INTENSITY/TIME PROFILES OF SOLAR PARTICLE EVENTS AT ONE ASTRONOMICAL UNIT

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ABSTRACT

A description of the intensity-time profiles of solar proton events observed at the orbit of the earth is presented. The discussion, which includes descriptive figures, presents a general overview of the subject without the detailed mathematical description of the physical processes which usually accompany most reviews.

1. INTRODUCTION

Major solar flares are often associated with the acceleration of energetic particles at the sun and their injection into the interplanetary medium where they can be detected by a variety of techniques. Only high energy particles could be detected at the earth prior to the space age since the particles had to have enough energy to be able to penetrate to balloon altitudes, or in rare cases, to ground-level detectors. Since the advent of the space era, data obtained from particle sensors on spacecraft throughout the heliosphere as well as improved balloon and ground-based instrumentation have greatly increased our understanding of solar particles and their propagation in the solar system. This paper presents a summary of the intensity/time profiles of particle events as detected at the earth's orbit.

2. SOLAR EMISSIONS

Solar flares are associated with electromagnetic emissions, acceleration of electrons and ions, and, if conditions are favorable, the injection of these particles into space. Each solar flare is unique, and the generation of these emissions can differ from event to event. Figure 1 is a representation of the propagation time of various types of solar emissions from the sun to the earth. Solar X-rays and other types of electromagnetic radiation reach the earth at essentially the speed of light - i.e. in approximately eight minutes. To a first order approximation, the intensity of the radio and soft X-ray emissions observable at one Astronomical Unit is independent of the location of the flare on the visible disk of the sun. Energetic solar particles reach the orbit of the earth from a few minutes, if the particles are relativistic, to hours for the lower energy particles. Both the measured onset time and maximum intensity of these particles are a function of the solar longitude of the flare with respect to the detection location. Enhanced solar plasma usually propagates to the earth within one or two days and can manifest itself by the occurrence of aurora and geomagnetic disturbances, the magnitude of which are dependent upon the interplanetary plasma and field characteristics at the time of the arrival of the plasma at the earth. Figure 2 illustrates the relative time of arrival of solar particle emissions at the earth. Note that the 1-8 Angstrom soft X-ray emission is often detected prior to the recorded onset of the solar flare in H-alpha; this is primarily a difference in the recording sensitivities.

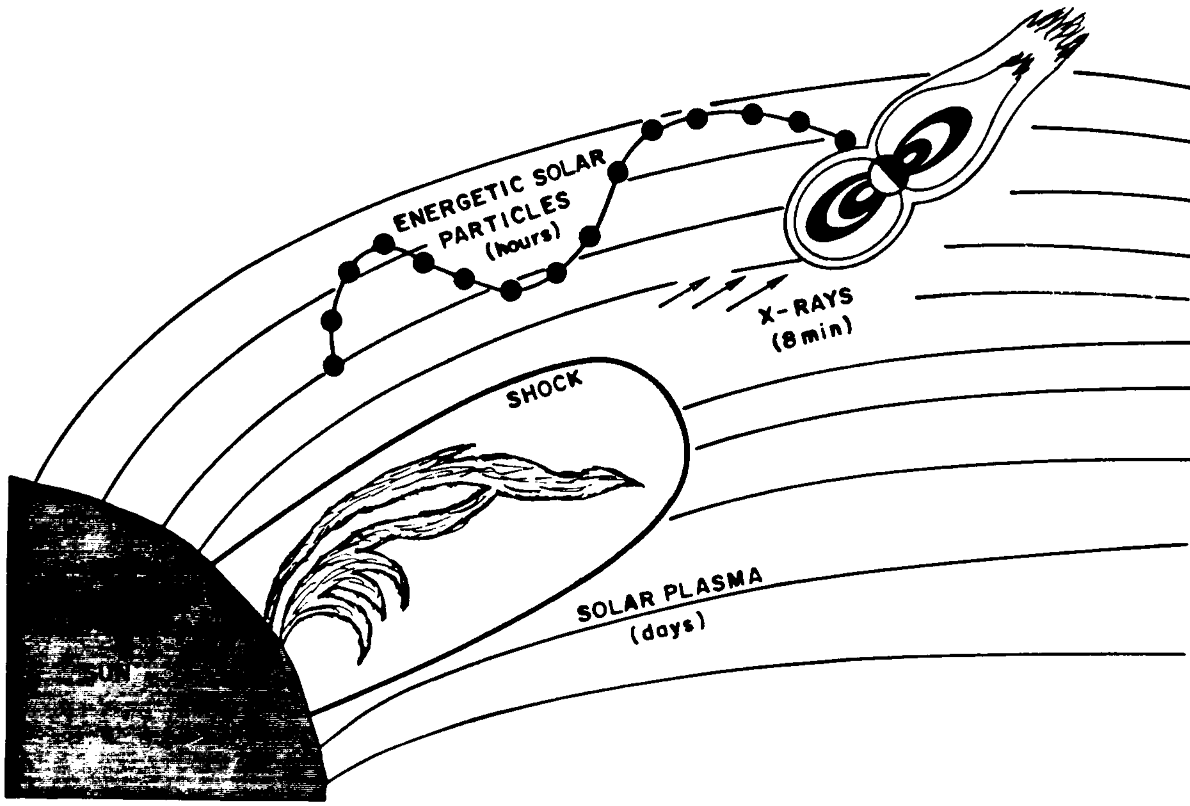

Figure 1. Pictorial representation of energetic particle propagation from the sun to the earth. The relative time scales are noted.

