High Energy Charged Particles in Space at one Astronomical Unit

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Abstract: Single event effects and many other spacecraft anomalies are caused by positively charged high energy particles impinging on the vehicle and its component parts. Here we review the current knowledge of the interplanetary particle environment in the energy ranges that are most important for these effects. State-of-the-art engineering models arc briefly described along with comments on the future work required in this field.

1. Introduction

This review is concerned with positively charged high energy particles (MeV energy range for protons) occurring in space, outside the Earth's magnetosphere. These particles impinge on the magnetosphere and propagate through it. The propagation of the particles within the magnetosphere and the changes in the energy distributions, ionization states and abundances within the magnetosphere are not dealt with in this review,

Although this article deals only with a specification of the particle environment in space, it is important to outline some of the effects of high energy particles on spacecraft and their component parts.

Single event effects (SEES) are caused by the deposition of a sufficient amount of energy (or charge) in a sensitive volume of an electronic device, by a single ion. Protons can produce SEES indirectly by creating secondaries from nuclear reactions in the vicinity of the sensitive node. The ability of a heavy ion to cause an SEE depends on its Linear Energy Transfer (LET) or the rate at which it loses energy along its path (measured in units of MeV/unit length or McV cm-2/g). The cross-section for an SEE will depend on the particular part and only particles with a LET above a threshold value are able to produce an SEE. Typical particle energies of interest are in the range 10-2 to 10S McV per nucleon. Although ions are the most important particles for SEES, there are no satisfactory statistical prediction models for interplanetary ions. It is the current practice to infer the expected ion fluxes and fluences from the modeled proton fluxes and fluences. This is an unsatisfactory procedure, since the relative abundances of heavy ions to protons varies from event to event. However it is the best that can be done until new models that directl y address ions are developed.

Many of the main effects of high energy charged particles on spacecraft arc due to total ionizing dose. These effects include, in addition to SEES, degradation of electronic parts, power loss in solar cells, material property changes (e.g., darkening of glasses). Total ionizing dose (TID) is the amount of energy deposited in a unit mass and the units that are commonly used are the rad (100 ergs/g) and the gray (1 Joule/kg). The absorbed dose will depend on the specific material and the notation employed should indicate the material in question (e.g., rads(Si) for the dose in silicon). Semiconductor devices affected by TID include p-n junction diodes, bipolar transistors, junction field effect transistors, MOSFETS, and integrated circuits based on the these discreet devices (bipolar, digital, analogue, MOS, VLSI, microprocessors, memories/DRAM, SRAM, EPROM and EEPROMS).

Major damage to solar cells is caused by an effect called "displacement damage" in which the lattice is damaged due to the displacement of atoms from their normal locations to interstitial sites, leaving a vacancy behind. These sites have a major influence on carrier recombination rates and since the cell performance is largely governed by this parameter, displacement damage can cause power reductions of the order of 30%. Consequently solar cell arrays have to be oversized to ensure that the end-of-life requirement is met. Because the cells are not shielded by the body of the spacecraft (as are the internal electronic devices), they have to be protected by cover glasses to reduce the radiation effects, The actual spectrum of the protons reaching the cell itself will depend on the thickness of these cover glasses. The effectiveness of a proton in causing displacement damage depends on its energy. The resultant degradation will be dependent on the energy spectrum of the external environment, the cover glass thickness and the type of cell. However, as a rough guide protons with energies in the range 1 to 10 MeV will be the most important.

Darkening of glasses is due to the formation of color centers caused by lattice defects. The absorption of light by these defects occurs by excitation of a trapped charge (electron or hole) from its ground state to a higher excited state. This same basic mechanism is responsible for changes in the optical properties and hence thermal performance of thermal control coatings. In this case it appears that the density of the active defects does not depend on the type of particle, the energy or the fluxes but on] y on the absorbed dose (Bourrieau, 1993).

In the vicinity of the Earth (i.e., outside the magnetosphere) energetic particles come from two main sources, galactic cosmic rays and particles associated with events taking place on the sun. The analysis of the expected fluxes and fluences is very different for the two cases because the time variations of the two components are so different. The galactic cosmic rays are present at all times and the major change in the flux is an 11 year solar cycle., 1 n contrast the particles associated with solar events are sporadic. The events with the largest fl uences (i.e., particle fluxes integrated over the event time) take place perhaps once or twice pcr solar cycle and have typical event times of several days. Because of these great differences, the two types of particles will be discussed separate] y.

2. Galactic Cosmic Rays

Galactic cosmic radiation is composed of high energy nuclei believed to propagate throughout all space unoccupied by dense matter. Its origin is still a matter of scientific debate and it may have both galactic and extra-galactic sources. The cosmic radiation incident on the Earth's atmosphere is called the primary cosmic radiation. Cosmic rays propagating through the atmosphere will undergo nuclear collisions and generate secondary cosmic rays consisting of all known nuclear and sub-nuclear species. The flux is believed to be essentially isotropic outside the region of space dominated by the particles and fields coming from the sun (the heliosphere) and within that region of space propagation effects cause an anisotropy of approximately 1%.

For galactic cosmic rays the heavy ion fluxes and fluences can be found by extrapolation from the hydrogen fluxes and fluences using elemental abundance ratios normalized to hydrogen (protons). The cosmic radiation observed in space at 1 AU consists of approximately 83% protons, 13% alpha particles, 1% nucleii of atomic number >2 and 3% electrons. This composition extends over an energy range from a few hundred MeV to > 10^{20} MeV. Figure 1 (Mewaldt, 1988) summarizes the relative elemental composition, normalized to $Si = 10^6$. Figure 2 (Mewaldt, 1984) shows typical quiet time low energy spectra for several elements. The intensity of cosmic rays is solar cycle dependent, decreasing as the sunspot number increases. This is reflected in the neutron monitor counting rate data shown in Figure 3.

For engineering purposes, the standard model now used is that of Adams (1986), which provides a descriptive model of cosmic rays in the near-Earth environment, based on extensive measurements of composition, energy spectra and solar cycle variations that have been made from spacecraft, balloon and ground observations over the past three decades. Probably the largest uncertainty in this model is in its ability to predict time variations in the flux of cosmic rays over the solar cycle. Currently the model uses assumed sinusoidal time dependence for fluxes at Earth, based on a fit to a combination of neutron monitor and ion chamber data taken over a period of

more than **40** years. Accuracies achieved using the mode] arc estimated to be within a factor of ~2 for predicted fluxes of low energy (100 MeV/nucleon) particles at a specific time and to within -+/- 30% for integral fluxes (or fluxes of GeV particles) at radial distances of 1 +/- 0.5 AU from the Sun and near to the ecliptic plane.

