A search for transient events in Konus-Wind data

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Abstract.
We present the search for and classification of hard X-ray and soft $\gamma$-ray transient events in the archive of continuous (waiting-mode) Konus-Wind observations. We found $\sim 26\,000$ transient events; among them, $\sim 12\,000$ are solar flares ($\sim 10\times$ as much as observed in triggered mode); and $\sim 5\,000$ are gamma-ray bursts (GRBs) or soft gamma repeaters (SGRs) confirmed by other space missions ($\sim 2\times$ as much as detected in triggered mode). The remaining $\sim 9\,000$ events include Galactic transients, unconfirmed GRBs and possible solar flares. We discuss the application of developed techniques for GRBs accompanied by supernovae, high-energy neutrinos and sources of gravitational waves.

1. Introduction
The continuing study of the high energy sky has revealed a large number of interesting astrophysical objects with quite different properties [1]. GRBs, SGRs, Galactic transients, and solar flares are the brightest objects in the hard X-ray and soft $\gamma$-ray ($\sim 10\,\text{keV} - 1\,\text{MeV}$) energy band. The study of these objects is providing us with the opportunity to explore a broad range of astrophysics and fundamental physics. For example, it may improve our understanding of the process of jet formation and particle acceleration in GRBs and rapid conversion of magnetic energy in SGRs.

Transient phenomena cover various timescales from milliseconds to many years and demonstrate unpredictable activity - so, to obtain a good rate of detection of transients, we need instruments with very large field of view or even all-sky monitoring missions. Thus, almost 25 years of continuous observations of the whole sky by the Konus-Wind (KW) spectrometer [2] provide a unique opportunity to study high energy transients. Several papers about specific transients in KW data have been published (X-ray pulsar GRO J1744-28 [3, 4]; Cyg X-1 [5]; flare star EV Lac [6]; and black hole binary V404 Cyg [7]), but the search of all KW data for transients has not been made yet.

The KW spectrometer consists of two identical NaI (Tl) detectors S1 and S2, observing the south and the north ecliptic hemisphere, respectively. The instrument operates in two modes: triggered mode and continuous (waiting) mode. In the triggered mode the count rates are recorded in three energy bands G1 (20-100 keV), G2 (100-400 keV), and G3 (400-1500 keV) with high time resolution (up to 2 ms), but the duration of the record for each event is limited to $\sim 230$ s. Also, due to rather strict KW trigger criteria, many transient events are too weak (and/or too smooth, or too soft spectrally) to trigger KW and can be detected solely in the waiting-mode data. The accumulation time of the continuous waiting-mode measurements is...
2.944 s; the data are available in G1, G2, and G3 for the whole time span of KW observations, except for ~ 1 hour gaps after triggers.

In this paper, we present an analysis of the continuous KW archival data. In Section 2, we briefly describe our analysis technique of the search and classification of transient events. In Section 3 we summarise the results and conclude.

2. Analysis technique
2.1. The search algorithm
To search for transients we perform a decomposition of the KW time histories for each detector (S1 and S2) in each energy band (G1, G2, and G3) into Bayesian blocks. The Bayesian blocks algorithm provides an optimal representation of light curve as a series of intervals over which the count rate is constant to within the statistical error [8, 9], the interval bounds are called change-points. The number of blocks are defined by just one parameter ($ncp_{prior}$), which can be determined empirically and interpreted as a control on the false-positive rate for detecting change-points. For the KW data, we calibrated the $ncp_{prior}$ for each energy band in such a way that an interval with $\gtrsim 4\sigma$ excess over background is separated into a block. The adopted values are $ncp_{prior} = 11$ for G1 and $ncp_{prior} = 9$ for both G2 and G3 energy bands. The source code used for the analysis is available at https://github.com/dsvinkin/b_blocks.

Using the obtained decomposition of time histories into blocks we searched for transient events in each energy band independently. By event we consider a set of consecutive Bayesian blocks with $> 4\sigma$ significance above the background. For the background level, we chose the nearest block with a duration longer than 350 s. Then, using the interval tree data structure (https://github.com/chaimleib/intervaltree), we searched for a simultaneous detection of the event in several energy bands or detectors (search for an overlapping interval). An event was selected for further analysis if it was detected simultaneously in both S1 and S2 or in more than one energy band in a single detector. We use this criterion to reject events associated with instrumental glitches or with strong background variations in the softest energy band (G1). Events detected only in G2 were also selected, since this band corresponds to the maximum energy release of GRBs; therefore, some weak GRBs may be detected only in G2.

The search covered a period of 8327 days (between November 1994 and August 2017).

Figure 1. Konus-Wind background count rates in G2 (left) and G3 (right). For each day, the count rate is given by the longest Bayesian block, with durations from 1000 to 83000 s. The $\sim 25\%$ decrease in background count rate in G3 during solar circle maxima is probably due to a superposition of multiple Forbush decreases.
2.2. Instrument background

The correct event identification is possible only on top of a stable background. The daily background count rates of both KW detectors are shown in Figure 1. The background above \( \sim 150 \) keV (G2 and G3) is dominated by secondary particles produced in local material of the detectors and the spacecraft structure. Below \( \sim 150 \) keV, the detector count rate is primarily due to the diffuse X-ray background (see, e.g., [10]). The long-term background variations reflect the solar modulation of galactic cosmic rays during solar cycles 23 and 24. Abrupt short-term (several days) increases in the background are caused by particles from coronal mass ejections. About 750 days (or 9% of the observations) were completely excluded from further analysis due to large number of data glitches or very high and variable background.

