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The slope of the energy spectra of 10-100 MeV protons

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Abstract. Energy spectra of protons in the 1-100 MeV range have been constructed from the observations of three energetic particle instruments aboard IMP-8, for near one hundred quiet-time periods between 1974 and 1991. The spectra were approximated by $J(E)=A.E^{-\gamma}+C.E^{\nu}$, where the first term is responsible for solar particles and the second describes the galactic (and possibly anomalous) component. Theoretically, a value of $\nu=1$ is expected in the low-energy (10-30 MeV) region where adiabatic cooling is predominant. Instead, in the majority of cases ν turns out significantly larger than unity. The distribution of ν was found to be slightly asymmetric with a peak around 1.2 and a shoulder below 1. ν does not exhibit any correlation with the other inferred parameters A and γ. Comparing ν with the count rates of the Deep River neutron monitor for the same time periods a slight positive correlation has been found. Theoretical implications and possible interpretations are discussed.

1 Introduction

Low energy galactic particles are effectively excluded from the heliosphere. What we observe in the inner heliosphere in the 10-100 MeV range are particles that had originally substantially higher energies. At low energies, where adiabatic cooling plays a primary role, the spectrum tends to be $j \propto E$, implying that in a broad range of the lowest energies we sample essentially the same part of the original interstellar spectrum. This effect can be best visualized in the framework of the force-field approximation (Gleeson and Axford, 1968), where particles entering the inner heliosphere lose a fix amount of energy, irrespective of their initial energy. In this solution the flux of modulated protons at low energies becomes proportional to their energy. Starting from a near-monoenergetic galactic spectrum Urch and Gleeson (1972) obtained a 'low-energy tail' with $j \propto E$ below 200 MeV. Experimentally, Rygg et al. (1974) found a larger exponent, $\nu \approx 1.4$ in 1970-71. This was considered unphysical (Moraal, 1976) since it implies a negative Compton-Getting coefficient.

Later, advanced 2-D and 3-D models and their numerical solutions have successfully explained many observed features. These solutions indicated that the energy spectrum depends on radial distance (Reinecke et al., 1993), however, in the adiabatic limit valid at lowest energies they also provide a slope equal to 1. Whereas in the outer heliosphere these solutions give higher slopes already above a few MeV ('bulging spectra', Moraal, 1993), the spectrum around 1 AU is convex at all energies and the calculated slope never exceeds 1. Based on small departures of observed proton spectra from these prediction allowed Mewaldt (1995) to detect the presence of anomalous hydrogen. In his Figure 2 in that paper the fitted linear trend to protons fluxes between 10 and 100 MeV gives $\nu \approx 1.1$ for 1975, and about 1.0 for 1976-78 (neglecting the 5 MeV point).

It was tempting to determine the shape of the energy spectrum at low energies (below 10 MeV), however, except for very quiet solar conditions, at these energies the spectrum is dominated by particles accelerated by solar/interplanetary processes. In the present work we attempt to provide an answer by selecting very low flux quiet periods and determining the shape of the spectrum individually. Although this provides larger experimental errors than long periods but guarantees to be free of solar effects and allows temporal variations of the spectrum.

