Features of Solar Energetic Particle Events During the 23rd Cycle Of Solar Activity and Their Relationship with Solar X-ray, Gamma-Emission and Coronal Mass Ejections

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Abstract.

The study on the relationship of solar cosmic ray events (in particular, the ratio of the maximum between the proton and electron fluxes) with X-ray and gamma radiation from solar flares, as well as with parameters of coronal mass ejections was carried out. It was done on the basis of SOHO/ERNE proton event catalog (http://newserver.stil.bas.bg/SEPcatalog/) and Solar Flares Catalog based on measurements of X- and gamma-emission (>50 keV) detected by SONG (CORONAS-F – Russian solar observatory) from August, 2001 till December, 2003 (http://swx.sinp.msu.ru/apps/solar_flares_cat/index.php). Solar electron flux (> 300 keV) were measured in the polar caps by MKL-instrument on board CORONAS-F satellite.

Introduction

Solar energetic particles (SEPs) – electrons, protons and heavy nuclei at energies from the keV up to the GeV range – together with X-ray and gamma-ray flares and coronal mass ejections (CMEs) are important components of space weather and topic of ongoing research [Lanzerotti, 2001, Jiggens et al., 2014]. The aim of this work is the comparison of the ratio of the maximum proton and electron fluxes of SEPs with the soft X-ray (SXR), hard X-ray (HXR) and gamma-ray flare intensity and the projected velocity of CME.

Experiments

The CORONAS-F Russian space solar (**C**omplex **OR**bital **O**bservation in **N**ear-Earth space **A**ctivity of the **S**un) observatory was launched on July 31, 2001, and operated until the end of 2005. At the beginning of its flight CORONAS-F had a quasi-circular orbit, with initial parameters: altitude 507±21 km, inclination 82.5 degrees, and period of revolution 94.5 min. The primary goal of the CORONAS-F experiment was to investigate nonstationary processes on the Sun and their impact on the interplanetary medium and the Earth's magnetosphere [Kuznetsov et al., 2014].

It is very important that on CORONAS-F observatory both neutral solar emission and charged particles were detected. Solar neutrons were measured on the lighted side of the Earth outside of the Earth's radiation belts, solar particles – both protons and electrons – in polar caps.

In the SONG (**SO**lar **N**eutrons and Gamma-quants) instrument CsJ-crystal is used for X-ray and gammas detection: it has rather smaller energy resolution comparing with NaJ, but impulse shape depends on specific ionization of the particle, therefore it is possible to differ impulses produced by gammas and neutrons. More detail the SONG instrument description you can find in *Kuznetsov et al.* [2014] and in the same Proceedings, paper *of* Bogomolov A. et al. [2019, this issue].

The MKL instrument which detected charged particles, both solar protons and electrons, consists of one block with radiation detectors, pulse generators, gate circuits, and voltage converters for the detectors and electronics along with a device for information output to the telemetry inside it.

Spectra of electron flux with energies of Ee 0.3–12 MeV and proton flux with energies of Ep 1–5 MeV are measured by means of telescopic system consisting of three detectors (see Fig. 1). Dt.3 is a thin n-p-detector of 10 mm diameter and 50 mkm thickness; Dt.4 is a thick n-p-detector of 12 mm diameter and 2,000 mkm thickness; Dt.5 is a jointed scintillation detector of Phoswich type. It consists of CsJ crystal of 10 mm diameter and height. CsJ has a higher density comparing with Si-detectors and allows to measure electrons with higher energy [Kuznetsov et al., 2014].

Data

In this work we used the peak flux of solar electrons with the energy 0.6-1.5 MeV from MKL instrument. For the solar proton peak flux we have used the reported values from the catalog lists the proton enhancements from the High Energy Detector (HED) aboard SOHO/ERNE instrument identified during solar cycle (SC) 23 (1996÷2008) and SC24 (2009÷2018), http://newserver.stil.bas.bg/SEPcatalog.

