29th International Cosmic Ray Conference Pune (2005) **2**, 247–250

Long-Term Modulation of the Cosmic Ray Fluctuation Spectrum: Spacecraft Measurements

S.A. Starodubtsev[a], I.G. Usoskin[b], A.V. Grigoryev[a], K. Mursula[c]

(a) Yu.G. Shafer Institute of Cosmophysical Research and Aeronomy SB RAS, 31 Lenin Ave., 677980 Yakutsk, Russia
(b) Sodankylä Geophysical Observatory (Oulu Unit), University of Oulu, FIN-90014,Finland
(c) Department of Physical Sciences, P.O.Box 3000, FIN-90014 University of Oulu, Finland
Presenter: S.A. Starodubtsev (starodub@ikfia.ysn.ru), rus-starodubtsev-S-abs1-sh34-poster

We have recently studied (Starodubtsev et al., 2004) cosmic ray fluctuations in the frequency range of $10^{-4} \div 1.5 \cdot 10^{-3}$ Hz (periods from about 10 min to 3 h) using measurements by ground-based neutron monitors. We found that the level of cosmic ray fluctuations is subject to long-term modulation in phase with the sunspot cycle. This result can only be applied to the energy range above several hundred MeV where galactic cosmic rays dominate. Here we extend this study using data of lower energy cosmic rays measured in the different energy channels of the IMP-8 spacecraft in 1974-2001 and the ACE satellite in 1997-2003. The lower energy cosmic rays are dominated by particles of solar and interplanetary origin. A dominant 11-year periodicity is found in the index of rapid cosmic fluctuation for all energy channels. However, interestingly, while the fluctuation index for the higher energy channels changes in phase with the sunspot cycle (similar to the result based on neutron monitor data), the index for lower energy channels has a phase roughly opposite to the sunspot cycle. We present these observations and discuss a possible scenario explaining the observed energy-dependent difference in the solar cycle variation of cosmic ray fluctuations.

1. Introduction

The intensity of cosmic rays (CR) varies at different time scales, from minutes to decades and even beyond. While long-term CR variations were extensively studied, much less attention has been paid to the short-term variations. Such short-term variations with periods from minutes to several hours (from 10^{-4} to $1.5\,10^{-3}$ Hz) are called rapid CR fluctuations. Rapid CR fluctuations have been studied since 1970's using data of the ground-based neutron monitor network [1, 2, 3]. Earlier results on rapid CR fluctuations can be summarized as follows:

1. The amplitude of rapid CR fluctuations is small, typically ≤ 1 %, and therefore special methods of spectral analysis should be applied;

2. Significant dynamical changes in the spectra of CR fluctuations are often observed about one day before and during large-scale IMF disturbances;

3. It was found that the CR fluctuations are of extra-terrestrial origin and not related to atmospheric or magnetospheric effects;

4. The power spectrum of rapid CR fluctuations is related to that of the turbulence of the IMF. However, due to different complicated physical processes affecting the interplanetary medium, the nature of this turbulence is not well known.

5. The level of rapid galactic CR fluctuations as recorded by ground-based neutron monitors is known to vary in phase with the solar activity cycle. On the other hand, there are indications that this relation may not be valid for lower energy cosmic rays of solar/interplanetary origin. Since low energy cosmic rays do not reach to the ground, one has to use satellite measurements in order to study them.

Table 1. Energy Channels of the Two Selected Space-Borne Cosmic Ray Experiments.

ACE/EPAM	Energy (MeV)	IMP-8/CPME	Energy (MeV)
P1	0.047–0.065	P1	0.29–0.50
P2	0.065–0.112	P2	0.50–0.96
P3	0.112–0.187	P3	0.96–2.00
P4	0.187–0.310	P4	2.0–4.6
P5	0.310–0.580	P5	4.6-15
P6	0.580–1.060	P7	15–25
P7	1.060–1.910	P8	25–48
P8	1.910–4.750	P9	48–96
–	–	P10	96–145
–	–	P11	145–440

In this paper we perform a thorough analysis of rapid CR fluctuations using data of space-borne CR measurements in different energy channels.

2. Data and analysis method

Cosmic rays are recorded onboard a number of spacecraft in a wide energy range, typically from tens of keV up to hundreds of MeV. For this study we need a stable, homogeneous and sufficiently long record of CR measured by the same instrument nearly continuously. The two most suitable spacecrafts for our purpose are ACE and IMP-8. The EPAM/LEMS30 experiment onboard the ACE spacecraft (located in the 1-st Lagrange point L1) provides a stable series of CR fluxes in different energy levels measured at 300 s time resolution since late 1997 (http://www.srl.caltech.edu/ACE/ASC/level2/lvl2DATA_EPAM.html). The bulk of ions detected by the EPAM experiment are protons. The experiment CPME/Protons onboard the geocentric IMP-8 satellite was in operation from 1973 until 2001, providing a stable record of CR fluxes at about 330 s time resolution. (http://hurlbut.jhuapl.edu/IMP/data/imp8/cpme/cpme_330s/protons.)

