

**Best
Available
Copy**

PREDICTING AND MODELING SOLAR FLARE GENERATED PROTON FLUXES IN THE INNER HELIOSPHERE

D.F. Smart and M.A. Shea

Space Physics Division, Geophysics Directorate
Phillips Laboratory (OL-AA)
Hanscom AFB
Bedford, Massachusetts, 01731 USA

ABSTRACT

Solar energetic particles are assumed to be accelerated above the solar active regions from the available coronal material. The composition of "large" solar particle events is consistent with an ion selection process based on the first ionization potential of the elements in the solar corona. The transport of solar protons in interplanetary space is controlled by the topology and characteristics of the interplanetary magnetic field. The topology of the magnetic field lines in interplanetary space is controlled by the flow speed of the ionized plasma and the rotation rate of the sun, resulting in the so called "Archimedean spiral" configuration. The particle flux longitudinal gradients observed in the inner heliosphere are variable, and local interplanetary conditions and structures greatly influence the time-intensity profiles observed. The most extensive solar particle measurements are those observed by earth-orbiting spacecraft, and forecast and prediction procedures are best for the position of the earth. These earth-based models can be extended to other heliolongitudes or to more distant locations in the inner heliosphere.

OVERVIEW OF CONCEPTS INVOLVED

The Solar Flare Source

Solar energetic particles are accelerated from the available coronal material during the solar flare process. (See Svestka, 1976, for a detailed discussion of the solar flare phenomena.) After the initial solar acceleration there may be further acceleration of the energetic particle population by interactions with interplanetary shocks, but these subjects are beyond the scope of this paper. The solar flare emissions that we observe at Earth are indicators, probably secondary manifestations, that particle acceleration is occurring. The particle acceleration site is probably high in the solar corona where we have no method of direct observation. The various emissions we associate with solar flares occur as the result of some of the accelerated particles travelling down from the probable high coronal acceleration site into the chromosphere and photosphere.

The English term "solar flare" is the name given to the sudden energy release of about 10^{32} ergs of energy in a relatively small volume of the solar atmosphere. The Russian term, which translates into English as chromospheric brightening is more descriptive of the observations, occasionally seen in white light, but usually observed in the hydrogen-alpha

line. The radio emissions result from energetic electrons at positions where the magnetic field is intense enough to confine the gyration radius of these electrons to a diameter consistent with the emission wavelengths. The solar X-rays are emitted from the hot plasma generated in the solar flare process, and gamma ray emissions occur at heights where there is sufficient density for the flare energized particles to interact with the ambient solar atmosphere.

The solar particles are apparently accelerated high in the solar corona. The composition of solar particles observed at the various interplanetary spacecraft is consistent with the particles having passed through less than 30 mg cm^{-2} of matter from the acceleration site to their detection location since the elemental and isotopic composition of the solar particles observed in space do not appear to have undergone fractionization due to interaction with significant mass.

Solar Particle Transport

Once the solar particles have been accelerated by the solar flare process, they must still escape the confines of the solar magnetic fields and be transported through the solar corona into space. Coronal propagation is a concept developed to explain the apparent transport of solar particles around the sun. It is assumed that there are intensity gradients in the solar flare particle distribution in the solar corona. Current ideas suggest that the magnetic structures in the corona extend into space and that the intensity in the solar corona can be mapped into interplanetary space (Reinhard et al., 1986). The coronal propagation characteristics are probably dependent on the coronal magnetic fields, which are poorly observed but are thought to be quite variable. The old ideas developed during the 60's that most of the particle diffusion occurred in space proved to be inconsistent with the satellite observations of later years from which apparent mean free path lengths derived for solar particles in interplanetary space ranged between approximately 0.1 to more than 1.0 AU, depending on the event. These large variations in the mean free path lengths are thought to be due to variations in the

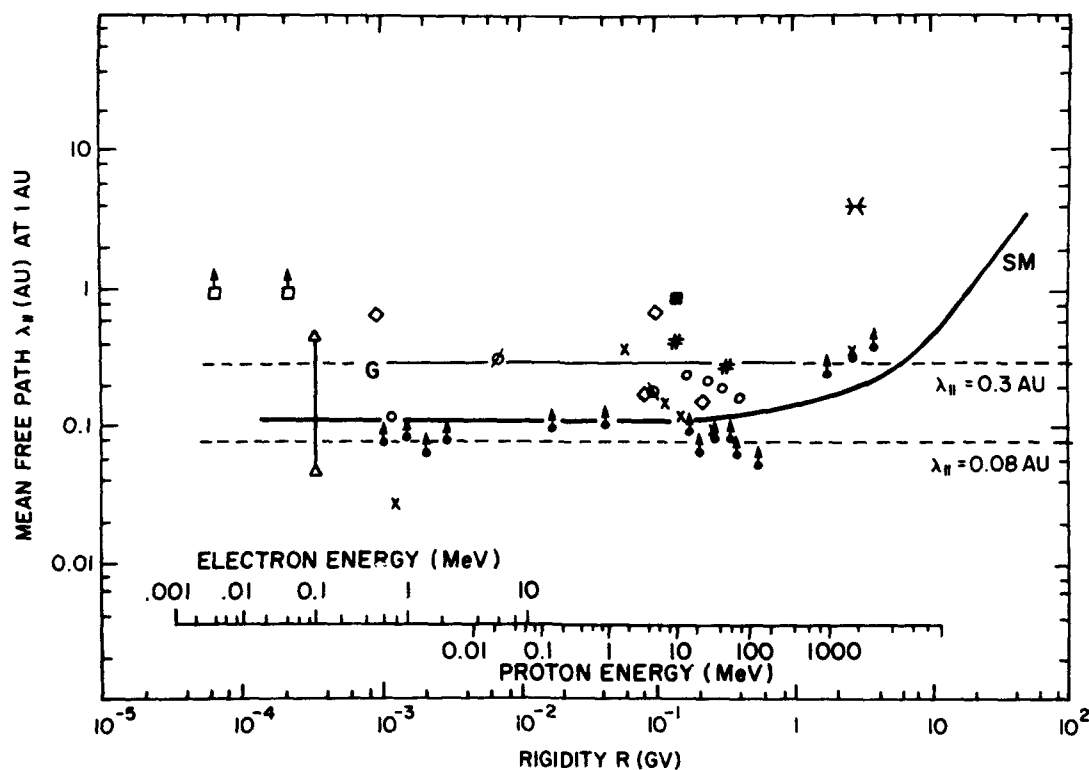


Figure 1. The variability in the mean free path (the distance between scattering events) for a number of interplanetary solar particle events. The solid curve labeled "SM" is from Morfill et al. (1976). A energy-to-rigidity conversion curve is given at the bottom of the figure for electrons and protons. After Valdes-Galica (1991).

turbulence of the interplanetary magnetic field. The variability in the mean free path (the distance between scattering events) for solar particles in the interplanetary medium is illustrated in Figure 1.

Interplanetary magnetic field topology. Charged particle transport in space is controlled by the interplanetary magnetic field topology. In organizing solar energetic particle data it is very useful to use the gross topology expected for the interplanetary magnetic field (Roelof 1973, 1975, 1976, Roelof and Krimigis 1973, Reinhard et al., 1986) as illustrated in Figure 2. The interplanetary medium in the vicinity of the earth is dominated by the plasma flowing out into space from the solar corona called the "solar wind". This plasma is highly ionized and therefore highly conducting; for most practical purposes the interplanetary magnetic field may be considered to be "frozen" in the solar wind. As a result of the outward flowing solar wind from a rotating source, in the regions of space not too far from the ecliptic plane, the idealized interplanetary magnetic field lines carried away from the sun into space have a characteristic curved shape, the mathematical form of an Archimedean spiral. Application of this mathematical form makes it possible to estimate the probable solar connection longitude of the interplanetary field passing near the earth or a spacecraft in the inner heliosphere. This simplified method of estimating the probable solar source location was formalized by Nolte and Roelof (1973). The basic procedure is to divide the distance from the sun to the observation location by the observed solar wind speed to obtain the travel time and then compute the amount of solar rotation that has occurred in that transit time. This method is still used because of its simplicity, and because there is no assurance that more complex formulations generate results that can be used with more confidence.

