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PPS-87: A NEW EVENT ORIENTED SOLAR PROTON PREDICTION MODEL

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ABSTRACT

A new event-oriented solar proton prediction model has been developed and implemented at the USAF Space Environment forecast facility. This new model generates predicted solar proton time-intensity profiles for a number of user adjustable energy ranges and is also capable of making predictions for the heavy ion flux. The computer program is designed so a forecaster can select inputs based on the data available in near real-time at the forecast center as the solar flare is occurring. The predicted event amplitude is based on the electromagnetic emission parameters of the solar flare (either microwave or soft X-ray emission) and the solar flare position on the sun. The model also has an update capability where the forecaster can normalize the prediction to actual spacecraft observations of spectral slope and particle flux as the event is occurring in order to more accurately predict the future time-intensity profile of the solar particle flux. Besides containing improvements in the accuracy of the predicted energetic particle event onset time and magnitude, the new model converts the predicted solar particle flux into an expected radiation dose that might be experienced by an astronaut during EVA activities or inside the space shuttle.

INTRODUCTION AND CONCEPT INVOLVED

A procedure has been developed to generate a computerized time-intensity profile of the solar proton intensity expected at the earth after the occurrence of a significant solar flare on the sun. This procedure is not a comprehensive, self-consistent, analytical method, but is a construction of selected experimental and theoretical results from the entire domain of solar-terrestrial physics. Many of the concepts used were first reported by /1,2/; extracts from the general procedure that relate to predicting the expected onset time and time of maximum at the earth after the occurrence of a solar flare are presented in this paper. A summary of the capabilities of this prediction procedure is given in Table 1.

Table 1. Summary of the PPS87 (ADVANCED PROTON PREDICTION SYSTEM) Capabilities.

INPUTS	OUTPUTS
Observables available to AWS*	18 channels of time-intensity profiles
Flare position	Peak flux
Electromagnetic emission	Event integrated fluences
Radio	Directly comparable with particle measurements
X-rays	14 outputs have adjustable energy ranges
Solar wind (default Algorithm)	4 outputs energy ranges adjusted to SMS/GOES*
	10 energy ranges set to AFGWC* specifications
	2 outputs for PCA* (day & night)
	2 outputs for radiation dose (EVA* & shuttle)
HEAVY ION PREDICTION CAPABILITY	**UPDATE CAPABILITY**
Alpha particles	Can normalize prediction to actual observations:
Iron nuclei	maximum flux and\or time of specified channel

Solar energetic particles are accelerated in solar active regions from the available coronal material selected by the first ionization potential during solar flare events. After the initial acceleration there may be further acceleration of the energetic particle population by interactions with shocks, but this subject is beyond the scope of this paper. The X-ray, radio and optical emissions during the solar flare event are the indicators (perhaps secondary manifestations) that proton acceleration is occurring. The solar protons emitted from the inner solar corona at a "favorable" position may intercept the earth. In organizing solar energetic ion data it is very useful to use the gross features of the interplanetary magnetic field topology determined by the solar wind outflow and the rotation of the sun.

*AWS: Air Weather Service
*EVA: Extravehicular Activity
*PCA: Polar Cap Absorption
*AFGWC: Air Force Global Weather Centre
*SMS/GOES: Synchronous Meteorological Satellite/Geostationary Operational Environmental Satellite

From examining the solar proton data acquired during the past three solar cycles, we can generalize and separate the propagation of solar protons from the flare site to the earth into two distinct and independent phases. The first phase is diffusion from the flare site through the solar corona to the "foot" of the idealized Archimedean spiral path formed by the interplanetary magnetic field line between the sun and the earth. The maximum possible flux is presumed to be at the solar flare site (perhaps a coronal hole opened by the energetic solar flare), 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 as the angular distance from the flare site increases. The second phase is the propagation in the interplanetary medium from the sun to the earth along the interplanetary magnetic field lines. Both of these phases are illustrated in Figure 1.

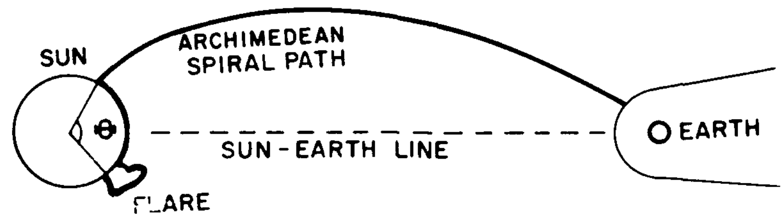

Figure 1. Illustration of the propagation concept. The coronal propagation distance Θ is illustrated by the heavy arc on the sun. Interplanetary propagation proceeds along the interplanetary magnetic field lines which, for a constant speed solar wind, forms an Archimedean spiral path from the sun to the earth.