3. **Solar Proton Events**

3a. Introductory Remarks

While the cosmic rays provide a steady background of high energy particles, those due to solar events dominate the environmental hazards for energies fror n 1 to 100 MeV/amu. From 1963 to the present proton fluxes have been observed using a series of closely related instruments on the IMP 1, 2, 3, OGO 1 and IMP 5, 6, 7, and 8 spacecraft. 'l'his long commensurate data set has permitted a good statistical sample of proton events to be assembled (Armstrong et al., 1983, sec also Fe ynman et al., 1993). Solar energetic particle events are very sporadic. The proton fluences observed in an event can vary from just above the cosmic ray background to, for example, the 1.3 xl 0^{10} protons/cm^2 that were observed at energies above 10 MeV during an event in October 1989 (Feynman et al., 1993). Event fluences above 1.5 x109 pr otons/cm^2 (E> 10 MeV) are very rare and only about 13 of them have occurred since 1963. No events with E>1 O MeV fluences greater than 1x1010 protons/cm^2 occurred between the famous event of August 1972 and the October 1998 event, a period of 16 years. The 1972 event and its associated geomagnetic storm caused widespread power outages in Canada and the United States and alerted spacecraft engineers to the importance of major solar proton events. The 16 year hiatus led to the impression that the 1972 event was of a different class than all other proton enhancements (King, 1974) and that this different class was very rare. However, major events had been observed before 1963 (Malitson and Webber, 1962, Feynman et al., 1988) and have been again observed in both 1989 and 1991. Major events appear to be the high fluence end of smooth distribution of particle fluences.

Recently it has become more evident that there are two different types of solar particle events in the energy range above **5** MeV, corresponding to two different types of solar X-ray flares, gradual and impulsive (Reames, 1994). In gradual events the decay of the X-ray intensity takes place over many hours. In impulsive events there is a sharp peak in X-ray emission (Figure **4).** The gradual events, often called LDE (Long Duration Events), are strongly associated with ejections of mass from the solar corona (CMEs) and tend to be the events with the largest proton fluences. They have elemental abundances and isotopic compositions that are characteristic of the corona (Reames et al., 1994) and apparently arise from regions having an electron temperature of 1 or 2 MK (million degrees Kelvin). The largest solar proton events often occur in association with series of major gradual flares from a single active region as it is carried across the face of the Sun. It is widely believed these particles are accelerated by a shock in the corona and lower solar wind (c. f. Gosling, 1993.). This shock, in turn is thought to be due to high velocity (up to 1,400 km/s) ejection of coronal plasma (CMEs) often associated with gradual flares. Particles propagating from the acceleration site to the spacecraft directly along the magnetic field lines in the solar wind will be anisotropic when they reach the Earth (see Figure 5). The majority of particles will be scattered many times on the way to the Earth and will therefore be isotropic. Most of the events observed at Earth with the largest proton fluences in the energy range >10 MeV appear to be due to acceleration near the Sun and subsequent scattering.

In contrast to the particles with energies> 10 MeV, protons with energies <5 MeV are typically accelerated by shocks traveling throughout the interplanetary medium. These particles often arrive at the Earth in close association with the shocks. Typically, peak fluxes are of the order of hundreds of particles /(cm' sters MeV)

The other type of particle event, impulsive events, show marked enhancements of heavy ions. Typically the Fe/O ratio is of the order of 1, in contrast to 0.1 or less in gradual events. In addition the He3/He4 ratio is two to four orders of magnitude larger than in the solar atmosphere or in the solar wind. These events arc generally dominated by electron fluxes and have smaller proton fluxes than the gradual events. These electrons do not represent a significant hazard to spacecraft. Studies of the composition indicate that the ions are from deep within the corona from regions having electron temperatures of 3-5 MK (Reames, 1994), These particles arc believed by many to be directly accelerated during solar flares. The majority of small solar particle events observed at Earth arc attributed to this type of event (Reames, personal communication, 1995).

3b. Proton fluxes

Typical time histories of the fluxes at energies >10 MeV are shown in Figure **6,** for two large events. Note that the particle fluxes rise over a time period of the order of a half to onc day. This is followed by a slower decay, which takes of the order of a few days. This is characteristic of proton events in general. However, the second strong increase at the end of the first decay phase is only found in very large events and is due to a series of CM Es. The rise time is a function of the solar longitude of the initiating CME or flare. The propagation time (i .c., the time between the solar event and the appearance of the protons at Earth) is also a strong function of the longitude of the solar event as shown in Figure 7. If the solar event is well placed, the particles may arrive at the Earth in the matter of tens of minutes. The solar longitude that is most effective in producing proton enhancements at Earth is around 30 degrees west. The longitude most effective for particles in the GcV range is close to the western limb of the Sun.

For some engineering applications the important quantity is the size of the peak particle flux. However, there is no probabilistic engineering model for peak fluxes (similar to the fluence model described below). Such a model would bc useful for the prediction, on a statistical basis, of instantaneous SEE rates during interplanetary missions. Currently the estimation of this parameter is calculated using a worst case approach based on the August 1972. event (Adams, 1988). In addition, the distribution of daily fluences has been generated for each of the energy ranges separate] y and is available in the literature (Feynman et al., 1993). An example is given in Figure **8.** These daily fluences may be used to give a very rough estimate of the peak flux but this involves using some estimate of the sharpness of the peak. This problem has not been well studied.

3c. Proton fluences

The interplanetary proton fluence below about 100 MeV is dominated by solar protons. The total fluence during a mission is due to the combined effect of the discrete energetic proton events that take place during that mission. The distribution of sizes of the proton events is such that the total fluence predicted for a mission will be due to a small number of very high fluence events if any such events take place (King, 1974, Feynman et al., 1 990). It is therefore very important to correctly estimate the probability of occurrence of large events. The occurrence frequency of the major events does not appear to be randomly distributed in lime. Instead they appear to be much more common in some solar cycles than in others. In particu lar, in the 25 years between 1963 and 1988 there was only one major event (August 1972). in contrast, 3 or 4 major events occurred in the short time period from 1957 to 1963, and 4 or 5 major events have occurred during last few years (1989 to 1991). It is therefore essential that the data set used is collected over several solar cycles so that it contains a good statistical sample of the major events. The model described uses a data set collected over such a long period of time that the population of major events is probably well sampled. We do not expect the distribution to be significantl y changed when more data becomes available in the years to come.