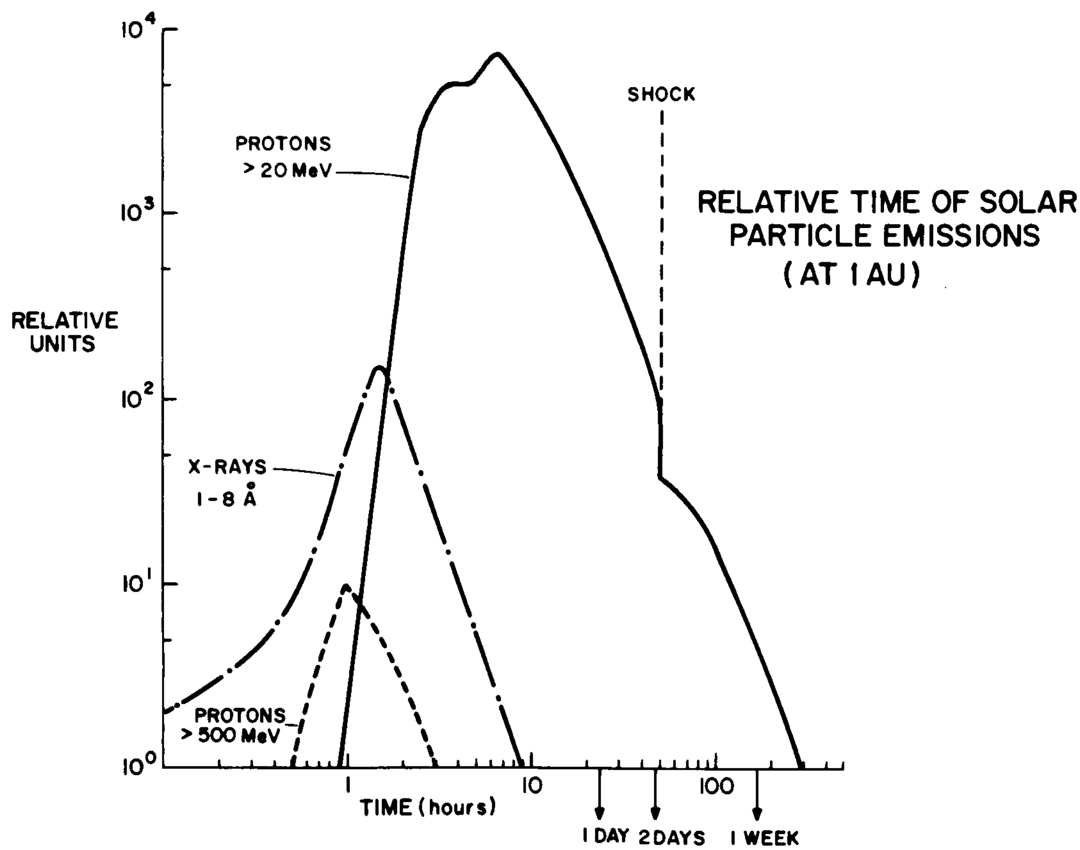

Figure 2. Time scales of solar particle fluxes at 1 AU.

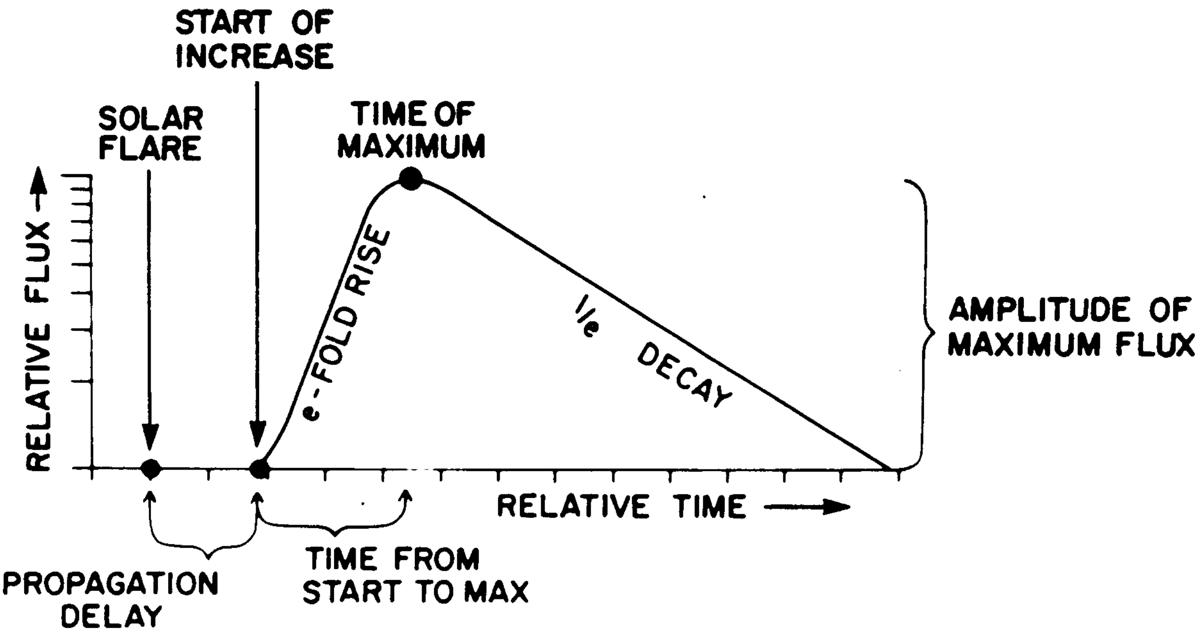

Figure 3. Characteristic solar particle intensity/time scale profile.

