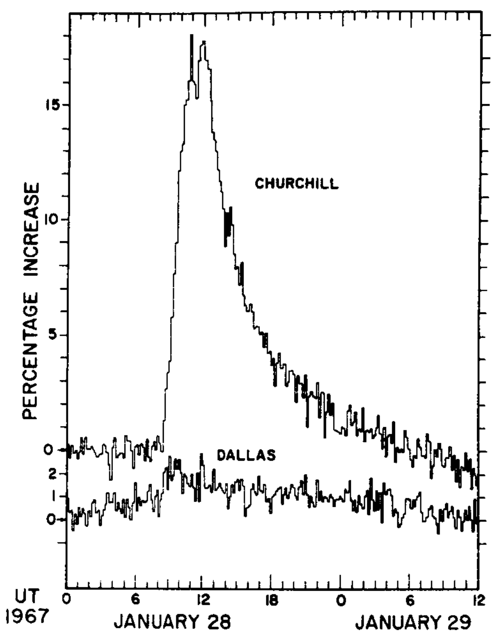

Fig. 2 Neutron monitor observations at Ft. Churchill and Dallas of the 28 January 1967 solar event

The time-intensity profile of the Churchill monitor response to the January 1967 event is quite typical of the classical, diffusive-like profiles recorded by high energy flare-particle detectors and will be discussed in more detail in Section V. In general in diffusive-like events, a rapid rise to the peak particle intensity is followed by a slower, exponential or power-law decay with time.

With the advent of instrumentation flown on spacecraft, the energy sensitivity threshold for the detection of solar particles was dramatically reduced. This reduction in the lower limit of the energy of particle detectability has continued until today measurements of 300-500 keV solar protons are routinely carried out. Accompanying this decrease in the energy sensitivity of particles that can be measured was an increase in the number of solar events that were observed. Furthermore, at the lower energies measured, the time histories of the events became complex with no simple relationships often evident between events.

The data plotted in Fig. 3 illustrates the enormous differences in the description of the interplanetary particle intensities that could be made during a one-month period depending upon the energy sensitivity limits available for analysis. The data were obtained by the solar proton monitoring experiment on the Explorer 41 satellite (C. O. Bostrom, private communication). If only the higher energy channel (E > 60 MeV) were available for analysis, only one large event (March 27) and a small event (March 24) would have been apparent. Although the decay times are longer, both of these events had a diffusive temporal appearance similar to the neutron monitor event of Fig. 2.

As the particle energy threshold in Fig. 3 is lowered, more solar events are detected. The event beginning on March 6 (when viewed in the E > 10 MeV channel) no longer has a diffusive shape. The solar fluxes in the 1-10 MeV channel of Fig. 3 are observed to remain above their background level through out the entire 31-day period plotted.

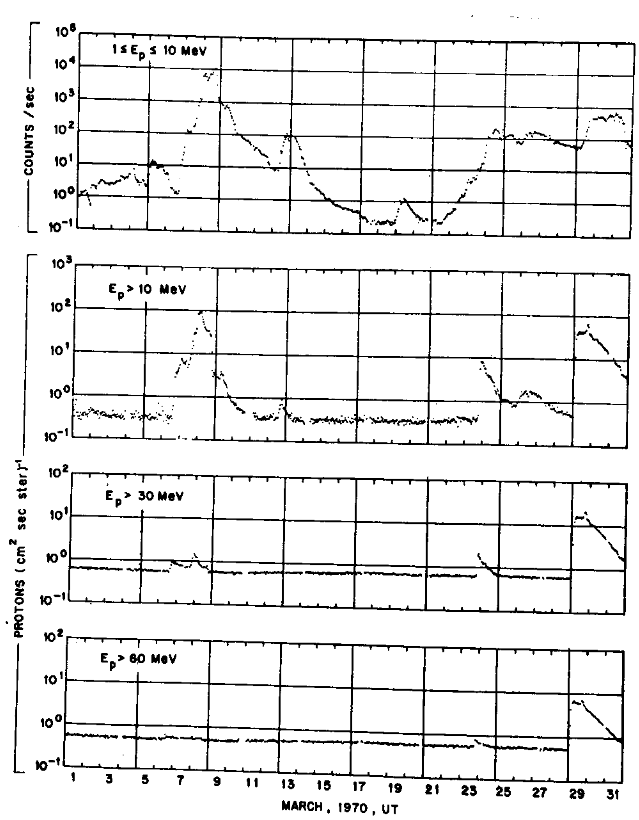

Figure 3. **Solar protons measured in interplanetary space by the solar proton monitoring experiment on Explorer 41 during March 1970. Data courtesy of C. O. Bostrom.**

Not all of the interplanetary particle enhancements result from discrete flare events. In general, flare-associated events occur in close association with solar X-ray and microwave emissions. Further, as noted above, the time-intensity profiles of flare-associated events tend to have a diffusive appearance. Three other types of particle enhancements, in addition to the flare-associated events considered in this paper, have been classified and discussed extensively in the literature. These are:

a) Particles associated with active centers: The onsets of these particles at the earth display no velocity dispersion and appear to be co-rotating with solar-active centers. Such enhancements have been observed to occur each solar rotation for many successive rotations (e.g., Fan et al., 1968; McDonald and Desai, 1971).

b) Recurrent events: These particle increases occasionally occur in the next solar rotation following a flare. They appear to originate from the same active region as that producing the flare (e.g., Bryant et al., 1965).

c) Energetic storm particles: Enhancements of low energy protons that appear for several hours around the time of occurrence of interplanetary shock waves (e.g., Axford and Reid, 1963; Bryant et al., 1965; Rao et al., 1967). Proton enhancements lasting for several minutes, apparently resulting from acceleration at the shock front, have been reported (e.g., Singer, 1970; Lanzerotti, 1969a, 1970a; Armstrong and Krimigis, 1970; Oglivie and Arens, 1971).

Although the three solar particle enhancements listed above are important for understanding solar processes and interplanetary propagation, they will not be elaborated upon here.

Data Organization

Although the intensity-time profiles of high energy flare particles are similar in their overall diffusive appearance, absolute differences as a function of particle energy are common. Cline and McDonald (1968) have shown that the time history of the high energy proton and electron fluxes from the 7 July 1966 solar flare is dependent upon particle velocity. This is evident in Fig. 4 where the observed-time profiles for three proton and one electron channel are plotted in Fig. 4a.

In Fig. 4b, the four particle flux channels have been normalized to their peak values and the abscissas have been transformed to represent the distance traveled from the flare occurrence.