The portion of space where the plasma outflow from the sun dominates the character of space is the heliosphere. The dimensions of the heliosphere are still a matter of scientific speculation, but the heliosphere is estimated to extend beyond 100 Astronomical Units (AU). (An Astronomical Unit is the distance from the sun to the earth, 149.6 million km.) The inner heliosphere is generally considered the domain from the sun to the earth and

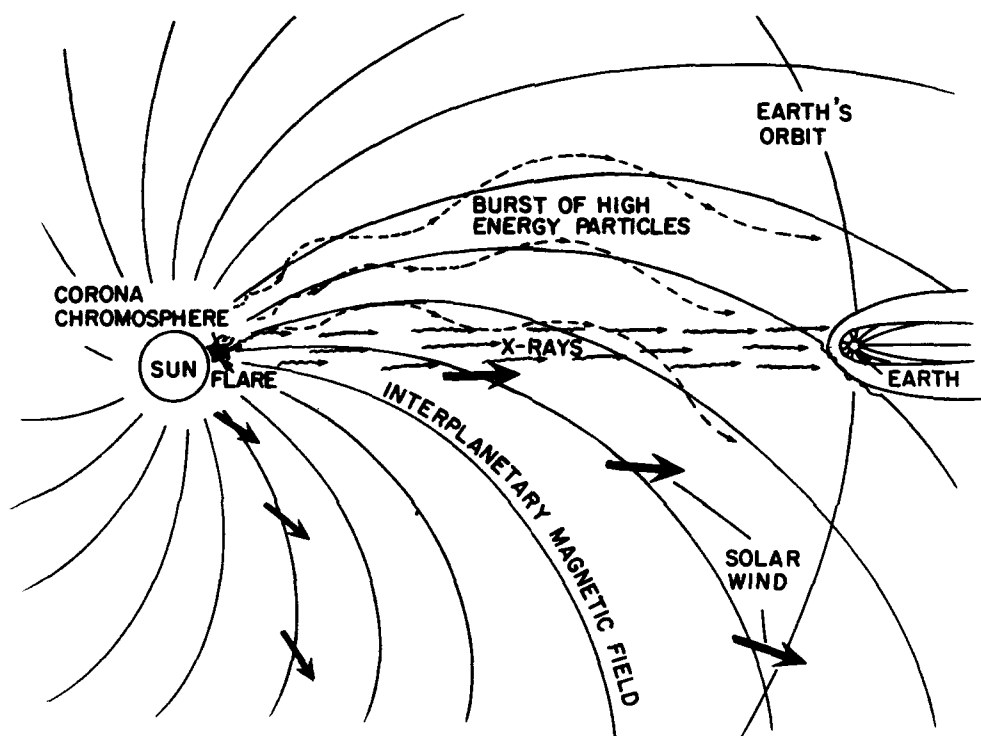


Figure 2. Illustration of the sun and the gross topology of the idealized structure of the interplanetary medium.

Codes

1/or

may include the orbit of Mars at ~1.5 AU. The outer heliosphere may begin about the distance of Jupiter and continue to the termination shock at the heliospheric boundary, the distance where the solar wind flow is hypothesized to change from super-sonic flow to sub-sonic flow. In the outer heliosphere, diffusion dominates the processes controlling energetic charged particle transport. In the inner heliosphere, at distances from "near sun" to about 1 AU, during "quiet" times, the transport processes controlling energetic charged particle motion is not diffusion dominated. However, the characteristics of the inner heliosphere are best described as "highly variable" and dominated by solar activity.

Particle transport by diffusion - elementary diffusion theory. From a theoretical standpoint the problem of particle diffusion in the interplanetary medium should be solvable with known equations. There are a large number of theoretical papers (not enumerated here) on this subject. The fundamental equations for transport of solar energetic particles were derived by Parker (1965). The spherical transport equation given below includes the effects of diffusive convection and adiabatic energy loss in the expanding solar wind:

$$\frac{\partial U}{\partial t} + \frac{1}{r^2} \frac{\partial U}{\partial r} \{ r^2 UV - r^2 K_r \frac{\partial U}{\partial r} \} - \frac{2V}{3r} \frac{\partial U}{\partial t} (\alpha TU) = 0. \quad (1)$$

In this equation, $U(r, T, t)$ specifies the differential number density, V the solar wind velocity, K_r the radial diffusion gradient, and T the particle kinetic energy. The parameter α is defined by

$$\alpha = (T + 2m_0c^2)/(T + m_0c^2). \quad (2)$$

When solving this equation, it is generally assumed that the diffusion constant, K_r , behaves as:

$$K_r = K_0 r^b, \quad (3)$$

where r is the radial distance from the sun, K_0 is the diffusion coefficient at 1 AU, and b is an exponent describing the interplanetary turbulence spectrum. This type of equation can be simplified and solved for the time of maximum particle flux resulting in:

$$t_{(\max)} = \frac{r^{(2-b)}}{3 K_0 (2 - b)}. \quad (4)$$

The fundamental problem using this type of equation in a prediction sense is the total dependance of the result on the interplanetary scattering parameters. It is precisely these parameters that are not known. From an academic viewpoint, after the occurrence of a solar particle event, the intensity-time profile can be analyzed to deduce what the scattering parameters were (Zwickl and Webber, 1977). Once these scattering parameters have been deduced, then it is possible to use diffusion models to describe the intensity-time profile through the heliosphere. Diffusion calculations are very successful in predicting the cosmic ray modulation throughout the solar cycle. For these type of calculations, even mean free path lengths of the order of 1 AU are small compared with the dimensions of the heliosphere. However, for solar particle propagation in the inner heliosphere, when the mean free path length is relatively long, there is not sufficient distance between the sun and the earth to permit diffusion to dominate the particle transport. Indeed, there are a number of suggestions that the solar particle event profile observed at 1 AU may be dominated by the injection and release of particles from the solar corona.

The "scatter free" approximation for solar particle transport. Since the apparent solar proton mean free path length derived from spacecraft observations is relatively long (a significant portion of an Astronomical Unit in many cases), Roelof (1975) and co-workers developed the concept of "scatter free" propagation where the solar particles are essentially confined to travel along the interplanetary magnetic field lines. This concept has been very useful in "mapping" particles back to the sun and deriving probable source locations. In the inner heliosphere, the "scatter free" approximation is often as successful as

the much more complex diffusion calculations. The utility and demonstrated simplicity of the "scatter free" concept makes it simple to apply to the solar particle prediction problem in the inner heliosphere. At large distances in the heliosphere, say beyond the orbit of Jupiter (5 AU), it has been demonstrated that diffusion dominates the transport of particles in space.

PREDICTION OF SOLAR PARTICLE EVENTS

The prediction of solar particle events depends on observable parameters on which to base a calculation. The questions to be answered by a prediction procedure are:

- (1) When will the event start?
- (2) When will the particle flux reach maximum intensity?
- (3) How large will the event be?
- (4) How long will the event last (at a specific energy or above a specific flux level)?

