Observations of γ-ray Bursts and Solar Flares with Granat

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1 Granat orbit

The *Granat* observatory was launched into a high apogee orbit on 1989 December 1 by a PROTON launcher. The initial *Granat* orbit had an apogee close to 200 000 km and a perigee of 2 000 km with an orbital period of 4 days. The satellite is entering the radiation belts for a few hours every orbit. Due to orbital evolution the perigee increased and the apogee decreased with time. After about 1.5 years of operation the perigee increased up to 20000 km. This has put the satellite completely outside of the proton radiation belts which makes the detector activation during the perigee passage negligible. Moreover, the satellite orbit is outside of the magnetosphere during the most parts of the mission. This makes such an orbit very attractive for high energy astrophysics missions which require low background level in order to achieve high sensitivity, and makes it essential for the investigation of the high energy transient phenomena such as cosmic γ-ray bursts and solar flares.

2 Instrumentation

The three instruments *PHEBUS* (6 BGO detectors situated at the different sites of the spacecraft), SIGMA (coded mask, position sensitive NaI detector with anticoincidence shield), and WATCH (rotation modulation collimatored all-sky monitor), are able to detect and investigate γ-ray bursts and high-energy solar flares in a broad energy range from 6 keV up to 100 MeV.

PHEBUS operates in the 100 keV – 100M eV energy range. Its sensitivity for gamma-ray burst detection is $\sim 10^{-6}$ erg cm^{-2} in almost 4π ster. The effective area of each detector is varying from 50 to 94 cm^2 depending on the GRB source position in the sky. All six detectors are recording the information about the burst simultaneously after a trigger which is provided by the *PHEBUS* electronics in the case if two detectors simultaneously detect count rate excesses at a level of 6σ in the 100 keV – 1.6 MeV energy range. Some prehistory of the background just before the γ-ray burst is also recorded.

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The effective area of each NaI and CsI scintillator detector of *WATCH* is 45 cm^2. The sensitivity of this instrument is S(6 – 120keV) $\sim 10^{-6}$ erg/cm^2. Four detector units of this instrument are mounted on the spacecraft along four tetragonal axes. The field of view of each detector is π ster.

The *SIGMA* coded mask telescope is able to detect γ-ray bursts both with CsI anticoincidence shield detectors and with the positional sensitive detector with coded mask. The high effective area of the positional-sensitive detector gives the possibility to search (with high sensitivity of $(3-8) \times 10^{-8}$ erg/cm^2) and to investigate γ-ray bursts occurring in the 4.7×4.3 deg^2 field of view.

3 Cosmic γ-ray bursts

On the basis of the data sets published in two *PHEBUS* catalogues (Terekhov et al. 1994, 1995), the spatial distribution of the observed GRB sources was found to strongly deviate from a homogeneous one. From 118 cosmic γ-ray bursts observed by the *PHEBUS* instrument a $< V/V_{max} >= 0.366 \pm 0.012$ is derived. This clearly shows that there is deficiency of weak GRB sources.

The question about the presence of lines in γ-ray burst spectra is important for the determination of the nature of GRB sources. Using spectral information from several detectors it is possible to increase the significance of observed line features, and to discriminate against artificial lines due to scattering or absorption from nearby mechanical hardware placed on the spacecraft. Statistical analysis of large sets of γ-ray burst spectra shows that there is no evidence of statistically significant emission features in the 511 keV region and below at the level of few percent of the continuum emission intensity (Lobachev et al. 1995).

Simultaneous observations of cosmic γ-ray bursts in different energy ranges shows that strong spectral variability during GRBs takes place. The results of the analysis of GRB920723 revealed evidence for the presence of at least four differently varying spectral continuum components.

- A soft, slowly varying component is observable between a few keV – few tens of keV. This component probably is dominating the X-ray rich GRBs observed by WATCH (Castro-Tirado et al. 1994).
- Spectral analysis of the *SIGMA* (Pelaez et al. 1994) data as well as *BATSE* (Schaefer et al. 1992) results show that the energy spectra of some γ-ray bursts are more compatible with broken power law (different spectral components below and above a certain break energy) rather than with a single component law. Detailed analysis of the *PHEBUS* data for GRB920723 shows that both these two components are varying with time during the GRB event (Terekhov et al. 1995b).
- In addition to these three components an additional very hard power law component appears sporadically during the GRB event for very short (less than 1 s) time intervals (Terekhov et al. 1995b). During its presence, such a component dominates the whole energy range above 100 keV.

The *WATCH* instrument observations of γ-ray bursts show that in some cases such as GRB920723 and GRB900222, the decaying flux of soft X-ray emission in the 6 – 20 keV energy range follows the GRB event during at least 40 s after main gamma-ray pulse with a typical duration of 10 sec (Terekhov et al. 1993; Castro-Tirado et al. 1994). About 10% of the *WATCH* γ-ray bursts display X-ray tails or X-ray precursor activity. There is no preferential concentration for such X-ray rich events (for instance to the galactic plane or galactic center). The isotropic sky distribution was found for all sets of γ-ray bursts (32 events) localised by the *WATCH* instrument (Castro-Tirado et al. 1994).