Although the general shape of the intensity/time profile, as shown in Figure 3, will differ from event to event and also with respect to the location of the flare on the sun with respect to the location of the detection point in the heliosphere, particle events can be characterized by the following: a propagation delay between the onset of the solar flare in H-alpha emission and the onset of the particle increase; a relatively rapid rise in intensity to a maximum value; and a slow decay to the background level. Although actual event profiles can be complicated by multiple particle injections or interplanetary perturbations, this simplified picture is appropriate for any one isolated event.

3. SOLAR PARTICLE PROPAGATION

The concept of solar particle propagation is discussed elsewhere in these proceedings (Smart, 1988) and will not be discussed in detail here. The essential fact is that solar particles propagate into the interplanetary medium along the interplanetary magnetic field lines. If a solar particle producing flare occurs near the "footpoint" of the interplanetary magnetic field line connecting the earth with the sun (which is nominally around 60° west longitude on the sun), then a detector located along this field line, e.g. the earth, should record the earliest onset time and the highest intensity of any detector located at the same radial distance but at different heliolongitudes. Figure 4 illustrates this favorable propagation path. If a flare occurs at any other solar longitude, the particles which reach the earth are first transported through the solar corona to the interplanetary field line connecting the sun with the earth whereupon they propagate along the field line to the earth.

Figures 5 and 6 illustrate typical intensity/time profiles that would be recorded at one Astronomical Unit from identical flares at different locations on the sun. The intensity/time profile shown on the right side of Figure 5 is typical for a flare that occurred at the "footpoint" of the interplanetary magnetic field line connecting the sun with the earth. Notice the rapid rise to maximum intensity. The particle flux would be maximum along the favorable propagation path (shown by the larger dots) whereas particles that diffuse through the solar corona to other field lines would have a smaller flux (shown by smaller dots).

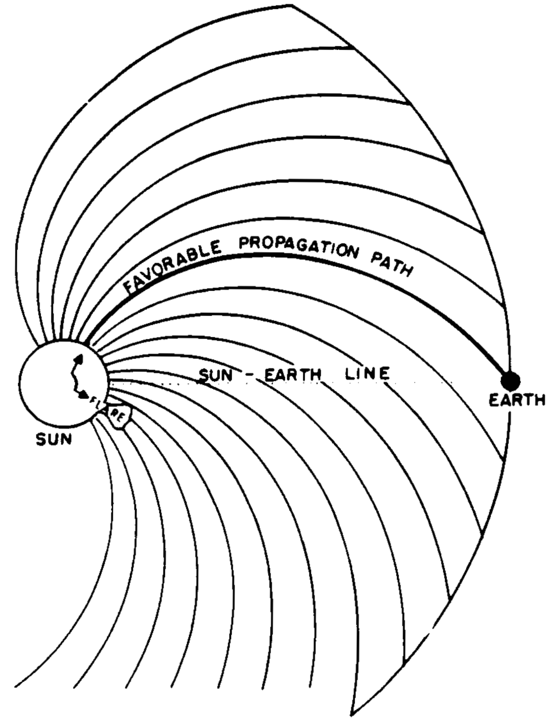

Figure 4. Idealized interplanetary magnetic field line between the sun and the earth with the favorable propagation path indicated.

