Proceedings of ICRC 2001: 3181 © Copernicus Gesellschaft 2001

ICRC 2001

About the energy spectra of solar energetic particle event heavy ions

D. G. Baranov[1], **V. A. Dergatchov**[1], **Yu. F. Gagarin**[1], **D. A. Mottl**[2], **and R. A. Nymmik**[3]

[1]Ioffe Physico-Technical Institute, Russian Academy of Science Politekhnitcheskaya 26, 194021, St.Petersburg, Russia
[2]Department of Physics, Moscow State University, 117321, Moscow, Russia
[3]Skobeltsyn Institute of Nuclear Physics, Moscow State University, 117321,Moscow, Russia

Abstract. The shapes and rigidity are analyzed in the particle (protons and Fe ions) fluences energy spectra of large SEP events of 29 September and 19, 22, and 24 October 1989 measured by different techniques within broad energy ranges. The analysis makes use of, in particular, the specified data on the energy spectra of Fe ion fluence measured on Mir space station. Our measurements have not shown any effect of the SEP event heavy ion energy spectrum becoming harder compared with the proton spectra, as claimed by Tylka et al. (1999b). The vast majority of the actual energy spectra of SEP event heavy ions have been shown to be softer that the proton spectra, just as found by us earlier (Nymmik, 1999a).

1. Introduction

The SEP energy spectra constitute one of the basic sources of information on the particle acceleration processes on the Sun and in interplanetary space. Numerous works have been devoted to analyzing the analytical form of proton energy spectrum and to comparing the spectral parameters with the parameters that characterize one or another acceleration mechanism.

Protons are the main component of the SEPs, whence the flux measurement results prove to be supported by the most reliable statistics. Nonetheless, the accuracy of measuring the proton component is still insufficient for any specified conclusion to be drawn from the theory-experiment comparison. Another reason is the methodological inaccuracy, which is exposed by comparing among the results of measuring the proton fluxes in the same SEP event by different instruments and methods.

Besides, the character of the SEP energy spectra changes at energies of about 30 MeV, thereby contributing to the uncertainy in measuring the proton spectrum. At energies above 30 MeV, the proton spectrum can properly be described by power-law function of rigidity (momentum), whereas at lower energies the spectral form remains much uncertain (Nymmik 1993,1999a).

The methodological troubles get even more enhanced when analyzing the form of the heavy particle energy spectrum. In fact, the heavy particle component is small (whence the high statistical errors), so the SEP event heavy particle fluxes are methodologically difficult to measure against the background of large proton fluxes. Nevertheless, analyzing the experimental data has shown that the changes in the character of the 30 MeV/nucleon heavy particle energy spectrum are the same as in the case of protons and that the high-energy heavy particle spectra can properly be described by power-law functions of momentum per nucleon (Nymmik, 1997, 1999a). It should be noted that the spectral indices of heavy ($z \geq 2$) particle fluxes are the same or alike. On the average, they are 1.26 times higher (the spectra are softer) compared with the proton spectra of the same SEP events (Nymmik, 1997, 1999a). Contrary to these conclusions, Tylka et al. (1997,1999a,b) claim that the energy spectra of high-energy heavy particles (O, Fe) in some of the large SEP events are more rigid that the proton spectra.

The present work is based on the results of measuring the Fe group particle fluxes by the authors in September-October 1989 and shows that our results concerning the heavy particle energy spectra in the analyzed SEP events being softer than the proton spectrum agree with the earlier conclusions (Nymmik 1997,1999a)

2. Experimental equipment and results

Since 1978, we have made the Platan experiments with measuring the fluxes of heavy nuclei in the near-Earth orbits of Salyut-6, Salyut-7, and Mir manned space stations (Baranov et al., in press). The heavy particles

Correspondence to: Gagarin Y.,Y.Gagarin@pop.ioffe.rssi.ru

(z>20) are measured using the chambers assembled of Lavsan layers.