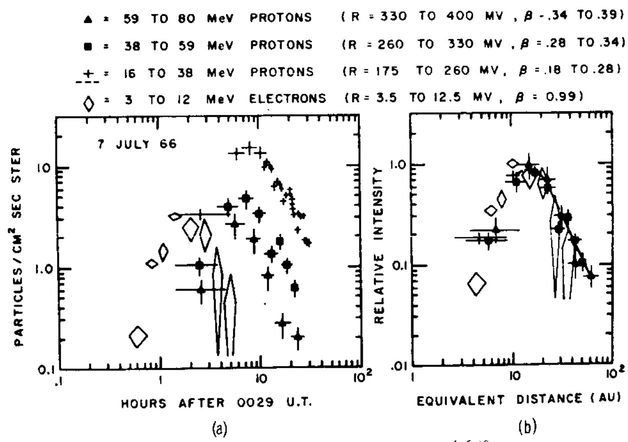

Fig. 4 (a) Profiles of the observed intensity of protons (16-38 MeV, 38-59 MeV, and 59-80 MeV) and electrons (>3 MeV) plotted versus time following the 7 July 1966 flare; (b) profiles of each particle channel relative intensity (I/I_{max}) plotted as a function of distance traveled ($x \cong vt$) where v is the mean velocity for each particle channel (Cline and McDonald, 1968).

Although the higher energy particle fluxes from this flare can be organized quite well by considerations of velocity-dependent travel, Lin (1970a) has shown that when electrons of energy > 45 keV from this event are included in the analysis, they show a broader curve than those in Fig. 4b. Furthermore, the E > 45 keV electrons appear to arrive earlier than the protons and electrons considered by Cline and McDonald (1968). Lin and Anderson (1967) and Lin (1970a) have interpreted this earlier arrival to low energy electron production either higher in the solar atmosphere or prior to the proton production.

III. COMPOSITION

The most recent reviews of solar cosmic ray composition are those of Biswas and Fichtel (1965) and Fichtel (1970). They discuss in detail the several counter and emulsion measurements made on balloons and rockets beginning during the maximum of solar cycle 19. The discussion here will be limited primarily to observations of solar alpha particles and electrons. Observations of higher-Z elements will be briefly outlined.

Solar Alpha Particles

The primary characteristic arising from the observations of solar alpha particles is that the ratio of the fluxes of solar alphas to solar protons appears to vary widely between individual events and even within a single event. Both of these characteristics can be seen from Fig. 5 (Durgaprasad et al., 1967). Here are plotted the proton to alpha ratios for several different events as a function of particle kinetic energy.

More recently, using satellite instrumentation, the solar alpha measurements have been extended to lower energies and the time resolution during a single event has been substantially improved (Armstrong et al., 1969; Lanzerotti and Robbins, 1970). A comparison of the intensity-time profiles of solar protons and alphas from the series of flares on 21 and 23 May 1967, is shown in Fig. 6 (Lanzerotti and Robbins, 1970). The overall appearance of the intensity profiles of the two species are similar although differences do exist. In particular, the energetic storm particle enhancement at the time of the sudden commencement (SC) on May 24 is not strongly evident in the alpha fluxes.

The detailed alpha to proton ratios throughout the May 23 event are shown in Fig. 7. Large changes in the ratios are observed, particularly at the low energies, for protons and alphas when compared as to equal energy and equal energy per nucleon

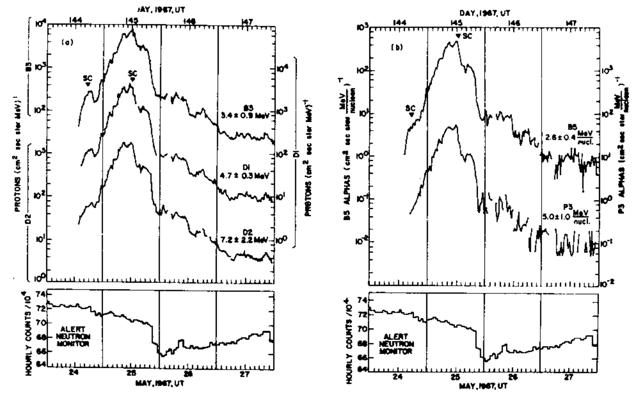

Fig. 6 Alpha particle and proton fluxes measured following the 21 and 23 May 1967 solar events. (Lanzerotti and Robbins, 1969).

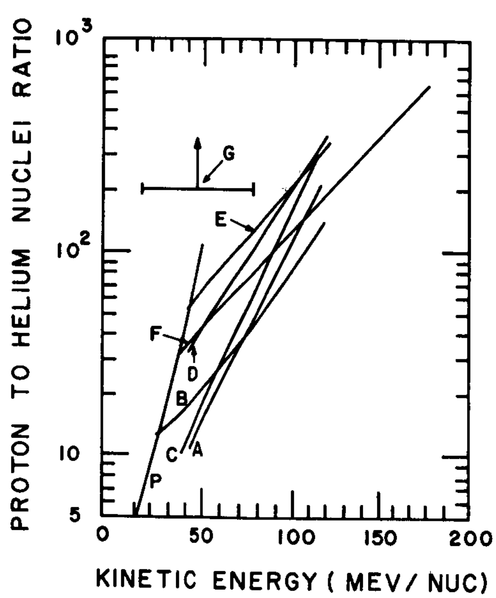

Fig. 5 Ratio of protons to helium nuclei as a function of kinetic energy per nucleon measured at different times in several solar events. The events in which the measurements were made are: A, B - 12 November 1960 (Biswas et. al., 1962); C, D, E - 15 November 1960 (Biswas et. al., 1963); F - 3 September 1960 (Biswas and Fichtel, 1964); G - 16 March 1964 and 5 February 1965 (McDonald et. al., 1965(; P - 2 September 1966 (Durgaprased et. al., 1967). (From Durgaprased et. al., 1967).

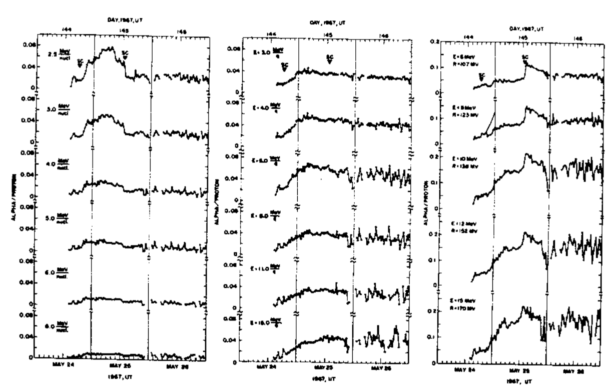

Fig. 7 Alpha particle to proton flux ratios compared as to equal particle energy, equal particle energy per nucleon (equal velocities) and equal particle energy per charge (Lanzerotti and Robbins, 1969).