We now describe a predictive engineering model for the interplanetary fluence of protons with energies >1, >4, >10, >30, and >60 MeV (Feynman et al., 1993). The model was derived from data collected by spacecraft at 1 AU between 1963 and 1991, The >10 MeV and >30 MeV data sets cover the period from 1963 to day 126, 1991. The >1, >4, and >60 MeV data sets were collected between 1973 and 1991. Both data sets contain several major proton events. The results were presented in a convenient graphical form that may be used to calculate the 1 AU fluence expected at a given confidence level as a function of the length of the mission. Such an estimate is often needed when spacecraft spend a significant amount oft i me in the interplanetary environment.

When the annual integrated fluence was generated it was found that tile sunspot cycle could be divided into two periods; a high fluence, active sun period of seven years and a low fluence quiet sun period of 4 years. The active period begins two years before the year of solar maximum and includes the fourth year after solar maximum (where "years" are defined relative to solar maximum determined to 0.1 of a year). See Figure 9. From this figure it is clearly useful to consider the statistical properties of the events occurring during the active period separately from those occurring during the quiet periods. Because the quiet periods are so quiet we can assume no significant proton fluence exists at 1 AU during those periods and that the only model needed is that for the active periods.

In the mode], the clustering of proton enhancements due to a series of gradual flares was taken into account by integrating over time periods during which the daily proton fluences exceed a selected threshold, The threshold was chosen separately for each energy range and can be considered to be an empirically determined quiet day fluence. The size distribution of the events was then determined for each integral energy range. An example is shown in Figure 10. The events have been ordered according to the log of the fluence and plotted against the percent of observed events that have a magnitude less than the given event. To be more exact, fluences were plotted against (ix 100)/(n+1) where i is the rank of the events used in the data set and n is the number of events in the data set. The horizontal axis of the plot is scaled so that a data set that is distributed log normally (the log of the fluences distributed as a Gaussian) will appear as a straight line. The straight line in the figure gives a comparison to a log normal distribution. Of course, the real distribution of the data is not log normal. In the real data there arc always more events the smaller the size of the event (Feynman et al., 1990). For a log normal distribution there is a mean event size and the number of events decreases for events both smaller and larger than that mean. For this reason the distributions can not be expected to be fit by a straight line. However, the estimate of the total fluence accumulated during a mission is dominated by the estimate of the probability of occurrence for large events. The fluence will not be changed due to an underestimate of the probability of occurrence of the small events. It is only impoi tant that the probability of occurrence of the largest events be estimated correctly. This is accomplished by fitting the line to the high fluence events as shown in Figure 10. There remains a certain amount of individual judgment in choosing the fitting curve and the fit shown is reasonably conservative. 1 'or E> 1 MeV to E>60 MeV energy ranges see Feynman et al. (1993). For higher energies an extrapolation must be made. This is done by using either a power law in energy or an exponential in rigidity. This problem needs further work,

The parameters describing the fits (mean and standard deviation of the Gaussians) were used in a Monte Carlo simulation to generate a curve giving the probability of exceeding a given fluence during a mission of a selected length. The results for a selection of mission lengths are shown in Figure 11 for energies> 10 MeV (see Feynman et al., 1993 for other energies). The figure gives the probability of exceeding a given fluence during the life of a mission outside the magnetosphere at 1 AU. Five mission lengths are shown. In calculating mission length only the time that the spacecraft spends in interplanetary space during the solar cycle active years should be included. To use Figure 11 to estimate mission fluences find the line that corresponds to the desired mission length and locate the "confidence" level required. Then the abscissa gives the value of the fluence that will not be exceeded (at the selected confidence level). Recall that a confidence level of 95% means that only 5% of missions identical to the one considered will have larger fluences (i.e., probability + confidence level = 100%). Note that the fluence is a steep function of the confidence level. In some applications a small lowering of the confidence level requirement may be acceptable and result in a large enough decrease in estimated fluence to eliminate an otherwise important problem. See Feynman et al. (1 993) for details and other energy ranges.

4. Heavy Ion Abundances

In addition to energetic protons, solar proton events produce helium and heavy ions, notably Fe and the C N O ions (carbon, nitrogen and oxygen). For studying the heavy ion abundance in solar events wc need again to distinguish gradual events from impulsive events, As discussed above, it has been shown that the impulsive events are enriched in I ıeavy elements relative to the gradual events. Elemental abundances of some of the elements important for S1 3E's are shown in Table 1 which contrasts the abundances seen in these two types of events (from Reames et al., 1994). Thus we see that heavy ion to hydrogen ratios depend on the size of the event, with the smaller events (flare accelerated) having a higher average ratio than the larger ones (shock accelerated).

Current] y there is no model for heavy ion fluences equivalent to the J PL 1991 proton model (Feynman et al, 1993). There is a definite need for such a model to allow accurate predictions of SEE rates in this environment (Feynman and Gabriel, 1988). The observed ratio of helium to heavy ions is less variable than that of the protons to heavy ions. As a first step in the construction of an ion model, a helium model could be developed and a more reliable estimate of the ion fluence could be inferred. This would reduce the current inaccuracies resulting from normalization of the heavy ion fluxes to proton fluxes (Feynman and Gabriel, 1988).

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Tables

Table 1. A comparison of elemental abundances in gradual and impulsive solar particle events (from Reames, 1994).

Figure Captions

Figure 1. Elemental abundance of galactic cosmic rays relative to silicon. (From Mewaldt, 1988).

Figure 2. Typical solar minimum spectra of low energy galactic cosmic rays (From Mewaldt, 1984).

Figure 3. Solar cycle dependence of neutron monitor counting rates. The counting rates are indicative of the fluences of high energy galactic cosmic rays.