Indicators of a Solar Proton Event

There are general relations between the electromagnetic emissions from a solar flare and the number of protons observed at the earth. The X-ray, radio and optical emissions during the solar flare event are the indicators (perhaps secondary manifestations) that proton acceleration is occurring. There are correlations between the observed proton flux in the ~10 MeV energy range and the electromagnetic emission from the solar flare. The best correlation coefficients for these "observables" are approximately 0.7 in both the microwave frequencies or the soft X-ray wave lengths. More relationships have been developed for radio emissions than for X-ray emissions. This is probably a result of the length of time these measurements have been available to researchers rather than any reflection on the physical processes involved. Algorithms that relate the emission power at various radio frequencies to the expected proton flux at 1 AU have been developed by several researchers including Cliver (1976), Cliver et al. (1978), Akun'yan et al. (1977), Akinyan et al. (1979), Smart and Shea (1979), and Chertok and Fomichev, (1984). Algorithms that relate the emission power at X-ray wave lengths to the expected proton flux at 1 AU have been developed by Kuck et al. (1971), Smart and Shea (1979), and Kuck and Hudson (1990). In a comparison of prediction methods Lantos (1990) found that the radio and X-ray peak flux proton prediction methods were equivalent.

Parameters Necessary for Solar Proton Event Model

In a real-time prediction mode, it is necessary to construct a model based on the information available at the time of the solar flare. We require some indication of the occurrence of a significant solar flare that is likely to accelerate and release particles into the interplanetary medium. We know of no unique parameter that indicates this situation. The best indicators, the big flare syndrome (Kahler, 1982), or the U-shaped peak power spectra (Castelli et al., 1967; Castelli and Guidice, 1976; Cliver et al., 1985), or the long duration soft X-ray event, all correlate at about the same level. Kuck and Hudson (1989) concluded that the correlation between the 1-8Å integrated soft X-ray emission and the peak >10 MeV proton flux is about 0.7. Mel'nikov et al. (1990) reported a similar correlation between the integrated microwave radio emission and peak >10 MeV proton flux. Once a likely solar flare is identified, it is essential to determine the position of the solar flare on the sun and calculate the energy in the solar flare electromagnetic emission. The peak proton flux expected at locations "well connected" to the solar flare site via the interplanetary magnetic field can be computed from selected algorithms that convert one of the electromagnetic emission parameters to expected peak proton flux.

It is possible to calculate (using the methods detailed below) the probable onset time and the expected time of maximum flux. This is done by separating the propagation of solar protons from the flare site to the observation location into two distinct and independent phases. Both of these phases, coronal propagation and interplanetary propagation, are illustrated in Figure 3. The first phase, coronal propagation, transports the particles

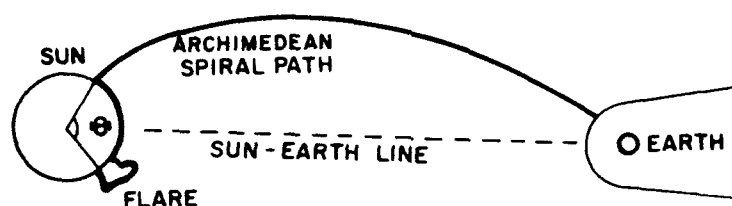


Figure 3. Illustration of the concept of two phases of solar particle propagation from the flare site on the sun to the earth. The coronal propagation distance on the sun is illustrated by the heavy arc. Interplanetary propagation proceeds along the interplanetary magnetic field lines which, for a constant speed solar wind, forms an Archimedean spiral path.

accelerated by the solar flare from the flare location to the "foot" of the interplanetary magnetic field line (Archimedean spiral path) between the sun and the earth. The coronal propagation phase is only weakly energy dependant, at least in the MeV energy range, and for our modeling purposes is assumed to be energy independent. The maximum possible prompt proton flux is presumed to be at the solar flare site, and it is further assumed that there is a gradient in the solar corona extending from the flare site. This gradient attenuates the maximum particle intensity one order of magnitude per radian of heliocentric angular distance from the flare site. The second phase, interplanetary propagation, transports the particles through the interplanetary medium from the sun to the earth along the interplanetary magnetic field. The interplanetary propagation phase is velocity dependant. For the particle onset phase, we use the "scatter free" approximation. Many of the concepts described here were first used by Smart and Shea (1979) and are summarized by Smart and Shea (1985).

Coronal propagation - theoretical expectations. The concepts we have used for the propagation of solar protons in the solar corona are similar to those originally advanced by Reinhard and Wibberenz (1974). We utilize the fundamental elements of solar particle diffusion theory as developed by early researchers (Reid, 1964; Axford, 1965; Krimigis, 1965; Burlaga, 1967; Wibberenz, 1974) and assume that almost all of the major diffusive effects occur in the solar corona. We make very few assumptions as to the manner of coronal transport except that stochastic processes dominate the particle transport between their source at the flare site and their release point along an interplanetary magnetic field line. We consider that the time required for coronal propagation is a function of heliocentric angular distance θ . From diffusion theory we would expect it to be proportional to θ^2 . [See Wibberenz (1974) for a discussion of diffusion theory relating to coronal propagation.] For large coronal propagation distances, the propagation delay time would be dominated by the coronal diffusion time rather than interplanetary propagation time.

We expect that there is a solar particle gradient existing in the solar corona such that the proton intensity decreases as a function of distance from the flare site. There has been considerable observational evidence of a coronal gradient (McCracken and Rao, 1970; McCracken et al., 1971; Roelof, 1973; Roelof et al., 1975; Gold et al., 1975; McGuire et al., 1983). The observations suggest that the gradient varies from case to case. We use an average gradient of a factor of 10 per radian of heliocentric propagation distance. This means that the expected flux observed at some position in space removed from the Archimedean spiral path of the interplanetary magnetic field line from the presumed particle source (i.e. the flare location) is expected to be reduced by a factor of 10 per radian of heliocentric angular distance.

Coronal propagation - comparison with observations. The onset times of particle events at the earth have been catalogued since the early satellite observations, (Barouch et al., 1971; Lanzerotti, 1973). When these earth-acquired data sets are organized in a heliographic coordinate system they show that the minimum time from the flare onset to particle detection occurs in a broad range of heliolongitudes around 60° west of solar central meridian, and that the longest times between the associated flare and the onset of particles observed at the earth are for flares on the eastern side of the visible solar disk. More recent data sets tend to confirm the general trends noted by the earlier investigators.

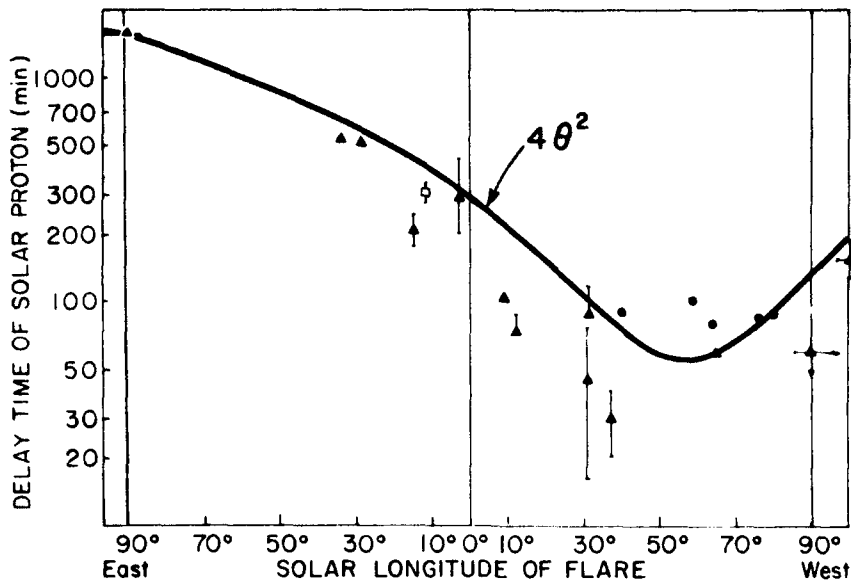


Figure 4. Distribution of the onset time of 30 MeV protons observed at the earth as a function of solar longitude. The data points are the measurements of Barouch et al. (1971).