(equal velocity). However, the central panel of Fig. 7 indicates that after the increases in the ratios following the May 24 sudden commencement, the ratios remain constant throughout the remainder of the event for particles compared as to equal energy per charge. Lanzerotti and Robbins (1970) have interpreted the increases in the alpha to proton ratios observed after the sudden commencement on May 24 as a source effect. They suggest that the solar particles observed prior to the SC were predominantly from flares on May 21 whereas those particles observed after the May 24 increase were from flares on May 23. They also suggested that the constancy of the ratios for equal energy per charge may indicate an important role for electric fields in low energy particle propagation and/or acceleration. Similar behavior of the alpha to proton ratios following other flare events have been noted (Lanzerotti, 1970a; Lanzerotti and Graedel, 1970).

Heavy Nuclei

Heavy solar cosmic ray nuclei ($Z \geq 3$) were first detected in nuclear emulsion stacks flown on a rocket during the 30 September 1960 event (Fichtel and Guss, 1961). The evidence gained from a number of balloon, rocket, and satellite experiments in the early 1960's indicates that the spectral forms for solar heavy nuclei and solar alpha particles are the same in any one event for particles down to ~30 MeV/nucleon (Fichtel, 1970).

A statistical study using satellite data has been made of the ratio of solar alphas to $Z \geq 3$ nuclei for a number of events in 1967-1968. The study indicates that for particles of $E > 0.5$ MeV/nucleon, the spectral behavior observed at the higher energies continues to hold (Armstrong and Krimigis, 1971). It was found that the event-integrated alpha to heavy ratio was ~20 ± 10 for most events, a value substantially smaller than the ratio of 48 ± 8 reported by Durgaprasad et al. (1968) after the 2 September 1966 event in the 12-35 MeV/nucleon range. It is also smaller than the weighted mean of 58 ± 5 determined from six large events in 1960-1969 (Fichtel, 1970).

Solar Electrons

The first direct observation of solar electrons was made from data obtained on a balloon flight by Meyer and Vogt (1962) three days after a large flare on 20 July 1959. They detected highly relativistic electrons of energy 100-1000 MeV. Non-relativistic electrons ($E > 45$ keV) were first measured in interplanetary space by Van Allen and Krimigis (1968) using an instrument flown on Mariner IV. Since that time, the time-intensity profiles of relativistic solar electrons (e.g., Cline and McDonald, 1968; Simnett et al., 1969) and non-relativistic solar electrons (Anderson and Lin, 1966; Lin and Anderson, 1967; Anderson, 1969; Lin, 1970a, 1971) have been intensively studied.

The temporal characteristics of relativistic electrons following the 6 July 1966 flares are shown in relationship to the proton component in Fig. 4. It was found that for this flare the electron and proton components could be organized in time by considerations of particle velocities alone. However, it was noted that Lin (1970a) showed that the low energy ($E > 45$ keV) electrons apparently arrived first, before the more energetic particles.

An example of a comparison of the electron intensity-time profiles for a single event is shown in Fig. 8 (Lin, 1970b, private communication; Lanzerotti, 1970a). These data, from a west limb flare, show rather similar time profiles for a wide range of electron energies. The similarities in the temporal profiles are in contrast to those observed in the case of protons (e.g., Fig. 3; see also Lanzerotti, 1970a, for proton temporal profiles measured during the same period as the electron data of Fig. 8). This could be due to a more direct propagation of electrons to the earth with less interplanetary diffusion and scattering than in the case of protons.

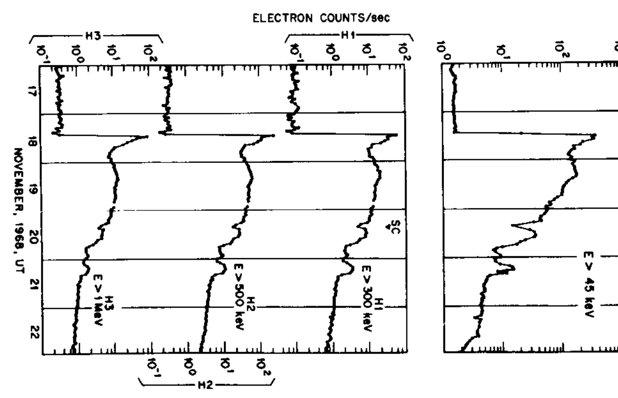

Fig. 8 Time variations of the solar electron fluxes measured following the west limb event on 18 November 1968. The $E > 45$ keV data are from Lin (1970b; private communication). The higher data are from Lanzerotti (1970a).

IV. SPECTRA

As might be expected, solar flare particle spectra have large variations in intensities and spectral shapes both between individual events as well as within a single event. Representative proton, alpha particle, and electron solar flare particle spectra are discussed separately.

Proton Spectra

The solar proton spectra, particularly for higher energies, generally steepen with time after the flare. That is, as time progresses, relatively few higher energy particles as compared to the lower energies are present. The proton energy spectra measured in several of the large events during the last decade were found to fit very well a spectral representation with a rigidity dependence. This spectral shape can be expressed as (Freier and Webber, 1963)

$$\frac{dJ}{dR} = \frac{dJ_o}{dR_o} \exp[-R/R_o(t)] \qquad (1)$$

where R = Mv/c is the proton rigidity. It was found that this spectral representation was particularly applicable during the decay phase of an event for protons of energies $\gtrsim$ 20 MeV.

Six proton energy spectra obtained during several large events of the last solar cycle are plotted in Fig. 9. These spectra exhibit the exponential-in-rigidity spectral shape (Freier and Webber, 1963). Solar cosmic ray spectra such as those of Fig. 9 are very steep compared to the galactic cosmic ray spectra (e.g., Fichtel and McDonald, 1967).

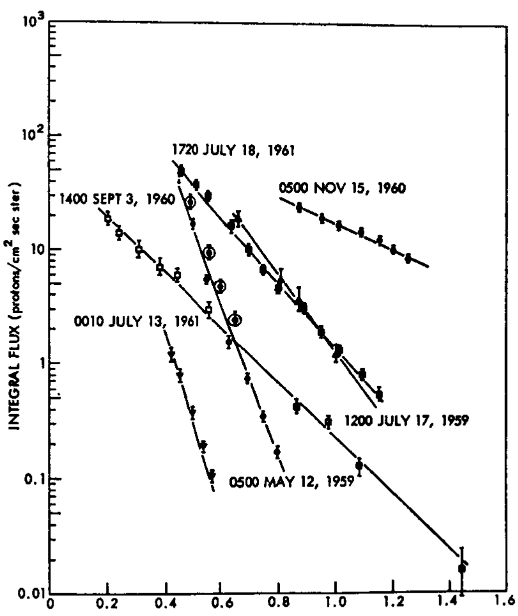

Fig. 9 Solar proton spectra measured in several solar events (Freier and Webber, 1963).