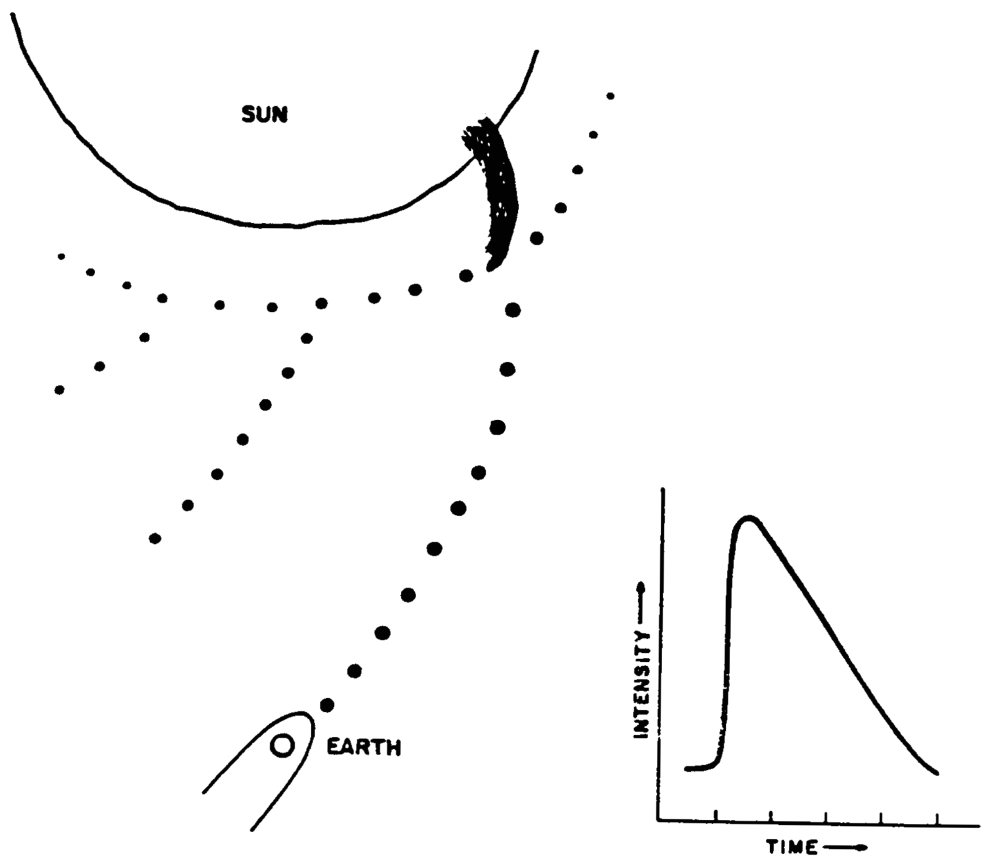

Figure 5. Graphic representation of particle propagation along the interplanetary magnetic field line from the sun to the earth from a solar flare at the "footpoint" of the field line. The larger the dot, the larger the flux. A typical intensity/time profile for this event, as measured at the earth, is shown on the right.