Parameters of the energy channels in the selected experiments are given in Table 1. The ACE data in the energy channels P5–P8 are well related to the IMP-8 data in channels P1–P4. On the other hand, the more energetic IMP-8 channels extend to much higher energies, covering also the energy range dominated by galactic CR. Using the above mentioned two data sets allows to study CR fluctuations in the wide energy range from tens of keV to hundreds of MeV. While low-energy CR are of local heliospheric origin (solar and/or interplanetary), the more energetic particles (above some hundred MeV) are predominately of galactic origin.

Since the IMP-8 satellite has an elliptic geocentric orbit with a rotation period of about 12.5 days, it spends a part of the time inside the Earth's magnetosphere (about 5 days per revolution on average). In order to avoid the magnetospheric effect in the analyzed data, we excluded all those periods using the orbital information of IMP-8 provided at ftp://nssdcftp.gsfc.nasa.gov/miscellaneous/orbits/imp8. We note that not all IMP-8 channels were stable in time, and mid-energy channels suffered a normalization error in 1989 [4], which makes them difficult to be used after 1989. However, the low (P1–P2) and high (P11) channels were quite stable throughout the whole interval since 1974, and we base our analysis mostly on these channels.

The calculation procedure used here is the same as in [2].

3. Results

Let us now study the IMP-8 data which covers almost three solar cycles. First we have tested the results for the galactic CR obtained earlier from the ground-based neutron monitor data. The NM data should be comparable with the most energetic P11 (145–440 MeV) channel of IMP-8, which also registers CR of predominantly galactic origin. Time variations of the CR indices (flux, level P of rapid fluctuations and the spectral index α of rapid fluctuations) are shown in Figure 1(left) in comparison with sunspot numbers.

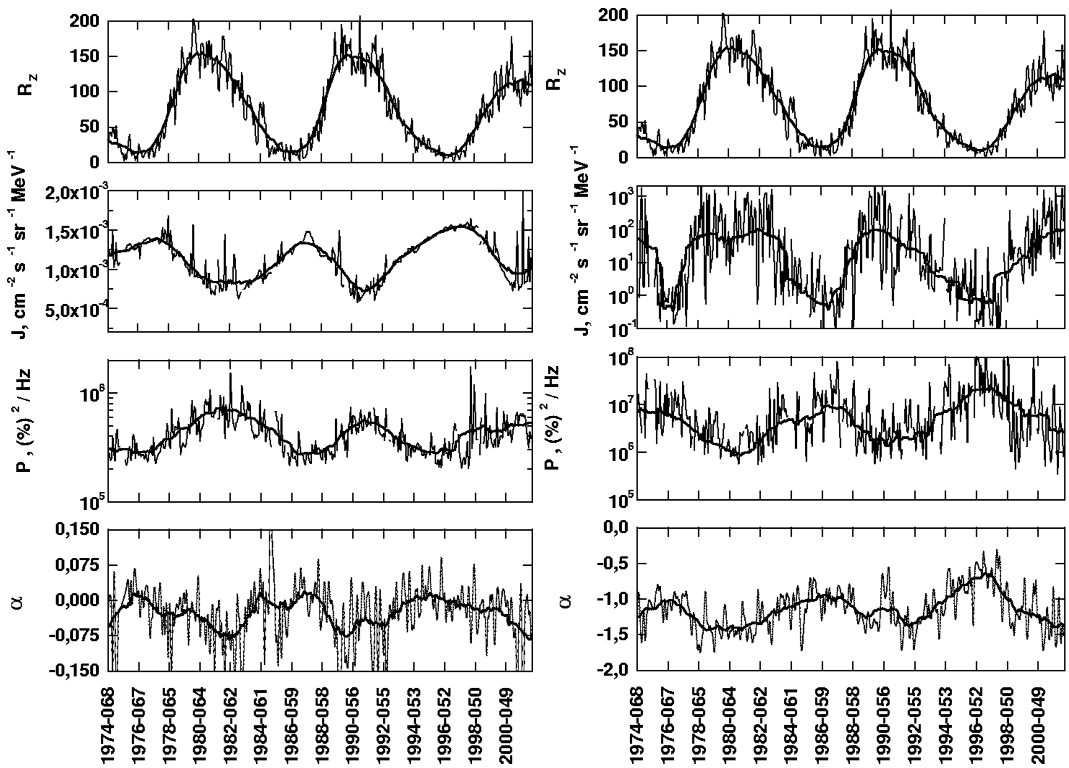

Figure 1. Time profiles of the sunspot number R_z, CR flux J, CR fluctuation level P and the PSD spectral index α for IMP-8/CPME (channel P11, left and channel P2, right) data. All data are 27-day averaged. Solid lines depict the corresponding 2-year running means. Time is given in year-DOY.