WATCH is able to set upper limits for the X-ray flux from any point in the sky which is in its field of view. This means that it would detect any significant X-ray activity from γ-ray bursts which is precisely localised. The *WATCH* localisation accuracy is less than 1° error radius. No quiescent radiation is detected neither before nor after γ-ray burst events from the γ-ray burst sources. The upper limits for the quiescent emission fluxes from GRB920723 as well as from other GRB sources are $\sim$50 mCrab for time scales of hours and $\sim$20 mCrab for time scales of days.

A large fraction of the cosmic γ-ray bursts detected by the *PHEBUS* instrument are short. About 30% of the events have durations less than 2 s. Such events have energy spectra which are significantly harder than the energy spectra of the long γ-ray bursts. It is interesting to note that in spite of the short duration the time histories of such events are very complex. Time histories of short γ-ray bursts consist of individual flashes with duration 2 – 10 ms and with the separation between individual flashes of the order of 10 ms. Some individual pulses have very sharp front and decay edges with characteristic times 0.2 – 0.4 ms as in the case of GRB900320 (Terekhov et al. 1992).

The *SIGMA* telescope was pointed towards the galactic center for almost 18% of its observing time. For an object placed at the distance of the galactic center the threshold burst luminosity in the 40 – 90 keV energy range is 3×10^{38} erg s^{-1}, thus only slightly exceeding the Eddington luminosity for a neutron star. The absence of weak GRBs from the galactic center direction indicates that either the luminosity of typical GRBs is below 10^{38} erg cm^{-2} or, alternatively, the luminosity is higher than 10^{40} erg s^{-1} (Sunyaev et al. 1993). Note that recent observations of the *BATSE* instrument gave detailed constraints based on the absence of the GRB source clustering to the galactic plane and LMC reported by Meegan et al. (1994) for local disk and extended halo models (Hartmann 1995).

Observations of extragalactic sources with the *SIGMA* telescope gave constraints for the frequency of the appearance of GRB events for different extragalactic objects in a suggestion that GRBs are of extragalactic origin. Upper limits can be derived for the density of GRB sources per one solar mass of the matter for some of the extragalactic objects (Sunyaev et al. 1993).

4 High-energy solar flares

Granat carried out its observations during the solar maximum which took place in 1990-1991. During this time interval very high solar activity was observed by *Granat* instruments. The most interesting data on observations of high energy solar flares in the 100 keV – 100 MeV energy range were obtained by the *PHEBUS* instrument. Some of these bursts have also been observed up to 15 MeV by the *SIGMA* anticoincidence shield (Pelaez et al. 1992). Over 80 solar flare events with significant emission above 100 keV were detected during 1990-1993.

About 26% of these solar flares are associated with extremely intense GOES X-class events. Among these solar flares there are several extraordinal events with significant emission up to 100 MeV. Among the most interesting solar flares is SF900524 – a classical example of the high energy solar flare. During this flare a complex of high energy phenomena was observed which usually are associated with high energy solar flares: photons with energy up to 100 MeV, π^0 decayed photons, high energy neutrons, 2.2 MeV line associated with deuterium synthesis on the solar surface, fast protons appeared in a very short time after the beginning of the x-ray event (Terekhov et al. 1993,1995c; Talon et al. 1993).

In the flare SF910125 γ-rays up to 10 – 16 MeV are detected. No emission in the 65 – 124 MeV energy range is found for this flare. The flux of this flare in the energy range 1 – 4 MeV was by a factor of 30 lower than one for SF900524. It is interesting to note that according to GOES classification based on soft X-ray observations these two flares have nearly equal intensities: X9.3 for SF900524 and X10.0 for SF910125. The heliocentric angle was also not dramatically different for these flares: 81° for SF900524 and 77° for SF910125.

Some solar flares detected by the *PHEBUS* instrument have quasi-periodic pulsations of the intensity with the typical period of ~10 s. SF900524 and SF910125 also have such important feature in their light curves. The Q-factors (number of separate pulses with the typical period) of these two flares are different. While $Q = 16$ for SF910125, it is only 4-5 for SF900524. The modulation depth of the emission can be estimated as ~0.32 for SF900524 and ~0.27 for SF910125.

Deep modulation of hard X-ray and microwave emission with a period ~10 s was explained in terms of Alfvenic oscillations of a single flaring loop (Stepanov et al. 1992). In this model these pulsations are driven by Alfvenic oscillations of a flare loop excited due to upward motion of chromospheric evaporated plasma. According to this model one can estimate the density n and temperature T of the evaporated plasma as well as the flare loop magnetic field B and loop length L. It is possible to also estimate the pulsations (Stepanov et al. 1992), and that the lengths of the loops L of these two flares are nearly the same and equal to $\sim 10^9$cm ($L_9 \sim 1$). Based on this model it is possible to find that during SF900524 $T \approx 4.7 \times 10^7 L_9^2$ K which is about a factor two higher than in SF910125, $n \approx 1.5 \times 10^{12} L_9^3 G$ one order of magnitude higher and $B \approx 6.1 \times 10^2 L_9^{5/2} G$ which is 4 times higher than in the case of SF910125. These differences probably play an important role in extremely unusual properties of the SF900524 solar flare during which particles were accelerated up to very high energies.

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