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Toward a Descriptive Model of Solar Particles in the Heliosphere

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ABSTRACT

During a workshop on the interplanetary charged particle environment held in 1987, a descriptive model of solar particles in the heliosphere was assembled. This model includes the fluence, composition, energy spectra, and spatial and temporal variations of solar particles both within and beyond 1 AU. The ability to predict solar particle fluences was also discussed. Suggestions for specific studies designed to improve the basic model were also made.

1. INTRODUCTION

In March 1987 a two-day Workshop on the Interplanetary Charged Particle Environment was held at the Jet Propulsion Laboratory in California. The objective of this workshop was to review current models of the interplanetary charged particle environment in the energy range above approximately 1 Mev/nucleon in an effort to provide to system design engineers a composite model of the spatial environment for planning future space missions; see Robinson (1988) for a short summary of some of the proposed NASA mission. Of particular concern was the ability to estimate the energetic charged particle environment a spacecraft is likely to experience so that the effects of these particles on microelectronic devices operating in space can be predicted and adverse effects can be mitigated. Although the participants were initially requested to provide data and/or models appropriate for the projected Magellan mission (an eight-month mission around Venus), the scope of the workshop was extended to include a descriptive energetic charged particle environment for the heliosphere.

The workshop participants were divided into two working groups, one to consider galactic cosmic rays (Mewaldt et al., 1988) and one to consider solar particles. This is a report of the solar particle working group, written from notes prepared during the workshop itself and does not include an extensive review of the literature. This report is confined to a brief description of the fluence, composition, spectra, spatial and temporal variations of solar particles within approximately 5 AU. The ability to predict solar particle fluences from solar observations was also discussed in conjunction with a "detect and avoid" scenario. Areas where future research is necessary were identified, and suggestions for future workshops and/or symposia were also made.

2. SOLAR PARTICLE EVENTS

2.1 Events and Fluences

Solar particle events can occur at any time in the solar cycle although the events containing the highest fluences are likely to occur during the "active years" distributed around sunspot maximum (see Figure 1). There are basically three solar cycles of solar particle event data. The major events during the 19th solar cycle occurred prior to routine spacecraft measurements, and the fluxes, fluences and spectra for those events must be inferred from the ionospheric response to solar particles and from ground-based neutron monitor data.

There are basically three different solar particle fluence models. The original proton fluence model, which was based on solar cycle 20 spacecraft measurements, was derived by King (1974); this model has also been incorporated in the Adams (Adams et al., 1981; Adams, 1986) model. There exists a heavy ion, primarily iron, fluence model based on solar cycle 21 measurements (Chenette, 1984). Finally, there is a new proton fluence model, developed by Feynman (1988a,b), based on a composite of all available proton measurements, both direct and inferred, from 1955 through 1985.

For the purposes of this workshop we established a working definition of "major" proton events as those having a fluence of more than 1.0×10^{10} protons with energies greater than 10 MeV. The frequency with which this type of major event might be experienced is dependent upon the model chosen. The group consensus was that the most conservative estimate was three such major events in 21 years, a conclusion based on the frequency of events during solar cycles 19-21. The least conservative estimate would be one such event in 12 years. This was based on the frequency of events which occurred during the "active years" of cycles 20 and 21. For purposes of this report, the "active years" included the period from two years prior to solar sunspot maximum through four years after solar sunspot maximum.

