SH 1.4.25

Variation of quiet-time and quasi-stationary proton energy spectra between 1984 and 1991

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Abstract

Temporal variations of spectral parameters of about 1-100 MeV proton energy spectra during quiet solar activity periods in 1984-91 are investigated. The data basis used is daily average fluxes of the EIS and CRNC instruments aboard IMP-8. The differential energy spectra are modeled by a simple analytic form of $J(E)=AE^{-\gamma}+CE$ which provides satisfactory fits at most times, although some spectra are difficult to approximate. The variation of spectral parameters A, γ, and C with solar activity are obtained from least squares fits. As expected, A and C exhibit positive and negative correlation with solar activity, respectively, while γ slightly decreases as activity becomes stronger. It is pointed out that for a fixed γ value, as a first approximation, the spectra are shifted along energy axis with the variation of solar activity.

1 Introduction:

Fluxes of several MeV protons undergo large variations in the interplanetary space over the solar activity cycle (SC). The variations of temporal intensity and energetic proton spectra have been investigated since 1964 (c.f. Zamow, 1975). Our previous studies of spectra during most quiet periods between 1984 and 1991 indicated that the minimum of the energy spectrum denoted E_{min} increases with increasing solar activity (Zeldovich et al., 1995, Logachev et al., 1998). We have shown that this minimum which crudely represents a transition between two different particle populations - solar/heliospheric and galactic - depends on solar activity level and changes from 7-10 MeV at solar minimum up to 25-30 MeV at maximum. A continuation of these studies, the present paper is devoted to spectrum variations during the most quiet and quasi-stationary periods observed in different phases of the SC.

2 Observations:

Daily average proton fluxes of the EIS and CRNC instruments aboard IMP-8 constitute the data basis used in the present study. The measurements of EIS (energy range: 1.4-12.5 MeV) and CRNC (11.3-95 MeV), both using semiconductor telescopes with anticoincidence shielding provide homogeneous sets of data for the years of 1984 through 1991. Both measurements exhibited a very stable level during the period studied with proton fluxes as low as $2\times10^{-5}/(cm^2\ s\ sr\ MeV)$ at energies around 10 MeV. The EIS flux data used here are count rates without any pulse height information. It should be noted that in the lowest channel of EIS (1.4-2.3 MeV) only one detector is employed with an anticoincidence shield, therefore the rates obtained are contaminated by He nuclei of the same total energy. In general, a large contribution of instrumental origin to these lowest fluxes cannot be excluded, in particular near E_{min} during solar minima, however, no clear sign of a lower boundary can be observed in the spectra at most cases.

Based on daily average fluxes from these measurements altogether 66 differential energy proton spectra have been obtained for the period of 1984-1991. Quiet-time periods were selected by requiring that the flux of 1 MeV protons do not exceed 10^{-2} particles/(cm^2 s sr MeV) during a time interval of at least 2-3 days (only 5 cases were one day intervals allowed). The selection criterion for quasi-stationary periods was that the variation of the flux of 1 MeV protons must be less than 5-10% over a period of at least 0.5 day. Their level is usually higher than that of quiet-time fluxes, sometimes by a factor 10 and more. Such periods are observed when a solar energetic particle event or other enhancement ends as new accelerating processes in interplanetary space take over which make particle escape difficult, that is, a dynamic equilibrium between the escape and another source of particles may exist during such time periods. Additional particles might be accelerated on the Sun as well, for instance, in microflare events. It should be noted that the escape from the inner heliosphere becomes more difficult at higher solar activity due to enhanced level of turbulence of the interplanetary magnetic field.

3 Proton energy spectra:

The energy interval under consideration includes both solar and galactic protons. Up to several MeV at SC minimum and up to 20-30 MeV at maximum protons have been argued to be predominantly of solar origin (Zeldovich et al., 1995). The energy of the minimum intensity denoted E_{min}, above which the galactic population becomes dominant. In general, the low energy branch is represented mostly by EIS points, while galactic spectra are based on CRNC data.

The energy spectra have been fitted by a three-parameter function $J(E)=AE^{-\gamma}+CE$, where E stands for proton kinetic energy (see Logachev et al., 1998). The spectral parameters A, C and γ were obtained from least square fits to the logarithms of the flux values. Using the best-fit parameters the values of E_{min} and $B= J(E_{min})$ have been calculated. The statistical errors of the fits are in the range of 10% for A and C, about 0.2 for γ, and below 20% for both B and E_{min}.

