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Gamma-ray lines in solar flares with proton spectra measured by PAMELA experiment

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Abstract. During the solar flares protons and heavier ions are accelerated up to GeV energies. Accelerated ions can escape the Sun and be registered directly on spacecraft or penetrate into the solar atmosphere and then produce gamma-ray lines as the result of nuclear reactions. Previous studies revealed very poor correlation between fluxes of interplanetary ions and gamma-ray line emission. In this work we focus on joint observations of interplanetary solar energetic particles registered by PAMELA experiment and gamma-ray emission registered by Konus-*Wind* instrument in hard X-ray and soft gamma-ray ranges. This study confirmed the previous results: during the period from 2006 to 2014 there were only two solar flares registered both by PAMELA and Konus-*Wind* at energies above 1 MeV. We analyze gamma-ray spectrum for one of these flares and make suggestions about the reasons for the low correlation between interplanetary solar accelerated ions and accelerated ions interacted in the solar atmosphere.

1. Introduction

Solar flare is a brightening of the solar emission observed at different wavelengths from radio to gamma-ray ranges caused by an abrupt energy release in the solar atmosphere. Solar flares may be accompanied by different phenomena such as coronal mass ejections (CME), solar energetic particle events (SEP), filament eruptions, etc.

SEP are protons and heavier ions accelerated during solar flares, which escape the Sun and are registered in the interplanetary space. But those accelerated particles which penetrate into the solar atmosphere produce gamma-ray line emission as the result of numerous nuclear reactions. Ions in the relatively low energy range ($\sim$1–20 MeV nucleon^{-1}) interact with the ambient plasma for the most part through inelastic scattering. Interacted nuclei transit from an excited state to the ground state through the emission of characteristic gamma-quanta [1], [2], [3], [4]. Protons and α-particles in energy range $\sim$10–300 MeV nucleon^{-1} produce neutrons in $p-p$, $p-He^4$ and $\alpha-He^4$ reactions [5]. Some of these neutrons escape the Sun and can be registered *in situ*, some neutrons reach solar chromosphere, thermalize and are captured by protons with emission of a narrow line at 2.223 MeV [6]. Positrons born in nuclear reactions can slow down in the solar atmosphere and annihilate with electrons producing a gaussian line at 511 keV when annihilating from a singlet state or a continuum below 511 keV when annihilating from a triplet state [7]. High energy ions ($\geq$300 MeV) produce pions in nuclear reactions. Neutral pions decay into photons, $\pi^0 \rightarrow \gamma\gamma$, that form a very broad peak with the mean at $\sim$60 MeV [8].

Surprisingly, intensities of SEP events and gamma-ray emission from solar flares do not correlate [9]. In [9] and [10] flares accompanied by ion acceleration are divided into two groups:

(i) impulsive gamma-ray/proton (GR/P) flares which have more spiky time profiles in hard X-rays and are rich in gamma-ray emission but poor in proton fluxes registered in interplanetary space; and (ii) gradual GR/P flares which are characterized by longer durations, high fluxes of interplanetary protons and low or undetectable gamma-ray emission. This low correlation can be explained either by high anisitropy of the accelerated ions or by different acceleration mechanisms responsible for interplanetary particles and for particles interacting in solar atmosphere. The special case of the latter explanation is that particles in SEP events come through the second stage of acceleration [9].

Mechanisms responsible for the differences between SEP-related flares and gamma-ray flares are still under discussion [11], [12], [13].

The PAMELA experiment for the first time in December, 2006 measured solar cosmic ray spectra with high precision [14]. PAMELA was the first instrument which obtained solar neutron spectra and since 2006 and till 2014 PAMELA probably observed energy spectra of the neutrons born in 14 solar flares [15]. This gives new opportunities for the joint observations of interplanetary particles and particles interacted in the solar atmosphere and thus to improve our understanding of these phenomena. In this work in addition to PAMELA data we used observations of Konus-*Wind* instrument [16] in the gamma-ray range.

2. Instrumentation

2.1. PAMELA instrument

PAMELA [17] is a space-based experiment designed to study cosmic rays of galactic and solar nature in a wide energy range (0.1– 1000 GeV) with great precision. The experiment, housed on board the Russian Resurs-DK1 satellite, was launched on 15 June 2006 and made significant scientific contributions until 2016, when communication with the satellite was lost. The instrument is built around a permanent magnet spectrometer with a Silicon microstrip tracker that provides rigidity and energy loss information. Lepton/hadron identification is performed by an imaging Silicon-Tungsten calorimeter and a Neutron detector is placed at the bottom of the device. A Time of Flight (ToF) system, made of three layers of plastic scintillators, is used to measure the velocity and charge of the particle. An anticoincidence system made of scintillators surrounding the instrument is used to reject false triggers coming from the satellite and albedo particles. The instrument provides the isotopic composition of nuclei from hydrogen to boron at energies of 0.1-1 GeV/nucleon for solar cosmic rays and the neutron detector can be used to search for solar neutrons with energies of ∼10–1000 MeV during solar flares.