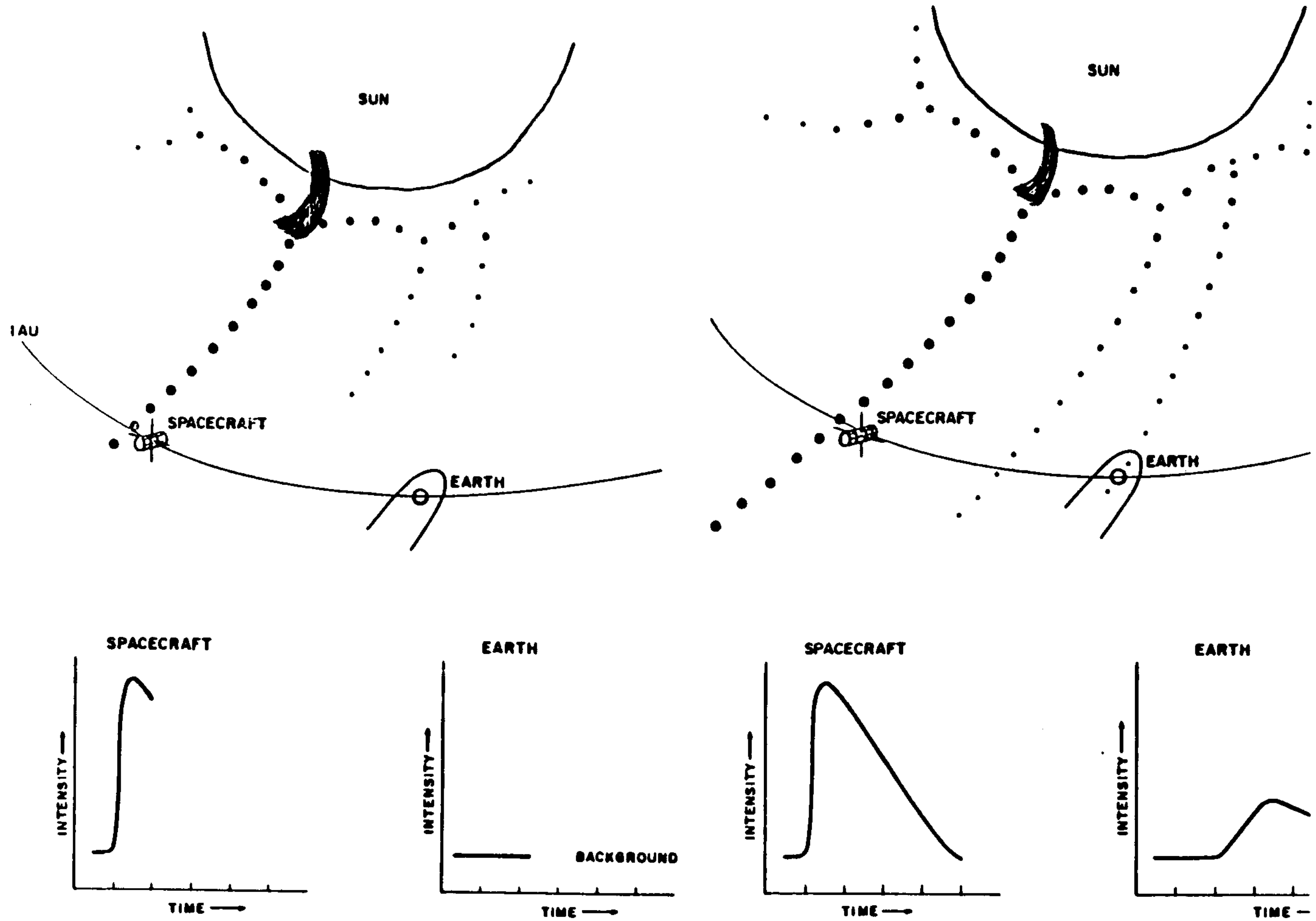

Figure 6. Part A. Solar particle propagation along the interplanetary magnetic field line from a hypothetical flare east of the sun-earth line to a satellite at 1 AU. The larger the dots, the larger the flux. Coronal propagation and particle transport along other field lines are also indicated by smaller dots. The bottom section of Part A on the left side shows the initial intensity/time profile at the spacecraft directly connected to the flare site via the interplanetary magnetic field line; the right side shows coincidental background flux as measured by a satellite at the earth. Part B. Solar particle propagation along the interplanetary magnetic field line and in the inner heliosphere from a hypothetical flare east of the sun-earth line to satellites at 1 AU. The larger the dots, the larger the flux. The bottom section of Part B on the left side shows the intensity/time profile of solar particles for the entire event as measured at the spacecraft directly connected to the flare site via the interplanetary magnetic field line; the right side shows the intensity/time profile of solar particles for the entire event as measured by identical instrumentation on an earth-orbiting spacecraft in the interplanetary medium.

Figure 6 illustrates the particle flux in the inner heliosphere from a flare to the east of the earth-sun line. In Part A the maximum flux (shown by the large dots) would be along the interplanetary magnetic field line from the flare location to the hypothetical spacecraft located at one Astronomical Unit. While particles from this flare are propagating along the field line to the satellite, they are also propagating, albeit with a reduced intensity, through the solar corona to other field lines. Those particles which reach the interplanetary field line connecting the earth with the sun have started to propagate along this field line to the earth; however, as seen from the lower section of this figure the particle intensity at the earth is still at the background level whereas at the spacecraft the maximum intensity has already been measured. The top section of Part B illustrates the particle intensity in the inner heliosphere a few hours later when both the spacecraft to the left, and a hypothetical spacecraft at the earth, would be responding to an enhanced solar particle flux. The lower section of this panel shows the intensity/time profiles which would have been recorded by both spacecraft during this event. The spacecraft at the earth would have recorded a later onset time, slower rise time, smaller maximum flux, and longer decay time than the spacecraft located along the field line connected to the flare site.

At times major flares can populate the entire inner heliosphere with solar particles as illustrated in Figure 7. On 8 and 9 August 1970 particle increases on the Pioneers 8 and 9 space probes together with the small increase on the IMP 5 satellite at the earth could not be associated with any solar activity on the visible hemisphere of the sun; however, Dodson-Prince et al. (1977) noted that active region 10882, which produced particle events on 13 and 14 August 1970, was on the invisible hemisphere of the sun about three days before east limb passage. Since Pioneer 9 had the largest maximum increase on 8 August, and Pioneer 8 had a smaller increase with maximum intensity on 9 August, a possible flare located approximately 40° behind the east limb was assumed to be the source of this particle event. The small increase observed on IMP 5 is consistent with this flare location.

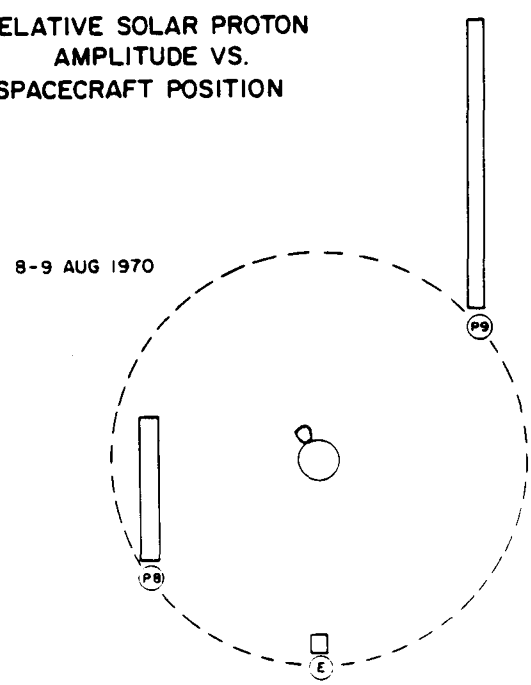

Figure 7. Relative solar particle intensity (on a log scale) as measured on Pioneer 9, Pioneer 8 and IMP 5 (at the earth) for the particle event of 8-9 August 1970. The bars representing the particle flux are placed at the location of the indicated spacecraft. This event has been attributed to a solar flare approximately 40° behind the east limb of the sun. The Pioneer measurements were for particles above 14 MeV; the IMP measurements were for particles above 10 MeV.

4. SPECIFIC EXAMPLES

Figures 8 and 9 illustrate specific examples of intensity/time profiles as measured at the earth during June 1972. Figure 8 shows the particle event on 8 June 1972 as detected on the earth-orbiting Explorer 43. This event exhibited a rapid rise and fast decay associated with a flare to the west of the sun-earth line and possibly close to the west limb. Solar flare observations did not indicate any flare that could be reasonably associated with this particle event. Examination of data from the Pioneer 6 and 10 space probes coupled with the knowledge that an active particle producing region had just rotated over the western limb of the sun led to the assignment of a flare in this region as the possible producer of this particle event (Shea and Smart, 1975).

