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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.

Introduction

The modulation of galactic cosmic rays (GCR) by solar activity has been a target of intensive study both experimentally and theoretically. It has been established that the cosmic ray flux anticorrelates with solar activity and the proton flux at 1 AU in the energy range 10-100 MeV increases linearly with $J_p \propto E$ as explained by various theories of modulation. At low energies where adiabatic cooling plays the primary role, particles entering the inner heliosphere lose a fix amount of energy, irrespective of their initial energy if radial diffusion coefficient $\kappa_{rr} \propto VP$ (V denoting solar wind speed and P - particle rigidity). In this force-field approximation [1] the flux of modulated protons at low energies becomes proportional to their energy. This approximation is only valid in the weak modulation limit, that is if $\kappa \gg rV$. Advanced 2-D and 3-D models and their numerical solutions have successfully explained many observed features: dependence of the energy spectrum on radial distance [2], however, in the adiabatic limit valid at lowest energies they also provide an exponent in intensity dependence on energy equal to 1. Whereas in the outer heliosphere these solutions give higher exponents already above a few MeV ('bulging spectra', [3]), the spectrum around 1 AU is convex at all energies and the calculated slope 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 spectral index changes from <1 to >1 at 1 AU in dependence on the assumed various dependences of κ on radial distance [4]. Experimentally, [5] found a spectrum with exponent larger than 1, i.e. $J_p \propto E^\nu$, where ν ~□ 1.4 in 1970-71. This was, however, considered unphysical [6](Moraal, 1976) since it implies a negative Compton-Getting coefficient.

Data analysis

Daily averages of fluxes of protons recorded by IMP-7, -8, and SOHO near 1 AU during quiet solar activity periods in the 21st - 23rd solar activity cycles were used. The aim was to determine experimentally, whether the spectral exponent ν is indeed significantly larger than 1. In order to minimize contribution from solar/interplanetary particles a series of low-flux spectra obtained during quiet solar activity intervals were used (see Fig. 1). They were approximated by the spectral form $J(E)=AE^{-\gamma}+CE^{\nu}$, the two terms describing solar/heliospheric and galactic components, respectively. The best fitting parameters to the energy spectra were obtained using two separate 2-parameter fits for the low and high energy parts (which have relatively little overlap) in an iterative way. The procedure usually converged after 2 steps.

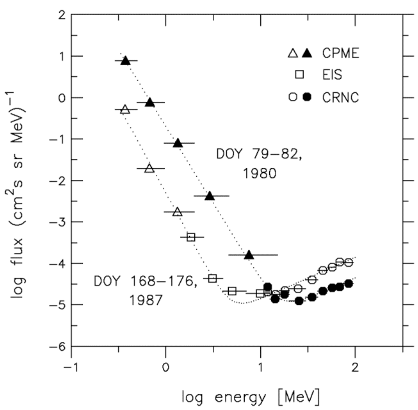

Figure 1: Two examples of quiet spectra at solar maximum (1980) and minimum (1987).

Results and discussion

By obtaining the statistically best-fitting values of the spectral parameters, correlations were made among them as well as with solar activity indices.

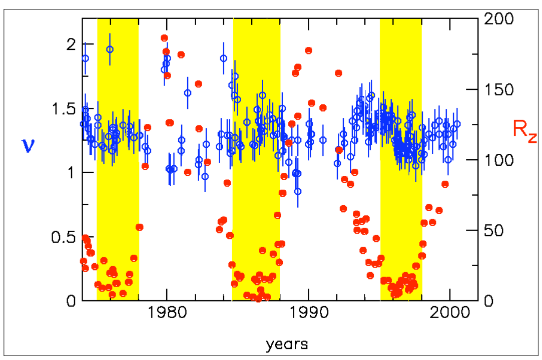

Figure 2: Time behavior of the spectral parameter ν with statistical errors between 1974 and 2001 together with the Wolf sunspot numbers. Shaded periods represent solar minima.

Fig. 2 shows some variation of ν with the level of solar activity, which is even better visualized in Fig. 3a, a scatter plot of ν vs the sunspot number and Fig. 3b, where ν is plotted against E_{min}, the minimum of the fitted energy spectrum. Both correlations can be interpreted as at solar minimum the solar/interplanetary part recedes, E_{min} becomes lower. This allows the lower part of galactic spectrum to reveal, which reaches its asymptotic slope value well below ~10 MeV.

