DETECTION OF ENERGETIC PARTICLE EVENTS WITH SOHO SPACE OBSERVATORY

DOLORES RODRÍGUEZ FRÍAS, RAÚL GÓMEZ HERRERO, JULIO GUTIÉRREZ, LUIS DEL PERAL
Departamento de Física, Universidad de Alcalá, E-28871 Alcalá de Henares, SPAIN

Abstract: An analysis of eighteen solar energetic particle (SEP) events measured with the EPHIN instrument on board the SOHO spacecraft has been performed. Differences among individual events have been shown by the parametrization of temporal profiles. The detected differences are found to depend on the particle acceleration, the magnetic connection with the acceleration zone and the interplanetary physical characteristics transported to the observing point.

1 Introduction

The SOHO spacecraft was launched in December 1995 and it was injected into a halo orbit around the inner Lagrangian point, L1, reaching its final destination, in February 1996. It is observing the Sun continuously from its privileged position outside the Earth magnetosphere. SOHO is a 3-axis stabilized spacecraft where its sensors point to the nominal interplanetary magnetic field direction at 0.99 AU and 45° West of the spacecraft-Sun line. A set of four particle detectors are shipped on board SOHO satellite for detection of suprathermal and energetic particle populations of solar, interplanetary and galactic origin. They are: LION, Low Energy Ion and Electron Instrument; EPHIN, Electron Proton Helium Instrument; LED, Low Energy Detector and HED, High Energy Detector. All of them cover the detection of electrons in the 44 keV - 50 MeV energy range, together with the 44 keV/n - 540 MeV/n energy range for ions.

From its privileged position outside the Earth's magnetosphere SOHO is able to perform direct detections of the heliospheric plasma particles, providing us with particle intensity, anisotropy, composition and energy spectra data.

Detected particles come from different origins: solar energetic particle (SEP) events, interplanetary shock accelerated particles, low energy galactic cosmic radiation modulated by the heliospheric magnetic field, anomalous cosmic radiation, particles accelerated in planetary magnetospheres, etc.

2 Observations

On flight particle identification is obtained from the ΔE-E technique with the Goulding algorithm. Heavy ion identification is not performed on flight because it requires more exhaustive calculations; a mass resolution as high as 0.15 amu for carbon with the HED detector is obtained. The EPHIN instrument obtains a mass resolution of 0.01 amu for hydrogen, and 0.02 amu for Helium isotopes.

The events analyzed in this work have been selected among more than 60 SEP events registered by SOHO sensors during 1996, 1997 and 1998. The first half of this period showed relatively quiet particle fluxes, corresponding to minimum solar activity. During the second half of this period, solar activity increased gradually, corresponding to the rising phase of the 23rd solar cycle, and extremely large GSEP (Nov 97 and Apr 98) were detected. These events have a wide variety of observational features (composition, spectra, duration, etc), and there is an adequate sample of the differences that can be found studying SEP events. Nevertheless, most of the events may be classified into two broad categories: Impulsive Solar Energetic Particle (ISEP) events and Gradual Solar Energetic Particle (GSEP) events. The observational characteristics of these two categories have been widely described by many authors ([1], [2], [3]). GSEP events show large increases in particle fluxes; they are commonly associated with Coronal Mass Ejections (CMEs) and interplanetary shock waves. They are also long duration (several days) events, and their composition is similar to that of the solar wind and corona. On the other hand, ISEP events are characterized by low particle fluxes, short duration, heavy ions and ^{3}He enrichment, and for the fact of being commonly associated to impulsive X-ray flares.

The start and end times of individual events have been identified using proton differential fluxes (4.3-7.8 MeV/n). These two times delimit the temporal period analyzed for each SEP event. Particle fluxes, global spectra of ^{1}H and ^{4}He, temporal spectral evolution, and isotopic composition have been determined for all the events in order to obtain observational parameters to classify them as ISEP or GSEP events.

3 Gradual Solar Energetic particle events

November 28, 1996. This SEP event presents composition features typical of GSEP events, with coronal abundances of He (He/p=0.023) and low abundances of ^{3}He (^{3}He/^{4}He<0.01). This SEP event is dominated by protons. Although some solar flares have been observed, the SEP event seems to be related to a CME observed at 16:50 UT of 970 km/s with a driven shock arriving at Earth at 00:33 UT on December 1, 1996, that should accelerate particles. The proton and Helium energy spectra have a very similar spectral index, that means a common shock acceleration without preferential acceleration. On December 3, at 00:41 UT, a second shock arrived and a halo CME was detected at 15:35 UT with 613 km/s; this was observed by LASCO, reaching the SOHO position at 12:00 UT on December 5.