2 Selection of quiet periods, energetic proton data

In order to minimize the contribution from particles accelerated on the Sun and in the interplanetary medium, time periods of low solar/interplanetary activity were selected using a method worked out earlier (Kecskeméty et al., 1999). The selection criterion was that the 1 MeV proton flux remained constant within 50% for at least one day. At low solar activity these quiet-time periods lasted sometimes 3-5 days and more, whereas at enhanced activity on the Sun their duration shortened but even at the solar cycle maximum the requirement of stable flux lasting at least one day was kept. The proton energy 1 MeV here chosen for spectral investigations seems to be the most acceptable as higher energy protons (e.g., above 10 MeV) are only slightly susceptible to magnetic field changes in the heliosphere keeping approximately stable flux except for periods of powerful solar particle events on the Sun. On the contrary, <1 MeV proton fluxes are very unstable and sensitive to the slightest disturbances of interplanetary magnetic field and/or weak solar activity. Such a selection is in general stricter and excludes periods, which were judged quiet on the basis of higher energy profiles. However, at higher energies the long-term behaviour of particles after large solar particle events is not well understood and they might still be present to some extent in our quiet periods. Nevertheless, their contribution is probably small and can only result in a small change of the slope. Another contribution can be expected from anomalous H (c.f. Mewaldt, 1995). Here, the stationary quiet periods have been chosen on the basis of daily average flux data obtained by instruments aboard IMP 7 and 8 at 1 AU. The instruments involved CPME (JHU/APL, period 1974-91), EIS (CalTech, 1984-91), and CRNC (Univ. Chicago, 1974-91).

3 Experimental data analysis

In this paper primary attention is paid to the low-energy part of the galactic spectrum above the minimum ranging from E_{min}=7-10 MeV to E_{min}=30-40 MeV. During the period studied that covered almost two solar cycles, 116 quasi-stationary time intervals have been selected. For 99 of those the energy spectra were constructed over the energy range of 1–100 MeV. For the remaining quiet-time intervals the measurements were either not available for the complete energy intervals (as a rule because in high solar activity spectra the spectral minimum E_{min} shifted to higher energy range having values up to about 100 MeV) and/or data from different s/c controversial and insufficient to obtain smooth energy spectra. From the 99 spectra we have selected 85, which satisfied the following criteria. The spectra with E_{min}<40 MeV were considered because for those having higher minima ν could not be determined with satisfactory accuracy (±20%) within the energy range of the instruments. The spectra in this energy interval have been described using two functions: $J(E)=A.E^{-\gamma}$ for solar branch of the spectrum and $J(E)=C.E^{\nu}$ for galactic particles. 10 spectra were excluded as the large scattering of spectral points from different devices did not allow obtain reliable values of ν. In some cases, the solar branch could not be fitted with a single exponent, either turning to be flatter below ~5 MeV, or on the contrary, exhibited a break point near this energy (always below the spectral minimum) and became harder above that. Since we are interested at energies above the spectral minimum, in these cases the lowest energy points were excluded from the fits.

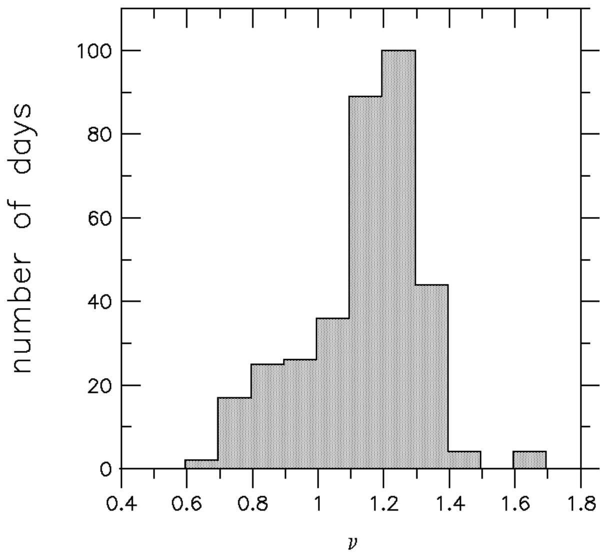

Fig. 1 The total number of daily intervals in ν bins.

In order to avoid problems arising from 4-parameter fits and because the overlapping range of the two spectral branches is relatively small, they have been fitted separately and finally their sum provided the total spectrum: $J(E)=A.E^{-\gamma} + C.E^{\nu}$. The procedure actually used was that first, A and γ have been determined from a 3-parameter fit to the energy range below E_{min} in the form of $A.E^{-\gamma} + B.E$ used earlier (Kecskeméty et al., 1999) which provided acceptable fits to the lower part up to just above the minimum. Second, the contribution of the solar part, $A.E^{-\gamma}$ was subtracted from the measured spectrum and the function $C.E^{\nu}$ was fitted to the remainder. The final values were of the parameters were obtained using a weighted least-squares method which provided the statistical errors.