Once the solar flare accelerated energetic ions arrive at the earth, we can generalize the characteristics of the time-intensity profile observed at any energy above the solar wind domain as illustrated in Figure 2. First there is a propagation delay from the time of the solar flare until the first particles are observed at the earth. After the initial onset of particles, there is a rise in the solar proton flux until a maximum flux is observed, and after the time of the maximum solar proton intensity, there is a slow general exponential decay of the particle flux to background levels. The shape of an individual event may be distorted by features which happen to be present in the interplanetary medium at the time of the solar particle event, and the decay of the solar particle event may be further disturbed by travelling interplanetary shocks, but the general features are always recognizable.

We utilize the concepts of coronal propagation; however, we make very few assumptions as to the manner of coronal transport except that some stochastic processes dominate the particles between their source at the flare site and their release point along an interplanetary magnetic field line. In this context we take the fundamental elements of solar particle diffusion theory as developed by early researchers and assume that almost all of the major diffusive effects occur in the solar corona. For events observed at the earth, the distance the solar particles travel in the solar corona from the presumed source (i.e. the solar flare site) to the foot of the Archimedean spiral path from the sun to the earth is designated by the symbol Θ. From diffusion theory we would expect it to be proportional to Θ^2, (see /3/ for a discussion of diffusion theory relating to coronal propagation). For large values of Θ the propagation time to the earth is dominated by the coronal diffusion rather than interplanetary propagation.

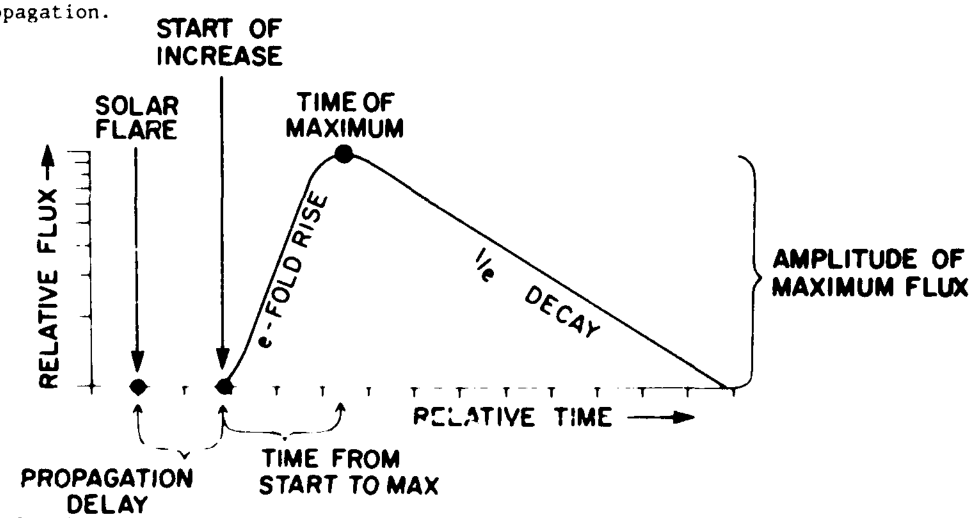

Figure 2. Illustration of the general characteristics of solar proton events.

After the particles propagate through the solar corona and are released into the interplanetary medium, they essentially propagate along the interplanetary magnetic field line. During this phase of their propagation we assume that their mean free path length is of the order of 0.1 to 0.3 AU. We make the simplest possible assumptions regarding transport in the interplanetary medium as follows:

a. The particles travel essentially along the interplanetary magnetic field lines with a velocity which is a function of the particle energy.
b. Diffusion perpendicular to the interplanetary magnetic field is assumed to be negligible.
c. The minimum distance to travel from the sun to the earth is the distance along the Archimedean spiral path.

The minimum propagation delay will be for particles that essentially travel along the interplanetary magnetic field lines with very little scattering, so for scatter free onsets the propagation time from the sun to the earth will be the distance traveled divided by the particle velocity. After the initial onset it is reasonable to expect that some scattering has taken place and that some aspects of diffusion theory are applicable. We obtained the distance traveled from the sun to the earth by integration of the polar form of the Archimedean spiral equation. The time for the propagation of any specified ion along this path is merely the path distance divided by the ion velocity which is determined by the kinetic energy of the ion. Almost all theories involving differential transport show that the time of maximum is proportional to the square of the distance traveled. When data sets containing onset times or the time of solar particle event maximum at the earth are organized in a heliographic coordinate system they show that the minimum time from the flare to particle onset or particle maximum at the earth occurs in a broad range of heliolongitudes around 60 degrees west of central meridian and that the longest times between the associated flare and the particle onset or particle maximum observed at the earth are for eastern heliolongitude flares. The distribution of onset times expected for 30 MeV protons for nominal solar wind speeds is shown in Figure 3a, and the variation shown by the data points are typical. To our prejudice eye, a reasonable fit to the onset data at any specific energy has the functional form of 4 Θ^2 as illustrated by the heavy line. The distribution of the observed time of maximum as a function of heliolongitude is illustrated in Figure 3b. Again, to our prejudice eye, a reasonable fit to the time of maximum data has the functional form of 8 Θ^2 and the data points illustrate the variations that can be expected.