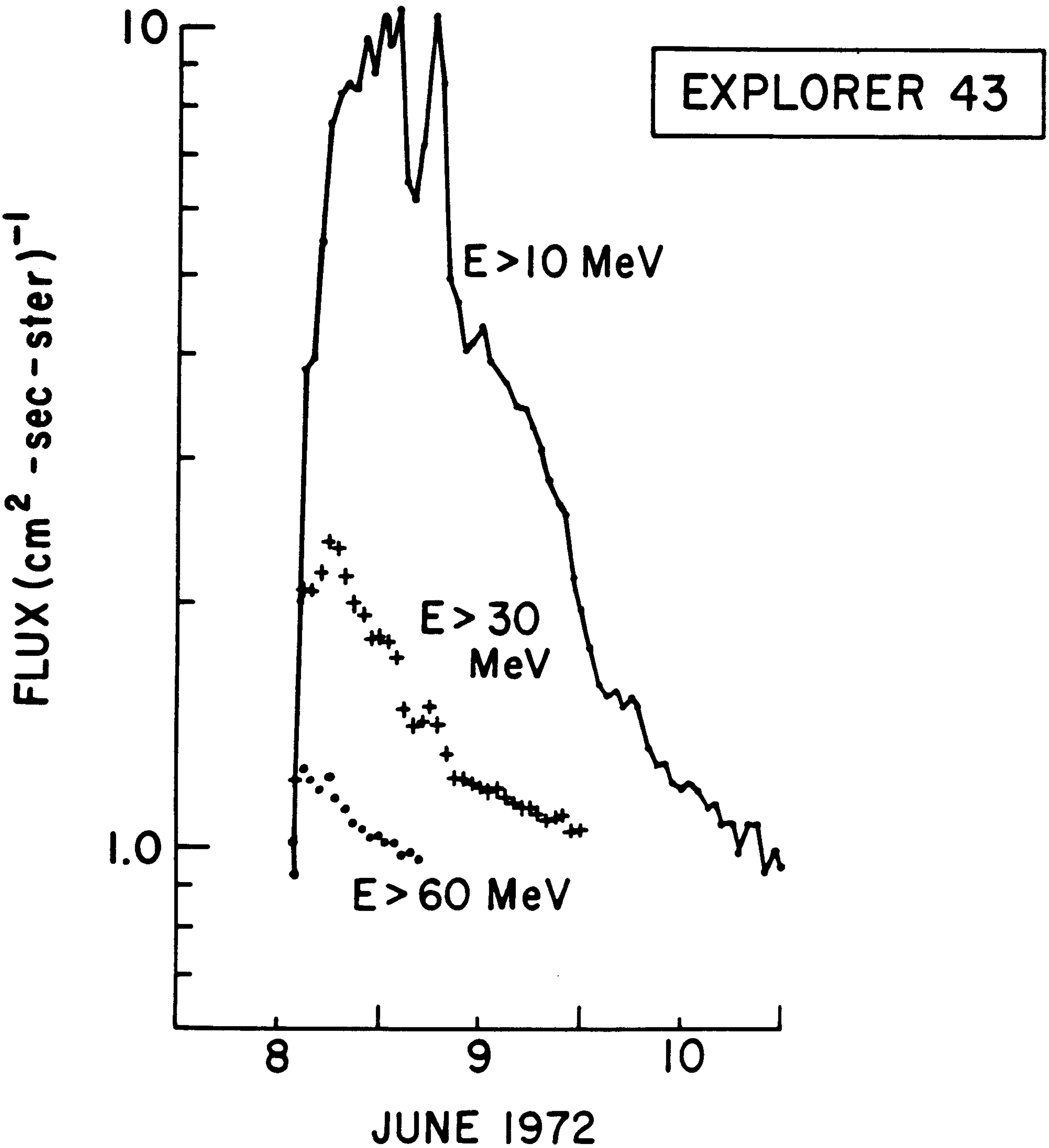

Figure 8. Intensity/time profiles for three proton channels on the Explorer 43 spacecraft for the event with onset on 8 June 1972.

Another particle event occurred later in the same month as shown in Figure 9. There were two possibilities for the solar activity associated with this event - a series of flares near the central meridian of the sun and eastern limb activity which might have been associated with a flare behind the east limb. Because of the large variations in the intensity/time profiles as measured on different spacecraft it has not been possible to associate a specific flare to this event except to assume that more than one solar event on the eastern hemisphere may have contributed to the total flux at the earth. The particle flux profile shown in Figure 9 is indicative of a source region (or regions) to the east of central meridian.