December 24, 1996. The SEP event on December 24, 1996, had a very low abundance of Helium and a low e/p ratio with a hard proton spectrum ($\gamma_p = 2.33$) and no ^3He is found (Figure 1). It had not been observed a shock arriving at the SOHO position while a magnetic cloud in coincidence with the SEP event had been detected. This suggests us to classify this event as GSEP.

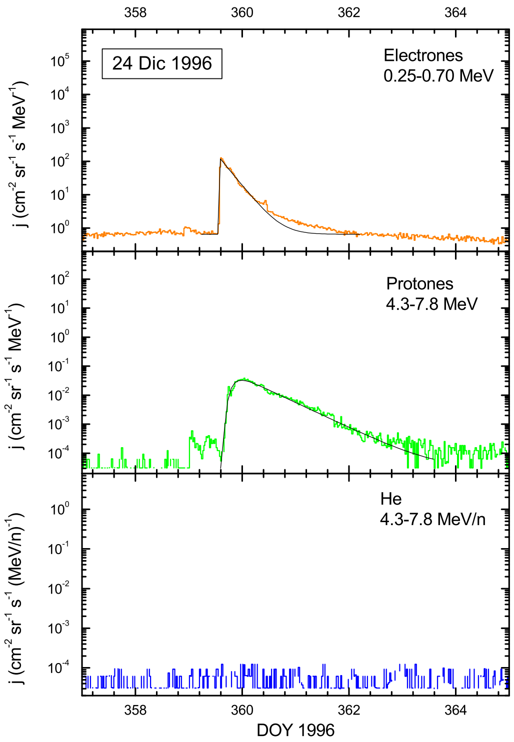

Figure 1: December 24 GSEP event particle temporal profiles.

April 1, 1997. This was another GSEP with low e/p and He/p ratios. It was East connected to the M1.9/1B solar flare on S25E16 location. A hard energy spectra, $\gamma_p = 1.95$ and $\gamma_{He} = 2.46$ was reached with proton acceleration above 25 MeV. No shock was detected and only 296 km/s CME was reported by LASCO. A 3% of Helium was found to be ^{3}He. Therefore, the event should have been gradual although no shock was observed that produced particle acceleration.

April 7, 1997. This was a typical GSEP event associated with the C6.8/3N solar flare on S30E19, started at 13:50 UT on April 7. A shock, driven a 800 km/s fast CME observed at 14:27 UT by LASCO, arrived at 13:00 UT on November 10 and should have accelerated particles with a very similar spectral index, $\gamma_p = 2.65$ and $\gamma_{He} = 2.85$. Following the shock, the leading edge of the CME happened at 6:00 UT on April 11 up to the trailing edge at 19:00 UT. After the shock passage the spectral index remained constant for protons and Helium. Moreover, low e/p, He/p and $^3He/^4He$ ratios were registered.

September 20, 1997. It was a GSEP event with some features typical of ISEP events. There was a solar flare (0087 B8.01) that may have generated SEP 1 MeV electrons observed at 3:35 UT by EPHIN and 5 MeV protons observed at 13:43 UT. The electron to proton ratios were low. A coronal abundance He/p ratio was found, but more ^{3}He than expected in this kind of events was detected. The passage of a CME with a velocity value between 264.9 km/s and 265.9 km/s was caused by a shock driven at 12:00 UT of DOY264. The spectral index of Helium and protons was very similar. This leads us to the conclusion that the acceleration took place under the same conditions, with no preferential acceleration mechanisms.

September 24, 1997. This was a SEP event with a very hard proton spectra, $\gamma_p = 1.48$. The e/p ratio, low Helium abundances and the absence of ^{3}He lead us to classify this event as GSEP. The problem is that no shock was found that could accelerate SEPs. On September 23 a halo CME could have been the responsible of the SEP generation. The CME had a 760 km/s speed and was observed at 22:02 UT. Thus, when in the NOAA 8088 region a M5.9/1B solar flare started at 2:43 UT on S31E19 location, the CME-driven shock was travelling through the interplanetary medium. This shock should have accelerated particles generating the observed SEP population. The proton spectral index found suggests a very strong shock associated.