Essentially all of the solar flare particle spectra taken during the last solar cycle were obtained by rocket or balloon-based instruments. Frequently, little of the time history of an event was obtained. Hence, relatively greater emphasis appears to have been placed on the spectra of the different events. During the present solar cycle, with essentially continuous monitoring of an event's time profile and with the measurement of lower energy particles, less emphasis has been placed on the individual event spectra. This neglect of spectral emphasis partly arises, of course, because the spectra changes during an event, particularly for the events which do not exhibit a diffusive temporal profile at the lower energies (e.g., several of the events in Fig. 3). Hence, it is impossible to categorize an event simply with only one or two spectra. However, unlike the more energetic particles, and as will be discussed in Section V, the decay of low energy particles during events that do have a diffusive character appears to be energy independent. In this case, a single spectral shape would indeed describe much of the event's spectral form.

A single power-law in energy was fit by Lanzerotti (1969c) to the half-hour averaged proton spectra (E_p = 0.58 to 18.1 MeV) measured during the event plotted in Fig. 6. He found that the spectra became significantly softer during the storm particle event on May 24 and for the next two and one-half days following the SC on May 25. At both times the exponent n changed from ~1.3 to ~2.0.

The low energy proton spectra measured by Bell Laboratories' instruments on Explorers 34 and 41 near the intensity maximum of several solar flare events in the past several years are plotted in Fig. 10. The spectra are plotted on log-log scales to emphasize deviations from simple power-law relationships at these energies. In particular, the spectrum from the 2 November 1969 flare has a pronounced peak at E ~ 3.5 MeV which may signify particle propagation delays from the flare region (on the extreme west limb).

A study of the response of the world-wide network of neutron monitors to the 28 January 1967 event (see Fig. 2) has been made by Heristchi and Trottet (1971). They used the global distribution of neutron monitors as an energy spectrometer to determine a possible upper cutoff in the energy spectrum of the flare-produced protons from this event. They found an energy cutoff of 4.3 ± 0.5 GeV. This energy is 10^2 - 10^3 eV lower than that predicted by a flare acceleration model of Friedman and Hamberger (1969).

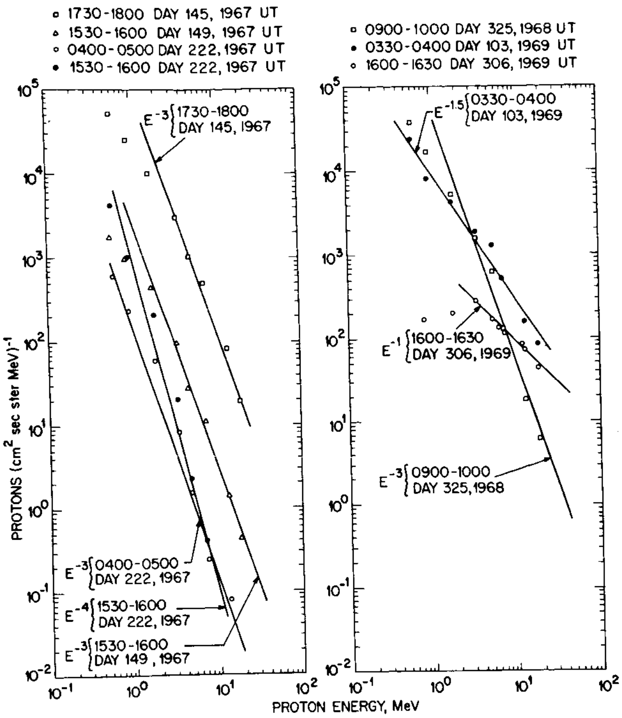

Fig. 10 Low energy solar proton spectra measured on Explorers 34 and 41 near the maximum of several solar events.

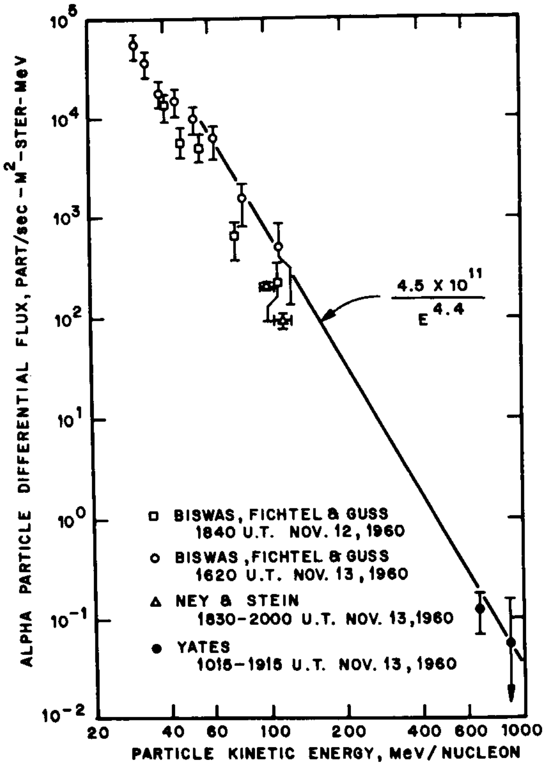

Fig. 11 High energy solar alpha particle Fluxes measured by several observers following the 12 November 1960 solar event (from Yates, 1964).

Alpha Particle Spectra

High energy ($E \gtrsim 30$ MeV/nucleon) alpha particles were observed in a number of solar events to have spectra similar to those of the protons. Frequently, differential rigidity spectra (Eq. 1) were applicable to both particle species during an event, although the e-folding rigidity value R_o might at times be different for the two species (e.g., Biswas et al., 1963; Durgaprasad et al., 1968).

Solar alpha particles were studied over a very wide energy range during the 12 November 1960 solar event. The differential alpha fluxes measured between ~31 and ~100 MeV/nucleon by several workers are presented in Fig. 11 (Biswas et al., 1962; Ney and Stein, 1962). Also shown are two high energy alpha flux measurements from the work of Yates (1964) during the same event.

The flux measurements of Yates (Fig. 11), if expressed on an exponential-in-rigidity basis, would fall considerably above what would be predicted by an extrapolation of the lower energy data (Yates, 1964). Yates' measurements were challenged by Waddington and Freier (1965) as perhaps being contaminated by the high fluxes of slow protons present during the event. The controversy appears still to be unresolved (Yates, 1965); very high energy measurements of solar alpha particles need to be made during other large events.

As noted in Section III, recent years have seen an increase in the time resolution of low energy solar alpha particle observations by satellite. Studies of the changes in the alpha spectra during a single event have become feasible, although little emphasis has been placed on this aspect of the observations. Lanzerotti (1969 c) studied the power-law exponent of the alpha spectra for the May 1969 event (Fig. 6). He found that during the period between the two sudden commencements (May 24 and May 25), the alpha particle spectra were somewhat harder than that for protons; however, after the May 25 SC, both proton and alpha particle power law exponents in Eq. (2) were ~2. The low energy alpha particle spectra measured by Bell Laboratories' instruments on Explorer 34 and Explorer 41 near the maximum of several solar events of the last several years are plotted in Fig. 12. These spectra give a representative example of low energy alpha spectral shapes and intensities.

