Energy spectra of protons, deuterons, and helium nuclei during quiet solar activity periods in 1996-97

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Abstract

A background reduction method based on pulse-height analysis (see accompanying paper by Valtonen et al.) is applied for the data of the ERNE and EPHIN energetic particle telescopes aboard SOHO. Energy spectra of protons, deuterons, ^{3}He and ^{4}He nuclei have been obtained during very low activity periods in 1996-97 in the energy range of 1.3 to 22 MeV/n. The proton spectra are comparable to the lowest spectra of the Ulysses (COSPIN/LET, 1996) and near-Earth IMP-8 (1985-87) measurements. Deuterons and ^{3}He are only significantly seen above about 10 MeV/n, their spectra are consistent with an increase proportional to kinetic energy, expected for purely galactic origin.

1 Introduction:

The recent minimum of solar activity in 1996-97 provided an opportunity to reconsider the issue of the nature of the energy spectra of charged particles, particularly those of protons and helium nuclei, at the lowest fluxes near the solar minimum. Studies of near-Earth interplanetary energetic particle data obtained during earlier minima indicate the presence of a relatively stable population of protons, probably of solar/heliospheric origin (Király and Kecskeméty, 1998). However, most of the results available for earlier periods are based on rates rather than on results of pulse-height analyses, therefore they are probably contaminated with a considerable amount of background, mostly due to higher energy galactic particles. At energies above 10 MeV where threefold coincidences can be employed, such a background can be eliminated with relative ease. However, at lower energies usually only coincidences of two sensors are used, necessitating a careful pulse height analysis. Presently applied pulse height analysis methods are satisfactory during high-flux periods, when the signal-to-noise ratio is sufficiently large, but low-flux periods require a more accurate determination of the background.

This paper presents energy spectra of protons, deuterons, ^{3}He and ^{4}He nuclei obtained using a new sophisticated method (see accompanying paper by Valtonen et al., 1999) for the analysis of data from the LED sensor of the ERNE experiment, as well as for the EPHIN telescope, both aboard the SOHO spacecraft during low-flux periods under solar minimum conditions in 1996 and 1997.

2 Instrumentation and data analysis:

The SOHO spacecraft, launched in December 1995, is carrying aboard three instruments for the registration of energetic particles; the data of two of them, which provide pulse height information are analyzed here. The low energy detector LED of the ERNE instrument is a simple telescope with an anticoincidence detector underneath the energy loss (comprising 7 components in parallel of 2 different thickness) and residual energy detectors. The two front detectors are pulse-height analyzed. The energy range is about 1.5-13 MeV/n, while the total geometry factor is 0.260+0.655 cm^{2} sr. The Electron Proton Helium Instrument (EPHIN) of the COSTEP is a 5-layer telescope surrounded by a plastic scintillator providing the anticoincidence signal. The two top sensors are divided into 6 segments for the purpose of position sensing. The geometry factor is 5 cm^{2}sr for the full telescope reduced to 1 cm^{2}sr when parallel geometry (coincidence of corresponding segments of the two top sensors) is applied. The energy interval is from 4.3 MeV/n to >53 MeV/n for hydrogen and helium isotopes. During low-flux periods all pulse heights of the detectors of both LED and EPHIN are recorded.

3 Proton energy spectra:

3.1 ERNE-LED: Based on the pulse height analysis method presented in Valtonen et al. (1999) the background level of LED was found to be practically independent of time and the same for all detectors of the same type. The energy range 1.5-12 MeV was divided into 6, logarithmically equal bins. A total of 295 days between March 1996 and September 1997 were selected as without obvious contribution from solar and interplanetary events keeping only periods with measured fluxes below 3×10^{-3} protons/(cm^2 s sr MeV) in the 1.5-2.2 MeV channel. From these data a two-dimensional background distribution was constructed in the logarithmic PIN-total energy plane and the fluxes of protons and helium nuclei determined.

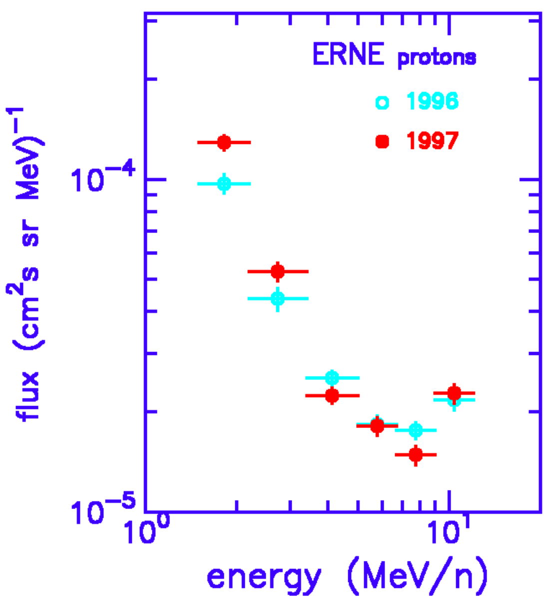

Figure 1: Quiet-time proton fluxes of ERNE LED in 1996 and 1997. Vertical bars: statistical errors, horizontal bars: energy range.