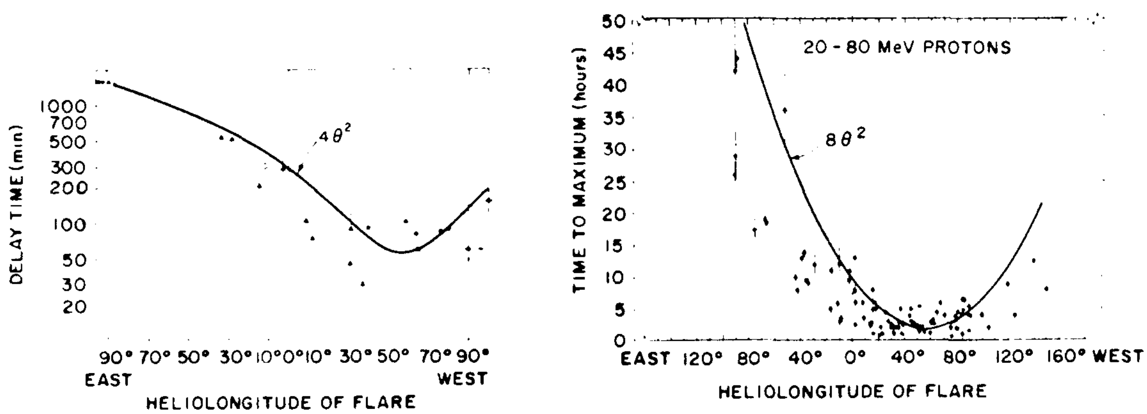

Figure 3. Left: the distribution of onset time of 30 MeV protons observed at the earth as a function of heliolongitude/4/. Right: the time from onset to the maximum 20 - 80 MeV proton flux as a function of the heliolongitude /5/.

EVENT DECAY

The decaying portion of the event can be modeled after the principles of collimated convection /6/. 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 interplanetary magnetic field falls off as r^{-2}, and that the particle flux gradient is field aligned and small), an 1/e decay constant can be derived which is a function of the distance along the Archimedean spiral path, the solar wind velocity, and differential energy spectral exponent.

HEAVY ION EVENTS

The same principles involved for organizing and estimating the proton (ions with Z=1) arrival and time-intensity profile are also applicable to heavy ions. These data are conveniently organized by kinetic energy or momentum per unit charge (particle rigidity). It is reasonable to assume that the same principles of coronal propagation and interplanetary propagation apply to all ions independent of the mass or atomic charge. There is a major problem 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 /7/ for a recent review. A general summary may be that "small" events have the greatest variability in elemental composition and the hydrogen to helium ratios are the most variable. The elemental abundance ratio seems 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. For "large" events; the heavier elemental abundance ratios seem to be in general agreement with the ratios expected from normal coronal material organized by first ionization potential. Unfortunately, most of the solar particle data currently available are for protons. As an expediency, we utilize an assembly of the currently available solar flare heavy ion data /8,9/ normalized to hydrogen and estimate the probable heavy ion fluence from the predicted proton fluence.

APPLICATION TO RECENT EVENT

The first significant solar particle event of the new solar cycle occurred on 2 January 1988. This was an average solar proton event from the 3B solar flare at heliographic coordinates S 38, W 18, with an X-ray onset at 1213 UT. This solar flare event (X-ray classification X1.4) generated a solar particle event with a peak flux of protons at energies > 10 MeV of 98 $(cm^2\text{-}sec\text{-}ster)^{-1}$. The initial prediction generated by PPS87 was "on time" but a factor of three too low in predicted peak flux at energies > 10 MeV. The update ability was utilized in order to normalize to the observed peak proton flux with energies > 10 MeV, and from this the projected future particle time-intensity profile was generated. A summary of this prediction for this "average" solar particle event is given in Table 2.

Table 2. Prediction summary for the 2 January 1988 Solar Proton Event

PREDICTION SUMMARY: > 10 MeV/Nucleon

ION	PEAK FLUX	EVENT FLUENCE
Z = 1	98.	6.0×10^6
Z = 2	2.7	1.6×10^5
Z = 26	1.2×10^{-1}	7.6×10^3

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