The distribution of the best fitting ν values for the 86 spectra is presented in Figure 1, where the ordinate stands for the total number of days. The majority of the days (276 of the total 346) have ν ≥ 1, but the distribution is slightly asymmetric. One can see an approximately Gaussian peak near 1.2 with a standard deviation of 0.15, representing about 80% of the time. On the other hand, the shoulder on the low side can be modelled by another Gaussian with an average of 0.85 and width of 0.13. The typical error of is about 0.05, although in several cases it is near 0.1.

While most cases fit into the two groups mentioned, some have strongly different slopes demonstrating either weak modulation of galactic cosmic rays ($\nu \approx 0.6$), or very strong ($\nu \approx 1.6$). Weak modulation can occur in the case of a depressed spectrum of magnetic irregularities in the region of wavelengths corresponding to low-energy part of GCR spectra (10-50 MeV), and strong modulation - in the opposite case. It should be noted that the little amount of cases in second distribution maximum is connected mainly with far more little amount of quasi-stationary periods of proton intensity during high solar activity than during periods near minimum of the SC.

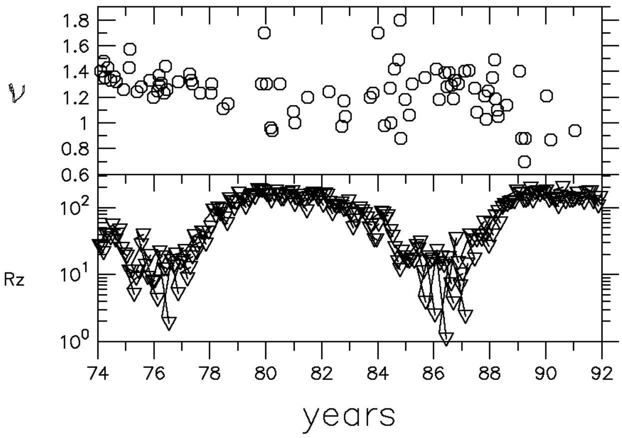

Fig. 2. Time variation of *n* in parallel with the Wolf sunspot number.

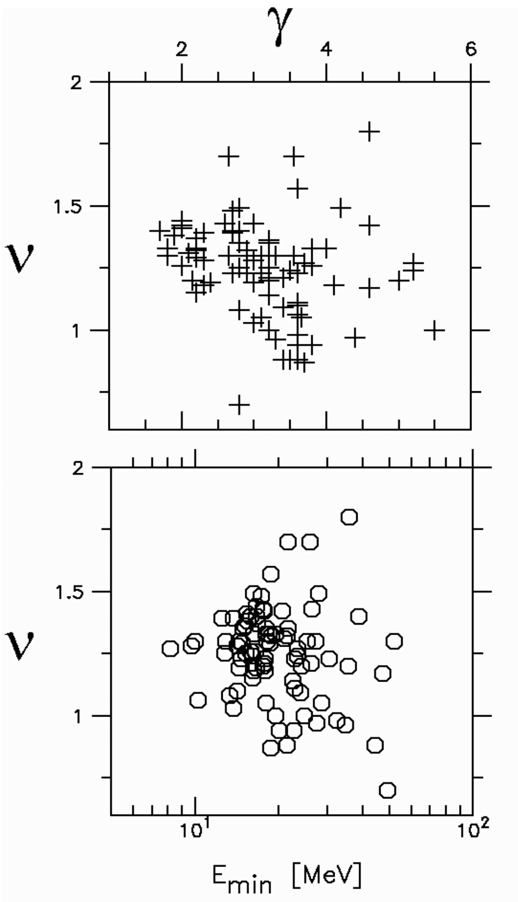

Fig. 3. Dependence of *n* on parameter gamma (upper panel) and on the minimum of the energy spectrum (lower panel).