November 4, 1997. This GSEP event was related to a X2.1/2B flare on the NOAA 8100 active region at 5:52 UT on S14W33 and a halo CME at 6:10 UT with a driven shock reaching the Earth vicinity. The CME passage occured during the detection of a SEP on November 6, 1997. The event showed coronal abundances with low e/p=25.9, ^{4}He/p=0.022 and ^{3}He/^{4}He$<$ 0.01 ratios, high energy particle generation (i.e. e^- >10 MeV, p and He >130 MeV/n) (Figure 2). The event was detected at ground level by neutron monitor arrays. The electron, proton and Helium energy spectra showed the same temporal behaviour and values accounting for an unique origin of the SEP. This GSEP event is west correlated showing a fast increase and an exponential decay in the temporal profile. The spectral index $\gamma_p = 2.02$ indicates a strong shock.

November 6, 1997. A second GSEP event was observed in the same NOAA active region, located on S18W63. The event was associated to a new X9.4/2B solar flare started at 11:49 UT on November 6, 1997. A fast CME was detected by LASCO at 12:00 UT on November 6. This CME was very fast and the spectral index of the

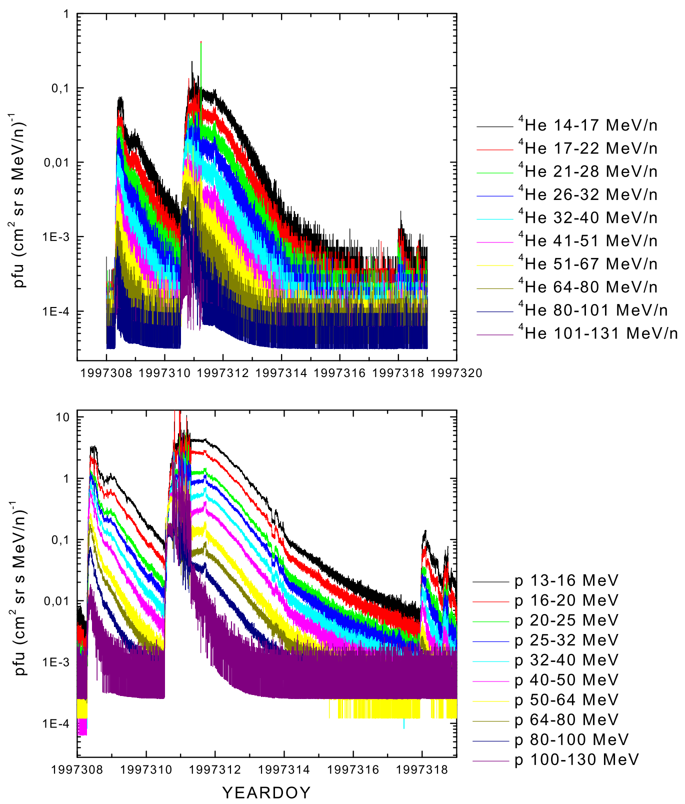

Figure 2: November 1997 LED proton and Helium temporal profiles.

SEP indicates a strong shock associated. Particles of hundredths of MeV/n were observed by LED (Figure 2). The energy spectral indices of protons and Helium are similar indicating, as in the previous event, shock acceleration of coronal material. The temporal profiles corresponded to a well magnetically connected west event. The SEP composition was exactly the same of the previous event; only, it is appreciated more ^{3}He and electrons than can be explained by a better magnetic connection of the observer that can allow the observation of ^{3}He and electrons accelerated at the flare region.

April 20, 1998. This was a typical GSEP event with high abundance of electrons and low ^{4}He and ^{3}He abundances. The event was associated with a M1.4 solar flare in the NOAA 8194 active region at S43W90 location, detected in X-rays at 9:38 UT on April 20, 1998. A fast CME was detected by LASCO at 10:07 UT on April 20. The shock arrived at the SOHO position at 16:48 UT of DOY 113. The shock was strong, generating a very hard energy spectrum of SEP ($\gamma_p = 1.16$)

4 Impulsive Solar Energetic particle events

July 9, 1996. This was an ISEP event related to a X2.6/1B flare, the corresponding X-ray emission starting at 09:07 UT on the NOAA active region 7978 located at S10W30 on the solar disk. A CME was observed by LASCO at 12:28 UT with a velocity value of 426 km/s, which did not generate an observable driven shock and it was probably not related to the solar flare because of the temporal separation involved. The SEP event observed was clearly associated with this flare. The SEP event features are clearly from ISEP events, with high abundance of He (He/H=0.139) and electrons (e/H=399.7). No special ^{3}He acceleration was observed in this event (^{3}He/^{4}He=0.01). The acceleration mechanism was able to accelerate electrons up to 5 MeV and protons and Helium up to 25 MeV/n. From particle transport calculations it arises a path for the particles of 1.16 A.U. into an ambient solar wind of 425 km/s. 1 MeV electrons were observed at 09:21 UT, 44 minutes before expected, and 5 MeV protons arrived at the SOHO position at 10:47 UT, 37 minutes before expectations. This should mean that SEP particles escaped from the flare region about 40 minutes before the X-ray emission that should have been generated by these electrons when they hitted the surrounding plasma.