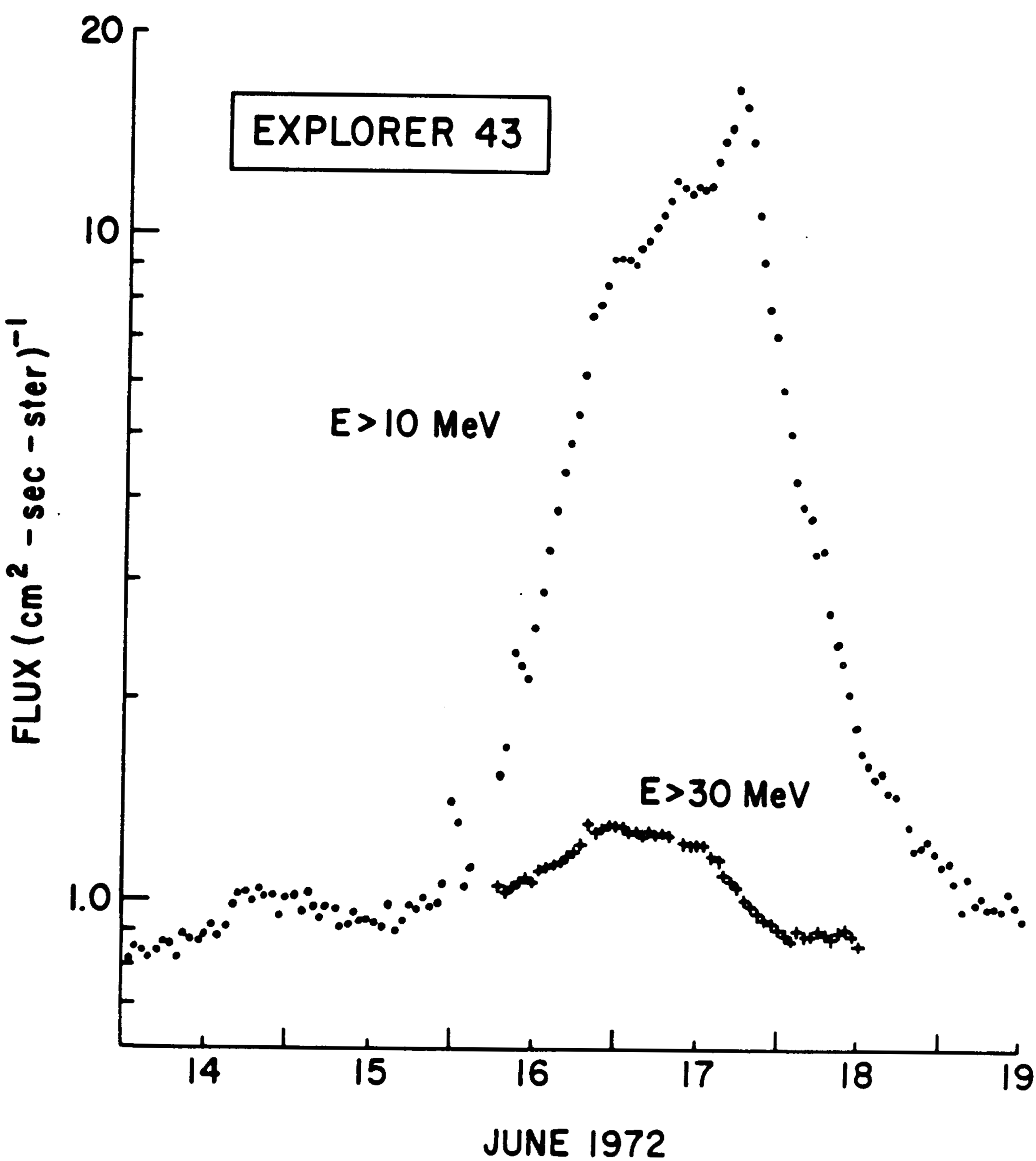

Figure 9. Intensity/time profiles for two proton channels on the Explorer 43 spacecraft for the event with onset on 16 June 1972.

5. DISPELLING POPULAR MYTHS

As in many scientific fields, a certain amount of folklore has been generated which may, or may not, have a factual basis. For example, it is often mentioned that relativistic solar particle events (i.e. the so-called ground-level events) occur on the rising and falling portion of the solar cycle, but not during solar maximum or solar minimum. Inspection of Figure 10 shows that of the 35 relativistic solar particle events between 1956 and 1984, two occurred in 1968 and one in 1979 - both years of sunspot number maximum, and one occurred in 1976 within three months of solar minimum. While most of these events do occur on the rising and falling portions of the solar cycle, a statement that they never occur at solar maximum or minimum is based on mythology.

Another myth which has been dispelled since the era of precise satellite measurements is that solar particle events are always associated with solar flares. First, one should define the term solar particle event which is usually defined as an increase in particle intensity associated with a solar flare. When a specific flare could not be located on the sun in reasonable time association with a particle increase as measured by satellites, a hypothetical flare was often identified as occurring during times of no flare patrol or on the invisible solar disk. With improved resolution of satellite measurements, particle increases have now been associated with disappearing filaments, interplanetary magnetic sector boundary crossings, coronal mass ejections, and acceleration by interplanetary shocks. Although the energies and flux associated with these events are generally relatively small, as shown in Figure 11, there have been exceptions such as the Fermi acceleration of protons to relativistic energies during the August 1972 solar-terrestrial events (Pomerantz and Duggal, 1974).