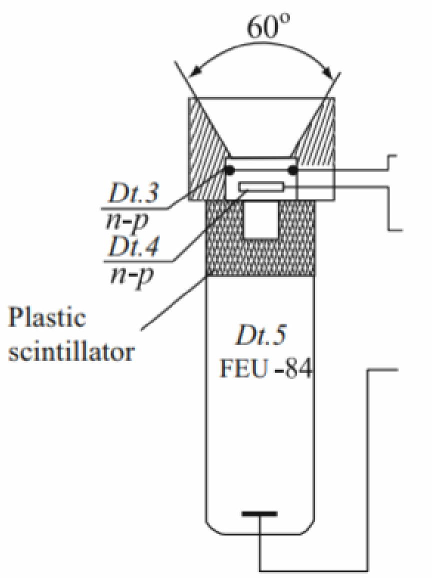

Fig. 1. Schematic arrangement of part of MKL instrument intended for the high-energy electron detection.

The catalog lists the peak intensity for the solar proton events in the different HED energy channels (in the range 14÷131 MeV) and additional information (GOES SXR flare class, linear speed of the CME in km s^{-1}) organized in table-form separately for SC23 and SC24. Proton peak was identified at the maximum of the particle profile (local enhancements are not considered). Onset time was identified as the time of 3-sigma intensity value above pre-event level. Peak time was considered as the time at the peak proton intensity. The peak proton intensity (Jp) was given after subtraction of the pre-event level in protons/(cm^2*s*sr*MeV). The reported there onset/peak times and Jp are based on 5-min averaged data.

We used the reported peak fluxes of solar protons from the SOHO/ERNE catalog and not measured by an MKL device, as was done for electrons, because SOHO/ERNE instrument has much higher sensitivity, which gave us the opportunity to analyze weak SEP events that were of considerable interest to us.

We compared the peak flux of solar protons with energies 17–22 MeV according to the SOHO/ERNE catalog, with the ones of solar electrons (Je) with energies of 0.6–1.5 MeV according to the MKL instrument.

For 125 SEP events from September 9, 2001 to December 2, 2003, peak proton (17–22 MeV) and electron (0.6–1.5 MeV) fluxes were analyzed, as well as the properties of the SEP solar origin: CME speeds, class of the X-ray flare, flare heliographic coordinates and gamma fluences with energies above 500 keV. We found that for 34 of these 125 proton events, the flux of solar electrons was not observed – probably due to insufficient sensitivity of the MKL device for weak events. For the remaining 91 events, we analyzed the ratio of the fluxes of solar protons and electrons.

Results and discussion

The correlation plot between the peak fluxes of solar protons with energies 17–22 MeV according to SOHO/ERNE catalog vs. the peak flux of solar electrons with energies of 0.6–1.5 MeV according MKL data is presented in Fig. 2.

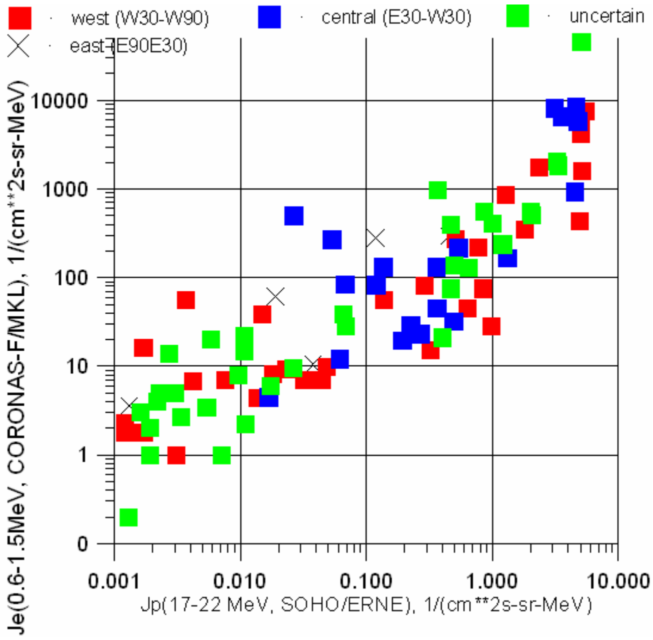

Fig. 2 Correlation plot between the peak flux of solar protons with energies 17–22 MeV according to SOHO/ERNE catalog vs. the peak flux of solar electrons with energies of 0.6–1.5 MeV according MKL data. For color code see text.