Figure 4. X-ray events detected by GOES '7 spacecraft in geosynchronous orbit. The vertical lines are hour markers. The lefthand panel shows an impulsive events at about 9:00 UT on May 3, 1992. The righthand panel shows a gradual event at about 15:45 UT on May 8, 1992. (From Solar-Geophysical Dat prompt reports, Number 574 -Part 1, June 1992, National Geophysical Data Center, Boulder Colorado,)

Figure 5 Propagation of solar energetic particles. Those propagating along the "favorable path" will be anisotropic at Earth. (Figure from Shea, 1988).

Figure 6. Proton fluxes for two major solar proton events (E>60 MeV). Data from IMP 8, T. Armstrong, T. P. personal communication).

Figure 7. Longitude distribution of propagation times of solar particles from the flare to the Earth (Barouch et al. 1971, see also Smart and Shea, 1985).

Figure 8. The distribution of measured daily fluences for protons with E>1 OMCV (from Feynman at al., 1993).

Figure 9. Solar cycle variation of yearly integrated fluences observed at 1 AU (from Feynman et al., 1990).

Figure 10. The distribution of event integrated proton fluences with E>10MeV AU (from Feynman et al., 1990).

Figure 11. The estimated fluences of protons E>1 O Mev for missions of selected lengths. The mission integrated fluences are shown as a function of confidence level (from Feynman et al., 1990.

Element/C versus Fe/C Regressions FOR Gradual and Impulsive Events

Abundance Ratio	Mean Enhancement Relative to Corona		Slope of Regression versus Fe/C	
	Gradual"	Impulsive	Gradual	Impulsive
N/C	0.97 ± 0.04	1.52 ± 0.34	+0.08 ± 0.05	$+0.15^{+0.51}_{-0.43}$
O/C	0.93 ± 0.04	1.10 ± 0.12	+0.13 ± 0.06	$+0.37^{+0.28}_{-0.22}$
Ne/C	0.92 ± 0.06	3.51 ± 0.50	+0.19 ± 0.09	$+0.73^{+0.46}_{-0.34}$
Mg/C	0.88 ± 0.06	2.35 ± 0.32	+0.24 ± 0.09	$+0.74^{+0.38}_{-0.30}$
Si/C	0.7950.05	2.76 ± 0.38	+0.45 ± 0.09	$+0.74^{+0.46}_{-0.34}$
S/C	0.79 ± 0.04	4.69 ± 1.04	+0.62 ± 0.08	$+0.68^{+0.60}_{-0.45}$
Fe/C	0.68 ± 0.03	6.67 ± 0.80	+1.00	+1.00

Note. -AH errors are given at the 95% confidence (2σ) level.

[a] Enhancements are of order unity for gradual events because "coronal" abundances are derived from them: thev decrease with Z because there are more Fe-poor than F e-rich events.

Table 1

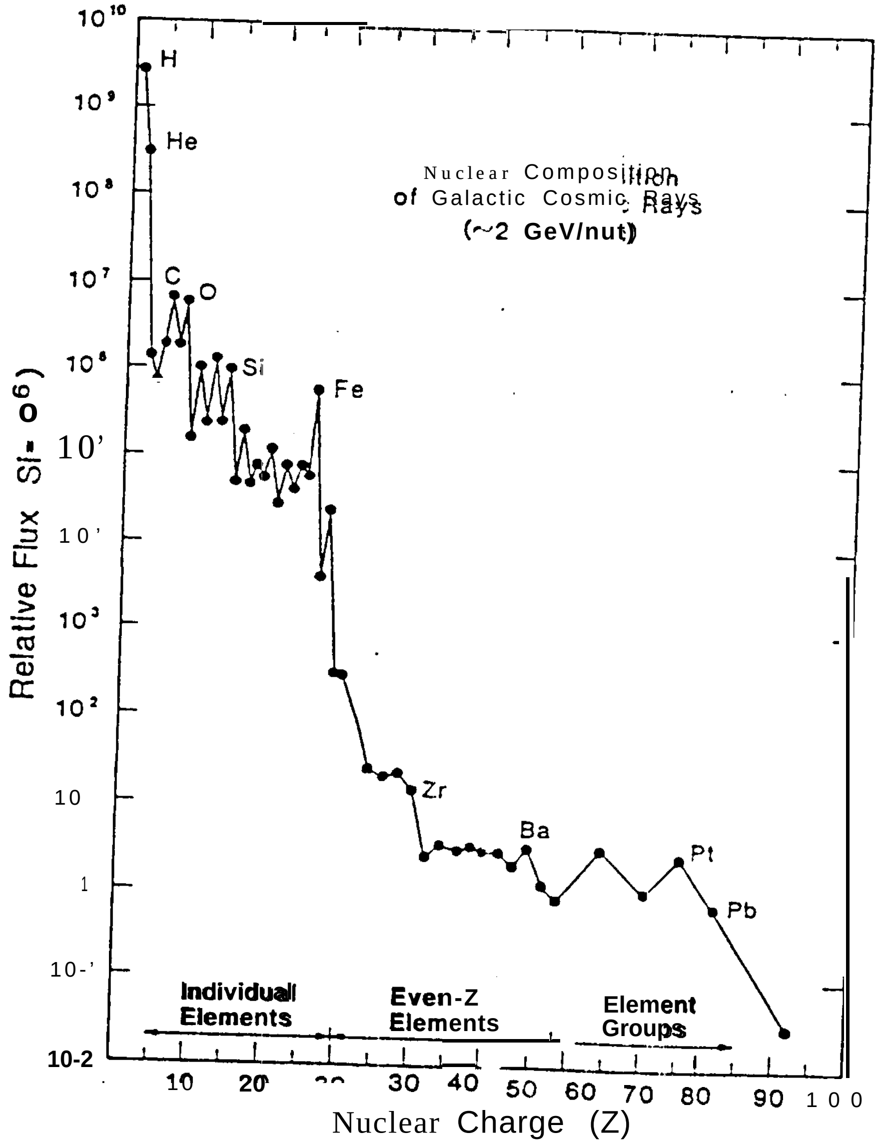
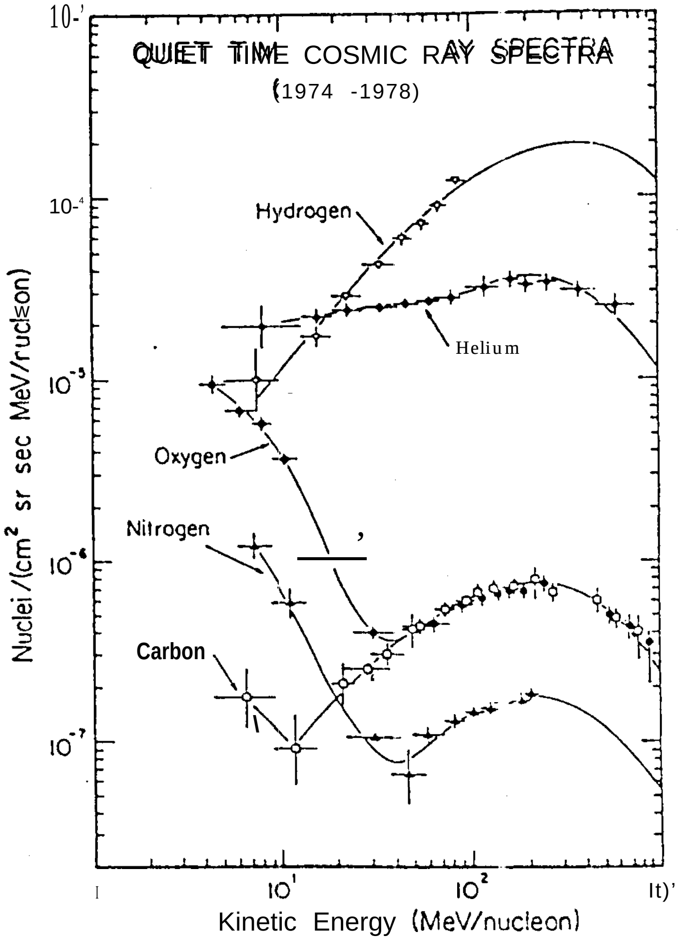