Displayed in Fig. 1 are the nominal values of proton differential fluxes obtained using the background reduction procedure for the 1996 and 1997 data separately. The counts from all detector pairs used in each energy channel were combined. The error bars to the fluxes in Fig. 1 are statistical errors. Total estimated errors are obtained by combining the Poissonian and systematic errors, the latter arising from the uncertainty of the fit procedure and are between -12/+16% at low energies and -20/+70% at high energies. From the total observed counts attributed initially to protons only 20-50% were found to be real protons.

The absolute proton fluxes above about 3 MeV match reasonably well for the two years. Both energy spectra exhibit a minimum near about 7.5 MeV, the average differential flux is 1.6×10^{-5} (cm^2 s sr MeV)$^{-1}$. The spectral indices fitted to the three lowest energy points are -1.6 and -2.1, respectively.

3.2 EPHIN: A contiguous very quiet period between DOY 50 and 110, 1996 was selected on the basis of rates of 4-8 MeV protons. The procedure described in Valtonen et al. (1999) has been carried out for both the parallel and wide geometry (in the latter case the PIN distributions around the maximum are asymmetric rather than Gaussian with a tail at larger PIN numbers, resulting in larger uncertainties of the parameters).

A quick comparison of the fluxes obtained for the two versions of geometry indicates that, in spite of the fact that the track of protons is defined better, the parallel geometry result in errors that are larger than those of the full, wide angle telescope by a factor of more than 2. The differences between the two fluxes are, however, somewhat unevenly distributed over the energy interval, for instance, between 5.8 and 9 MeV the parallel fluxes are considerably lower. On the other hand, the values match in all cases within two sigma statistical errors.

As clearly seen from a quick comparison of Figs. 1 and 2, the energy ranges of EPHIN complement those of LED to some extent: EPHIN has all but one point on the rising branch of the spectrum while LED covers mostly the falling branch. The spectral shapes are therefore hard to compare, nevertheless, the energies of the fitted minima are close to each other, about 6.2 and 7.5 MeV, respectively. A more difficult task is to explain the difference between the flux values derived. In the overlapping energy windows between 5 and 12 MeV, the LED (1996) fluxes are systematically larger (by a factor of 1.9 on the average), the ratio LED/EPHIN decreasing with energy from about 2.2 to 1.7. This can only be partly due to the different selection of quiet time intervals as the LED fluxes exhibit a smaller variation than that over the selected intervals. Another possibility is that the geometry factor used for ERNE to derive fluxes is somewhat underestimated, but this seems to contribute not more than a few per cent. The LED background can still be underestimated as it has a worse signal-to-noise ratio

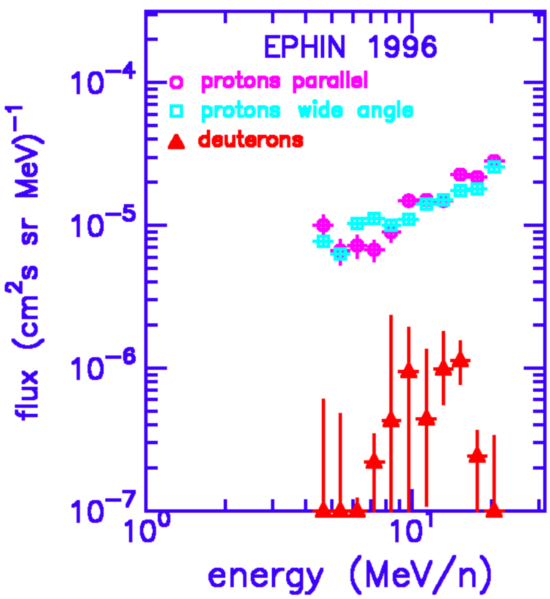

Figure 2: Quiet-time proton (for parallel and wide geometry) and deuteron fluxes of EPHIN in 1996.

due to the lack of anticoincidence shielding, moreover, the background was determined without making use of high-flux data to find the shape of the PIN distribution of true particles. A similarly systematic though smaller difference was found between the helium fluxes (see next section).

The direct comparison of the absolute fluxes with other experiments indicates that the EPHIN minimum fluxes are indeed very low, lower than most of near-Earth measurements obtained during former solar minima at IMP-8, and comparable to the fluxes obtained during a similar period at Ulysses by the COSTEP/LET instrument (Király et al. 1999).