2.2. Konus-Wind instrument

Konus is a joint Russian-US instrument onboard *Wind* spacecraft launched in November, 1994 for gamma-ray burst and solar flare studies in hard X-ray (HXR) and soft gamma-ray ranges [16]. Konus-*Wind* works in the interplanetary space (since July, 2004 it is orbiting near Lagrange point L1) and thus doesn't suffer from Earth occultations and has exceptienally stable background. The instument operates in two modes: the waiting mode and the triggered mode. In the waiting mode time profiles are recorded in three wide energy bands: G1 (∼20–80 keV), G2 (∼80–300 keV) and G3 (∼300-1200 keV) with time resolution equal to 2.944 s. Swithing to the triggered mode occurs at a statistically significant background excess in G2 channel. In the triggered mode time profiles in the same bands G1, G2, G3 are available with high time resolution (from 2 to 256 ms) during ∼4 minutes. Also 64 multichannel spectra are accumulated in two partially overlapping energy ranges: the first range PHA1 from ∼20 keV to ∼1200 keV contains 63 energy channels and the second range PHA2 from ∼0.4 MeV to ∼15 MeV contains 60 energy channels. The accumulation time for the first four spectra is fixed at 64 ms, for the last eight spectra – at 8.192 s, and accumulation time for the remaining spectra varies from 256 ms to 8.192 s according to the intensity in G2 channel: for more intense emission accumulation times are shorter. After the end of the triggered record Konus-*Wind* is inactive for ∼1 hour because of the data readout and only time profiles in G2 channel with time resolution of 3.68 s are available. Thus Konus-*Wind* can observe only part of long duration events.

3. Observations

During 2006–2014 years PAMELA registered accelerated particles from 28 solar flares [18] including about 14 flares with the measured neutron spectra fragments [15]. As the emission from gamma-ray lines becomes significant at MeV energies, we composed a list of solar flares registered by Konus-*Wind* in the triggered mode at energies above 1 MeV during 2006-2014, which contains 23 solar flares. Surprisingly, there were only two intersections between this list and PAMELA list. Characteristics of these two flares are presented in Table 1.

Table 1. Solar flares jointly observed by PAMELA and by Konus-*Wind* at energies ≥1 MeV.

No.	Konus-*Wind* trigger	SEP event	GOES class	Location	PAMELA[1]
1	2012 Jul 06, 23:04:30	2012 Jul 07, 00:05	X1.1	S13W59	p, n
2	2014 Feb 25, 00:42:44	2014 Feb 25, 03:00	X4.9	S12E82	p

[1] Particles registered by PAMELA experiment.

4. Data analysis

For the detailed spectral analysis we selected the 2012-Jul-06 flare for the following reasons: first, because Konus-*Wind* observed the bulk of its gamma-ray emission, and, second, the flare was located on the solar disc and gamma-ray lines suffered less from the attenuation in the solar atmosphere in contrast to the limb events. Konus-*Wind* time profiles in G1, G2 and G3 energy bands for the 2012-Jul-06 flare are plotted in Figure 1.

Spectral fitting was performed using XSPEC package [19] for the second energy range PHA2 as it is not distorted due to different instrumental effects typical for intense events. Time interval for the fitting was selected from the beginning of high energy emission and till the end of multichannel spectrum accumulation, i. e. between 23:05:41 and 23:06:47 (grey area in Figure 1). The bremsstrahlung continuum was fitted by a combination of simple power law model (PL) and a power law with exponential cutoff at higher energies (CPL) [20]. As the deexcitation lines from close nuclear levels are hardly distinguishable, authors in [4] developed spectrum template based on common conditions in the solar atmosphere. We took this template from the OSPEX package [21] and added it to XSPEC. Emission from electron-positron annihilation was also fitted by a template taken from OSPEX, which accounts for both 511 keV line and continuum, caused by e^+–e^- annihilation from triplet state [7]. Emission from a neutron capture by a proton was fitted by a gaussian line with maximum at 2.223 MeV and σ=0.1 keV [6].