The distribution of onset times at the earth for 30 MeV protons is shown in Figure 4. The data points shown on the figure indicate typical variations that may be expected. The minimum in the figure corresponds to a flare at the "foot point" of the Archimedean spiral path between the sun and the earth (57° west of central meridian). To our prejudiced eye, a reasonable fit to the onset data at the earth for this specific energy has the functional form of $4\theta^2$.

The distribution observed at the earth for time of maximum as a function of heliolongitude is illustrated in Figure 5. The data points taken from Van Hollebeke et al., (1975) show the typical range of variations that can be expected. The minimum in the curve corresponds to a flare at the "foot point" of 57° for the Archimedean spiral path between the earth and the sun computed from a nominal solar wind of 404 km/sec. It is our opinion that a reasonable fit to the onset data at the earth for this specific energy has the functional form of $8\theta^2$. Other data sets can be plotted in this manner and illustrate the same general characteristics.

Propagation in the interplanetary medium. After the particles propagate through the solar corona and are released into the interplanetary medium, we assume that they propagate along the interplanetary magnetic field lines. In the inner heliosphere the minimum interplanetary propagation time will be for particles that essentially travel along the interplanetary magnetic field lines with very little scattering, so for "scatter free" (Roelof, 1975) onsets the propagation time from the sun will be the distance traveled (i.e. the length along the Archimedean spiral path divided by the particle velocity). After the initial onset it is reasonable to expect that some scattering does occur and that some aspects of diffusion theory are applicable. The time for the propagation of any specified ion along this path is the Archimedean spiral path distance divided by the velocity which is determined by the kinetic energy of the ion.

We make the simplest possible assumptions regarding transport in the interplanetary medium as follows:

- a. Diffusion perpendicular to the interplanetary magnetic field is assumed to be negligible.
- b. The particles travel essentially along the interplanetary magnetic field lines with a

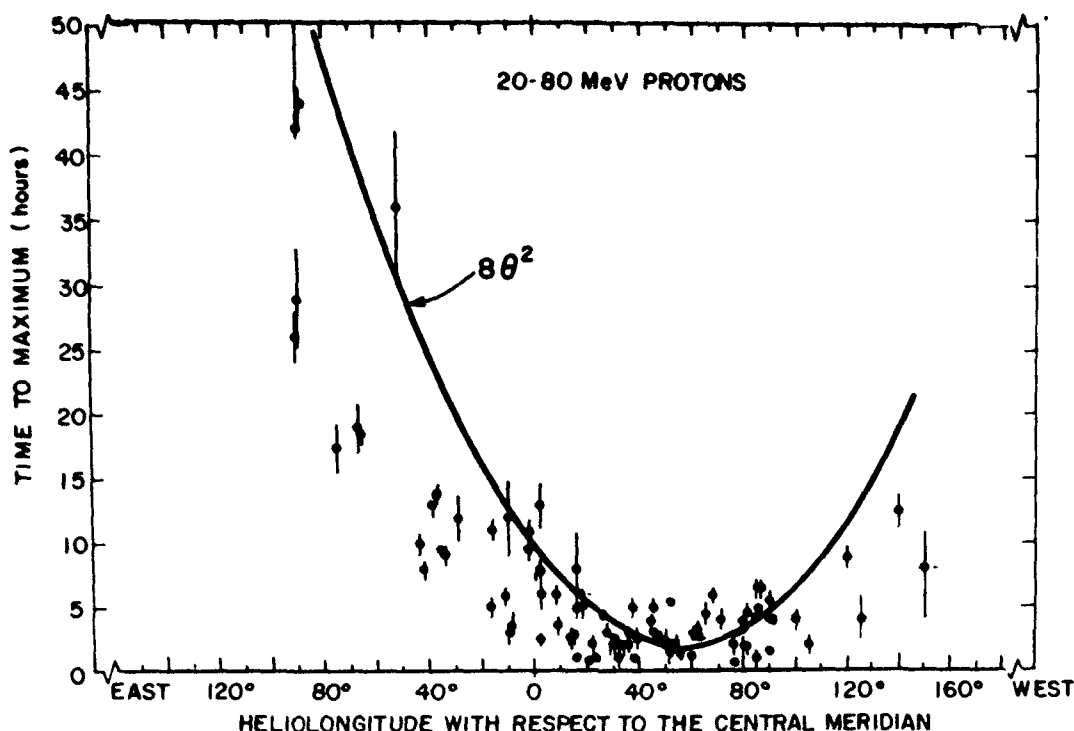


Figure 5. The time to the maximum 20 - 80 MeV proton flux observed at the earth as a function of the heliolongitude of the associated solar flare. The data points are from Van Hollebeke et al. (1975) and the heavy solid line is the $8\theta^2$ curve for a nominal solar wind speed.

velocity which is a function of the particle energy. We will use the symbol β to denote the speed of a solar proton as a ratio of the speed of light. β is given by

$$\beta = \{ 1 / (1 - [(E/mc^2) + 1]^2) \}^{0.5} \quad (5)$$

where E is the kinetic energy of the particle in MeV, and mc^2 is the mass-energy equivalence of a proton which is 938.323 MeV.

c. The distance traveled from the sun to the observation location in space is the distance along the Archimedean spiral path. The length of the Archimedean spiral path can be obtained by integration of the polar form of the Archimedean spiral equation.

From these assumptions, detailed below, we can calculate the expected propagation delay time and the time to peak particle flux.

Event decay. The decaying portion of the event can be modeled after the principles of collimated convection originally developed by Roelof (1973). After making a number of simplifying assumptions (some of which are that the particle flux can be represented by a simple power law, the anisotropy of the particle flux is small, the magnitude of the interplanetary magnetic field falls off as r^{-2} , and the particle flux gradient is field aligned and small), a $1/e$ decay constant can be derived which is a function of the distance along the Archimedean spiral path, the solar wind velocity, and the magnitude of the differential energy spectral exponent as follows:

$$T_d = 3D / [4V_{sw} (\gamma + 1)] \quad (6)$$

where T_d is the $1/e$ decay constant, D is the distance along the Archimedean spiral path, V_{sw} is the solar wind velocity, and γ is the solar proton energy differential spectral exponent.

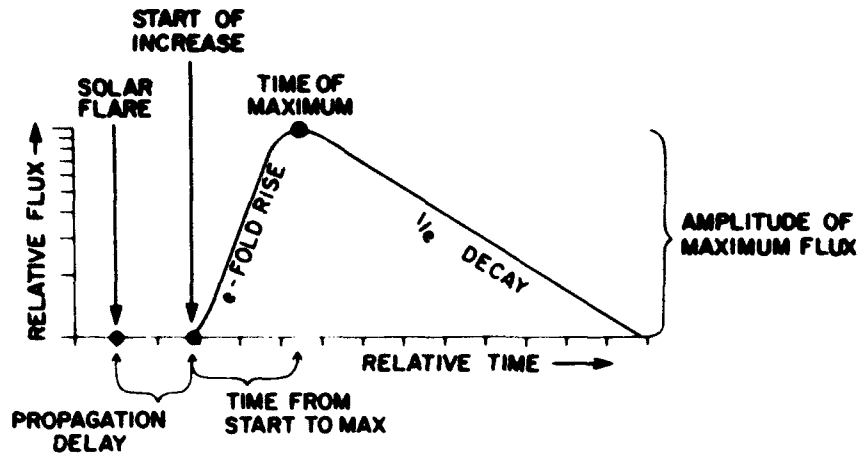


Figure 6. Illustration of the general characteristics of solar proton events. The large dots indicate the critical information that must be known to construct this type of event profile.