Electron Spectra

Since the number of published observations of solar electrons is substantially less than for protons, detailed information on electron spectra is less plentiful. Lin (1970a) has compiled electron spectra from four solar events in 1967 as measured by

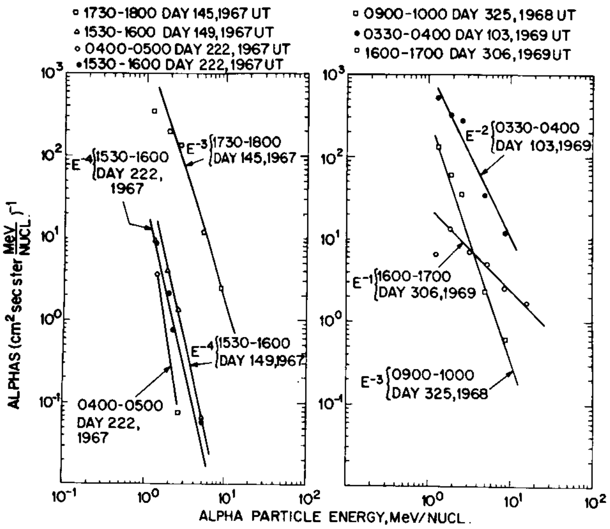

Fig. 12 Low energy solar alpha particle spectra measured on Explorers 34 and 41 near the maximum of several solar events.

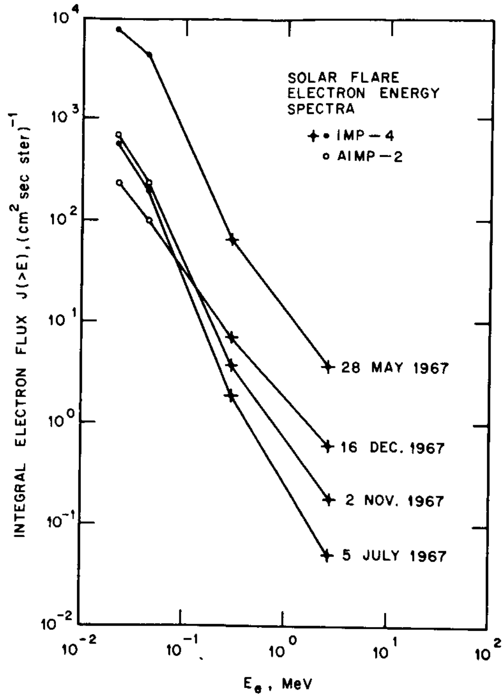

Fig. 13 Solar electron spectra measured during four events in 1967 (Lin, 1970a).

instruments on Explorers 34 and 35. These spectra are shown in Fig. 13. Lin finds that if he fits the spectra to a power law (Eq. 2), the events in Fig. 13 have exponents $n \sim 2.3$-3.5.

V. PROPAGATION

After acceleration, the flare-produced solar particles must escape from the active region and propagate through interplanetary space to the earth. Interplanetary space is permeated by the solar magnetic field. The nature of this field configuration was predicted by Parker (1960) to consist of spiral lines emanating from the sun. This prediction was subsequently confirmed by extensive satellite measurements (e.g., Ness et al., 1964). This spiral interplanetary magnetic field controls much of the propagation of the flare particles. The guiding center of the solar particles tend to follow the spiral nature of the field. However, the small-scale irregularities in the field act as scattering centers and perturb, or scatter, the particles, moving them to other field lines. Extensive theoretical work (not discussed here) has been carried out in recent years in determining the solar particle diffusion coefficients due to these random scatterings (e.g., Jokipii, 1966, 1967, 1968; Roelof, 1966, 1968; Hasselmann and Wibberenz, 1968; Jokipii and Parker, 1969).

The propagation characteristics of solar particles have been reviewed recently (Fichtel and McDonald, 1967; Axford, 1970). The first considerations of a diffusion model for solar particle propagation was that of Parker (1956) and Meyer et al. (1956). The broad considerations and the development of isotropic diffusion theory for solar particles, i.e., solutions to a diffusion equation of the form

$$\frac{\partial n}{\partial t} = r^{-2} \frac{\partial}{\partial r} \left(r^2 \kappa \frac{\partial n}{\partial r} \right) , \qquad (3)$$

have been due to Parker (1963). In Eq. (3), $n(r,t)$ is the mean density of solar particles with velocity v and $\kappa = \frac{1}{3}v^2\tau = \frac{1}{3}\lambda v$ is the diffusion coefficient and is, most generally, a tensor quantity (Jokipii, 1966). τ is the mean particle "collision time" for interaction with the interplanetary magnetic irregularities and can be determined from the interplanetary field fluctuations (Jokipii and Coleman, 1968). Most commonly, solutions to Eq. (3) have assumed $\kappa = \kappa_o(T)r^\beta$ where T is the particle kinetic energy and β is time-independent.

Solutions to Eq. (3) have chiefly considered two different boundary conditions. The first of these that has been used has taken $\beta=0$ and has assumed a perfectly absorbing boundary ($n=0$) at some $r = r_b >$ 1 a.u. The solution to Eq. (3) at times $t \gg r_b/\kappa_o$ after the flare yield an exponential decay for the fluxes

$$n(r,t) \sim \frac{1}{r} \sin \frac{\pi r}{r_b} \exp \left[\frac{-\pi^2 \kappa_o t}{r_b^2} \right] \qquad (4)$$

where the decay time is given as

$$\tau_D = \frac{r_b^2}{\pi^2 \kappa_o} \qquad (5)$$

This solution to the model has been utilized by Bryant et al. (1962) and Hofmann and Winckler (1962) in analyzing solar particle events. They found that the absorbing "boundary" r_b was at $r \sim 2$ a.u. Although the 2 a.u. boundary may indicate that the hydromagnetic waves producing the interplanetary irregularities are being damped out at this distance (Jokipii and Davis, 1969), Axford (1970) has maintained that an exponential decay of κ with distance r will also produce the same results.

A number of solar events have been fit by Krimigis (1965) using a solution of Eq. (3) assuming a radial dependence to the diffusion coefficient (i.e., $\beta \neq 0$) and no boundary r_b (Parker, 1963). This solution can be expressed as

$$n(r,t) \propto f(\kappa_o,\beta,T)\left[t^{3/(2-\beta)}\right]^{-1} \exp\left[-\frac{r^{2-\beta}}{(2-\beta)^2}\,\frac{1}{\kappa_o t}\right] \qquad (6)$$

A plot of $\ln[n(r,t)t^{3/(2-\beta)}]$ versus t^{-1} should yield a straight line for the proper choice of $\beta(<2)$. Krimigis found that for protons in the energy range 50-500 MeV, good agreement with observations was obtained for $\beta \sim 1$ and $\lambda \sim 0.1$ a.u.