The best-fit parameters are listed in Table 2 and the spectrum is plotted in Figure 2. Along with the two components of bremsstrahlung continuum the flare demonstrates a significant flux from e^+–e^- annihilation and the distinguishable contribution from nuclear deexcitation lines which proves the presence of nuclear reactions in the solar atmosphere. Surprisingly, we found no evidence for 2.223 MeV line and were able to estimate only upper limits on its flux.

5. Discussion

This work confirms the previous results: despite the fact that both solar gamma-ray lines and solar energetic particle events (SEP) are caused by ion acceleration in solar flares, the

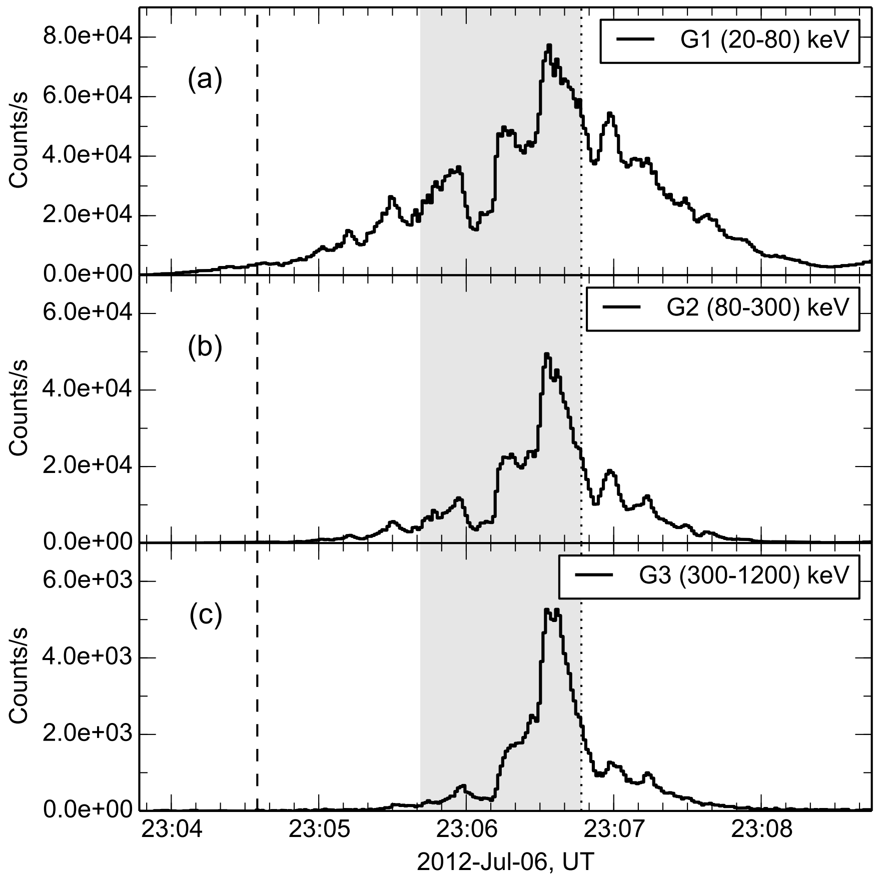

Figure 1. Time profiles of the 2012-Jul-06 solar flare in Konus-*Wind* channels G1, G2, G3. Dashed line indicates the Konus-*Wind* trigger time, dotted line corresponds to the end of multichannel spectrum accumulation, grey area hightlights the time interval used for spectral fitting.

Table 2. Best-fitting spectral parameters.

Parameter	Value
PL index	2.56±0.11
PL norm at 500 keV	$(3.30\pm0.16)\times10^{-2}$ phot cm^{-2} s^{-1} keV^{-1}
CPL index	-1[2]
CPL norm at 500 keV	$(5.7\pm1.8)\times10^{-3}$ phot cm^{-2} s^{-1} keV^{-1}
CPL cutoff energy	2.9±0.5 MeV
e^+–e^- annihil. flux	0.13±0.06 phot cm^{-2} s^{-1}
Nuclear deexc. line flux	0.4±0.3 phot cm^{-2} s^{-1}
Neutron capt. line flux	≤0.06 phot cm^{-2} s^{-1}

[2] Parameter was fixed at a given value.

correlation between them is very weak, if present. In addition, joint observations of PAMELA and Konus-*Wind* brought more puzzles. Solar neutrons are born in nuclear reactions, mostly