Solar Proton Event Model Construction

We now have the necessary information to construct a prediction for the proton intensity as a function of time. We can define the critical points needed to construct a predicted intensity-time profile for the specified energy. These are: the propagation delay between the solar flare and the proton onset at the earth, the time of the predicted flux maximum, the amplitude of the predicted flux maximum, and the predicted decay rate of the maximum flux as illustrated by large dots in Figure 6. An exponential curve is fitted between the proton onset and the maximum. Then the maximum flux is predicted to decay at the $1/e$ decay rate obtained from equation 5.

Solar proton onset time. The solar proton onset at the earth will be the solar flare onset time plus the propagation delay time. In our model, the propagation delay time is the sum of the coronal propagation time, and the interplanetary propagation time along the length of the Archimedean spiral from the sun to the earth for the fastest (highest energy, scatter-free) protons being detected. This propagation delay time, $T_{(pd)}$, after the solar flare onset time can be represented by:

$$T_{(pd)} = 4 \theta^2 + 0.1333 D / \beta. \quad (7)$$

In this and the following equations, time is specified in hours, the coronal propagation heliocentric distance θ is in radians and the distance along the Archimedean spiral from the sun to the earth, D , is in Astronomical Units.

Solar proton maximum time. The time of the solar proton flux maximum at the earth will again be the sum of the coronal propagation time and the interplanetary propagation time along the length of the Archimedean spiral from the sun to the earth. For this computation, several additional factors influence the interplanetary propagation calculation. Almost all theories involving differential transport show that the time of maximum is proportional to the square of the distance traveled (See Wibberenz, 1974). Also, the "steep" solar proton energy spectral slope results in most of the flux in a specific energy interval to be at the lowest energy being detected. Hence, for the time of maximum we compute the particle velocity for the lowest energy protons being detected. Since we also assume some scattering is applicable, we do not use the "scatter free approximation, but assume that the "average pitch angle is 60° to the interplanetary magnetic field direction, and hence the average "forward" speed is one-half the proton velocity around the interplanetary magnetic field line.

The time of maximum intensity $T_{(m)}$, can be calculated by:

$$T_{(m)} = 8 \theta^2 + 2 (0.1333 D^2 / \beta). \quad (8)$$

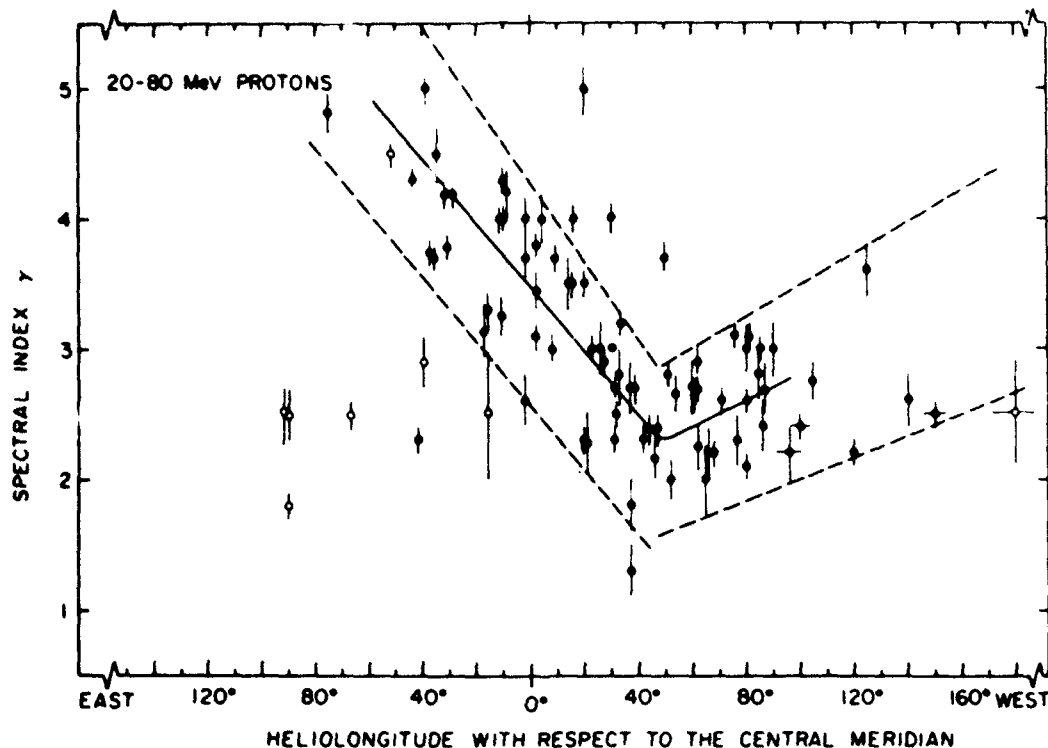


Figure 7. The variation of the solar proton spectral exponent in the 20 - 80 MeV energy range as a function of heliolongitude. The data points are from Van Hollebeke et al. (1975).

Solar proton maximum flux amplitude. The maximum proton flux expected is obtained by converting the selected electromagnetic emission parameters to predicted proton flux along the Archimedean spiral path leading from the solar flare position. By assuming an average coronal gradient of a factor of 10 per radian from the presumed particle source (i.e. the flare location) to the release point of solar protons "favorable" to the observation location (i.e. the "foot" of the Archimedean spiral of the interplanetary magnetic field line between the observation position and the sun) it is possible to estimate particle intensity.

Solar proton energy spectrum exponent prediction. There are few predictors of the slope of the solar proton spectrum. Some of the early work attempting this prediction from the maximum and minimum flux values in the radio peak power spectrum (Bakshi and Barron 1974, 1975, 1979) has not proven extremely reliable. The statistical tendencies of the exponent of the proton energy spectral slope noted by Van Hollebeke et al. (1975) shown in Figure 7 have demonstrated usefulness. These data can be ordered by the same parameter used to order the other solar proton flux parameters, the heliocentric angular distance from the solar flare location to the probable "root" of the Archimedean spiral path (interplanetary magnetic field lines) from the detection location to the sun. A prediction of the magnitude of the exponent of the solar proton differential energy spectral slope, γ is given by the equation:

$$\gamma = 2.7 [1 + \theta / 2] \quad (9)$$

EXTENDING PROTON PREDICTED FLUXES TO HEAVIER ELEMENTS

The same principles involved for organizing and estimating the proton (ions with $Z=1$) arrival and time-intensity profiles are also applicable to heavy ions. It is reasonable to assume

