Energy Dispersion In Solar Ion Events Over 4 Orders Of Magnitude: SOHO/COSTEP And Wind/STICS

Arik Posner and Horst Kunow
IEAP, Universität Kiel, Germany

Abstract

The majority of solar particle events in the COSTEP observational range of 4 - 75 MeV/n reveals nucleon energy dispersion (NED), implying a flare-associated particle acceleration mechanism. Towards lower energies, the situation changes somewhat. Only in a minority of solar energetic particle (SEP) events can the effect of NED be followed into the lower keV range. We analyse the reasons for the distinctly different types of particle transport of >10 keV suprathermal up to 100 MeV energetic ions and conclude that the mean free path depends on rigidity.

1. Introduction and Instrumentation

Energy dispersion of electrons and nuclei is a well-known effect of solar energetic particle events. For nuclei in the MeV range the arrival time difference is on the order of hours. Theoretically, NED depends on the distance along the interplanetary magnetic field and on pitch angle according to the relation:

$$t = S(V_{sw})/V_{part}/cos(\alpha) \tag{1}$$

with S representing the distance to the Sun along the ideal Parker spiral and V_{part} and α the speed and average pitch angle (APA) of the particle.

The SOHO/COSTEP instrument [1] is optimized for the observation of protons and Helium ions of SEP events above ∼4 MeV. COSTEP EPHIN consists of a solid state detector stack within active anticoincidence. CELIAS HSTOF [2] uses flat electrostatic deflection plates. Incoming particles are selected in a multi-gap system followed by time-of-flight (TOF) and energy measurements. The energy range is ∼100 keV/n to ∼1 MeV/n. Here we also use Wind/SMS STICS [3], which combines electrostatic deflection with subsequent TOF and energy analysis. STICS observes ions of 6 to 200 keV/q and resolves charge states.

2. Nucleon Energy Dispersion

Our methodology uses pulse height analysed (PHA) data, i.e. the energy loss of particles is recorded. The advantage of PHA analysis over integrating

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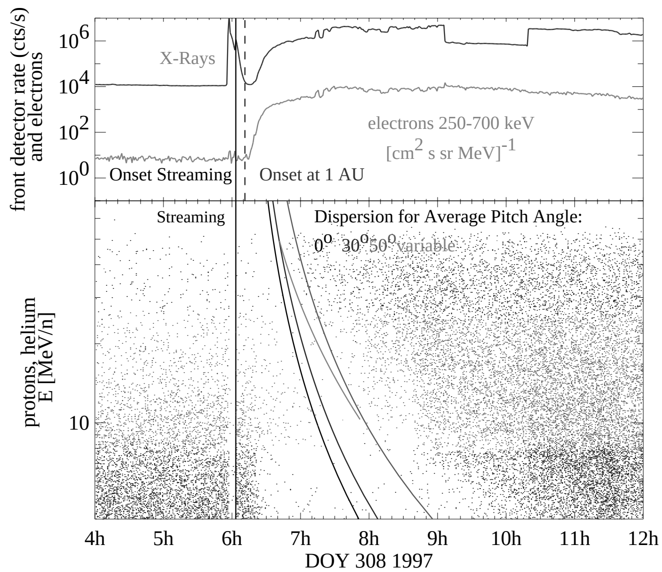

Fig. 1. SOHO/COSTEP observations on Nov. 04, 1997. On top, the front detector count rate (top curve, revealing X-ray events) and 250-700 keV electrons are shown. At bottom, PHA words for protons and helium are shown.

channels of a predefined energy width is that individual particles are used for analysis [e.g. 4]. With a data representation that shows energy per nucleon over time, NED of solar particle events can be easily identified. In the period 1996 - 2002 we found 146 SEP events with energy dispersion, while 183 nucleon enhancements did not reveal signs of dispersion (this includes CIRs, ICMEs).

We focus on the event of Nov. 04, 1997. A flare occurred on 06:09:58 UT at S14W33 in AR 8100, according to Yohkoh/HXT. A halo CME left the Sun on ∼0610 UT with the speed of 830 km/s as stated in the SOHO/LASCO CME catalogue. The solar wind speed at Earth was around 320 km/s (Wind/SWE), which is associated with the connection distance to the Sun of 1.24 AU. Energetic electrons and MeV nuclei show increases of about 2-4 orders of magnitude, clearly associated in time with the observed flare and halo CME. According to Wind/MFI, the magnetic field conditions at the time of the SEP event show θ in the ecliptic plane and ϕ at around 100°. Figure 1 shows the observations of SOHO/COSTEP for 8 hours on Nov. 04, 1997. The top panel shows the 150-700 keV electron time profile. The onset of the SEP event at 1 AU can be seen at around 0613 UT (dashed line). Onset of the X-ray event according to COSTEP would be at 0556 UT (0548 UT at the Sun). Around 0604 UT, relativistic electrons must have left the Sun (solid line). We have fitted the nucleon onset in the given energy range by assigning APAs to the streaming of particles. This is justified due to the interplay of a) adiabatic focusing of particles streaming out of a region of high magnetic field strength with b) frequent scattering of particles in the turbulent heliospheric field, which leads to frequent pitch angle changes. In