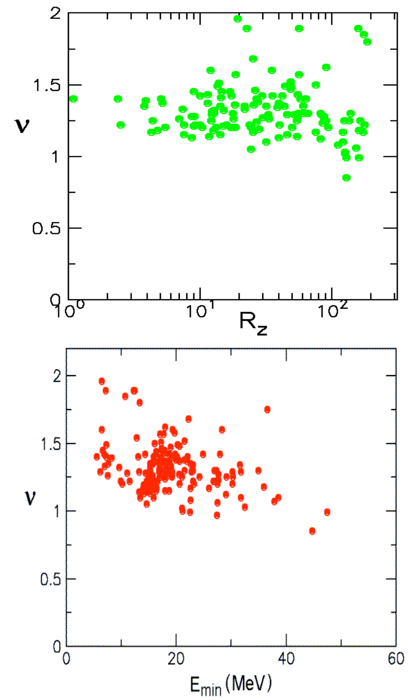

Figure 3: Scatter plots of the spectral slope vs. R_z (upper panel) and vs. the minimum of the energy spectrum (lower panel).

In the majority of cases we obtain experimentally that ν has an average value 1.3 ± 0.15, which is significantly steeper than the linear spectrum commonly expected. The frequency rate distributions of the ν values as depicted in Fig. 4 is nearly Gaussian, with a very small number of ν values near or below 1 during high solar activity which can be related to residual solar contribution.

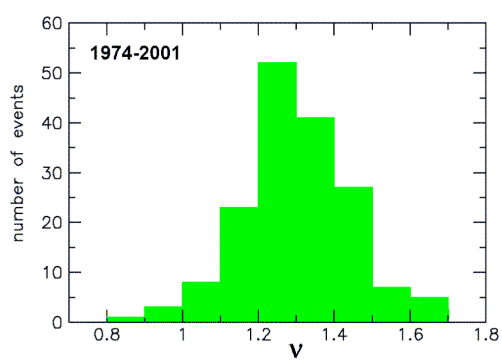

Figure 4: The overall distribution of ν values.

The distributions are further examined in Fig. 5 comparing subsequent solar minima. A characteristic difference can be observed between odd and even heliomagnetic cycles which may reflect the different drift processes in the heliosphere. Whereas in both qA>0 cycles the distributions look narrower, confined to the 1.1-1.5 range, in the qA<0 cycle it seems to consist of a distinct peak on a broad background.

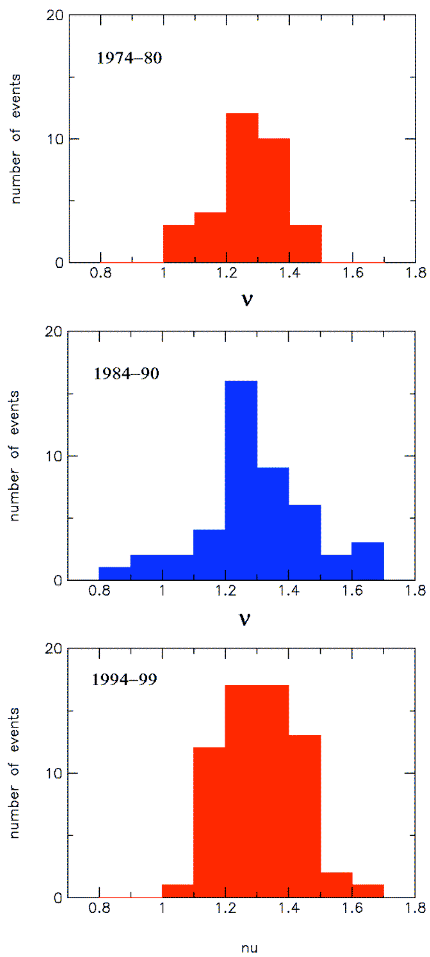

Figure 5: The total number of quiet periods in ν bins. Top panel: 1974-99 (qA>0), middle: 1984-90 (qA<0), bottom: 1994-99 (qA>0).

Numerical results and discussion

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 6 shows that the spectral exponent ν below about 30 MeV is above 1 within 20 AU.

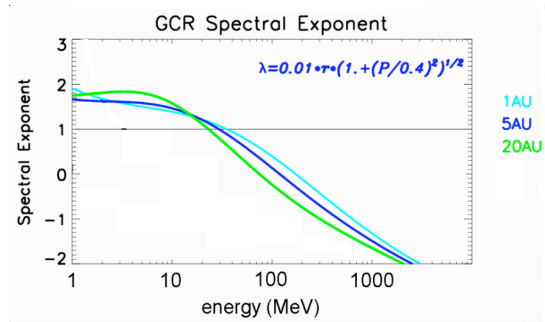

Figure 6: Variation of the spectral exponent with energy from a numerical simulation assuming spherical symmetry and $\lambda = 0.01\ r\ (1 + (P/0.4)^2)^{1/2}$ [AU] at 1, 5, and 20 AU.

An inversion of the energy spectrum ($\nu > 1$) 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.

Acknowledgment

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