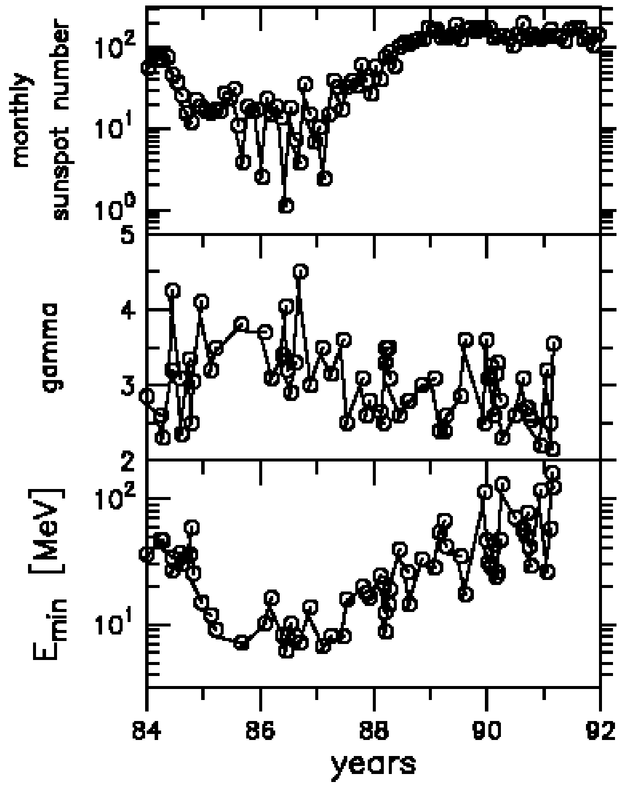

Figure 1: Variation of Wolf sunspot number spectral index γ and minimum energy E_{min} from 1984 to 1991.

4 Results of spectral analysis:

Figure 1 shows the time profiles of E_{min} and γ from 1984 to 1991 along with monthly average sunspot number R_z. The close correlation seen between E_{min} and R_z indicates the increase of low-energy particle generation with solar activity and the increased modulation of galactic protons and subsequent spectrum shifting to higher energies. One can also observe a slight decreasing tendency for γ while solar activity increases, that is, on average, low γ spectra occur more often during high solar activity periods.

Fig. 2 displays the distribution of γ values for the above period. The number of quiet-time periods as well as the number of days with γ falling into the respective intervals are represented. Two main subsets of spectra can be clearly distinguished: one with $\gamma \leq 2.9$ and another with $3.0 \leq \gamma \leq 3.9$. We may note also another small subset with $\gamma \geq 4$. When solar activity changes, the mutual connections of parameters A, C, B, E_{min}, and γ are expected to change also with the change of the proton spectrum.

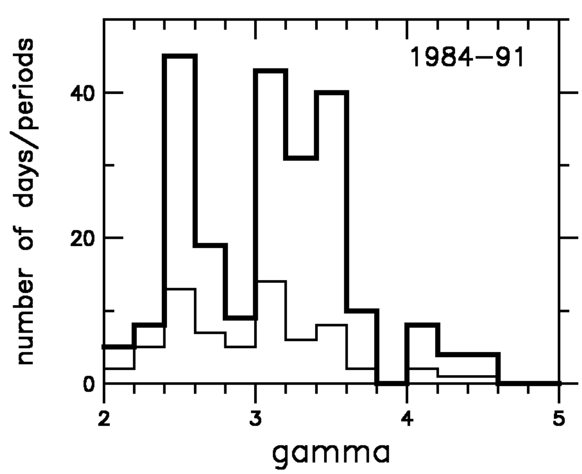

Figure 2: Distribution of γ values: thick line number of days, thin line - number of periods

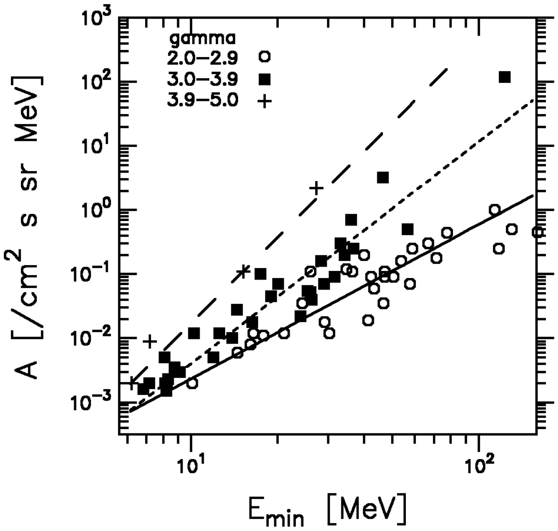

Figure 3: A vs. E_{min} for various γ values. Straight lines represent best-fit α values for each group.