The differential energy spectra of protons was lightly harder that the transport theoretical predictions, with a 3.13 value and Helium had a harder energy spectrum than protons, showing how the acceleration mechanisms accelerated Helium nuclei more efficiently than protons, and thus energizing Helium easily that protons.

July 12, 1996. The NOAA 7978 active region generated a second flare C4.9/1F at 15:13 UT on July 12, 1996, at S11W72 location on the solar disk. The associated SEP event had similar composition features than that on July 9, although more ^{3}He was detected in this last event, perhaps because of his better magnetic connection. The energy spectra of protons and electrons were softer than for the July 9 ISEP event. The particles travelled through a 450 km/s solar wind by 1.139 A.U. The arrival time of the 1 MeV electrons is in good correlation with the arrival time but the 5 MeV protons arrived 31 minutes before they were expected.

November 25, 1996. This SEP event was probably associated to a C8.0/1N solar flare starting at 00:19 UT on the SO3E18 position of the NOAA 7999 active region, that was magnetically bad connected with SOHO. This SEP event showed a proton differential energy spectrum as soft as $\gamma = 5.33$, while the Helium spectral index was harder: $\gamma = 3.71$. No ^{3}He was detected in this SEP event, perhaps because of the very bad magnetic connection involved. Moreover, it was an electron rich event with an e/p ratio value of 388. From the composition features detected we have classified it as an ISEP event.

There were two correlative SEP events probably related to two solar flares B9.0 in S03E16 and B8.9/SF. The He abundance detected was high, with an energy spectrum becoming harder with time in the first event. Moreover, a low electron to proton ratio was found. No shock or CME was reported.

Although we have classified the first event as an ISEP event, the second one should be a shock accelerated SEP event, that is, a GSEP event.

August 10, 1997. This was the first ^{3}He-rich event detected by SOHO/EPHIN, with 28% of Helium, that is, with a high He/p=0.284 value. Moreover, a high population of electrons (e/p=658) was detected. The event was associated with a B1.6 solar flare at 17:15 UT on August 10. It was a SEP event with clear features, typical of an ISEP event. 1 MeV electrons began to be detected at 17:45 UT while 5 MeV protons were detected at 20:52 UT.

September 17, 1997. Associated with a M1.0/SF solar flare at the N21W84 location of the NOAA 8084 active region, at 17:45 UT, another ^3He-rich ISEP event was detected by SOHO/EPHIN. It presented a $^3He/^4He = 0.18$ ratio and high abundance of electrons, e/p=527, and Helium, He/p=0.155. A halo CME at 20:28 UT was observed by LASCO, driven by a shock. The CME passage seemed not to contribute to the acceleration in the impulsive flare. The SEP travelled through a 350 km/s solar wind plasma, reaching 5 MeV protons to SOHO/EPHIN at 20:52 UT. The event was a joint of two events, and the second one was related to the solar flare on September 8, at 1:39 UT in the 8085 NOAA active region.

November 28, 1997. This event presented the highest ^3He enrichment of all the events analyzed in this work (Figure 4). A 32 % of the Helium population observed was ^{3}He. This Helium enrichment is also inferred from the He/p=0.144 relative abundance ratio. Neither shock or CME occurrence were associated to the event. The possible source of the SEP was a solar flare X2.6/2B located on the NOAA 8113 active region at N17E63 with a very bad magnetic connection. The observation of an ISEP event with so bad magnetic connection is a rather peculiar fact. It could have been possible that the strength of the flare could have made possible the SEP observation. If this is the situation, probably the ^{3}He/^{4}He ratio should be higher than what has been observed. Another different feature of the ISEP event was the generation of high energy particles, i.e. e^- >5 MeV and proton and He at > 25 MeV/n. Moreover, the energy spectra were harder than usual for ISEP events.