Table 1. Normalized Elemental Abundances of Solar Particle Events

	Adams et al. (1981) Mason et al. (1980) ~ 1 MeV	Gloeckler (1979) 1-20 MeV	Cook et al. (1984) 10 MeV	McGuire et al. (1986) 6.7-15 MeV
1	H	1.0	1.0	1.0
2	He	2.2×10^{-2}	1.5×10^{-2}	1.5×10^{-2}
3	Li	1.0×10^{-7}	4.8×10^{-8}	2.8×10^{-6}
4	Be	1.5×10^{-7}	6.0×10^{-9}	1.4×10^{-7}
5	B	1.5×10^{-7}	1.2×10^{-8}	1.4×10^{-7}
6	C	1.6×10^{-4}	1.2×10^{-4}	1.3×10^{-4}
7	N	3.8×10^{-5}	2.8×10^{-5}	3.7×10^{-5}
8	O	3.2×10^{-4}	2.2×10^{-4}	2.8×10^{-4}
9	F	4.3×10^{-7}	1.0×10^{-8}	1.4×10^{-7}
10	Ne	5.1×10^{-5}	3.1×10^{-5}	3.6×10^{-5}
11	Na	1.6×10^{-6}	3.5×10^{-6}	2.4×10^{-6}
12	Mg	4.8×10^{-5}	3.9×10^{-5}	5.2×10^{-5}
13	Al	3.5×10^{-6}	3.5×10^{-6}	3.3×10^{-6}
14	Si	3.8×10^{-5}	3.5×10^{-5}	4.2×10^{-5}
15	P	2.3×10^{-7}	4.3×10^{-7}	4.0×10^{-7}
16	S	1.8×10^{-5}	5.7×10^{-6}	7.8×10^{-6}
17	Cl	1.7×10^{-7}	7.1×10^{-8}	6.5×10^{-6}
18	Ar	3.9×10^{-6}	8.7×10^{-7}	7.3×10^{-7}
19	K	1.3×10^{-7}	1.0×10^{-7}	4.6×10^{-6}
20	Ca	2.3×10^{-6}	3.1×10^{-6}	3.2×10^{-6}
21	Sc		7.8×10^{-9}	
22	Ti	1.0×10^{-7}	1.2×10^{-7}	
23	V		1.2×10^{-8}	
24	Cr	5.7×10^{-7}	5.0×10^{-7}	
25	Mn	4.2×10^{-7}	1.8×10^{-7}	
26	Fe	4.1×10^{-5}	3.3×10^{-5}	3.4×10^{-5}
27	Co	1.0×10^{-7}	4.8×10^{-7}	
28	Ni	2.2×10^{-6}	1.2×10^{-6}	
29			1.4×10^{-8}	
30			3.8×10^{-8}	

that the same principles of coronal and interplanetary propagation apply to all ions independent of the mass or atomic charge. There is a major problem in anticipating the flux or abundance in finding a simple common factor for the elemental abundance ratios. There have been a number of papers reporting the variation of the elemental abundances in solar particle events; see Lin (1987) and Mason (1987) for recent reviews. A general summary is that "small" events may have the greatest variability in elemental composition. The elemental abundance ratios seem to have a slight variation according to the energy of the measurement. This may be a reflection of the "size" of the particle event since small particle events would not have many heavy ions at high energies. The hydrogen to helium ratios are the most variable even for "large" events; the heavier elemental abundance ratios seem to be in general agreement with the ratios expected from normal coronal material organized by the first ionization potential. Since the prediction parameters available convert from electromagnetic emission parameters to proton flux, it is necessary to extrapolate these proton predictions, by the expected ratio, to heavier elements. Initial estimates of these ratios have been done by Mart (1988) and are summarized in Table 1.

EXTRAPOLATION OF EARTH-BASED PREDICTION METHODS TO OTHER LOCATIONS IN SPACE

We assume that the maximum possible prompt solar proton flux would be at the position that is "well connected" to the solar flare source region. Using the intrinsic assumptions that the coronal particle intensity gradients control the particle flux observed around the sun it is possible to estimate the particle flux at any heliographic longitude. The arguments used for extrapolation of proton fluxes to other heliocentric distances rely on the assumption that the diffusion across magnetic field lines is negligible, and that the volume of the magnetic flux tube as the distance from the sun increases expands in the manner expected from classical geometry. In this case a power law function of the form R^{-3} can be used to extrapolate to other distances. Hamilton (1988) analyzed the probable effects of diffusion and suggested that $R^{-3.3}$ would be an appropriate factor.

Extrapolation at 1 AU Radial Distance to Other Heliocentric Angles

To extrapolate a prediction to other locations at 1 AU, it is necessary to use the Archimedean spiral and the coronal gradient concept. First, compute the longitude on the sun from which the interplanetary magnetic field line passing through the spacecraft position would originate. Then determine the heliocentric angular distance between the location of the solar flare and the solar longitude of the "root" of the idealized spiral field line passing through the spacecraft. Next multiply the coronal gradient per radian by the heliocentric angular distance between the two positions in order to estimate the flux diminution. Finally, multiply the peak proton flux expected at the "favorable" propagation path by this flux reduction factor.

Radial Dependence of Protons

The extrapolation arguments to other heliocentric distances rely on the volume of the magnetic flux tube behaving in a "classical" manner as the distance from the sun increases. If "classical" behavior is assumed, then a power law function can be used to extrapolate to other distances. Any distortion to the magnetic flux tubes are an unknown that we have no way of accurately estimating. Because of this there is no consensus view on the proper method for extrapolating solar particle fluxes and fluences from 1 AU to other distances in the heliosphere. The existing meager measurements are from comparisons of earth-orbiting satellite measured proton fluxes compared with space-probe measurements of the same event in the energy range of 10 to 70 MeV from 1 to 5 AU. These investigations of the radial dependence of the solar energetic particle flux have been done by Hamilton (1977, 1981, 1988) and Beeck et al. (1987).

Radial flux extrapolation from 1 AU. For distances greater than 1 AU extrapolate the expected proton flux at 1 AU using a functional form of $R^{-3.3}$ where R is the radial distance from the sun. This is the average solar proton radial gradient derived by Hamilton (1988) from a combination of Voyager and earth-satellite data. The limited measurements available suggest we should expect variations ranging from R^{-3} to R^{-4} . For distances less than 1 AU extrapolate the expected proton flux at 1 AU using a functional form of R^{-3} . Again, the limited measurements available suggest that variations ranging from R^{-3} to R^{-2} should be expected.

Radial fluence extrapolation from 1 AU. To extrapolate proton fluence from 1 AU to other distances in the heliosphere, use a functional form of $R^{-2.5}$ and expect variations ranging from R^{-3} to R^{-2} .

EXTRAPOLATION OF EARTH-BASED PREDICTION METHODS TO A MARS MISSION

In a mission to Mars, the radial distance will vary according to the spacecraft trajectory chosen. The shielding provided by the spacecraft must be consistent with constructing a minimum mass vehicle to minimize the exposure to galactic cosmic ray secondaries generated in the vehicle, and yet provide adequate protection against a very large solar proton event. As

discussed elsewhere in this volume, approximately 15 g cm^{-2} of shielding appear to be sufficient to reduce the dose of a "major" solar proton event to a "tolerable level". (A much more detailed discussion of this issue is given by Wilson et al., 1991.)

The solar proton particle flux is expected to vary as a power law with radial distance from the sun. As discussed in the previous section, a power law exponent of -3 would be expected from magnetic flux tube geometry. Since the radial distance to Mars is $\sim 1.5 \text{ AU}$, then the flux at the orbit of Mars would be expected to be about $1/3$ of the flux at 1.0 AU along the same spiral path. This variation should be contrasted with the average helio-longitudinal gradient of one order of magnitude per radian of heliocentric angular distance. A consideration of these expected variations suggest that the proton prediction problem for Mars is not dramatically different from the earth. Sensors on-board the spacecraft viewing in the optical, radio and soft X-ray wavelengths should be able to provide useful prediction information.