Anisotropic Diffusion

The isotropic solar particle diffusion model discussed above is not able to explain several important characteristics of the solar particles observed at the earth. One of these is the direction of the non-radial anisotropy of the particles measured at the earth. The anisotropy at the beginning of events is aligned along the spiral field direction, outward from the sun (McCracken, 1963; McCracken et al., 1967). (Later in the events the anisotropy becomes much less and the direction changes to radial or nearly so (McCracken et al., 1967; Rao et al., 1969).) The second problem with isotropic models is that they can not treat the observations that show that the particle fluxes arising from flares in the eastern hemisphere of the sun tend to increase more slowly to maximum intensity than those that originate from west hemisphere flares (e.g., Fichtel and McDonald, 1967; Burlaga, 1967).

Reid (1964) has considered a solution to the east-west effect by postulating a thin diffusing shell around the sun. Particles originating from flares in the eastern hemisphere would diffuse (isotropically) across the solar surface to the spiral field lines connecting the sun to the earth and then propagate along the field lines to the earth (Fig. 14). Reid's model of diffusion across the solar surface must be combined with an interplanetary propagation model to provide a complete description of the particle event as seen at the earth. Since inclusion of the

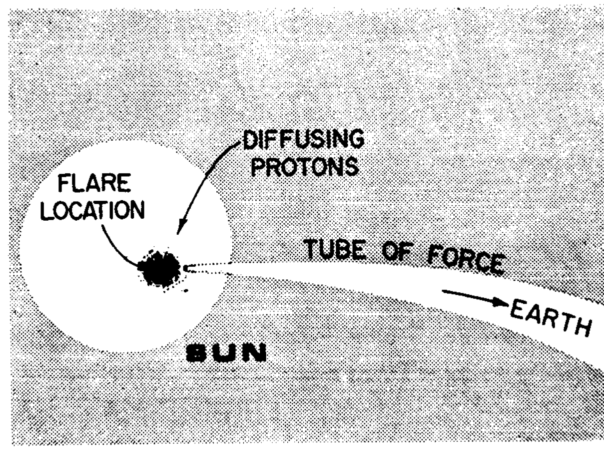

Fig. 14 Illustration depicting solar particle diffusion across the solar surface to the interplanetary flux tube linking the sun to the earth (Reid, 1964).

solar-surface diffusion increases the number of parameters that can be adjusted, it is likely that most diffusive-type observations could be fit with such a model. Indeed, a solar diffusing layer was one of the features included in a recent computational model for solar flare propagation (Englade, 1971).

The consideration of an anisotropic diffusion coefficient to solve the east-west problem was first made by Axford (1965). Burlaga (1967) solved the diffusion equation considering particle diffusion transverse to the spiral interplanetary field as well as along it and neglected Reid's diffusion layer around the sun. Expressed in spherical coordinates, Burlaga solved the equation

$$\frac{\partial n}{\partial t} = \frac{1}{r^2}\left[\frac{\partial}{\partial r}\left(r^2 \kappa_{\parallel} \frac{\partial n}{\partial r}\right)\right] + \frac{1}{r^2}\frac{\partial}{\partial \mu}\left[\kappa_{\perp}(1-\mu^2)\frac{\partial n}{\partial \mu}\right] + \frac{1}{r^2 \sin^2\theta}\frac{\partial}{\partial \varphi}\left[\kappa_{\varphi}\frac{\partial n}{\partial \varphi}\right] \qquad (7)$$

where $\mu = \cos\theta$ and $\kappa_{\parallel}$, $\kappa_{\perp}$, and κ_{φ} are the components of the diffusion tensor.

Burlaga (1967) took the parallel diffusion coefficient $\kappa_{\parallel}$ to be a constant, independent of the radial position, the transverse coefficient $\kappa_{\perp}$ proportional to the square of the radial distance ($\kappa_{\perp} \propto r^2$), and an absorbing boundary at $r_b > 1$ a.u. Solving Eq. (7) with the above boundary conditions and assuming n to be independent of φ, he obtained quite satisfactory fits for a number of different flare events distributed over the solar disk. The event decay time resulting from his solution can be written as

$$\tau_D = \frac{r_b^2}{\pi^2 \kappa_{\parallel}} \; . \qquad (8)$$

Eq. (8) is of the same form as the decay time derived for isotropic diffusion (Eq. 5) with the isotropic diffusion coefficient κ_0 replaced by $\kappa_{\parallel}$.

Two examples of Burlaga's fits to particle fluxes resulting from flares at two separate solar locations are shown in Fig. 15. The angle θ_0 noted on the figure is the angle, measured from the center of the sun, between the flare location and the location on the sun of the interplanetary field line passing through the earth. Fits of the model to both the neutron monitor observations of the 23 February 1956 event and the balloon observations of E > 80 MeV protons from the 20 July 1961 event are seen to be quite good.

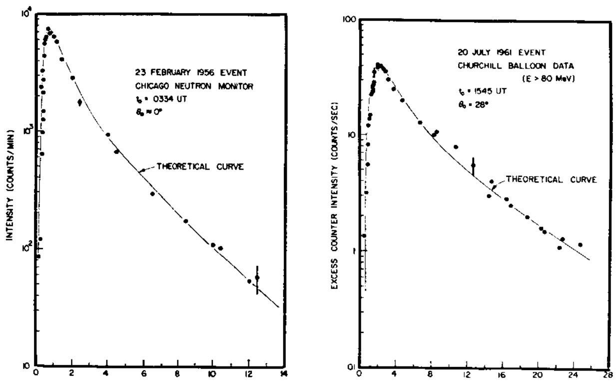

Fig. 15 Fit of the anisotropic diffusion-with-a-boundary solar particle propagation model to an event measured by a neutron monitor and an event measured by a balloon-based detector (from Burlaga, 1967).

Low Energy Propagation

It is clear from data such as those of Fig. 3 that at lower energies solar flare particles do not often have diffusive intensity-time profiles. Substantial modulation of these low energy particles by solar wind discontinuities, shock waves, and magnetic field sector boundaries must be occurring. Although there are events where the low energy particles exhibit diffusive-type profiles, the applicability of an anisotropic diffusion model such as Burlaga's to these observations is highly suspect (Forman, 1970). Forman has maintained that the "equilibrium" anisotropy present during the decay phase of an event (McCracken et al., 1967) and the evidence that the diffusion coefficient becomes small at low energies (Jokipii and Coleman, 1968) indicate that solar wind convection, and the resulting particle energy loss, is an important mode of low energy particle propagation. (The anisotropic diffusion model of Burlaga (as well as the isotropic models) considers convection effects to be negligible for the higher energy particles, and rightly so.) Forman (1971) cites as further evidence for the importance of convection the fact that the reported decay times for both protons and alphas were essentially energy-independent for 1-20 MeV/nucleon particles after the 28 May 1967 flare (Lanzerotti, 1969a).

