Probing solar accelerated particles with Konus-Wind data

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2019

Ioffe Workshop on GRBs and other Transient Sources: 25 years of Konus-Wind

September 9–13, 2019, St. Petersburg, Russia
Summary of Konus-\textit{Wind} solar observations.

Advantages of Konus-\textit{Wind} for solar flare physics.

Short elementary bursts as the probe for electron acceleration.

Gamma-ray emission and ion acceleration.

The puzzle of behind-the-limb flares.
Since 1994 Konus-Wind observed

- ~13000 solar flares in the waiting mode,
- 1042 solar flares in the triggered mode and among them,
- 94 solar flares at energies > 1 MeV.
- All the data on solar flares registered by Konus-Wind in the triggered mode are available online via http://www.ioffe.ru/LEA/kwsun.
Advantages of Konus-Wind instrument for the Sun observations

- Operates since November 1, 1994 till present time – more than two full solar cycles.

- Continuous observations of the Sun in the 20–1200 keV band in the waiting mode. Konus-Wind is an analogue of GOES instrument in Hard X-rays.

- High time resolution (up to 2 ms) in the triggered mode.

- Energy range in the triggered mode (∼ 20 keV–15 MeV) covers emission from accelerated particles (both electrons and ions).
Elementary bursts and electron acceleration

- What are the shortest acceleration time scales?
- Are short bursts and longer bursts produced by different acceleration mechanisms?
- Are longer bursts superposition of shorter bursts?
- We selected short “elementary” bursts for estimation of electric field accelerating the particles.

Lysenko et al.  
Konus-Wind solar observations
Acceleration times $t_{acc} < 50 \text{ ms}$.

Electron energy $E \sim 500 \text{ keV}$.

Acceleration length $L_{acc} \sim <v> t_{acc} \sim 10 \text{ Mm}$.

Electric field $E > A/L_{acc} \sim 0.1 \text{ V/m}$, which is one order of magnitude larger than the typical values of the Dreicer field ($\sim 10^{-2} \text{ V/m}$).

The strongest solar flare of solar cycle # 24 in soft X-rays.

One of the strongest photospheric magnetic field $\sim 5,500$ G (Wang et al. 2018) and strongest coronal magnetic field $\sim 4,000$ G (Anfinogentov et al. 2019) ever observed.

Impulsive phase occurred during “nights” of both *RHESSI* and *Fermi*.


- Accelerated electrons and positrons produced in nuclear reactions $\rightarrow$ continuum, BPL model.
- Accelerated ions $\rightarrow$ nuclear reactions $\rightarrow$ nuclear deexcitation lines ($\sim 2$–30 MeV ions), $\rightarrow$ neutrons $\rightarrow$ neutron capture line at 2.2 MeV ($\sim 20$–300 MeV ions), $\rightarrow$ positrons $\rightarrow$ positron-electron annihilation line at 511 keV (from $\sim 2$ MeV to $\geq 300$ MeV).
Low energy part of continuum shows soft-hard-soft evolution.

BPL power law indices and amplitudes at 100 keV and 10 MeV do not correlate!
- Second stage electron acceleration?
- Contribution from the ultrarelativistic positrons?
- Other than bremsstrahlung emission mechanisms?

Ratio of neutron production rate to nuclear deexcitation lines fluxes $F_{\text{nuclear}}$ is very sensitive to the power law index $s_{\text{ion}}$ of the accelerated ions.

Based on time evolution of $F_{2.2}$ and $F_{\text{nuclear}}$ we estimated limits for $s_{\text{ion}}$ with high ($\sim$30 s) time resolution.

Power law index of the low energy part of the continuum and ion power law index do correlate!
“Ordinary flare”

- Correlation between time profile in hard X-rays and derivative of time profile in soft X-rays – Neupert effect.
- Soft-hard-soft spectral evolution in hard X-rays.

- BTL flare footpoints are located rather far (10–50 degrees) behind the solar limb.
- We observe high coronal sources, stronger footpoint emission is occulted by the limb.
- BTL often show very different behavior relative to “ordinary” flares.
Example of behind-the-limb (BTL) flare: SOL2002-10-27T22:51


- Was located $\sim 50^\circ$ behind the solar limb.
- Demonstrated hard-soft-hard spectral evolution.
- Low response in soft X-rays (GOES 1–8 Å band).
- Soft X-rays derivative is ahead of hard X-rays.
Example of behind-the-limb (BTL) flare: SOL2014-09-01T10:59


- Was located $\sim 44^0$ behind the solar limb.
- Stereoscopic observations were performed by STEREO-B spacecraft.
- No response in soft X-rays (GOES 1–8 Å band).
- High correlation between hard X-rays, microwaves and gamma-rays $> 100$ MeV.
- No spectral evolution in hard X-rays, spectral index $\gamma \sim 2$.

![Graphs and diagrams showing solar flare observations](image-url)
Search for behind-the-limb flares in homogeneous Konus-Wind waiting mode observations

- Criterium for behind-the-limb candidate selection was low response in GOES 1–8 Å channel relative to intensity in Konus-Wind.
- This criterion yielded \( \sim 300 \) behind-the-limb candidates out of \( \sim 16000 \) events.
- For these candidates we used localisations from different instruments \((RHESSI, NoRP, OVSA Nancy)\).
Search for behind-the-limb flares in homogeneous Konus-Wind waiting mode observations

- We found 20 behind-the-limb flares including 3 known from previous studies.

“A Cold Flare with Delayed Heating” by Fleishman et al., 2016, ApJ.

Thank you for attention
Temporal evolution of the 2.223 MeV line in the absence of the ion spectral evolution can be described as (Prince et al., 1983):

\[ F_{2.2}(t) \propto \int_{-\infty}^{t} S(t') R(t, t') \, dt' \]  

(1)

where \( S(t') \) – is the neutron production time profile \( \propto F_{\text{nuclear}}, R(t, t') \) – response function, giving 2.223 MeV line at time \( t \) from a neutron born at time \( t' \propto \exp(- (t - t')/\tau) \), \( \tau \sim 100 \text{s} \) Murphy et al., 2007.

We replace the integral by the sum (Kurt et al., 2017):

\[ F_{2.2}(t_i) \propto \sum_{j=0}^{i} F_{4-7}(t_j) \exp \left( - \frac{t_i - t_j}{\tau} \right) \Delta t_j \]  

(2)

The reason of the discrepancy between data and modeling is the decrease of neutron production after 11:56:36. Why?
Neutron capture line

- Neutron production reduced at least in $r_n \sim 5$ times.
- Possible reason – abrupt steepening of the ion spectrum after the main peak.

Taking the mean ion power index $s_{\text{mean}} \sim 4$ and the neutron reduction rate $r_n \sim 5$ we estimated upper limit for $s_{\text{before}}$ before the peak and the lower limit for $s_{\text{after}}$ after the main peak.

![Graph showing flux vs. time and proton power index vs. s](image-url)