The probability of a "surprise", a solar proton event being detected when there is no visible preceding solar activity, is significantly larger for the Mars radial distance. At the earth, about 20% of the recorded solar proton events are not associated with visually observed solar flares. It is presumed that the origin of "major" proton events not associated with visual solar flares have their source from solar activity from behind the western limb of the sun as viewed from the earth. See Figure 15 of Shea and Smart (1992) for assumed source location on the sun for solar cosmic ray events from 1956. This same type of distribution is present for major non-relativistic solar proton events. Similarly, for the position of Mars, we would expect that $1/2$ of the detected solar proton events would have their source on the portion of the sun that is not observable from Mars. Consider the probable "favorably connected" heliolongitude for Mars. At 1.5 AU distance the sun-Mars transit time for a 400 km sec^{-1} solar wind would be about 6.5 days. During that time the sun would have rotated $\sim 86^\circ$. This is essentially at the western limb of the solar disk visible from Mars. Assuming that the solar proton flare distribution is symmetrical in heliolongitude, then approximately $1/2$ of the source solar proton flares cannot be observed from the Mars orbital distance.

This situation strongly argues for on-board particle and radiation sensors on a Mars mission. If we consider the intensity-time profile of a solar particle event, then the critical factor is the time from event onset to "hazardous" radiation levels. Depending on the propagation conditions even for "well connected" events, this is likely to be of the order of an hour. The most "dangerous" particle radiation will be the ions that penetrate the shielding and stop in blood forming organs (thus depositing most of their energy in these organs). These will be the protons between 70 and 150 MeV assuming that there is $\sim 5 \text{ g cm}^{-2}$ of shielding provided by the body structure. The typical intensity-time profile observed in this energy range at 1 AU and expected at 1.5 AU provides for about an hour from particle onset until the maximum proton flux will be observed. We suggest that prudent mission planning would allow for movement of personnel to a more heavily shielded area or the re-distribution of mass on this time scale.

SUMMARY

We have discussed the procedures we use to model the intensity-time profile of solar protons expected in space after the occurrence of a significant solar flare on the sun. The particle flux detected at any point in space is a function of the location of the flare on the sun with respect to the detection position. The procedures and techniques used for predicting solar proton fluxes at the earth can be extrapolated to help predict solar particle fluxes at other locations in space including the orbit of Mars.

REFERENCES

Adams, J.H., Jr., Silberberg, R., and Taso, C.H., 1981, "Cosmic Ray Effects on Microelectronics, Part I: The Near Earth Particle Environment", NRL Memorandum Report 4506, Naval Research Laboratory, Washington, D.C.

Akun'yan, S.T., Fomichev, V.V., and Chertok, I.M., 1977, Determination of the parameters of solar protons in the neighborhood of the earth from radio bursts, 1 Intensity functions, *Geomag. and Aeron.*, 17: 5.

Akinyan, S.T., Fomichev, V.V., and Chertok, I.M., 1979, Quantitative forecasts of solar protons based on solar flare radio data, 3:D14, in: "Solar-Terrestrial Prediction Proceedings", R.F. Donnelly, ed., U. S. Department of Commerce, NOAA/ERL, Boulder, Colorado.

Axford, W.I., 1965, Anisotropic diffusion of solar cosmic rays, *Planet. Space Sci.*, 13: 1301.

Bakshi, P., and Barron, W., 1974, Spectral Correlations Between Solar Fare Radio Bursts and Associated Proton Fluxes, I, AFCRL-TR-74-0508, Air Force Cambridge Research Laboratories, Hanscom Air Force Base, Massachusetts.

Bakshi, P., and Barron, W.R., 1975, Spectral Correlation Between Solar Flare Radio Bursts and Associated Proton Fluxes, II, AFCRL-TR-75-0579, Air Force Cambridge Research Laboratories, Hanscom Air Force Base, Massachusetts.

Bakshi, P., and Barron, W.R., 1979, Prediction of solar flare proton spectral slope from radio burst data, *J. Geophys. Res.*, 84: 131.

Beeck, J., Mason, G.M., Hamilton, D.C., Wibberenz, G., Kunow, H., Hovestadt, D., and Klecker, B., 1987, A multispacecraft study of the injection and transport of solar energetic particles, *Astrophys. J.*, 322: 1052.

Barouch, E., Gros, M., and Masse, P., 1971, The solar longitude dependence of proton event delay, *Sol. Phys.*, 19: 483.

Burlaga, L.F., 1967, Anisotropic diffusion of solar cosmic rays, *J. Geophys. Res.*, 72: 4449.

Castelli, J.P., Aarons, J., and Michael, G.A., 1967, Flux density measurements of radio bursts of proton-producing flares and nonproton flares, *J. Geophys. Res.*, 72: 5491.

Castelli, J.P., and Guidice, D.A., 1976, Impact of current solar radio patrol observations, *Vistas in Astronomy*, 19: 355.

Chertok, I.M., and Fomichev, V.V., 1984, Development of the quantitative proton flare diagnostics technique by radio burst data, p. 270 in: "Solar-Terrestrial Prediction Proceedings: Proceedings of a Workshop at Meudon, France, June 18-22, 1984", P.A. Simon, G. Heckman and M.A. Shea, ed., U. S. Department of Commerce, NOAA/ERL, Boulder, Colorado.

Cliver, E.W., 1976, Parent Flare Emission at 2.8 GHz As A Predictor of the Peak Absorption of Polar-Cap Events, NELC-TR-2015, Naval Electronics Laboratory, San Diego, California.

Cliver, E.W., Secan, J.A., Beard E.D., and Manley, J.A., 1978, Prediction of solar proton events at the Air Force Global Weather Central's Space Environment Forecasting Facility, p. 393, In: "Proceedings of the NRL Symposium on the Effect of the Ionosphere on Space and Terrestrial Systems", Naval Research Laboratory, Washington D. C.

Cliver, E.W., McNamara, L.F., and Gentile, L.C., 1985, Peak flux density spectra of large solar radio bursts and proton emission from flares", *J. Geophys. Res.*, 90: 6251.

Cook, W.R., Stone, E.C., and Vogt, R.E., 1984, Elemental composition of solar energetic particles, *Astrophys. J.*, 297: 827.

Gloeckler, G., 1979, Composition of energetic particle population in interplanetary space, *Rev. of Geophys.*, 17: 569.