Forman (1971) has solved the Fokker-Planck equation first derived by Parker (1965) for particle transport including convection and diffusion:

$$\frac{\partial n(r,t)}{\partial t} + \nabla\cdot\left\{V\left(n - \frac{1}{3}\frac{\partial}{\partial T}(\alpha T n)\right) - \kappa\cdot\nabla n\right\}$$

$$= \frac{V}{3}\frac{\partial}{\partial r}\frac{\partial}{\partial T}(\alpha T n) \qquad (9)$$

Here V is the solar wind velocity, T is the particle kinetic energy, and $\alpha = (T+2Mc^2)/(T+Mc^2)$. The diffusion models discussed above all neglected the terms in Eq. (9) containing the solar wind velocity V. Forman obtained an analytic solution to Eq. (9) assuming that $\kappa_{\perp} = \kappa_1 r^2$, $\kappa_{\parallel} = \kappa_2 r$, and that there was a diffusing boundary at $r = r_b$. Forman's model predicts very well the equilibrium residual anisotropy during the decay phase of an event as observed by McCracken et al. (1967) as well as the magnitude (~14-18 hours) of the energy-independent decay time for both alphas and protons as observed by Lanzerotti (1969a).

From her solution to Eq. (9) Forman (1971) has shown that in the decay phase of the event

$$N(r,t) \propto f\left(\frac{r}{r_b}\right) r^{(V/2\kappa_2 - 1)} \exp(-t/\tau_D) \quad (10)$$

where the decay time τ_D is given as

$$\tau_D = \frac{4r_b}{V}\frac{V/\kappa_2}{\left[j_{\eta,1}(V/\kappa_2)\right]^2} = \frac{4r_b}{V}\, g(V/\kappa_2). \quad (11)$$

In Eq. (11) $j_{\eta,1}$ is the first zero of the Bessel function of order η. Forman has found that for r_b = 2.3 a.u. (a representative value determined from the model fits of Burlaga, 1967), τ_D has a broad maximum of ~15-17 hours for $\kappa_{\parallel} = \kappa_2 r$ between $\sim 3\cdot 10^{19}$ and $3\cdot 10^{20}\,cm^2 sec^{-1}$ (reasonable values for $\kappa_{\parallel}$ as determined from the power spectra of the interplanetary magnetic field near the earth by Jokipii and Coleman, 1968). Forman's model has recently been applied successfully to the low energy proton observations from the 7 June 1969 event (Murray et al., 1970).

The energy-independence of the decay times for both protons and alpha particles during a diffusive-type event is shown in Fig. 16 for the 13 April 1969 event (Lanzerotti and Graedel, 1970). The intensity-time profiles of the proton fluxes in the $0.56 \leq E \leq 0.60$ MeV channel is shown as an insert in the figure. This event, probably originating from a flare behind the east limb, demonstrated a diffusive-type appearance even in the lowest energy-channel measured. This was quite unlike the 28 May 1967 diffusive event where energetic storm particles greatly enhanced the lower energy proton fluxes (Lanzerotti, 1969a). Also plotted in Fig. 16 are the decay times for $E > 10$, >30, and >60 MeV protons measured by the solar particle monitoring experiment on the same satellite (Solar Geophysical Data, 1969). The decay time varied from ~28 hours at 0.58 MeV to ~19 hours at 60 MeV. Over the range 0.58 MeV to 20 MeV, the decay time decreased by only ~4 hours.

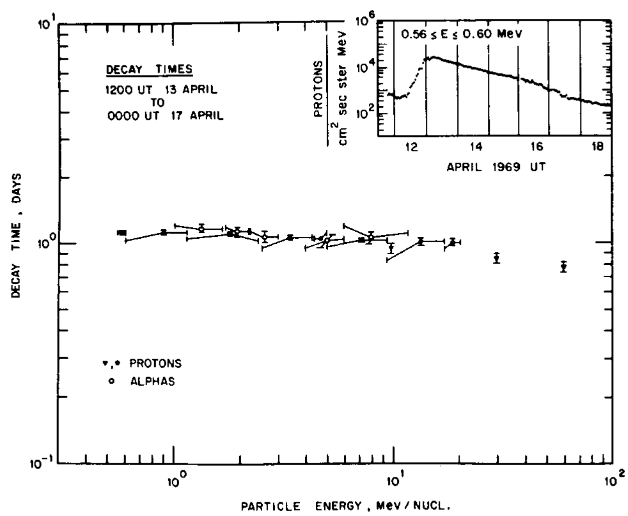

Fig. 16 Proton and alpha particle decay times following the 13 April 1969 solar event. The intensity-time profile for the $0.56 \leq E \leq 0.60$ MeV proton channel is shown as an inset to the figure (Lanzerotti and Graedel, 1970).

VI. FLARE PARTICLE EFFECTS

Two consequences of solar flare particle effects are discussed below. The first of these is the effect of energetic flare particles in producing polar-cap cosmic noise absorption and the detection of this enhanced absorption by riometer techniques. The second is the effect of solar particles, penetrating into the outer magnetosphere, on satellite solar cell lifetimes.

Riometer Absorption

The first indication of the production of enhanced ionosphere ionization by solar flare particles was the strong absorption of cosmic radio noise in the polar cap regions that Bailey (1957) correlated with the flare of 23 February 1956. Since that time, enhanced riometer absorptions in the auroral and polar cap regions during solar events have been studied as basic geophysical phenomena and as diagnostic tools for studying solar and magnetospheric processes (e.g., Bailey, 1964; Reid, 1970). Indeed, the significance of energetic storm particles was first outlined by Axford and Reid (1963) using riometer data.

Through the work of Potemra et al. (1967, 1969, 1970) good agreement has been achieved in calculating the expected riometer response from a measured incident solar flux. Potemra and his collaborators have calculated the expected total absorption A at a radio wave angular frequency ω from the formula

$$A(dB) = \int 1.16\times10^{6} \frac{n_e}{\nu_m} C_{\frac{5}{2}}\left(\frac{\omega\pm\omega_H}{\nu_m}\right)dh \qquad (12)$$

obtained from the theory of Sen and Wyller (1960). In Eq. (12) ω_H is the angular gyro frequency, dh is the increment of ionization height in 10-km units, $C_{5/2}$ is an integral function, n_e is the electron density and ν_m is the mean electron collision frequency. Using specific ionization rates due to G. W. Adams and Adams and Masley (1965) and ν_m and recombination coefficients deduced from the September 1966 event, Potemra et al. (1970) have predicted the observed absorption for high latitude riometer observations during a number of 1967 PCA events. Their calculations, using satellite measurements of the solar proton fluxes over the polar caps, are compared in Fig. 17 to the observed riometer day and night absorption measurements following the 28 January 1967 solar event. The agreement is quite good for both the day and the night observations. (It is interesting to compare these lower energy proton observations of Fig. 17 with the neutron monitor profile for the same event in Fig. 2.)