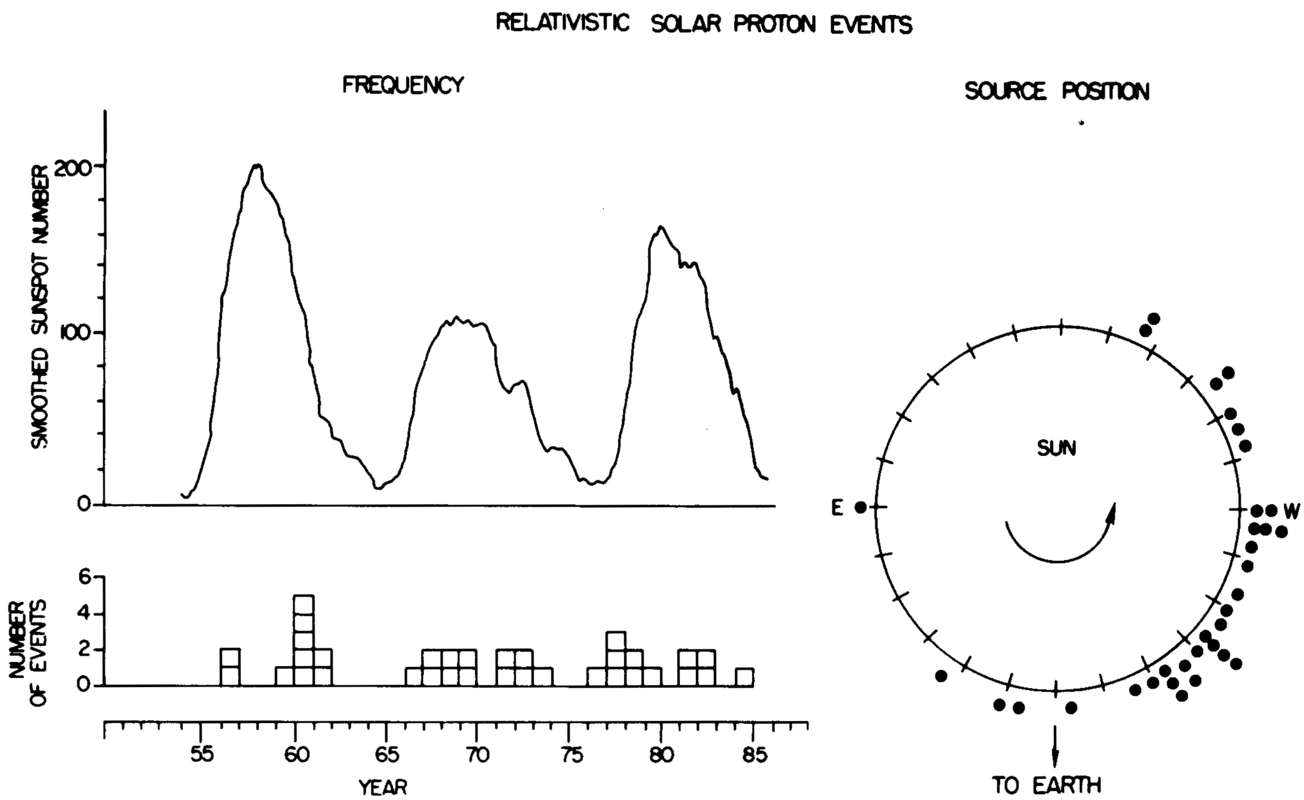

Figure 10. Left Side: Frequency of relativistic solar proton events throughout three solar cycles as shown by the smoothed sunspot number. Right Side: Location on the sun of the flares associated with relativistic solar proton events.

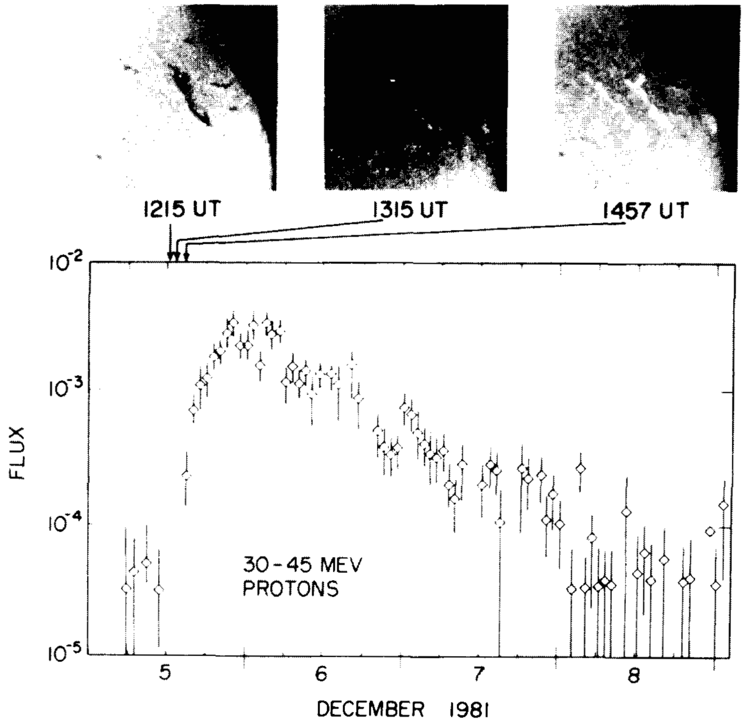

Figure 11. Solar particle increase associated with a disappearing filament on 5 December 1981. (From Kahler, et al., 1986)

6. CONCLUDING REMARKS

Solar particle events can occur at any time in the solar cycle. They come in various sizes and with different intensity/time profiles usually dependent upon the location of the flare with respect to the detection site and the characteristics of the interplanetary medium at the time of the event. There is no guarantee that specific events will or will not occur during a projected mission time frame. The only guidelines that can be given will be generated from statistical studies of ground-based and spacecraft measurements conducted over the past three solar cycles.

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