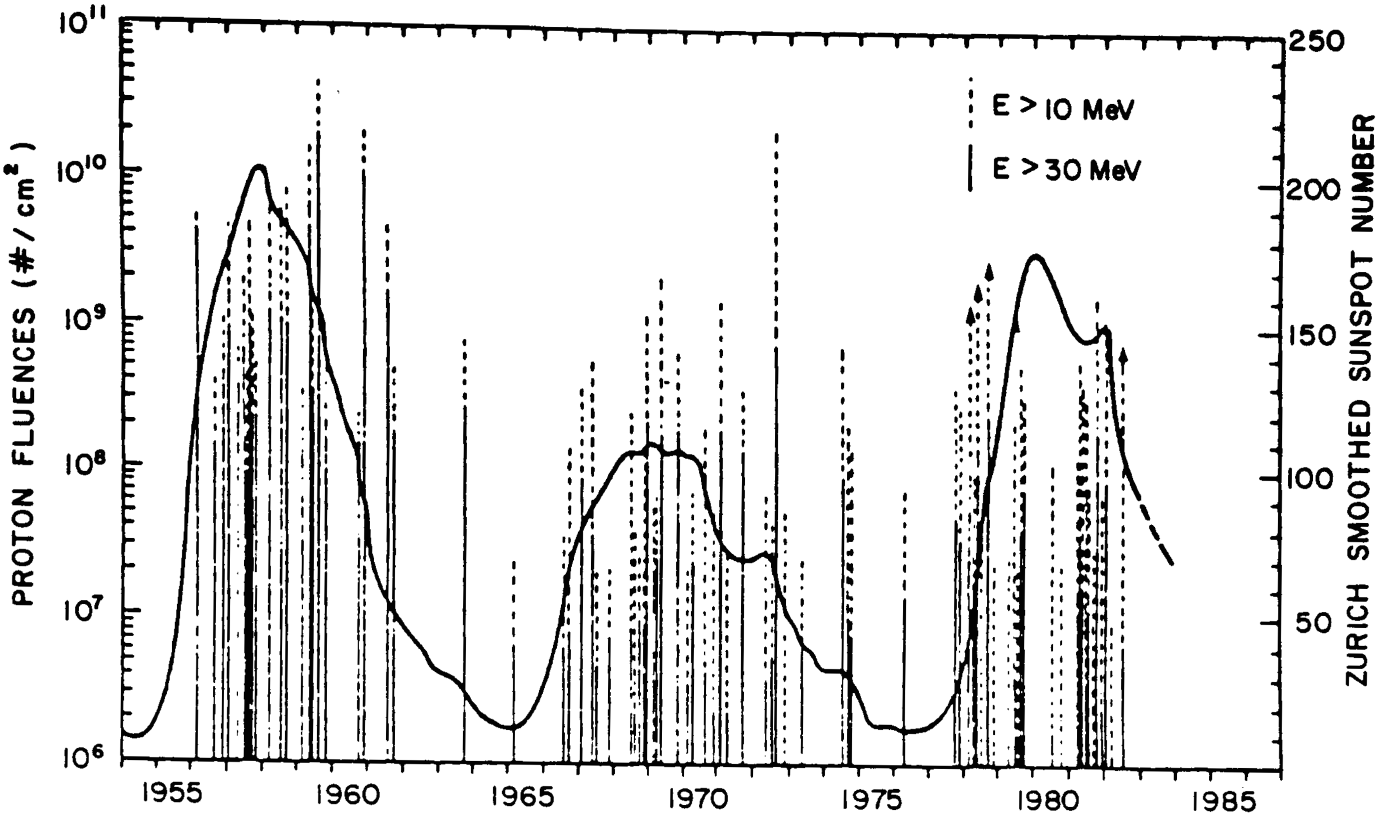

Figure 1. Occurrences of solar proton events as observed at the earth. The vertical bars indicate the fluence for each event. The sunspot number is the dark curve and is labeled on the right axis.

2.2 "Worst Case" Scenarios

The group was also asked to consider the "worst case" scenario for long term mission planning. The group consensus was that a "worst case" scenario would be three "major events" in seven years.

The "worst case" scenario also includes an estimate of what would be the heavy ion component. The consensus view deviated slightly from the estimates given by the Adams model. It has been observed, from the available data, that the heavy iron to hydrogen ratios are dependent on the "size" of the events. The "smaller" events have a higher average ratio than the "larger" events. The ratio of Fe/H utilized by Adams is 4.1×10^{-5} taken from the results published by Mason (1980). More recent data (Cook et al., 1984), acquired at around 10 MeV/nucleon, allows derivation of a Fe/H ratio of 3.4×10^{-5}.

The group was asked to consider a "worst case" heavy ion scenario. In this "worst case" scenario, we projected the Fe/H ratio to be $4.1\ 10^{-4}$ (an anomalously high ratio) for the ions with energies greater than 1 MeV/nucleon. A 90% "worst case" proton event would have fluences exceeding 2.5×10^{7} protons/cm2 with energies greater than 10 MeV. However, the probability of having a "worst case" solar particle event possessing a "worst case" Fe/H ratio was estimated to be 1 in 100 years. This is a committee "guesstimate" prepared at the request of the meeting sponsors and is very uncertain.

2.3 SHOCK ACCELERATED EVENTS

There was a general consensus that the shock acceleration phenomena exist (see Lee, 1988 for a more detailed discussion), and that they play a role in modifying the energetic charged particle population flux and spectra. However, there was no consensus as to the exact manner in which an interplanetary shock (or an ensemble of several shocks) would modify a specific energetic charged particle population, or to the longitudinal extent of such a modification. There was general agreement that the solar flare generated energetic particle flux observed at the earth after the occurrence of the 4 August 1972 solar flare was modified by the presence of converging interplanetary shocks. It may be such a sequence of relatively rare events (frequency about once a solar cycle) that is responsible for the largest observed fluences. Some of the extraordinary large solar particle fluences observed in the 19th solar cycle may have been the result of sequences of events in which the solar energetic particle population was modified by the presence of interplanetary shocks.