During the Platan-3 measurement period from 26 February 1988 to 11 January 1990 (Gagarin et al. 1998), the extremely large Fe fluxes from the solar flare sequence of 29 September – 3 October and 10-27 October 1990 were recorded with a 6.2-mm thick chamber of 600-cm^2 area. In the experiment, the particle fluences were determined by two methods. In plotting the 45-210 MeV/nucleon Fe energy spectra, the particle charge was found by the LR method (Fleisher et al. 1975). The 7-130 MeV/nucleon data processing rate was raised using the proximate method for estimating the particle charges, use is made of the number of the detector layers that got etched-through (Baranov et al., in press). The 45-130 MeV/nucleon Fe spectra obtained by two different methods are identical, thereby indicating that the proximate techniques are reliable and effective. The proximate method has made it possible to construct the differential Fe energy spectrum supported by the statistic data, which have increased 5-fold since the time of the earlier publication (Baranov et al., in press)

Fig. 1 shows the resultant measured total Fe ion fluxes from the SEP events of 1989 in the Mir space station orbit. Having known the transmission function for the periods of large SEP events in September-October 1989, we scaled the spacecraft-measured energy spectrum to the space radiation environment beyond the magnetosphere. The transmission function was calculated in terms of the Tsyganenko (1989) magnetospheric model as described in (Nymmik, 1999b). In the calculations, the mean charge of Fe ions was taken to be 15.8.

The experimental data were approximated, according to (Nymmik, 1993, 1999a), by the power-law function of particle rigidity (1), which describes the spectra of protons and heavy particles most adequately:

$$F(E)dE = F(p)\frac{dp}{dE}dE = C\cdot\left(\frac{p}{p_o}\right)^{-\gamma}\cdot\frac{dE}{\beta}, \qquad (1)$$

where $\beta = p\Big/\sqrt{p^2+\left(2mc^2\right)^2}$ is relative particle velocity; p is the particle momentum per nucleon, $p=\sqrt{E\left(E+\left(2mc^2\right)^2\right)}$; $p_o = 239$ MV/nucleon. The resultant and initial spectra can well be approximated by formula (1) if we admit a certain droop of the <30 MeV spectra, which is described by reducing the spectral index (Nymmik, 1993):

$$\gamma = \gamma_o\cdot\left(\frac{E}{30}\right)^{\alpha}, \qquad (2)$$

where γ_o is the spectral index at ≥30 MeV; α is the spectral droop index.

3. Discussion

We have compared the recovered extramagnetospheric spectrum with the spectrum measured with the IMP-8 flown VLET (5-50 MeV/nucleon) and CRT (50-800 MeV/n) instruments. For that purpose, we summarized the IMP-8 data from Tylka and Dietrich paper (1999a) over the 29 September – 4 October and 19-27 October SEP events. The result was approximated by two power-law functions (curves 3 and 4 in Fig. 1) for either of the instruments separately. From Fig. 1 it follows that the VLET-measured spectrum is the same as the spectrum obtained in our experiment. At the same time, the CRT-measured differs from ours and is inconsistent with the VLET-measured spectrum. At the 50 MeV/n intermediate energy, which separates the VLET- and CRT-measured energy ranges, the absolute fluence sizes get stepwise different five-fold, thereby indicating some methodological errors in either VLET or CRT. The comparison of the VLET- and CRT-measured spectra with our data shows that the CRT data are probably incorrect.