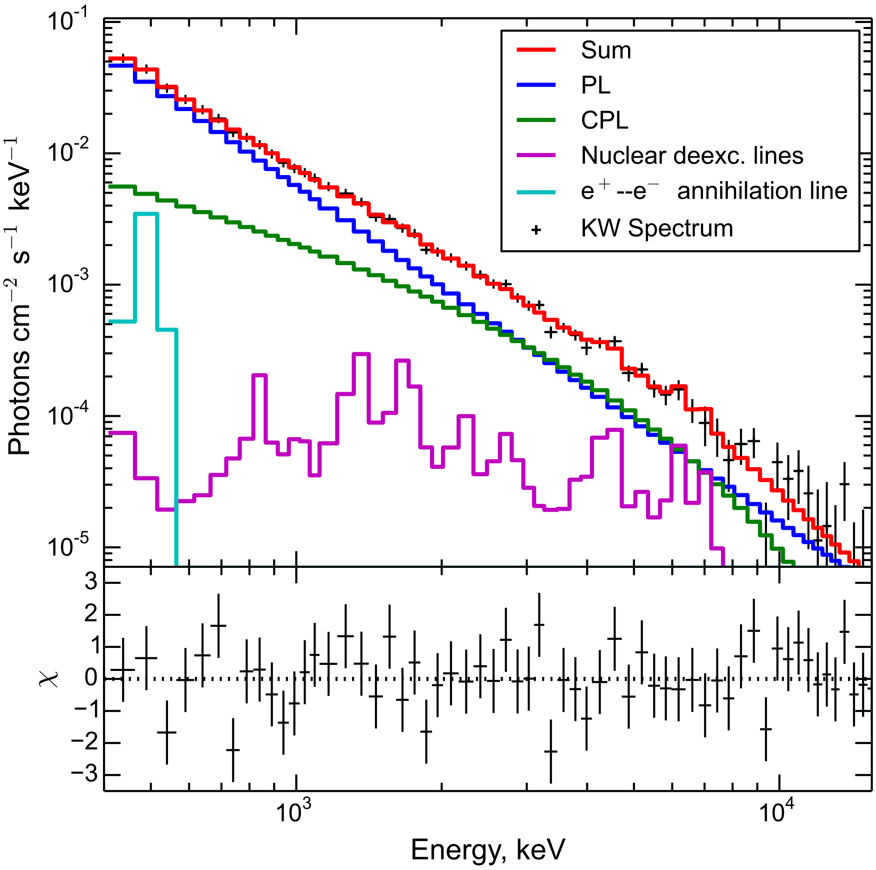

Figure 2. Fitting the multichannel Konus-*Wind* spectrum accumulated for 2012-Jul-06 solar flare between 23:05:41 and 23:06:47. The lower panel shows the fit residuals.

between accelerated protons and protons from the ambient plasma, with a threshold energy E_{th}∼300 MeV, and between accelerated protons and ambient He^4 (E_{th}∼30 MeV) [5], while, for the nuclear deexcitation lines, ∼1–20 MeV nucleon^{-1} ions are responsible [2]. Assuming that accelerated ions have a power-law spectrum falling with energy, the nuclear deexcitation lines should be presented in gamma-ray spectrum every time when neutrons are produced, which is not the case: for 14 solar flares with measured neutron spectra [15] only one flare demonstrated and one more flare could demonstrate emission in nuclear deexcitation lines.

In [11] the relationship was studied between interplanetary protons measured by 3D Plasma & Energetic Particle (3-DP) experiment onboard *Wind* spacecraft and gamma-ray emission registered by Reuven Ramaty High Energy Solar Spectroscopic Imager (*RHESSI*). For two jointly observed flares, the authors found the proton power-law indices measured directly by 3-DP to be very similar to those estimated by *RHESSI* from gamma-ray spectra.

The explanation of non-correlation between gamma-ray flares and SEP events could be that, for the SEP events, additional second-stage acceleration is involved as compared to gamma-ray line events. The mechanism behind this acceleration doesn't change the spectral shape significantly, but it shifts the spectrum towards higher energies. Thus, during the 14 SEP-related flares with measured neutron spectra the amount of low-energy ions (≤20 MeV) was insufficient to produce a significant nuclear deexcitation line emission, but there were enough moderate energy protons to produce neutrons.

The studied X1.1 class flare on 2012-Jul-06, which demonstrated both nuclear deexcitation line emission in the Konus-*Wind* spectrum and solar neutrons registered *in situ*, is in turn very unusual, because there were no evidence for neutron capture line at 2.223 MeV. This can be explained by (i) high anisothropy of flare-produced neutrons; or (ii) high energies of the produced neutrons, thus solar neutrons penetrate deep in the solar atmosphere before being thermalized and 2.223 MeV line is attenuated.

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