3. SPECTRAL FORM OF ENERGETIC PARTICLE EVENTS

An estimate of the spectral form is required in order to extrapolate the models to various energies. Rather than derive new and independent spectral models, the group considered that the available models were generally useful for mission planning and, with care, can be extrapolated to other positions in the heliosphere. The group further recommends that certain models might be more appropriate for specific applications. We recommend the Adams (1981, 1986, 1988) model employing a Fe/H ratio of 3.4×10^{-5} rather than an extreme worst case scenario for computing peak flux estimates and for computing single event upset (SEU) probabilities. We recommend use of the Feynman (1988a, 1988b) model for computing probable fluences that will be experienced during a specific mission and for computing the probability of "latch up" events.

4. SPATIAL DEPENDENCE OF SOLAR FLARE GENERATED ION FLUXES IN THE HELIOSPHERE

Most of the available data base of ion fluxes consists of measurements made on spacecraft orbiting the earth at one Astronomical Unit. There are some data extending out into the heliosphere, and some limited data between 1 and 0.3 AU; however, the preponderance of data on which the models are based are from spacecraft observations at about 1 AU near the ecliptic plane. Future plausible mission profiles range from near-sun missions to the most distant heliosphere at latitudes considerably beyond the ecliptic plane. Therefore, the committee was tasked to give recommendations of how to extrapolate the current 1 AU based models to other positions in the heliosphere.

4.1 RADIAL DEPENDENCE OF IONS

The data base from which the following recommendations are derived is based on measurements in the energy range of 10 to 70 MeV from 1 to 5 AU. The committee was unable to reach a consensus for a specific relationship to be recommended when extrapolating solar particle fluxes and fluences from 1 AU to other distances in the heliosphere. Previous workshops considering a similar problem suggested several methods of estimating the particle flux at distances close to the sun (Neugebauer et al., 1978), however, each method produced significantly different results. For this workshop Hamilton (1988) has prepared a more discussion of the radial dependence of the solar energetic particle flux. The committee recommends using a power law function to extrapolate to other distances.

4.1.1 Flux Extrapolations

To extrapolate proton fluxes from 1 AU to other distances in the heliosphere, the following are recommended in lieu of more accurate knowledge:

From 1 AU to > 1 AU, use a functional form ranging from R^{-4} to R^{-3}.

From 1 AU to < 1 AU, use a functional form ranging from R^{-3} to R^{-2}.

For heavier ions, use the existing elemental abundance ratios to extrapolate from proton fluxes to expected heavy ion fluxes. Table 1 lists observed (normalized to hydrogen) elemental abundance ratios derived by several independent investigators.

4.1.2 Fluence Extrapolations

To extrapolate proton fluence from 1 AU to other distances in the heliosphere, the following are recommended in lieu of more accurate knowledge:

From 1 AU to > 1 AU, use a functional form ranging from R^{-3} to R^{-2}.

From 1 AU to < 1 AU, use a functional form ranging from R^{-3} to R^{-2}.

For heavier ions, use the existing elemental abundance ratios to extrapolate from proton fluences to expected heavy ion fluences. The elemental abundance ratios given in Table 1 can also be used to extrapolate to heavy ion fluences.

4.2 ANGULAR DEPENDENCE AT THE SAME RADIAL DISTANCE

The committee view was that the "worst case" solar particle events would be those events that are "well connected" to the solar flare source region. The intrinsic assumption is that the interplanetary magnetic field topology basically follows an Archimedean spiral structure that has not been substantially modified by interplanetary shocks, and that the flow of energetic particles is along the interplanetary magnetic field lines. With these assumptions it is possible (at least to a zeroth order approximation) to "map" the interplanetary magnetic field lines from an observational point in space to a high coronal source. "Well connected" means that the flare position is close to the "root" of the Archimedean spiral path extending to the observation location.

For a position at 1 AU and for a "nominal" solar wind we assume that the "well connected" location is at about one radian west of the central meridian on the sun (i.e. at about 57 degrees west). For observational points at other radial distances it would be necessary to compute the probable "foot point" of the Archimedean spiral path based on observed or nominal solar wind speeds using some appropriate method such as the EQRH approximation (i.e. ballistic solar wind) originally derived by Nolte and Roelof (1973).