Different colors represent events depending on the localization of the SEP-related solar flare on the solar disk according to the SOHO/ERNE catalog: west events (W90–W30 degrees) in red color, central events (W30–E30 degrees) – green, east events (E30–E90 degrees) – oblique crosses. Events for which localization by the SOHO/ERNE catalog has not been determined in Fig. 2 (and in all next figures) are shown in green. From Fig. 2 it is clearly seen that there is a number of non-localized events, especially among the weak SEP events (with proton flux in 17–22 MeV less than 0.01 particles per cm^2-s-sr-MeV).

Figure 2 also shows that there is a linear relationship between the maximum intensity of proton and electron fluxes in SEPs, both for western and central flares as well as strong non-localized ones, except for a few events.

In order to investigate this feature in more detailed, we have analyzed the dependence of the ratio of peak flux of protons and electrons (Je/Jp) on the flux of protons (left panel of Fig. 3) and electrons – right panel of Fig. 3).

As can be seen from the left panel of Fig. 3, in the case of dependence on the proton flux, a declining trend is obtained: for a higher proton flux – a lower ratio Je/Jp was observed, except for four events.

As for the dependence of the ratio Je/Jp on the peak solar electron fluxes, there is a more complex relationship. In the right panel of Fig. 3, two branches are visible. The first is a linear relationship at high peak electron fluxes, where the ratio 100–1000 is obtained, which includes events generated primarily by central and western flares. The second is also linear, but with medium peak solar electron fluxes (<100 particles per cm^2*s*sr*MeV), and the ratio is substantially higher, with most events being the result of western or non-localized flares.

It is possible that there are at least two types of flares for which the conditions for acceleration and escape from the Sun of protons and electrons are different. Namely, there are a number of relatively weak events, where the flux of solar electrons is nevertheless significant. Since among such events there are practically no events generated by central flares, it can be assumed that in such cases it is more difficult for solar protons to reach Earth orbit than for the electrons originated in the same flare.

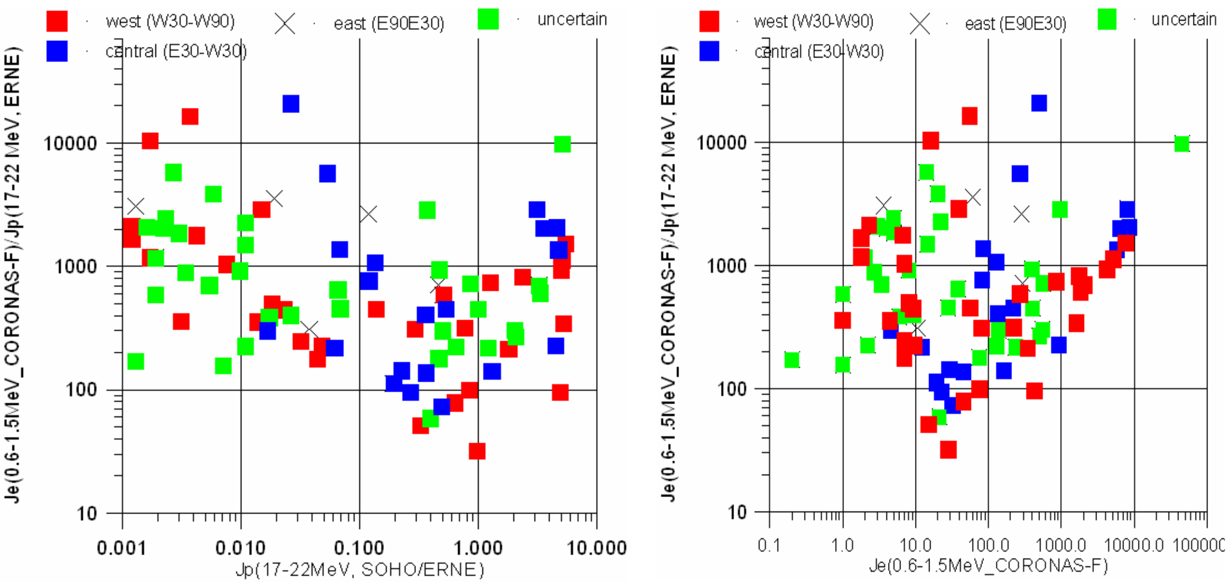

Fig. 3. Correlation plots between the ratio of the peak flux of protons and electrons on the proton flux (left panel) and electron flux (right panel).