Nuclear Composition
of Galactic Cosmic Rays
(~2 GeV/nut)
H
He
C
O
Si
Fe
Zr
Ba
Pt
Pb
Relative Flux Si = 10^6
Individual Elements
Even-Z Elements
Element Groups
Nuclear Charge (Z)

Fig 1



QUIET TIME COSMIC RAY SPECTRA
(1974 -1978)
Hydrogen
Helium
Oxygen
Nitrogen
Carbon
Nuclei /(cm² sr sec MeV/nucleon)
Kinetic Energy (MeV/nucleon)

Fig 3 Fig 2

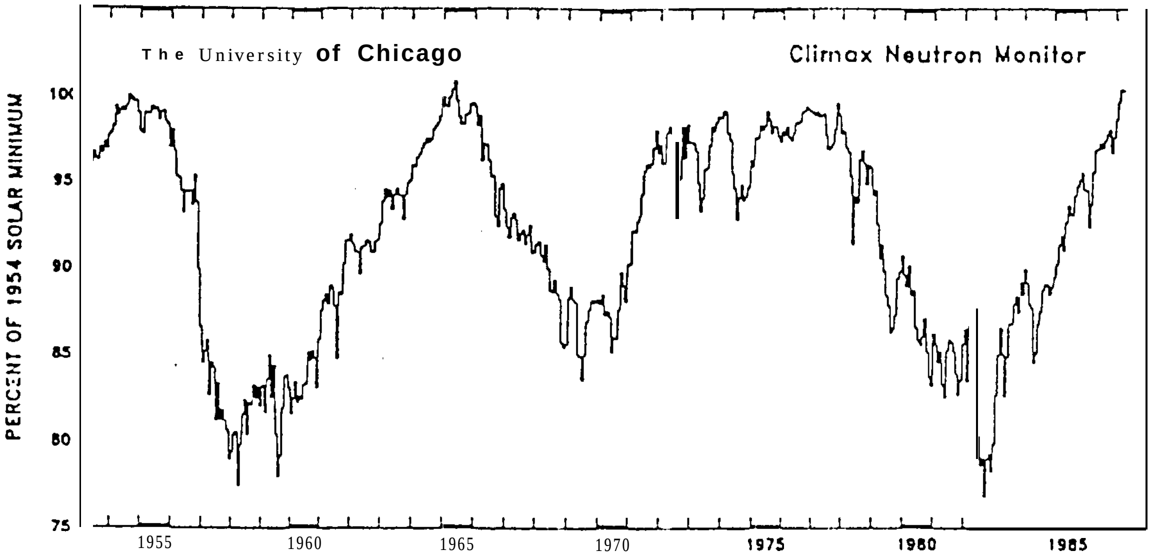

The University of Chicago
Climax Neutron Monitor
PERCENT OF 1954 SOLAR MINIMUM
100
95
90
85
80
75
1955
1960
1965
1970
1975
1980
1985