One can see that the temporal variations of the flux and the level of rapid fluctuations of these energetic CR indeed depict the same pattern as those from neutron monitors [2]: the CR flux J varies in anti-phase with the sunspot cycle (the cross-correlation coefficient between 2-year averaged values is $r = -0.79$); the fluctuation level P follows the sunspot cycle ($r = 0.75$); the spectral index α is around zero, indicating the flat shape of the power spectrum of rapid CR fluctuations. It is interesting to note that, while the spectral index α is consistently around zero, it still shows some small variation in anti-phase with the solar cycle ($r = -0.79$), likely due to the residual contribution of lower energy particles. Accordingly, the pattern found for the galactic particles measured by IMP-8 is the same as the one found earlier in neutron monitor data. This ultimately confirms the space origin of the modulation of the CR fluctuation level over the solar cycle.

The pattern is opposite for the low-energy (solar/interplanetary) particles, as depicted in Figure 1(right). The CR flux measured by the P2 channel of IMP-8 varies in phase with the sunspot cycle ($r = 0.84$), in a good agreement with the solar/interplanetary origin of these particles. However, the level of rapid CR fluctuations in this energy range changes in anti-phase with the solar cycle ($r = -0.84$), opposite to the galactic particles. The power spectrum is not flat and the spectral index α varies between -0.5 and -1.75 in anti-phase with the solar cycle ($r = -0.78$). Data of the ACE spacecraft (not depicted here) show a very similar pattern.

The other energy channels (not depicted here) can only be studied during a shorter time period (1974–1989) because of the instrument failure [4]. Channels P3–P5 (below 15 MeV – see Table 1) reproduce the pattern typical for solar particles depicted by the channel P2. Channels P8–P10 (above 25 MeV) are similar to the highest P11 channel, while the pattern found in channel P7 is a somewhat irregular mixture of the two modes.

4. Conclusions

Using data of space-borne measurements by ACE and IMP-8 spacecrafts, we have studied the rapid CR fluctuations in different energy channels for about three solar cycles since 1974. Our conclusion is that solar/interplanetary and galactic cosmic rays depict very different patterns over the solar cycle. With increasing solar activity, the flux of low energy solar/interplanetary particles increases, the power spectrum of their fluctuations becomes softer, and the level of these fluctuations decreases. On the other hand, the flux of galactic particles decreases (solar modulation of CR), but their fluctuation level increases with increasing solar activity, the power spectrum remaining nearly flat. The latter result is in agreement with previous studies based on ground neutron monitor data and directly proves the extra-terrestrial source of the fluctuations.

A possible scenario is suggested to explain such a behaviour. Fluctuations of galactic CR are caused by turbulence in the IMF which can be initiated/enhanced by the lower energy solar CR. The power of low-energy CR fluctuations is expected to be transferred to the magnetic turbulence. A more detailed theoretical investigation should be undertaken to quantitatively explain the observed interesting relations.

5. Acknowledgements

This work was partly supported by the RFBR grant 03-07-90389 and the grant of Leading Scientific School by G.F. Krymsky 422.2003.2. Academy of Finland (grant 107796) is acknowledged. We thank the ACE EPAM instrument team and the ACE Science Center for providing the ACE data online. John Hopkins University and the IMP-8 CPME team are acknowledged for providing IMP-8 data.

References

[1] V.I. Kozlov et al., 13th ICRC, Denver (1973) 2, 939.
L.I. Dorman andI.Ya. Libin, Soviet Physics - Uspekhi, 28, 233 (1985)
[2] S.A. Starodubtsev et al., Solar Phys., 224, 335 (2004)
[3] A.J. Owens, J. Geophys. Res., 79, 895 (1974)
E.G. Berezhko. and S.A. Starodubtsev, Izv. AN SSSR, Ser. Fiz., 52, 2361 (1988) (in Russian).
[4] D. Lario and G. M. Simnett, in: "Solar Variability and its Effects on Climate", Geophys. Monogr. Series, 141, eds. J. M. Pap and P. Fox, 195, AGU, Washington DC. (2004)