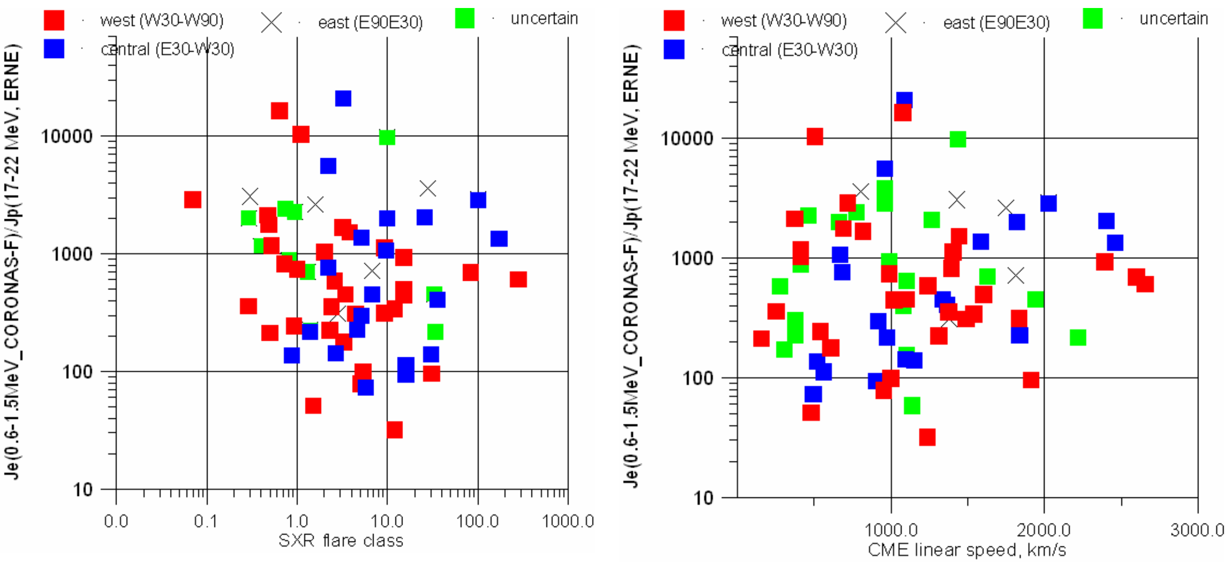

Fig. 4. Dependences of the ratio of the peak flux of protons and electrons (Je/Jp) on the SXR flare class (left panel) and on the CME speed (right panel).

Our next step was to study the dependence of the Je/Jp ratio on (a) the class of the parent flare in SXRs (left panel of Fig. 4) and b) on the speed of the CME associated with this SEP event (right panel of Fig. 4). The values for both the flare class and the speed of the CME were taken from the SOHO/ERNE catalog.

As it can be seen from both panels of Fig. 4, it is difficult to make any definite conclusions. For the left panel in Fig. 4 it is possible to see a growth in the ratio of Je/Jp with the decrease in the SXR flare class (which coincides with the conclusions from the left panel of Fig. 3, since the higher peak proton flux more often corresponds to the higher class of the flare in SXRs). There is no correlation between the ratio of Je/Jp and the linear velocity of the CME, at least for these data.