- Gold, R.E., Roelof, E.C., Nolte, J.T., and Krieger, A.S., 1975, Relation of large-scale coronal x-ray structure and cosmic rays: 5. Solar wind and coronal influence on a Forbush decrease lasting one solar rotation, *Proc. 14th International Cosmic Ray Conference*, 3: 1095.
- Hamilton, D.C., 1977, Radial transport of energetic solar flare particles from 1 to 6 AU, *J. Geophys. Res.*, 82: 2159.
- Hamilton, D.C., 1981, Dynamics of solar cosmic ray bursts at large heliocentric distances (≥ 1 AU), *Adv. Space. Res.*, 1: 25.
- Hamilton, D.C., 1988, The radial dependence of the solar energetic particle flux, in: "Proceedings of the JPL Workshop in the Interplanetary Charged Particle Environment", 1: 86, J. Feynman and S. Gabriel ed., NASA JPL Publication 88-28, Jet Propulsion Laboratory, Pasadena, California.
- Kahler, S.W., 1982, The role of the big flare syndrome in correlations of solar energetic protons and associated microwave parameters, *J. Geophys. Res.*, 87: 3439.
- Krimigis, S.M., 1965, Interplanetary diffusion model for the time behavior of intensity in a solar cosmic ray event, *J. Geophys. Res.*, 70: 2943.
- Kuck, G.A., Davis, S.R., and Krause, G.J., 1971, Prediction of Polar Cap Absorption Events, AFWL-TR-71-1, Air Force Weapons Laboratory, Kirtland AFB, New Mexico.
- Kuck, G.A., and Hudson, S., 1990, Prediction of solar proton fluxes from X-ray Signatures, 1: 422, in: "Solar-Terrestrial Prediction Proceedings: Proceedings of a Workshop at Leura, Australia, October 16-20, 1989", R.J. Thompson, D.G. Cole, P.J. Wilkinson, M.A. Shea, D.F. Smart, and G.R. Heckman, Eds., U. S. Department of Commerce, NOAA/ERL, Boulder, Colorado.
- Lantos, P., 1990, Evaluation of proton events prediction, 1:487, in: "Solar-Terrestrial Prediction Proceedings: Proceedings of a Workshop at Leura, Australia, October 16-20, 1989", R.J. Thompson, D.G. Cole, P.J. Wilkinson, M.A. Shea, D.F. Smart, and G.R. Heckman, Eds., U. S. Department of Commerce, NOAA/ERL, Boulder, Colorado.
- Lanzerotti, L.J., 1973, Coronal propagation of low-energy solar protons, *J. Geophys. Res.*, 78: 3942.
- Lin, R.P., 1987, Solar particle acceleration and propagation, *Reviews of Geophysics*, 25: 676.
- Mason, G.M., 1987, The composition of galactic cosmic rays and solar energetic particles, *Reviews of Geophysics*, 25: 685.
- Mason, G.M., Fisk, L.A., Hovestadt, D., and Gloeckler, G., 1980, A survey of ~ 1 MeV nucleon⁻¹ solar flare particle abundances, $1 < Z < 26$, during the 1973-1977 solar minimum period, *Astrophys. J.*, 239: 1070.
- McCracken, K.G., and Rao, U.R., 1970, Solar cosmic ray phenomena, *Space Science Reviews*, 11: 155.
- McCracken, K.G., Rao, U.R., Bukata, R.P., and Keath, E.P., 1971, The decay phase of solar flare events, *Sol. Phys.*, 18: 100.
- McGuire, R.E., van Hollebeke, M.A.I., and Lau, N., 1983, A multi-spacecraft study of the coronal and interplanetary transport of solar cosmic rays, *Proc. 18th International Cosmic Ray Conference*, 10: 353.
- Morfill, G., Volk, H., and Lee, M.A., 1976, On the effect of directional medium-scale interplanetary variations on the diffusion of galactic cosmic rays and their solar cycle variations, *J. Geophys. Res.*, 81: 5841.

- McGuire, R.E., Von Rosenvinge, T.T., and McDonald, F.B., 1986, The composition of solar energetic particles, *Astrophys. J.*, 301: 938.
- Nolte, J.T., and Roelof, E.C., 1973, Large scale structure of the interplanetary medium, 1: High coronal structure and the source of the solar wind, *Solar Physics*, 33: 241.
- Mel'nikov, V.F., Podstrigach, T.S., Dajbog, E.I., Logachev, Yu.I., and Stolpovskij, V.G., 1990, 1: 533, in: "Solar-Terrestrial Prediction Proceedings: Proceedings of a Workshop at Leura, Australia, October 16-20, 1989", R.J. Thompson, D.G. Cole, P.J. Wilkinson, M.A. Shea, D.F. Smart, and G.R. Heckman, Eds., U. S. Department of Commerce, NOAA/ERL, Boulder, Colorado.
- Parker, E.N., 1965, The passage of energetic charged particles through interplanetary space, *Planet. Space Sci.*, 13: 9
- Reid, G.C., 1964, A diffusive model for the initial phase of a solar proton event, *J. Geophys. Res.*, 69: 2659.
- Reinhard, R., Roelof, E.C., and Gold, R.E., 1986, Separation and analysis of temporal and spatial variations in the 10 April 1969 solar flare particle event, in: "The Sun and the Heliosphere in Three Dimensions", p. 297, R.G. Marsden, ed., Proceedings of the XIX ESLAB Symposium, Astrophysics and Space Science Library, D. Reidel Publishing Co., Dordrecht.
- Reinhard, R., and Wibberenz, G., 1974, Propagation of flare protons in the solar atmosphere, *Sol. Phys.*, 36:473.
- Roelof, E.C., 1973, New aspects of interplanetary propagation revealed by 0.3 MeV solar proton events in 1967, p. 411, in: *Solar-Terrestrial Relations*, University of Calgary, Canada.
- Roelof, E.C., 1975, Scatter-free collimated convection and cosmic-ray transport at 1 AU, *Proc. 14th International Cosmic Ray Conference*, 5:1716.
- Roelof, E.C., 1976, Solar Particle Emissions, in: "Physics of Solar Planetary Environments", p. 214, D.J. Williams, ed., American Geophysical Union, Washington, D. C., USA.
- Roelof, E.C., Gold, R.E., Krimigis, S.M., Krieger, A.S., Nolte, T.J., McIntosh, P.S., Lazarus, A.J., and Sullivan, J.D., 1975, Relation of large-scale coronal x-ray structure and cosmic rays: 2, Coronal control of interplanetary injection of 300 keV solar protons, *Proc. 14th International Cosmic Ray Conference*, 5: 1704.
- Roelof, E.C., and Krimigis, S.M., 1973, Analysis and synthesis of coronal and interplanetary energetic particle, plasma and magnetic field observations over three solar rotations, *J. Geophys. Res.*, 78: 5375.
- Shea, M.A., and Smart, D.F., 1992, History of energetic solar protons for the past three solar cycles including Cycle 22 update, in "Biological Effects and Physics of Solar and Galactic Cosmic Radiation", C.E. Swenberg, G. Horneck and E. G. Stassinopoulos, ed., this volume.
- Smart, D.F., 1988, Predicting the arrival times of solar particles, in: "Proceedings of the JPL Workshop in the Interplanetary Charged Particle Environment", J. Feynman and S. Gabriel, ed., NASA JPL Publication 88-28, 1: 101, Jet Propulsion Laboratory, Pasadena, California.
- Smart, D.F., and Shea, M.A., 1979, PPS76 - a computerized "event mode" solar proton forecasting technique, 1:406, in: "Solar-Terrestrial Prediction Proceedings", R.F. Donnelly, ed., U. S. Department of Commerce, NOAA/ERL, Boulder Colorado.

Smart, D.F., and Shea, M.A., 1985, Galactic cosmic radiation and solar energetic particles, Chapter 6 in: "Handbook of Geophysics and the Space Environment", A.S. Jursa ed., Air Force Geophysics Laboratory, Bedford, MA.

Svestka, Z., 1976, "Solar Flares", Volume 8, Geophysics and Astrophysics Monographs, D. Reidel Publishing Co., Dordrecht, Holland.

Valdes-Galica, J.F., 1991, Transport of energetic particles in the interplanetary medium, in "Solar and Galactic Cosmic Rays, Proceedings of the 12th European Cosmic Ray Symposium", P.R. Blake and W.F. Nash, ed., Nuclear Physics B (Proc. Suppl.) 22B:46, North Holland, Amsterdam.

Van Hollebeke, M.A.I., Ma Sung, L.S., and McDonald, F.B., 1975, The variation of solar proton energy spectra and size distribution with heliolongitude, Sol. Phys., 41: 189.

Wibberenz, G., 1974, Interplanetary magnetic fields and the propagation of cosmic rays, J. Geophys., 40: 667.

Wilson, J.W., Townsend, L.W., Schimmerling, W., Khandelwal, G.S., Ferdous, K., Nealy, J.E., Cucinotta, F.A., Simonsen, L.C., Shinn, J.L., and Norbury, J.W., 1991, Application to space exploration, Chapter 12 in "Transport Methods and Interactions for Space Radiation", NASA Reference Publication 1257, NASA, Washington, D. C.

Zwickl, R.D., and Webber, W.R., 1977, Solar particle propagation from 1 to 5 AU, Sol. Phys., 54: 457.