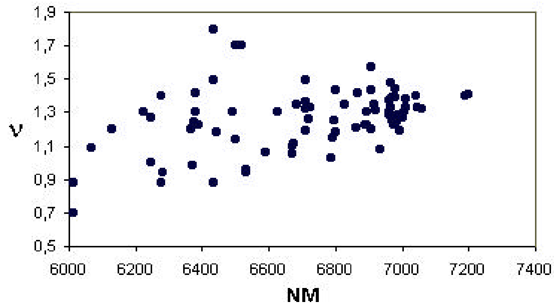

Fig. 4 Correlation of with Deep River neutron monitor counting rate.

Figure 2 displays the temporal variation of *n* and the Wolf sunspot number to indicate the level of solar activity. At solar minima *n* tends to exhibit smaller fluctuations and concentrated around 1.2, that is, belong to the higher Gaussian. A minor difference between the two minima indicates less scatter of points in 1975-77 than in 1986-87. At higher solar activity, as the elevated solar branch of the spectrum leaves less experimental points to build the galactic energy spectrum, one sees larger fluctuations, however, not symmetrically with respect to the Gaussian, but mostly on the low side.

The two panels of Figure 3 present the dependence of ν on *g* and E_{min} and indicates the absence of clear correlation of the index *n* with any of them.

In Figure 4 presented is the dependence of ν on Deep River neutron monitor counting rates for the same time intervals as in Figures 2 and 3. These count rates undergo the strongest dependence on ~1000 MeV proton intensity which like those <100 MeV protons under consideration is modulated by solar activity although in a weaker degree. The figure indicates a slight dependence of ν on neutron monitor count rate.

4 Conclusion

We find that during quiet solar conditions the modulation processes lead to energy spectra with ν=1.21±0.15. Another group of spectra with ν=0.86±0.13 has been found for periods of enhanced solar activity. Other few cases with ν=0.5-0.8 or ν above 1.6 have also been observed. This means that during the dominant part of the SC modulation mechanisms are those that provide $\nu \approx 1.2$, during other time periods different processes operate which lead to $\nu \approx 0.9$, and sometimes weak ($\nu \approx 0.5$) or stronger ($\nu \approx 1.7$) modulation of galactic cosmic ray particles happen.

The exponent in the 1.2 range, if confirmed, poses an intriguing question to modulation theories. A value of $\nu > 1$ corresponds to a negative Compton-Getting factor. We emphasize that this challenging but not unphysical. $\nu > 1$ may be expected if the radial component of the diffusion tensor $\kappa_{rr} < r.V$. This condition is easier to meet in the outer heliosphere, where field lines are largely azimuthal rendering the parallel diffusion ineffective in the radial transport. In the inner heliosphere, however, this would require a small mean free path in the MeV range, which seems contrary to presently accepted values.

An alternative explanation of the higher slope would be that an additional source of protons exists in the 50-100 MeV range, possibly anomalous protons. In general, anomalous particles are more sensitive and have larger gradients thus one would expect that their spectrum is softer than that of galactic particles. The problem of the too soft spectrum, however, would not be solved as such a population has to undergo adiabatic cooling as well.

The index of GCR proton spectrum branch in the energy range of 10-100 MeV depends on many parameters of interplanetary medium, which determine the modulation processes in the heliosphere. First, these parameters are the spectrum of magnetic irregularities of the interplanetary magnetic field in different areas of space and different characteristics of conditions in the interplanetary medium: the diffusion coefficient and its dependence on radial distance, latitude and longitude, radial and latitude gradients, etc. Although the values of these parameters are not sufficiently known throughout the heliosphere, their different combinations may lead to any spectrum slope with index ν between about 0.5 and 2.

Taking into account the complicated relation between the slope of the modulated proton GCR spectrum and heliospheric parameters we can only point out that the dominant conditions in the interplanetary space give rise to a proton spectrum with ν around 1.2 under low solar activity conditions.

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