Fig 3

SOLAR-TERRESTRIAL ENVIRONMENT
May 1992

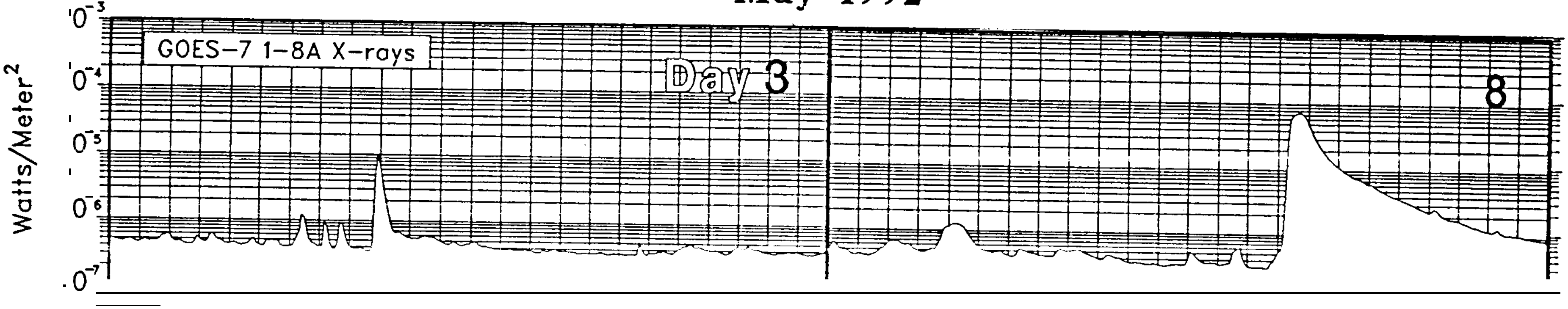
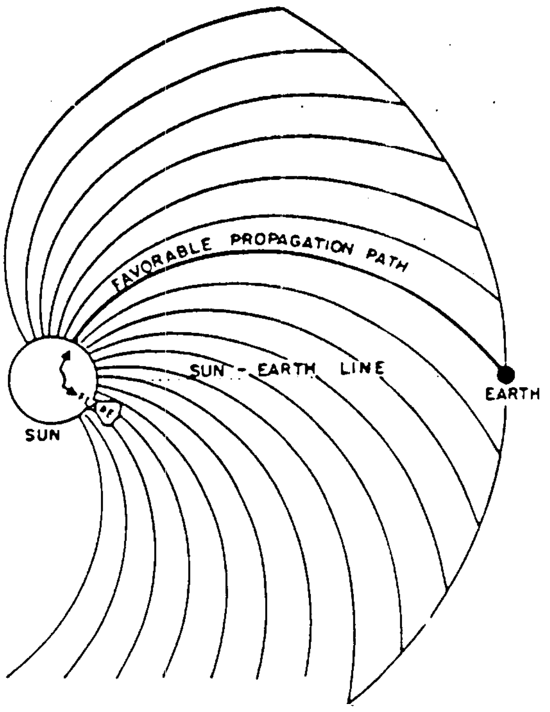


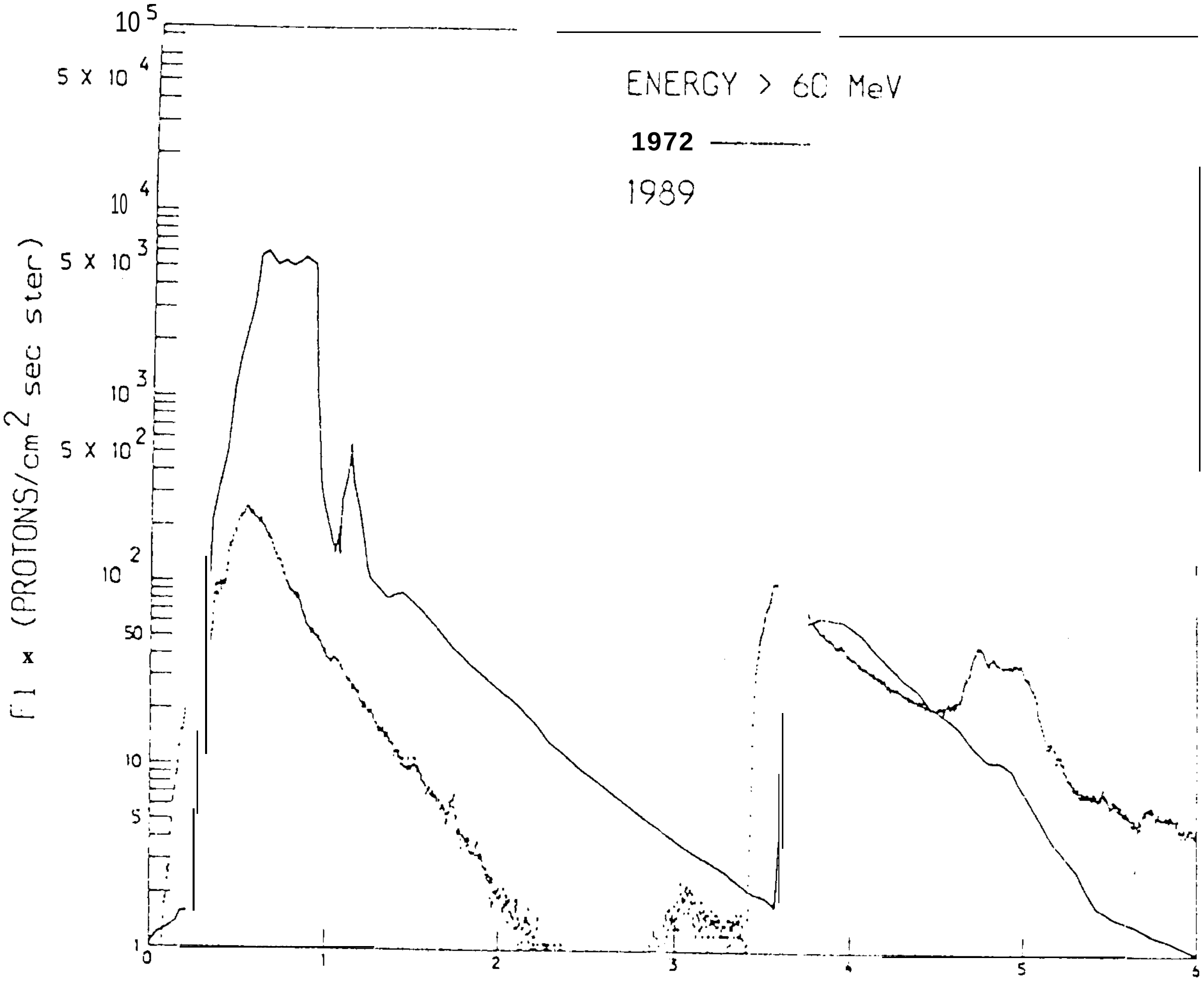
Fig 4



Idealized interplanetary magnetic field line between the sun and the earth with the favorable propagation path indicated.

