Modulation of the galactic proton energy spectrum in the inner heliosphere

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Abstract: Proton energy spectra in the 1-100 MeV energy range are studied experimentally and found to be significantly steeper at low energies than predicted by the force-field approximation. The distribution of the spectral slopes is studied as a function of various parameters over 3 solar activity cycles. Possible interpretations are discussed.

The energy spectra of protons in the 1-100 MeV range are studied under quiet solar activity periods during the 21st - 23rd solar activity cycles using data sets from the IMP-8 near-Earth spacecraft. In order to minimize contribution from solar/ interplanetary particles a series of low-flux spectra is approximated by the form $J(E)=AE^{-\gamma}+CE^{\nu}$, the two terms describing solar/heliospheric and galactic components, respectively. By determining the best fitting parameters to the energy spectra, correlations are made among them as well as with solar activity indices. Fig. 1 shows a clear dependence of ν on the level of solar activity. In the majority of cases we obtain experimentally that ν has a mean value of 1.2 ± 0.15, which is significantly steeper than the linear spectrum commonly expected $\nu = 1$, predicted by the force-field approximation. Out of the total of 346 days, ν was >1 during 276 days.
At the same time the value of the energy minimum (E_{min}) of the proton spectrum that divides the two populations – solar and galactic - is shifted towards higher values with increasing solar activity (Fig. 2).
The frequency rate distributions of the ν values exhibit a two-peak structure and dependence on the heliomagnetic cycle phase, i.e. they appear to be different for odd and even cycles (Figure 3) probably reflecting the different drift processes in the heliosphere. Two main subsets of spectra can be clearly distinguished: one with $\nu \le 1.2$ and another with $1.2 < \nu \le 1.5$. While most cases fit

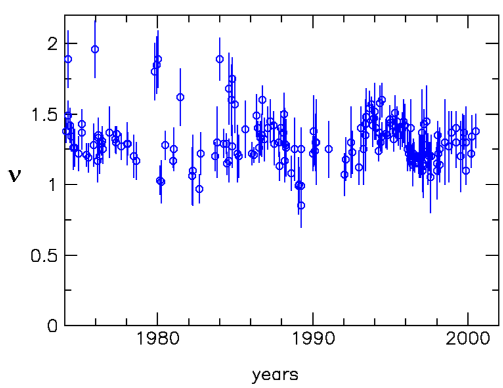

Figure 1. Time behavior of the spectrum parameter ν with statistical errors between 1974 and 2001.

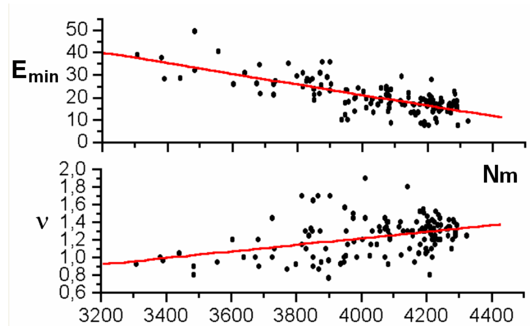

Figure 2. Dependences of the minimum of the energy spectrum E_{min} and ν (bottom panel) on the Climax neutron monitor count rate.

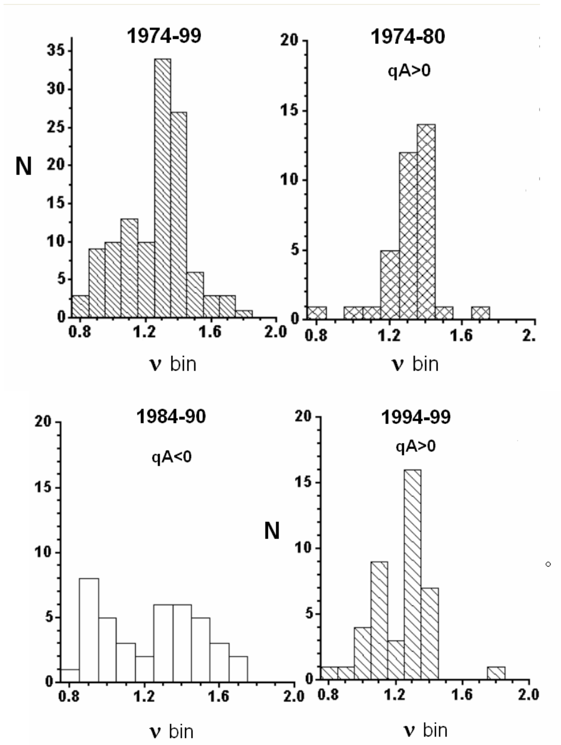

Figure 3. The total number of quiet periods in ν. bins. Upper panels: for 1974-99 and 1974-80 (qA>0). Lower panels: for 1984-90 (qA<0) and 1994-99 (qA>0).

into the two groups mentioned, some have strongly different slopes demonstrating either weak (ν ~ 0.6) or very strong modulation of galactic cosmic rays (ν ~ 1.6). By fitting low-flux Ulysses COSPIN data in 1994 measured between 1.5 and 4 AU also provided ν values between 1.2 and 1.5.

In modulation theories ν > 1 corresponds to a negative Compton-Getting factor posing a challenge. Whereas in the outer heliosphere these solutions give higher exponents already above a few MeV ('bulging spectra' [1]), the spectrum around 1 AU is convex at all energies and the calculated slope (exponent) never exceeds 1. Sophisticated numerical solutions of the one-dimensional transport equation for GCR protons using different radial dependencies of the coefficient κ_{rr} showed that the spectrum slope index (changes from <1 to >1 values around 1 at 1 AU in dependence on the assumed various dependences of K on distance [2].

We solved the modulation equation numerically assuming spherical symmetry and that the radial and energy dependence of the scattering mean free path is separable: $\lambda = \lambda_0(r)\ B(P)$. Figure 4. shows that the spectral exponent ν below about 30 MeV is above 1 until 20 AU.

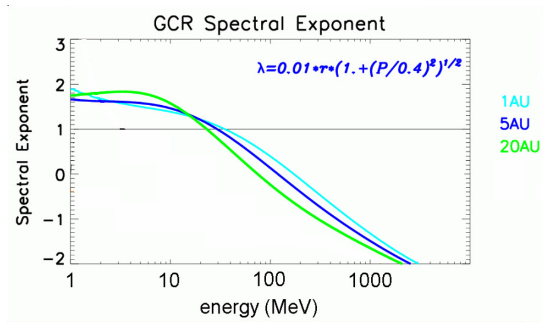

Figure 4. Variation of the spectral exponent with energy from a numerical simulation assuming spherical symmetry and $\lambda = 0.01\ r\ (1+(P/0.4)^2)^{1/2}$. [AU]. at 1, 5 and 20 AU.

An inversion of the energy spectrum (ν > 1) may occur if $\kappa_{rr} < rV$ (κ_{rr} denoting the radial diffusion coefficient, r distance and V solar wind speed), then, most of the lower energy particles reaching 1 AU have been cooled down in the inner heliosphere (within 1 AU) and are subsequently convected outward by the solar wind. This condition is easier to fulfil in the outer heliosphere as parallel diffusion becomes ineffective in the radial transport. In the inner heliosphere this requires a short mean free path in the MeV range.

References

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