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Radial variation of energy spectra of low-flux MeV protons aboard Helios in 1975-77

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Abstract. Pulse height data obtained by the Univ. Kiel energetic particle telescopes aboard Helios 1 and 2 at very low-flux quiet activity periods during the 1975-77 solar minimum are analysed by using a statistical background reduction method. The energy spectra of protons in the energy range of 4-27 MeV exhibit systematic radial variation. The shape of the energy spectra exhibit little variation with radial distance. The results are compared with simultaneous IMP-8 data at the same solar activity minimum and SOHO measurements in 1996, respectively. The analysis allows determining the radial gradient of the low-flux population as well as comparing the absolute fluxes at the two minima thus providing information about the origin of the particles.

1 Introduction

Energetic charged particles with energies of a few MeV are practically always present throughout the heliosphere. Their origin is clearly identifed during high activity periods of the Sun when linked to observed solar phenomena. At low solar activity periods, however, their properties, including energy spectrum, spatial variation, angular distribution, etc. are known to a little extent. Interplanetary energetic particle data obtained during solar minima indicate the presence of a relatively stable population of protons (Király and Kecskeméty, 1998) as well as of higher mass ions (Reames, 1999). Near the minima of the energy spectra anomalous rays dominate for some species, however, this source seems to be insignificant for protons, at least below about 20 MeV. Other possible sources include minor solar events (microflares), local turbulence of interplanetary medium, corotating interaction regions, and decelerated (and possibly reaccelerated) galactic cosmic rays.

Recent studies indicated that at lowest fluxes the measurements are contaminated by a significant amount of background arising from instrumental effects, high-energy particles, etc. and their removal results in very low values considering the small aperture of the available devices. Kecskeméty et al. (1999) and Valtonen et al. (2001) were able to obtain proton energy spectra with fluxes as low as 10^{-5} /(cm^{2}s sr MeV) and less in the energy range near the spectral minimum around 5 to 10 MeV. Most of the information about energetic particles in these periods has been obtained near 1 AU as no systematic study of low-flux periods away from the Earth orbit has been published yet. The Helios spacecraft offer a unique possibility to explore the variation of quiet-time particle energy spectra in the innermost part of the heliosphere. It can contribute to understanding quiet solar activity processes by checking whether the Sun is constantly accelerating charged particles the when no solar energetic particle events are observed.

2 Instrumentation, observational data

Launched on December 10, 1974 and on March 15, 1975, respectively, Helios 1 and 2 has been so far the only space probes, which penetrated into the region of the close vicinity of the Sun having similar perigees of 0.3 AU and apogees of 0.98 AU. Although they recorded many solar events, they spent their first three years among quiet, low solar activity conditions.

The University of Kiel experiment measured protons and higher energy nuclei above 1.7 MeV/nucleon and electrons above 0.3 MeV aboard both solar probes. They were operating successfully until the probes stopped providing data in March 1980 (Helios 2) and in 1986 (Helios 1). The telescopes consisted of five semiconductor detectors (see Kunow et al., 1977) and a

Èerenkov detector, all surrounded by an anticoincidence scintillator. The geometry factor of the instrument was 0.48 cm^2sr for nuclei below 51 MeV/n and a full opening angle of 55°. The pulse height information of the last 3 penetrated detectors was stored and sent to Earth. Under low-flux conditions, the pulse-height data of practically all nuclei (about 95%) including protons were registered.

Kunow et al. (1976) published a preliminary analysis of quiet time spectra obtained by the Kiel experiment. They compared a sample of ~14 days around perihelion with another period of ~23 days around aphelion. Whereas they concentrated on and were able to confirm the presence of anomalous He between 0.4 and 0.3 AU, they found no significant radial variation for >10 MeV protons. Below that energy the perihelion fluxes tended to be higher but the result was not conclusive.

In order to determine the energy spectra with a maximum possible accuracy by reducing the influence of instrumental and physical background we adapted a method developed by Valtonen et al. (1999, 2001). This sophisticated procedure allows separating the background for two-detector configurations even under low-flux conditions by analyzing the shape of the distribution of energy losses in two detectors near the track of genuine particles and provides a statistical estimation of its parameters.

As a first step, the temporal variation of the rate information was plotted and a reasonable value of the level was determined which was observed during quiet conditions without the presence of any clear events. A total period of 5 years was studied including 1975-77 for Helios 1, and 1976-77 for Helios 2.

The rate data were obtained from an onboard analysis of combinations of the detector coincidences by determining their location in the E_1- E_2 plane, where E_1 and E_2 represent energy losses in the front and second detectors, respectively. This level turned to be $3\times10^{-4}/(cm^2 s\ sr\ MeV)$ in the 4-13 MeV energy channel. This relatively high level is due to the fact, as subsequent analysis of the corresponding pulse heights confirmed, that about 90% of these counts arose from misidentification of a different particle species, or represented protons outside of the energy interval in question. Although we thrived to maximize the statistics, time intervals shorter than a half-day have not been included. The above selection resulted in a total length of time periods of quiet conditions of 624.7 days over the total five years of the two s/c (408.7 days for H1 and 216 days for H2).