3.3 EPHIN deuterons: In the bottom portion of Fig. 2 the energy spectrum of deuterons are shown. Any contribution above a flat background is barely visible on the PIN histograms at energies below about 10 MeV/n, therefore the spectral points can only serve as upper limits. (The deuteron peak appears to be clearly present, however, in the PIN distribution of solar particles obtained during the 6 November 1997 SEP event.) At higher energies, however, the deuteron fluxes become significant and even a slight increase with energy can be guessed (apart from the two highest energies the spectrum can reliably be approximated by a linear energy dependence). The flux values obtained are somewhat lower than those found by Sierks (1997) for a longer, but not strictly quiet period. They are, however, very close the EIS/IMP-8 points found during the 1975 solar minimum by Mewaldt (1995), but lower than in the 1976-78 period. The deuteron/proton ratio of EPHIN data is between about 0.02 and 0.05.

4 Helium spectra:

4.1 ERNE-LED: The method applied for the tracks of ^{4}He nuclei resulted in the energy spectra for the 1996 data presented in Fig. 3. The anomalous component can clearly be resolved down to about 3 MeV/n. In the region where anomalous helium is predominant, the 1997 spectrum (not shown) is identical within the error limits. From about 4 MeV/n up to the highest operational energy of LED, the spectral index is about +0.8. At still higher energies, a flattening of the spectrum is expected (see EPHIN data in Fig. 3) and ultimately a slight down-turn before the dominant role of galactic cosmic rays sets in (see Fig. 1 of Torsti et al., 1997).

Below about 3 MeV/n in the 1996 spectrum and already at higher energies in 1997, a source different from anomalous cosmic rays seems to contribute significantly in the intensities and masks anomalous helium. The contribution of this source in the 1997 data is about twice as high as in 1996. In the energy range of 6-12 MeV/n the present fluxes agree within the error limits with previous ERNE results (Torsti et al. 1997), whereas at these lowest energies the present intensities are significantly lower. This is partly due to the better background reduction in the present work and partly due to a more careful selection of the quiet time periods. Still, below 3 MeV/n there is a clear contribution in the helium intensities from a source probably of solar or interplanetary origin and different from anomalous cosmic rays, in agreement with the conclusions of Cummings et al. (1984).

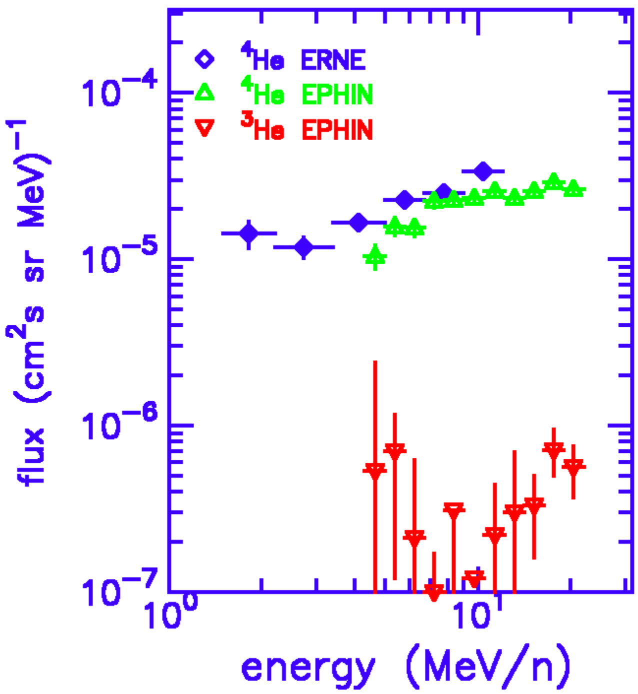

Figure 3: ^{4}He and ^{3}He quiet-time ERNE and EPHIN energy spectra in 1996.

4.2 EPHIN ^{4}He: Fig. 3 also presents the ^{4}He fluxes obtained from the EPHIN quiet-time data in 1996. The shape of the spectrum runs nearly parallel to the LED points, although within the overlapping range they are lower by a factor of 1.1 to 1.5. All the energy range is clearly dominated by the anomalous component. A recent study based on the data of the large geometry WIND/EPACT telescope obtained during the same time period reported a very similar spectrum (Reames et al., 1997), the fluxes are within 10% to the EPHIN level below 7 MeV and about 20-30% less above.

4.3 EPHIN ^{3}He: The EPHIN data allowed to determine the fluxes of ^{3}He nuclei as well. Similarly to the deuteron data, the number of counts significantly exceeding a flat background can only be seen at the upper part of the energy range, above about 10 MeV/n. If one is to accept the 3 lowest points to be real, a minimum would be at about 8 MeV/n, and the lower branch would then be of solar origin with a ^{3}He/^{4}He ratio of 4 to 5 percent which might indicate some component left over from ^{3}He-rich solar events. This has to be confirmed, however, by extending our analysis to all low-flux days. Again, a slight increasing tendency towards higher energies can be discovered for the significantly non-zero points, which can be interpreted as proportional to kinetic energy as expected for exclusively galactic origin. A comparison with the fluxes obtained by Mewaldt (1995) for the 1975 minimum results in a very close match again in the energy range of 10-20 MeV/n. The flux of ^{3}He is about 1 to 2% of the ^{4}He flux near 20 MeV/n.

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