2.3. Event classification

First, we eliminated all non-astrophysical events. We use the auxiliary KW “Z” window \((E > 10 \) MeV), which serves as a monitor the cosmic-ray flux, to exclude solar energetic particle events. To eliminate softer particle events observed near crossings of the Earth radiation belts before mid-2004 we use the data provided by the 3-D Plasma and Energetic Particles (3DP) instrument installed on the board of Wind spacecraft [11]. In Figure 2 we show an example of particle event with simultaneous display of KW and 3DP data. As a result of the analysis, \( \sim 4000 \) particle events were identified and excluded from the analysis. The magnetospheric particle events have not been detected since the end of April 2004 when Wind moved to the halo orbit around the Lagrange point L1.

Solar flare candidates were identified using an automated procedure by their prominent features: approximately equal intensity in both KW detectors and high G1/G2 count ratio implying a soft spectrum. GRB candidates were identified as events with relatively hard spectrum. Galactic hard X-ray transients show a soft spectrum, complex light curve shape, and relatively long durations, usually longer than few minutes. Finally, we searched for event confirmations in GCN Circulars (https://gcn.gsfc.nasa.gov), the Astronomer’s Telegrams (https://astronomerstelegram.org), and other instrumental catalogs and databases.

2.4. Upper limits

The KW waiting-mode data are well-suited to the search, both blind and targeted, for gamma-ray transients in response to particular events, such as GRB-less supernova, high-energy neutrino events, or gravitational-wave (GW) binary merger candidates. In the case of non-detection, setting upper limits on soft gamma-ray emission from these events allows to constrain an energetics of possible accompanying GRB (long or short).

For any type of the event we usually estimate two types of upper limits. For a burst lasting less than 2.944 s and having a typical KW short GRB spectrum (an exponentially cut off power law with \( \alpha = -0.5 \) and \( E_p = 500 \) keV) we provide limit on the 10 keV - 10 MeV fluence. For a typical long GRB spectrum (the Band function with \( \alpha = -1, \beta = -2.5, \) and \( E_p = 300 \) keV) we derive limiting peak flux \((10 \) keV - 10 MeV, 2.944 s scale). The limits are given at confidence level \( P = 90\% \).

To calculate an upper limit, we estimate the background count rate \((C_{bg} \) counts per bin) and search for a bin with maximum count rate \((C_{max})\) in the interval of interest for all combinations of KW energy bands (G1, G2, G3, G1+G2, G2+G3, and G1+G2+G3). For the bin we define \( C_P \) so that the observed value \( C_{max} \) corresponds to inverse CDF of the normal distribution with mean \( C_P \), \( \sigma = \sqrt{C_P} \), and probability \( 1 - P \). We adopt the \( C_{UL} = C_P - C_{bg} \) as the upper limit on the source counts.

Using the current detector calibration we estimate the energy-to-count conversion factor \( k \) using KW detector response matrix for each energy band. The maximum value of \( kC_{UL} \) \((kC_{UL}/2.944)\) across the bands is adopted as the upper limit on fluence (peak flux).
Figure 2. Example of particle event on October 20, 2003. The top three panels show the KW data - count rates in G1, G2, G3 energy bands. The bottom two panels show the 3DP data - the fluxes (in units of $1/cm^2/ster/eV/s$) of electrons with energies of 30 - 500 keV and protons with energies of 70 keV - 6.8 MeV. It was verified that even the brightest GRBs and solar flares do not give a response in 3DP.

3. Results and conclusions
Using the search algorithm described in previous section, we found a total of 30635 events. Then, by a visual analysis of each event (using the developed web interface) the particle events and glitches were filtered out and $\sim 26,000$ events were selected for further analysis. Among them, $\sim 12,000$ are solar flares (near 10 times as much as observed in the triggered mode), and $\sim 5,000$ are GRBs and SGRs confirmed by other space missions such as Compton, BeppoSAX, Swift and Fermi (near 2 times as much as detected by KW in triggered mode). The remaining $\sim 9,000$ events include Galactic transient activity, unconfirmed GRBs, and possible solar flares. Example light curves of four detected events of different nature are shown in Figure 3. In Figure 4 we show detection statistics per year and the detection summary for the whole analysed observation period 1994 - 2017.

The KW spectrometer provides the largest sample of continuous observations covering 20 keV - 15 MeV energy band. It observed tens of thousands astrophysical events in hard X-rays and soft $\gamma$-rays from 1994 to the present time (March 2019), and we expect this sample to grow further in the forthcoming years. The obtained set of events is of high importance, as it allows us to continuously monitor the solar activity and the outburst activity of hard X-ray transients. In the multi-messenger context, GRBs are of particular interest with their association with the
Figure 3. Examples of the light curves of several detected events: the black-hole binary V404 Cygni (top, left), the black-hole binary Cygnus X-1 (top, right), the behind-the-limb (BTL) solar flare (bottom, left) and ultra long GRB 130925A (bottom, right).

sources of gravitational waves and high-energy neutrinos [12, 13]. The GRBs found in this work have been used to search for GWs signal in LIGO data. GRBs can also be associated with the supernova, currently there are several dozen of reliable identifications [14]. Using an approach described in section 2.4 we reported upper limits for supernovae [15, 16, 17] neutrino events (see, e.g. [18]) and gravitational wave events (see, e.g. [19, 20]).
Figure 4. KW transient statistic per year (top), KW transient summary (bottom).

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