The second step was to divide these time periods into seven 0.1 AU wide bins according to radial distance between 0.3 and 1.0 AU. Due to the elliptical orbit of the space probes, the residence time was not evenly distributed over radial distances, the longest period being spent near the apogee, in the >0.9 AU bin. The respective lengths of the quiet periods were 113, 60, 52, 58, 66, 83, and 193 days with increasing radial distance.

Data from each year were then analysed individually; for each radial distance bin the statistical pulse-height method mentioned above was performed. The identity of particles belonging to well-defined tracks on the E_1-E_2 plane was determined from the pulse height values of the first two detectors by calculating a particle identification number (PIN), practically a scaled mass number, PIN = $C(E_{tot}^{\alpha} - E_{res}^{\alpha})/t$. Here E_{tot} and E_{res} are the measured total and residual energies of the particle, t is the thickness of the energy loss detector, C is a scaling constant, and á is an empirical constant (here the value of 1.75 was used, which gives nearly vertical tracks in the PIN-E_{tot} plane). In the PIN-energy plane the particle tracks appear as practically vertical lines therefore allowing rectangular boxes to collect particles. The energy range was divided into 7 logarithmically spaced bins, which coincide with the two lowest energy windows used in the onboard analysis. The respective boundaries were 3.77, 5.12, 6.95, 9.44, 12.81, 16.38, 20.95, and 26.80 MeV.

The PIN distributions were then obtained by constructing histograms of PIN data in each radial bin and energy interval. Following the procedure described by Valtonen et al. (2001), a PIN histogram was constructed from pulse height data obtained during a 15 day high-flux period and the histogram was approximated by a Gaussian. Assuming that the shape and position of the PIN distribution is independent of the flux of genuine particles, Gaussian functions with a same expectation value and width were fitted to the low-flux distributions. Finally, assuming that the background unrelated to genuine particles is evenly distributed along the PIN-E_{tot} plane, the total values of the background was obtained by determining the average counts immediately outside the Gaussian distribution in each energy bin.

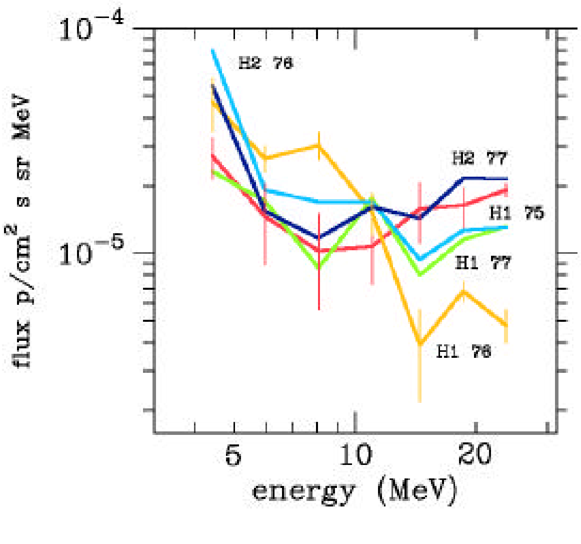

Fig. 1. Proton energy spectra observed between 0.3 and 0.4 AU aboard the two Helios probes during the 1975-77 solar activity minimum. Vertical bars stand for statistical errors.

3 Energy spectra

By analyzing 5 years of data (Helios 1 and 2 combined) the numbers of genuine counts as a difference of the total and background counts have been obtained and matrices containing fluxes in each energy and radial bin were determined. First, a check of internal consistency between data of consecutive years data and between the instruments aboard each Helios was performed.

Figure 1 displays a comparison of the energy spectra obtained in the innermost radial bin (0.3 to 0.4 AU) for the 5 years of data. Except for the Helios 1 spectrum in 1976 at four out of seven radial bins, all spectra match within statistical errors. A similar conclusion can be drawn for the rest of the radial bins, assuring that the selection of temporal periods was even and unbiased, the devices aboard both spacecraft had nearly identical characteristics and the variation between consecutive years was negligible.

Figure 2 illustrates the energy spectra recorded at various radial distances on the basis of the full five-year statistics of the two instruments. Nearly all spectra are coincident within statistical errors, apart from the 0.5-0.6 AU interval below ~8 MeV and the 0.3-0.4 AU interval

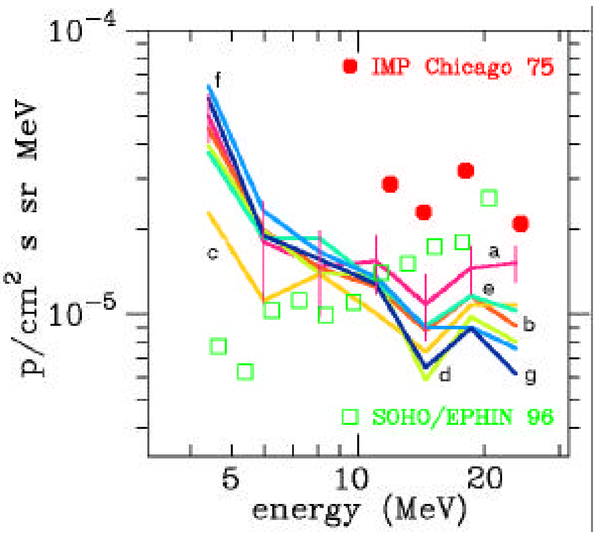

Fig. 2. Quiet-time energy energy spectra over the period of 1975-77 at radial distances (a) 0.3-0.4; (b) 0.4-0.5; (c) 0.5-0.6; (d) 0.6-0.7; (e) 0.7-0.8; (f) 0.8-0.9; (g) 0.9-0.98 AU. Full circles: IMP-8 /CRNC fluxes in 1975, open squares: SOHO/EPHIN fluxes in 1996.