Fig 5

August 1972, August 1989 solar proton events



24 hour intervals (from event onset)

Fig 6

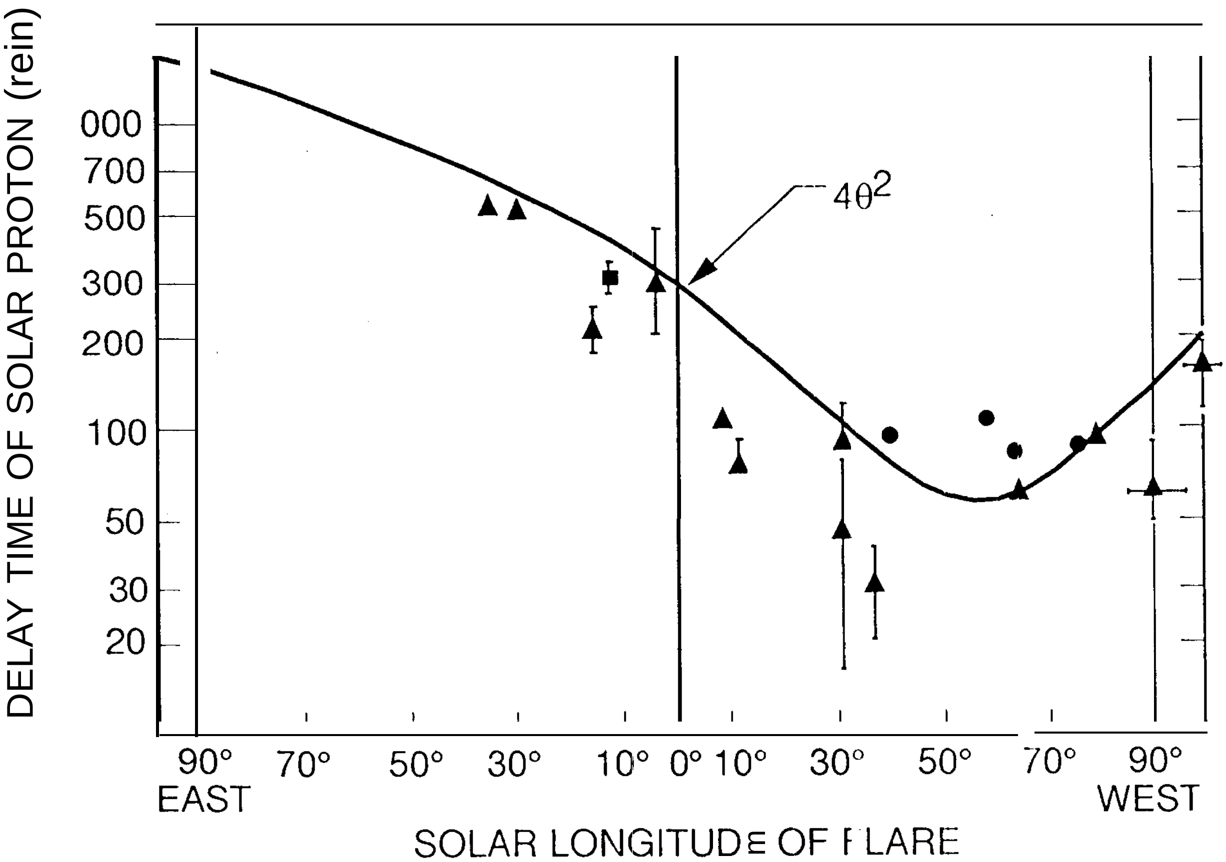
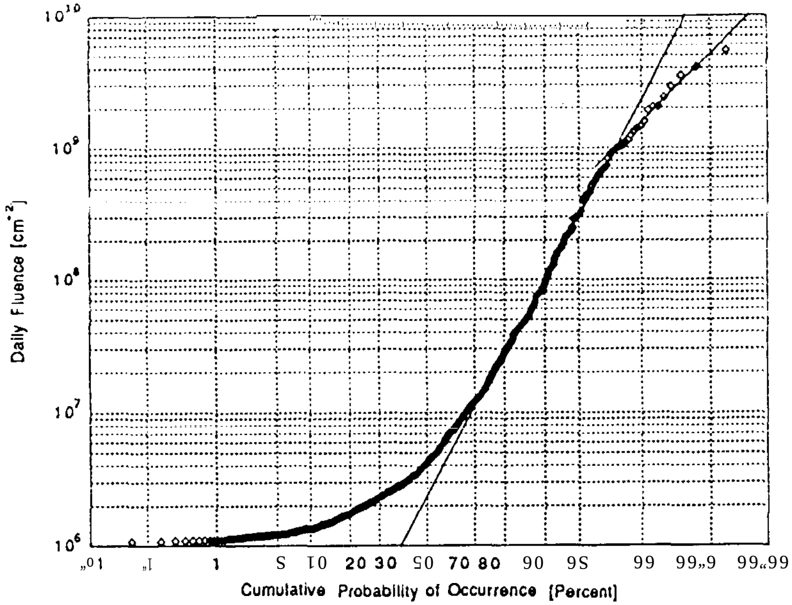

DELAY TIME OF SOLAR PROTON (rein)
000
700
500
300
200
100
50
30
20
$4\theta^2$
90°
EAST
70°
50°
30°
10°
0°
10°
30°
50°
70°
90°
WEST
SOLAR LONGITUDE OF FLARE

Fig 7



Daily Fluence [cm^-2]
Cumulative Probability of Occurrence [Percent]

Figure 8

YEARLY FLUENCES (>30 MeV)