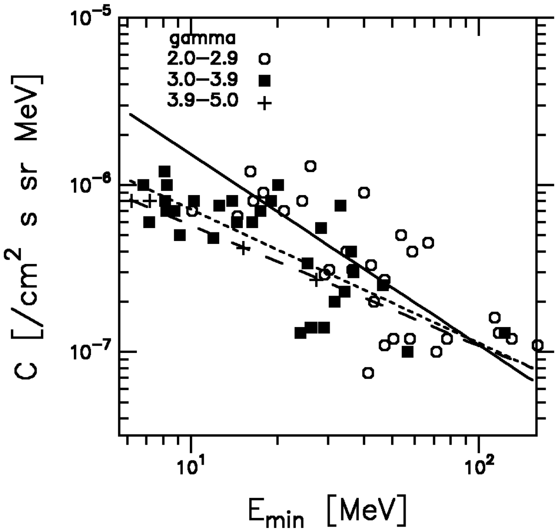

Figure 4: C vs. E_{min} for various γ values. Straight lines represent best-fit β values for each group.

Figures 3 and 4 exhibit scatter plots of the best fitting values of A and of C versus E_{min}. All the spectra under consideration have been grouped according to the distribution of γ seen in Fig. 2 with fitting using power functions $A \propto E_{min}^{\alpha}$ and $C \propto E_{min}^{-\beta}$. The power indices α for the groups ($\gamma_1 = 2.0 \div 2.9$, $\gamma_2 = 3.0 \div 3.9$, $\gamma_3 \geq 4$) and values of β are presented in Table 1.

Table 1

γ range	$<\gamma>$	α	β
2.0 ÷ 2.9	2.56	2.41	1.14
3.0 ÷ 3.9	3.27	3.46	0.80
≥ 4	4.07	4.50	0.72

5 Discussion:

Active processes on the Sun as well as in the interplanetary space accelerate low-energy particles and, via the interaction with the interplanetary magnetic field, they at the same time modulate galactic particles. When solar activity increases, the flux of particles of the left branch of the energy spectrum moves upward, while the galactic spectrum is shifted downward. These two processes occur together, although not exactly simultaneousl,y resulting in a modification of the proton spectrum. In particular cases the shift is almost parallel to energy axis, while the shape of the spectrum is preserved (γ=const., B=const.). The dependence of the spectral parameters on the minimum energy becomes then simply $A \propto E_{min}^{\gamma}$ and $C \propto E_{min}^{-1}$.

Table 1 demonstrates that as a first assumption all the three spectral subsets selected with different left branch (solar) slopes exhibit such a peculiar parallel shift because the average value of γ is near α and $\beta \cong 1$ in general. A more detailed analysis based on γ values with narrower groups ($\Delta\gamma = 0.2$) indicates that a relation between γ and α exists approximately as $\gamma = 3/4(\alpha+1)$. Using this relation and one can define more precisely those cases where $\gamma = \alpha$ i.e. when spectral variations result in driving the spectrum strictly along energy axis.

It should be noted, however, that the range of parameter A values is wider than that of C. This fact indicates that with increasing γ the response of low-energy particle generation processes is stronger than that of the galactic ray modulation. When $\gamma > \alpha$, the variation of solar branch of the spectrum dominates over that of the galactic, while for $\gamma < \alpha$ the solar part varies less dynamically, which might indicate the relative importance of the energy spent for the acceleration of particles and for the production of magnetic field irregularities, responsible for galactic modulation. A parallel shift of the spectrum may only occur in cases with $\gamma \cong 3$.

6 Conclusions:

The investigation undertaken showed that the 66 spectra obtained during quiet and quasi-stationary periods of solar activity exhibit wide variance of temporal variations. The main conclusions drawn are following:

(1) When A that characterizes the non-galactic proton flux ($A=J_p(1\ \mathrm{MeV})$) increases, the minimal spectrum energy E_{min} also increases.

(2) Variations of those spectra with $A \propto E_{min}^{\alpha}$ where $\gamma \approx \alpha \approx 3$ have been found to result in a shift of the spectrum as a whole parallel to energy axis (B remains unchanged).

(3) All spectra under consideration may be divided into 2 different subsets with different γ marking a value of 3 as a borderline. The first set with $\gamma > 3$ has best fitting α values $> \gamma$ and vice versa, for $\gamma < 3$ values $\alpha < \gamma$.

Acknowledgments: The authors thank R.A. Mewaldt for providing EIS data, while CRNC data were downloaded from the www site of the University of Chicago (PI: J.A. Simpson). All authors acknowledge financial support of the Russian-Hungarian Bilateral Intergovernmental S&T Cooperation RUS-5/96. K.K. also thanks Hungarian national grant OTKA-T-023210 for support. The present work represents a continuation of collaboration initiated during a workshop at the International Space Science Institute (Bern).

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