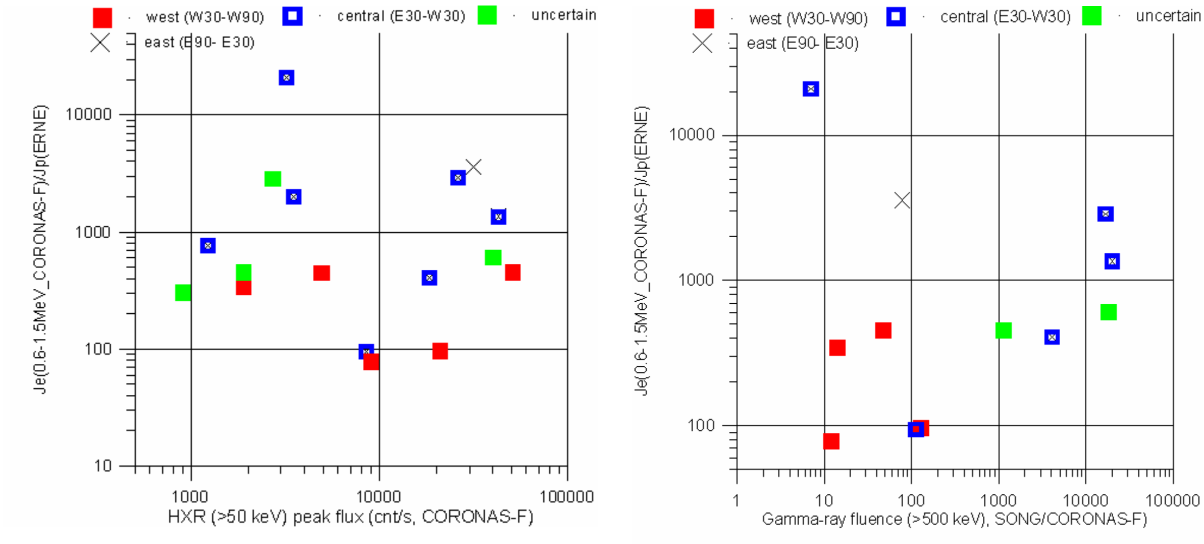

Fig. 5. Dependences of the ratio of the peak flux of protons and electrons (Je/Jp) on HXR (>50 keV) peak flux from SONG (CORONAS-F), left panel, and on gamma-emission fluence >500 keV from SONG (CORONAS-F), right panel.

Our last attempt to find a relationship of Je/Jp with parameters of the parent flares was to perform the correlation with the peak HXR fluxes with energy > 50 keV (left panel) and gamma fluence > 500 keV (right panel) both according to SONG (CORONAS-F). The results are presented in Fig. 5.

Among 70 flares in which the SONG instrument measured the HXR flux, only 17 of them were followed by SEP events, and only in 12 of these 17 flares the gamma-emission flux with the energy >500 keV was measured, which made it possible to calculate their gamma-fluence (the total number of photons with energies above 500 keV recorded during the flare). Figure 5 shows that there is no correlation between the peak of the HXR emission and Je/Jp. In the case of flare gamma-fluence, there is a tendency of increase of the ratio flux Je/Jp with the increase of gamma-fluence, which is expected, since the main part of gamma radiation belonged to the energy range up to 10 MeV, which corresponds to the acceleration of flare electrons.

Conclusions

The Je/Jp ratio in SEP events during 2001–2003 years was analyzed.

For the higher flux of the protons – lower ratio Je/Jp was obtained, except for four events.

The dependence of the ratio Je/Jp on the peak flux of solar electrons is complex – we have found two branches of this dependence, so it is possible that there are at least two types of flares for which the conditions for acceleration and escape from the Sun of protons and electrons are different. This deserves further investigation.

No clear correlations were found between the ratio Je/Jp with flare class, CME velocity and HXR peak flux.

Acknowledgment

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References

Bogomolov, A., Myagkova I., Miteva R., Danov D., Kashapova L. (2019) Parameters of Thermal and Non-thermal X-ray and Gamma Ray Emission of Solar Flares, Observed onboard Coronas-F, Proceedings of the WS-11 workshop, held in Primorsko, Bulgaria (this issue).

Jiggens, P., Chavy-Macdonald, M.A., Santin, G., Menicucci, A., Evans, H., Hilgers, A. (2014) The magnitude and effects of extreme solar particle events. Journal of Space Weather and Space Climate 4, A20. doi:10.1051/swsc/2014017.

Lanzerotti, L. J. (2001) Space weather effects on communications, in Space Storms and Space Weather Hazards, NATO Sci. Ser. II: Math., Phys. and Chem., vol. 38, edited by I. Daglis, 313 pp., Kluwer Acad., Dordrecht, Netherlands.

Kuznetsov, S.N., Bogomolov, A.V., Galkin, V.I., Denisov, Y.I., Podorolsky, A.N., Ryumin, S.P., Kudela, K., Rojko, J. (2014) Scientific Set of Instruments "Solar Cosmic Rays", in: Kuznetsov, V. (Ed.), The Coronas-F Space Mission, p. 289. doi:10.1007/978-3-642-39268-9_9.