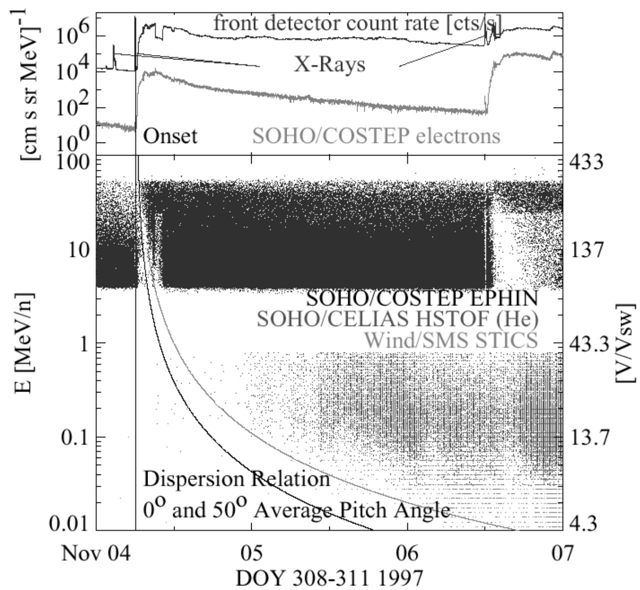

Fig. 2. The top panel contains SOHO/COSTEP electron data and front detector count rates. The lower panel shows combined PHA data of three instruments. The lines represent approximate release and onset times of particles.

general, the more frequent particles are scattered, the higher is the APA of these particles on the way from the Sun to 1 AU. The onset of protons and helium is significantly later than the ideal 0° pitch angle case (left curve). The highest energies are best fitted with $\alpha = 30°$ (second curve). At the lower end of COSTEP energies, which is ~5 MeV/n, particles show significant delays. The data is best fitted with an APA of 50° (right curve). The transition appears to be present in the energy range 50 MeV/n to 10 MeV/n. For this range we applied a fit assuming a logarithmic increase in pitch angle from 30° to 50° (connecting arc). Onset delays are common, as the analysis of 50 SEPs from 1996 - 2002 revealed [5]. Only 15 events out of 50 appear scatter-free, while delays of the other events range from 10% to 60% in travel time. 10% of these events show a significantly longer connection distance to the Sun, which is in agreement with [6].

In Figure 2, we present the combined data of three instruments. On top, SOHO/COSTEP electrons and the front detector counts are given for the extended period of Nov. 04-07. X-ray events are pointed out. COSTEP 4 MeV/n proton and Helium PHAs are shown in Figure 2 (top), combined with Helium from SOHO/CELIAS HSTOF (~50 keV/n - 900 keV/n). Lowest energies >10 keV/amu are provided by Wind/STICS for protons and He^{2+} ions (stepped energies). The scale on the right shows the speed of particles relative to the solar wind speed. Onsets of suprathermal particles connect directly with the SEP event, demonstrating a common acceleration process close to the Sun. We applied the fitting procedure to the whole range of energies. The left curve gives the idealized 0° pitch angle case. The right curve is the extension of the 50° APA. The latter agrees very well with the observed onsets of suprathermal particles.

From the 1996-2002 COSTEP set of dispersive events, 39 events were identified with continuous STICS data coverage during the following 5 days. We found in only 12 cases (or 31%) significant signs of NED below 200 keV/n. The reason could be limited angular extent of particle release at the Sun. Since 200 keV/n ions propagate >1 day to 1 AU, the Earth may meanwhile lose the magnetic connection to the field line range into which suprathermals are injected. Furthermore, in certain cases it is observed that transient compressions in the solar wind appear as barriers for suprathermal particles. Therefore, the presence of ICMEs may be the main cause for the lack of suprathermal NED signatures from SEP events at 1 AU. So far, limited statistics prevent us from quantifying the relative importances. For example, it is likely to see higher fractions of suprathermal dispersive events whenever the frequency of transients is low.

3. Discussion and Conclusions

Many SEP events reveal ion onset delays of ions relative to electrons. We attribute these delays to differences in interplanetary propagation. We found that the onset of particles over the full energy range can be matched by a simple equation incorporating a) the distance along the Parker spiral, b) the particle speed, and c) an assumed APA. For the Nov. 04, 1997 event the latter is found to change within the energy range 10 MeV/n ($\alpha = 50^o$) to 50 MeV/n ($\alpha = 30^o$). We conclude that here high energy particles are relatively less pitch angle scattered than low energy particles in the IMF between the Sun and 1 AU and therefore propagate more directly to 1 AU. Apparently, $\alpha = 50^o$ APA can be applied to the energies below 10 MeV/n. Statistically, NED below 200 keV/n is found in only 31% of SEPs. The reasons are still to be investigated.

4. Acknowledgements

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5. References

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