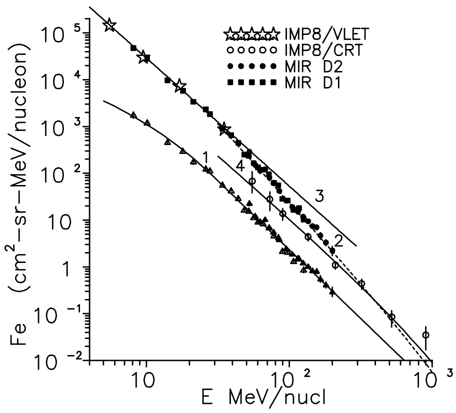

Fig. 1. The energy spectra of the total Fe fluences in the SEP events of 1989. The curve approximate the experimental data in terms of formulas (1) and (2) for the orbital Platan-3 measurements (curve 1), for the same data scaled to beyond the magnetosphere (curve 2), and for the IMP8 VLET and CRT data (Tylka et al., 1999a) (curves 3 and 4).

At the same time, two fundamental conclusions concerning the SEP event of 29 September 1989, namely,

1. the high-energy heavy particle spectrum is harder than the proton spectrum and
2. when presented as energy per particle, the high-energy heavy particle fluxes exceed the proton fluxes,

have been drawn in Tylka et al. (1999b) from just the CRT data, so we decided to verify the validity of the conclusions.

Fig. 2 presents the energy spectra of the fluences (not peak fluxes!) over the sum of the large SEP events of 1989 proton (Sauer, 1993) and our measurement Fe data. The comparison between the spectral indices of the differential energy spectra calculated by Eq. (1) for iron (γ=5.50) and protons (γ=4.53) has shown that the iron spectrum is softer, rather than harder, than the proton spectrum, just in agreement with our conclusions that we used to construct the our SEP flux model (Nymmik, 1999a). We have also calculated the iron spectrum in units of total energy per nucleus, which proved also to deny the conclusion of Tylka et al., (1999b) concerning the excess of the iron flux over the proton flux.

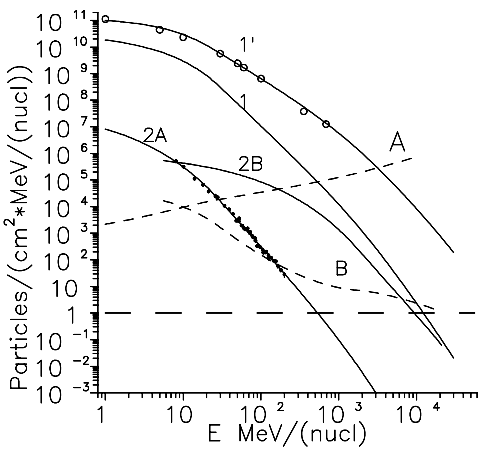

Fig. 2. The energy spectra of the extramagnetospheric total proton and Fe fluences in the SEP events of 1989: the GOES-measured integral energy spectrum of proton fluences (curve 1'), the differential proton fluence spectrum (curve 1); the Mir-measured differential energy spectra of Fe fluences in units of energy per nucleon and per particle (curves 2A and 2B, respectively).

Besides, we have analyzed the iron and proton fluence (not fluxes!) data of the 29 September 1989 SEP event (Fig. 3) using the Fe data from Tylka et al., (1999a) and proton data from Sauer, (1993). With that purpose, we approximated the CRT data (Tylka et al., 1999) by the power-law energy function calculated making allowance for the statistical errors of measurements (the spectral index $\gamma_E = 2.7$), which is close to the data ($\gamma_E = 2.5 \pm 0.2$) of Tylka et al., (1999a).

The energy spectrum of the 29 September 1989 SEP event proton fluence is somewhat harder ($\gamma_p = 4.53$) than the total spectrum over 1989. Having been transformed to the form of the dependence on total energy per nucleus, however, the iron spectrum is never in excess of the proton spectrum.

Therefore, even if the CRT instrument fluence data (which we consider suspicious) are used together with the evidently incorrect approximation of the spectrum by power-law function of energy (instead of power-law function of momentum per nucleon), which contradicts all the experimental SEP flux data, we cannot bear out the conclusions of (Tylka et al., 1999b).