The following is a possible recipe for estimating solar particle fluxes and/or fluences at various angular distances from the flare site.

1. Using the Archimedean spiral concept, compute the longitude on the sun from which the interplanetary magnetic field line passing through the spacecraft position would originate. This heliolongitude would be the location from which the maximum flux would be expected if the flare were to occur at that position.

2. Determine the heliocentric angular distance (i.e. the "great circle" 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.

3. Estimate the expected ion flux from the solar flare.

4. Extrapolate the ion flux expected along the Archimedean spiral path leading from the flare site to the Archimedean spiral path passing through the spacecraft by applying a "coronal gradient". In the absence of a known coronal gradient assume an average of one order of magnitude decrease in flux per radian angular distance away from the flare site using the expression $10^{-(F-A)}$ where F is the heliographic position of the flare and A is the heliographic position of the "root" of the Archimedean spiral passing through the spacecraft. Both F and A are expressed in radians. Extrapolate to other angular positions using the same functional form.

4.2.1 Longitudinal Dependence at the Same Radial Distance

Follow the general procedure outlined above assuming a coronal gradient of one order of magnitude per radian. Find the longitudinal difference between the spacecraft location and the flare location and extrapolate to the spacecraft longitude.

4.2.2 Latitudinal Dependence at the Same Radial Distance

Follow the general procedure outlined above assuming a coronal gradient of one order of magnitude per radian. Find the latitudinal difference between the spacecraft location and the flare location and extrapolate to the spacecraft latitude.

There is a systematic variation in the heliolatitude of solar flares throughout the solar cycle. A rough estimate of the flare latitude early in the solar cycle would be approximately 30 degrees from the solar equator. The average flare latitude decreases towards the equator throughout the solar cycle; late in the solar cycle the average flare latitude may be about 5 degrees from the solar equator.

5. REVIEW OF PROTON PREDICTION METHODS

It was the consensus of the panel that there is no useful ability to predict flares that will release protons into space 24 hours in advance of the event. However, when a flare occurs, it is possible to use the electromagnetic emission characteristics to predict the probable proton fluxes. In the United States both the major forecast centers have prediction algorithms to predict the proton flux expected at the earth after the occurrence of a "significant" solar flare. These predictions are usually within an order of magnitude of the observed flux. Statistics available from the jointly operated NOAA/USAF Space Environment Forecast Facility at Boulder, Colorado indicate a reasonable skill in forecasting if a specific flare will be a proton producer. Proton prediction statistics are available for the time period 1976 through 1984. During this time period predictions were made for 2247 solar flare occurrences. The "significant" particle flux threshold was that protons with energies greater than 10 MeV would exceed a flux of 100 protons/cm^2/sec/ster. The prediction results show that no significant event was predicted 2184 times; only 4 of these events exceeded the "significant" threshold. There were 63 predictions of a "significant" proton flux of which 44 events were actually observed; there were 19 cases where a significant proton event was predicted but not observed. This prediction skill is predicated upon being able to observe the solar flare position and the electromagnetic emission characteristics. Approximately 20% of the observed proton events at the position of the earth cannot be predicted because the flare occurs on the "invisible" hemisphere of the sun as viewed from the earth (Smart et al., 1976). It was the consensus of the group that there is no way to use earth-based real-time forecasts for the entire Magellan mission especially when the spacecraft has a large angular separation from the earth-sun line.

6. DETECT AND AVOID SCENARIO

It was the consensus group opinion that "detect and avoid" is a plausible operational scenario. If there are components on board that would be adversely affected by a large solar particle flux, automatic protective sequences would be preferable to remote decision and command sequences. Typical times from solar flare observation to maximum particle flux at 1 AU for 10 MeV protons are a few hours. As the energy of the ions increases, the time from solar flare observation to particle maximum may decrease to less than 30 minutes for GeV protons. The shortest observed times at 1 AU from relativistic GeV proton onset to maximum during ground-level events is six minutes. These short times may not allow enough time for remote observations of the particle environment to exceed some critical threshold which, in turn, would result in a specific command sequence from the spacecraft control center to the satellite for preventative action. This is particularly true for a spacecraft orbiting another planet which would not be in radio line of sight to the earth for a portion of its orbital period. If there should happen to be sensors whose possible malfunction during a large solar particle event would be mission threatening and it is possible to "shut down" these sensors, then an automatic on-board environmental shut down sequence could be actuated. Figure 2 illustrates a suggested scenario. The conditions are that there would be a threshold above which the sensors are likely to malfunction. As the particle flux approaches this threshold, simple on-board detectors would sense the particle flux and initiate the protective sequence. This protective sequence would remain in effect until either the flux drops below a specified "resume function" level or until specifically commanded from the spacecraft control center. The type of particle sensor envisioned would be a simple reliable omni-directional detector rather than a complex state-of-the-art system capable of accurately resolving particle energies and species.