Several authors (Van Allen et al., 1964; Juday and Adams, 1969; Reid, 1969, 1970) have used the empirical relation

$$(F)^{\frac{1}{2}} = R\times A \qquad (13)$$

to relate the integral fluxes F of protons above some energy E_{min} to the riometer absorption A at a given frequency. In Eq. (13), R is a constant, dependent only upon E_{min}. Potemra and Lanzerotti (1971), using solar proton data from the synchronous equatorial ATS-1 satellite, deduced R as a function of E_{min} from the 30 MHz riometer absorption observed at Byrd during the 28 January 1967 event. (Byrd ($L\sim7$) is at

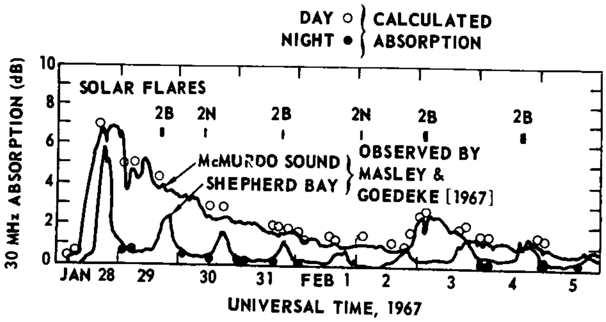

Fig. 17 Comparison of observed day and night riometer absorption and the calculated absorptions using polar cap-average solar proton data from satellite 1963-38C during the 28 January 1967 event (Potemra et. al., 1970).

nearly the same latitude as ATS-1 (L~6.4) but three hours earlier in local time.) They found Eq. (13) to be an excellent fit to the data, essentially independent of the value of E_{min}. The values of $R(E_{min})$ they found for E_{min} between 5 and 50 MeV are plotted in Fig. 18 as a function of E_{min}. Such R-values should be quite useful for the new solar proton event classification scheme (Shea and Smart, 1970).

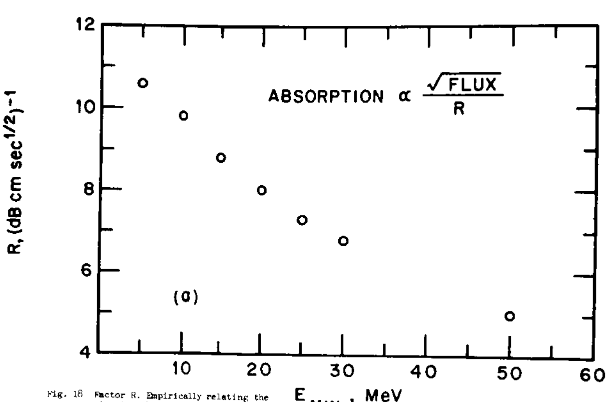

Fig. 18 Factor R. Empirically relating the riometer absorption to the square root of the integral proton fluxes plotted as a function of E_{min}, the lower energy limit on the integral fluxes. R was determined from the 28 January 1967 event (Potemra and Lanzerotti, 1971).

Solar Cell Damage

Solar protons appear to have ready access to the outer regions of the magnetosphere other than through the polar cap regions. The solar particles at synchronous altitude are observed to have essentially the same intensities and spectra as the particles in interplanetary space for protons as low as 1 MeV in energy (Lanzerotti, 1968, 1970b; Paulikas and Blake, 1969). These low energy protons could cause significant damage to unshielded solar cells on a synchronous satellite. It was pointed out by Lanzerotti (1969b) that the damage to unshielded cells from relatively low intensity solar events could dominate the normal synchronous altitude radiation (predominantly electrons) in producing damage. Indeed, anomalous, step-like changes in the short circuit current of unshielded cells in the ATS-1 solar cell damage experiment are observed in conjunction with solar flare events (Waddel, 1968).

An example of the solar proton damage to an unshielded solar cell on ATS-1 during the May 1967 events (Fig. 6) is shown in Fig. 19. The two lower bar graphs show the values of the short circuit current (in ma) measured each day for two 10 Ω-cm n-on-p type solar cells (R. C. Waddel, private communication). One cell was unshielded while the other had a 1 mil shield of 7740 glass. At the top are plotted the daily average of the integral half-hour average proton fluxes (E > 2.4 MeV) measured by the Bell Laboratories experiment on ATS-1. (No data were received on days 143, 144, and 147.)

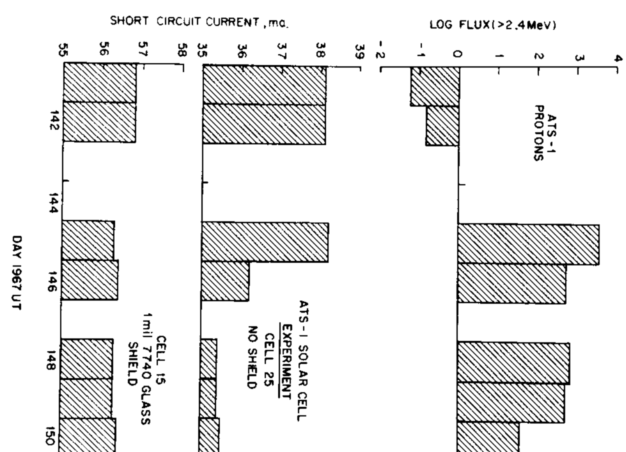

Fig. 19 Daily measurements of the short circuit current in an unshielded and a shielded solar cell in the solar cell damage experiment on ATS-1 (data courtesy of R. C. Waddel). Plotted at the top are the daily averages of the integral half-hour average proton fluxes (E > 2.4) measured on ATS-1 during the May 1967 solar events.

Prior to the major interplanetary enhancement on day 145, the proton fluxes at ATS-1 were very low. The day after the large ATS-1 enhancement on day 145 the short circuit current in the unshielded cell decreased sharply whereas only a slight decrease in the current was observed in the shielded cell.

Since a 1 mil shield will stop ~0.5 MeV protons, the data of Fig. 19 are indicative that protons with energies as low as this were producing the most significant damage. This could be due both to the penetration of 0.5 MeV solar protons to the synchronous orbit as well as to the fact that the magnetosphere boundary was pushed within the ATS-1 orbit for periods of time on days 145 and 146.

Even if shields were provided for synchronous satellite solar cells, the fluxes of low energy (0.5-3 MeV) solar protons penetrating to this altitude could still play an important role in the damage considerations. This is because in the manufacturing process the shields are often not deposited uniformly over the cell surfaces, leaving a small fraction of some cells uncovered (R. C. Waddel, private communication). Such partially unshielded cells would then be subjected to unexpected damage by the low energy protons.

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