4. Conclusion

This work is to draw the reader's attention to some circumstances of analyzing at large the experimental SEP flux data. First, we mean the occurrences of the methodological errors in the particle flux measurement data, which are exposed by comparing among the results of measuring the same fluxes with different instruments. Second, the data are often analyzed in terms of the interpolation functions that have never been corroborated. This relates primarily to analyzing (extrapolating, in particular) the SEP flux data in terms of power-law energy function and of any exponent. Combined with the statistical measurement errors (which are not always included correctly), the above circumstances clear the way often for invalid conclusions and unfounded physical inferences.

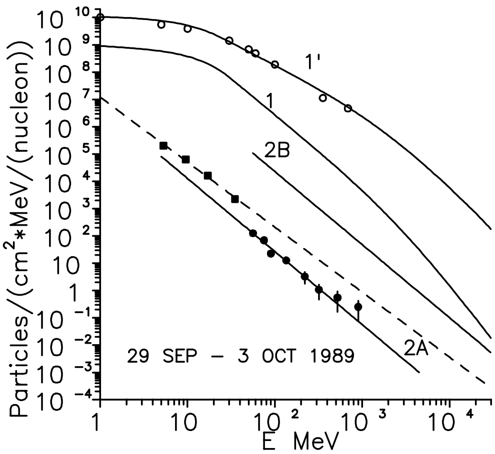

Fig. 3. The energy spectra of the proton and Fe fluences in the SEP event of 29 September – 3 October 1989: the GOES-measured integral energy spectrum of proton fluences (curve 1'); the differential proton fluence spectrum (curve 1); the IMP-8 CRT instrument-measured differential energy spectra of Fe fluences in unities of energy per nucleon and per particle (curves 2A and 2B, respectively), the IMP-8 VLET instrument-measured Fe fluence power-law of energy spectrum (dashed line).

References

Baranov D.G., Gagarin Yu.F., Dergachev V.A. et al., The HZE particle fluxes in orbits of manned space stations, *Rad.Meas.* (in press).

Fleischer R.L., Price P.B., Walker R.M., Nuclear tracks in solids, University of California press, Berkeley-Los Angeles-London, 1975.

Gagarin Yu.F., et al.. Heavy particle fluxes in Salyut station orbit, *Adv. Space Res.*, 21, (12), 1699, 1998.

Mottl D, et al, Spectra of solar energetic protons derived from statistical analysis of experimental data on a large set of events, *the paper at this Conference*, 2001.

Nymmik R.A. Averaged energy spectra of peak flux and fluence values in solar cosmic ray events, *Proc.23 ICRC*, 4, 29-32, 1993.

Nymmik R.A., Statistical-functional analysis of the characteristics of energetic particle spectra (1≤z≤28) solar cosmic rays, *Izv. Ross. Akad. Nauk,.ser. fiz,* 61(6), 1058-1061, 1997.

Nymmik R.A. Probabilistic model for fluences and peak fluxes of solar energetic particles, *Rad. Meas.*, 30, 287-296, 1999a.

Nymmik R.A. The problems of cosmic ray particle simulation for the near-Earth orbital and interplanetary flight conditions, *Rad. Meas.* 30, 669-677,1999b.

Sauer H.H., GOES observations of energetic protons E>685 MeV: ground level events from October 1983 to July 1992, in *Proc. 23 ICRC*, 3, 254-257, 1993.

Tsyganenko N.A., Magnetospheric magnetic field model with a warped tail current sheet, *Planetary and Space Science* (**37**, 5, 1989.

Tylka A.J.,et al., Observations of very high energy solar heavy ions from IMP-8, in *Proc. 25. ICRC,* 1 , 101-104, 1997.

Tylka A.J., and Dietrich W., IMP-8 observations of spectra, composition, and variability of solar heavy ions at high energies relevant to manned space missions, *Rad. Meas*. 30, 345-359, 1999a.

Tylka A.J., et al. High-Energy solar Fe ions in the 29 September 1989 ground level event, in *Proc.26 ICRC,* 6, 67-70, 1999b.