7. RECOMMENDATIONS FOR FUTURE WORK

1. The current data bases of energetic solar particle events should be enhanced. These data should be analyzed to determine the peak ion fluxes and fluences for all available energy channels.

a. The alpha particle measurements have not been organized in the same manner in which the solar proton event data have been organized. These data should be analyzed to determine the distribution of event fluxes and fluences.

b. The heavy ion particle data should be organized, as much as possible, in a manner similar to the solar proton event data. These data should be analyzed to determine the distribution of event fluxes and fluences.

c. Historical studies of major events should be added to the data base to determine the extreme values of the solar accelerated ion distribution functions. This would include ancient historical data from ice core results, moon rocks, fossil records, etc.

2. A model to predict solar alpha particle fluxes should be developed similar to the proton prediction model. This would include the time of particle onset at a point in space, the expected time of maximum and the expected maximum intensity.

Such a model would remove the ambiguity currently present by normalizing heavy ion fluxes to proton fluxes because the observed ratio of helium to heavy ions is less variable than the observed ratio of hydrogen to heavy ions. This alpha particle model would be the baseline for the development of a model for heavy ion prediction.

3. The radial dependence of peak ions fluxes and fluences within 1 AU should be determined. The HELIOS 1 and 2 data, together with the earth-orbiting IMP data, could be used to accomplish this.

4. The currently available measurements beyond 1 AU should be consolidated in an effort to determine a more accurate radial gradient of solar particle fluxes beyond 1 AU.

5. There is a need for study groups, workshops, and symposia to focus on the problems identified above. A Chapman-type conference on the state of the present knowledge of solar particle events would be useful; however, the leaders of such a conference should be required to produce a comprehensive review paper on the subject.

Table 1. NORMALIZED ABUNDANCES OF SOLAR ENERGETIC PARTICLE EVENTS

		Adams Mason et al (1980) 1 MeV	Gloeckler (1979) 1-20 MeV	Cook et al (1984) 10 MeV	McGuire et al (1985) 6.7-15 MeV
1	H	1.0	1.0	1.0	1.0
2	He	2.2 E-2	1.5 E-2		1.5 E-2
3	Li		1.0 E-7	4.8 E-8	2.8 E-6
4	Be		1.5 E-7	6.0 E-9	1.4 E-7
5	B		1.5 E-7	1.2 E-8	1.4 E-7
6	C	1.6 E-4	1.2 E-4	9.6 E-5	1.3 E-4
7	N	3.8 E-5	2.8 E-5	2.7 E-5	3.7 E-5
8	O	3.2 E-4	2.2 E-4	2.2 E-4	2.8 E-4
9	F		4.3 E-7	1.0 E-8	1.4 E-7
10	Ne	5.1 E-5	3.5 E-5	3.1 E-5	3.6 E-5
11	Na	1.6 E-6	3.5 E-6	2.6 E-6	2.4 E-6
12	Mg	3.9 E-5	3.9 E-5	4.3 E-5	?.2 E-5
13	Al	3.5 E-6	3.5 E-6	3.1 E-6	3.3 E-6
14	Si	3.8 E-5	2.8 E-5	3.5 E-5	4.2 E-5
15	P	2.3 E-7	4.3 E-7	1.7 E-7	4.0 E-7
16	S	1.8 E-5	5.7 E-6	7.8 E-6	6.5 E-6
17	Cl	1.7 E-7		7.1 E-8	
18	Ar	3.9 E-6	8.7 E-7	7.3 E-7	4.6 E-6
19	K	1.3 E-7		1.0 E-7	
20	Ca	2.3 E-6	2.6 E-6	3.1 E-6	3.2 E-6
21	Sc			7.8 E-9	
22	Ti	1.0 E-7		1.2 E-7	
23	V			1.2 E-8	
24	Cr	5.7 E-7		5.0 E-7	
25	Mn	4.2 E-7		1.8 E-7	
26	Fe	4.1 E-5	3.3 E-5	3.4 E-5	
27	Co	1.0 E-7		4.8 E-7	
28	Ni	2.2 E-6		1.2 E-6	
29				1.4 E-8	
30				3.8 E-8	

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