5 Conclusions

Six of the 18 events analyzed have been classified as impulsive: July 9, 1996; July 12, 1996; November 25, 1996; August 10, 1997; September 17, 1997 and November 28,

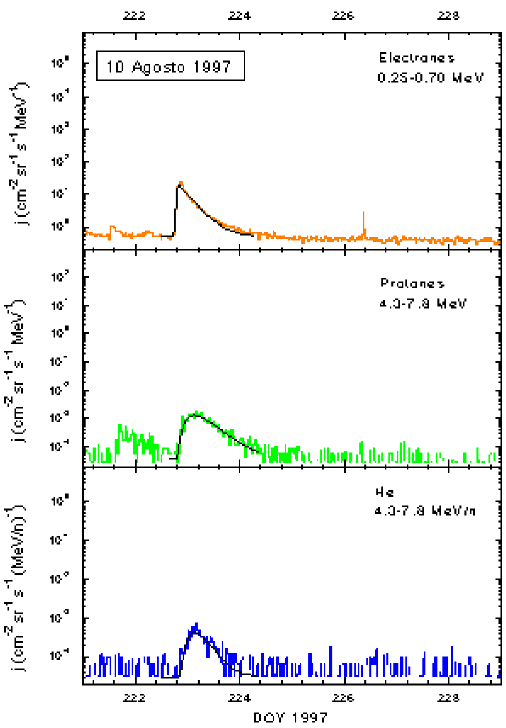

Figure 3: August 10, 1997 ISEP event.

1997. The most relevant observational features found in these events were:

- The event duration is less than 4 days.
- There is no significant proton acceleration beyond 25 MeV.
- High electron contents: in all cases e(0.25-4.25 MeV)/p(4.5-8.5 MeV) ratio reaches values greater than 100.
- High ^{4}He abundance in all cases ^{4}He/p(4.5-8.5 MeV/n) ratio reaches values greater than 0.1.
- Most of the events have ^{3}He/^{4}He(4.5-8.5 MeV/n) ratio greater than 0.01. In some cases this ratio is particularly higher (> 0.1).

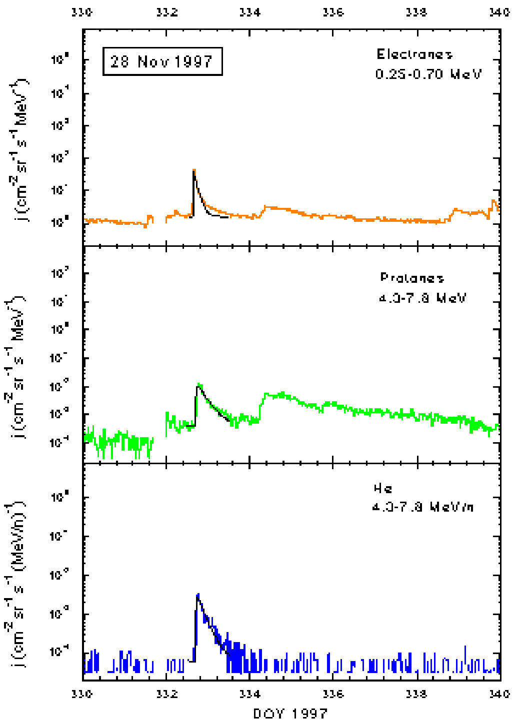

Figure 4: Temporal profiles of the November 28, 1997 ISEP event.

- In general, they have not associated neither CMEs nor interplanetary shock waves.
- Proton and ^{4}He spectra are relatively soft ($\gamma_p < 3.0$), except for the November 28 1997 event.

Seven events have been classified as gradual: November 28 1996, April 1 1997, April 7 1997, September 24 1997, November 4 1997, November 6 1997 and April 20 1998. These events present the following signatures:

- The event duration is greater than five days, exceeding 10 days in many cases.
- Protons are accelerated beyond 25 MeV.
- The electron content is, in general, lower than that of impulsive events. Although, some events have high electron abundance (April 20, 1998).

- $^4He/^1H$ ratio is close to coronal and solar wind abundance (typically between 0.02 and 0.05). In some events slight Helium acceleration is observed and the ratio becomes lower.

- ^3He can not be appreciably above background.

- Most of them have associated CMEs, and interplanetary shock waves (although in some cases it has not been possible to find any associated shock). Usually shock passage can be seen as transient hardening of spectral index, followed by long periods of invariant spectrum.

- Proton and ^4He spectra are hard ($\gamma_p < 3.0$), except for the November 28 1996 event.

November 25 1996, December 24 1997, and September 20 1997 events have mixed features, although the first one seems to be more impulsive and the last two ones more gradual events. August 13 1996 event shows some peculiarities and it has not been classified.

Acknowledgements: This work has been supported by the Ministerio de Ciencia y Tecnología (MCYT) of Spain, project BXX2000-0784 and the University of Alcalá, project UAH2002/081. SOHO is a project of international cooperation between ESA and NASA.

References

[1] Mason et al. 1986, ApJ, 303, 849
[2] Reames, D. V. 1993, Adv. Space Res., 13, 331
[3] Reames, D. V. et al. 1997, ApJ, 483, 515