above ~10 MeV. The slope of nearly all spectra is around –1 between 5 and 15 MeV, they exhibit minima near 15 MeV, although at the majority of the curves decline above 20 MeV. The cosmic ray data from the CRNC instrument (Univ. of Chicago) aboard the IMP-8 spacecraft near 1 AU, included for comparison, obtained during a 10-day low-flux period in 1975 give a profile similar in shape, but flux values about a factor of two larger probably indicating that, since the period was quiet, the background, either instrumental or physical, was higher. The proton flux values obtained by Valtonen et al. (2001) during the 1996 solar minimum from the EPHIN instrument aboard SOHO also near the Earth orbit, on the other hand, have an entirely different spectral shape with a minimum around 5 MeV. The SOHO fluxes tend to be smaller by a factor of 2 below about 10 MeV and higher by roughly the same amount at around 20 MeV, which can only partly be attributed to the different solar minimum investigated.

4 Radial variation

The other projection of the three-parameter flux distribution, comparing proton fluxes observed under quiet solar activity conditions as arranged according to radial intervals is depicted in Figure 3. The figure indicates that

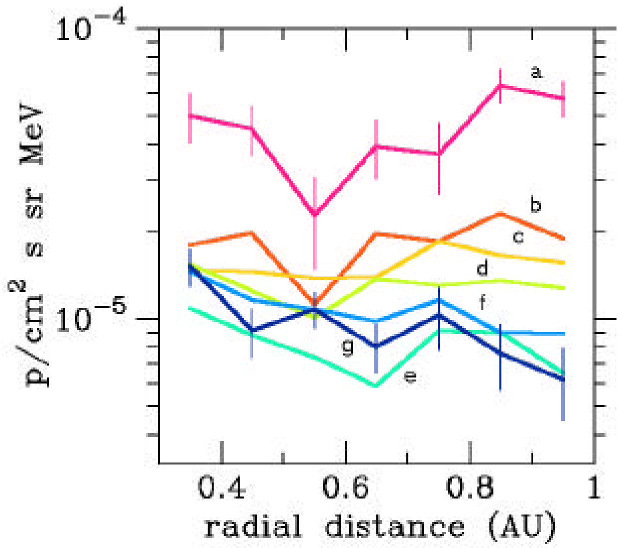

Fig. 3. Radial profiles of low-flux protons in 1975-77. Energy ranges: (a) 3.77-5.12; (b) 5.12-6.95; (c) 6.95-9.44; (d) 9.44-12.81; (e) 12.81-16.38; (f) 16.38-20.95; and (g) 20.95-26.80 MeV.

the fluxes are slightly, but significantly larger in the innermost radial bin as compared with the region of 0.4-0.7 AU. A relatively well-defined minimum can be observed around 0.6 AU (a bit closer to the Sun below about 13 MeV and further away above that energy). Beyond about 0.75 AU the middle energy profiles are flat, whereas the low-energy ones increase, the high-energy ones decline outwards. The radial gradients computed from the profiles fall between -30 to -15%/0.1 AU for the 0.3-0.5 AU region and 20 to –20%/0.1 AU between 0.7 and 1 AU variations as a function of radial distance, have spectral minima near 15 MeV and a negative slope close to –1 in energy the range of 5 to 15 MeV (all based on the larger values).

The radial variation found indicates that the Sun is an active and continuous source of MeV protons even in the absence of prominent solar events: a population of several MeV protons may exist with a density falling with the increase of distance from the Sun. On the other hand, the positive radial gradient is probably indicative of the presence of another quiet-time population, accelerated in the interplanetary space (probably in CIRs) which can represent particles streaming back from outer regions of the heliosphere.

5 Conclusions

The analysis of proton intensities as observed by Helios 1 and 2 between 0.3 and 1 AU during very low flux quiet solar activity periods of the 1975-77 solar minimum amounting to a total time period of about 1.7 years yielded the following results:

a) The flux values are very low (near $10^{-5}/(cm^2 s\ sr\ MeV)$) and coincide within a factor of 2 with other pulse-height based observations near 1 AU.

b) The shape of all energy spectra obtained within the region of 0.3 to 1 AU are consistent, exhibit little variation with energy.

c) The the larger radial variation at various energies possess a relatively well-defined minimum in the vicinity of 0.6 AU. All fluxes tend to be higher closer to the Sun, whereas further away from the Sun low-energy fluxes increase, the high-energy ones decline outwards. The difference between the minima and maxima of the radial profiles is between 40 and 60%.

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