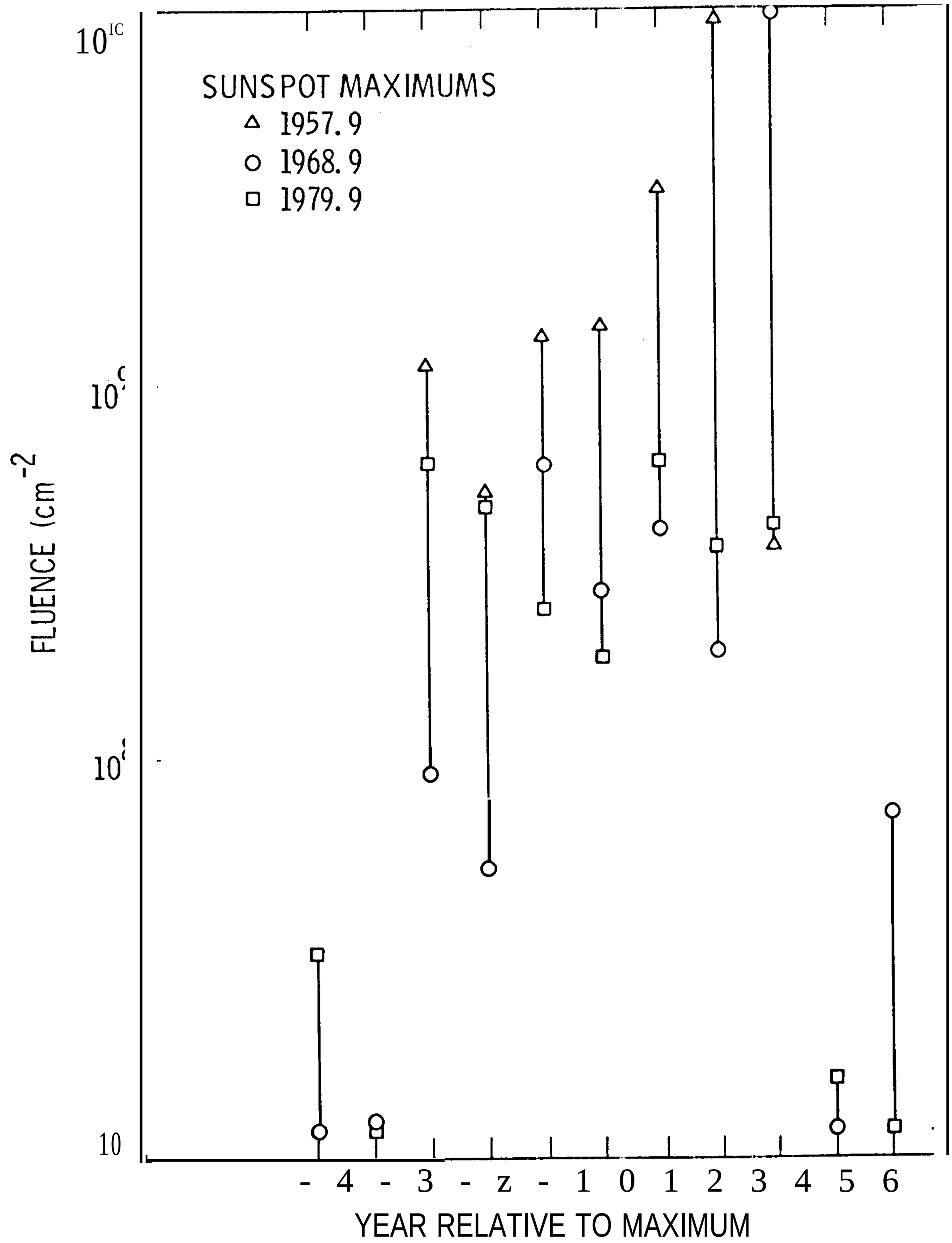


Figure 9

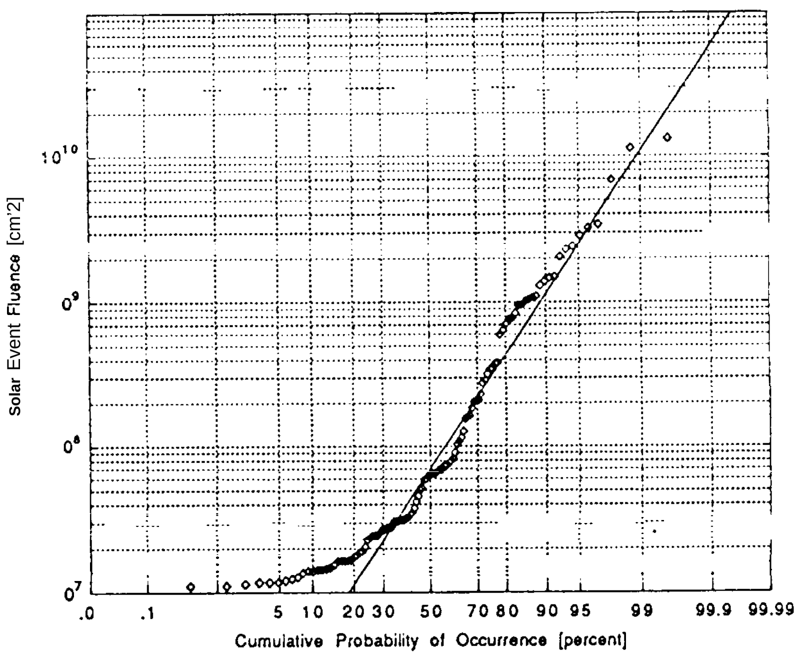

Solar Event Fluence [cm'2]
Cumulative Probability of Occurrence [percent]
.0 .1 5 10 20 30 50 70 80 90 95 99 99.9 99.99

Fig 10

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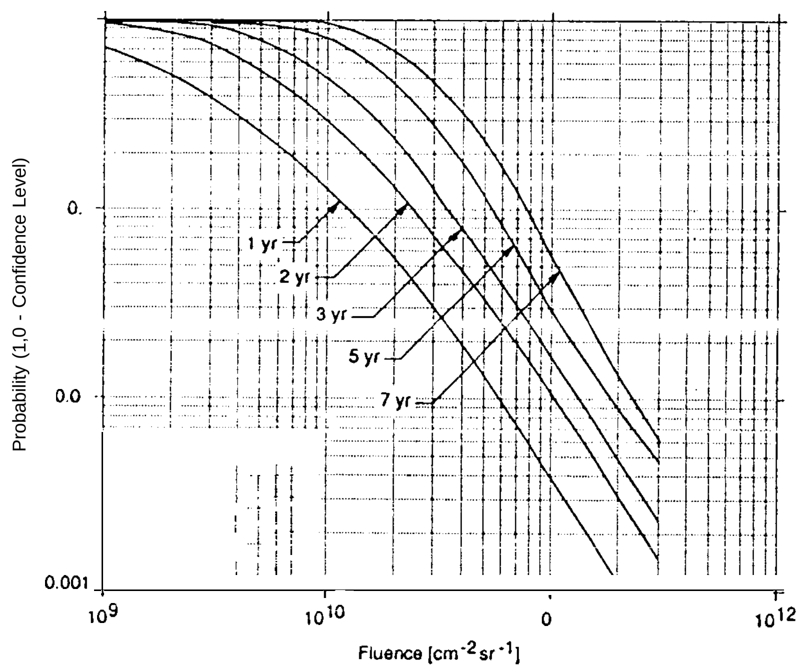

Probability (1,0 - Confidence Level)
0.
0.0
0.001
1 yr
2 yr
3 yr
5 yr
7 yr
10^9
10^{10}
0
10^{12}
Fluence [$cm^{-2} sr^{-1}$]

Figure 11