3.6.1. THE GAMMA-400 PROJECT. DIRECT MEASUREMENTS OF THE PRIMARY GAMMA-RADIATION IN THE ENERGY RANGE 30 GEV – 1 TEV

Main scientific goals

1. The measurements of the gamma-ray energy spectra of the Galactic diffuse radiation and some astronomical objects up to 1 TeV.

2. Search for monoenergetic gamma-ray lines, created by the annihilation of neutralinos, supersymmetric particles, which, as supposed, form Dark Matter.3. Long-time (about 5 years) observations of the strong gamma-ray sources.

3.6.1.1. Telescope GAMMA-400 has basically ordinary structure. It consists of following systems

1. Primary gamma-ray selection systems: veto-detector (AC), lead converter (C), scintillators (SU, SL) for detection of the conversion products.

2. Coordinate system (detectors CD) determining direction of charged particles.

3. System for measurement of electron cascade energy (sampling calorimeter SC) (Fig. 1).

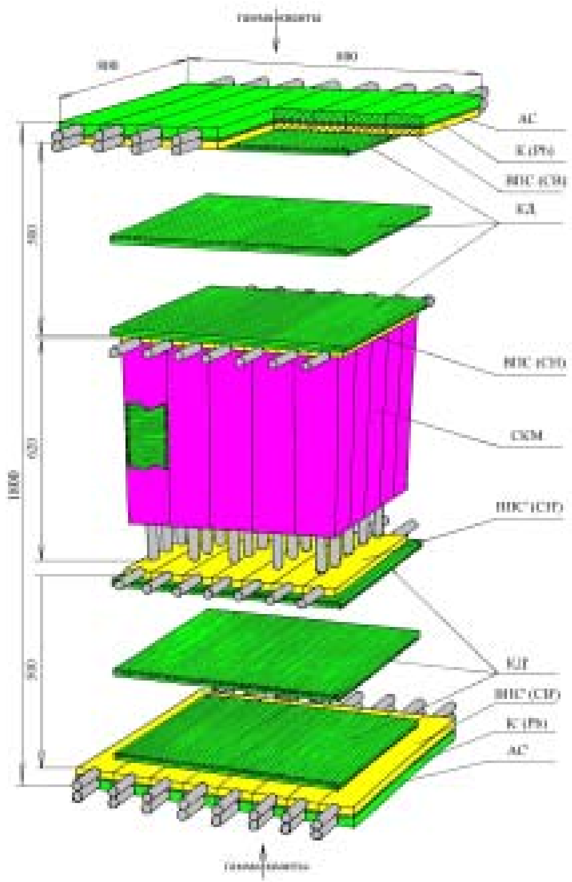

Fig. 1. The GAMMA-400 gamma-ray telescope

3.6.1.2. GAMMA-400 telescope possesses some specific features

1. All detectors used are plastic scintillators. It raises device reliability and lowers cost.2. There is special system to eliminate the influence of backward particles scattered from calorimeter to veto-detector. It gives possibility to measure the energy spectra up to several TeV.

3. Detectors of coordinate system are narrow scintillators (strips) with wavelength shifter (WLS) fibers collecting light. Low voltage silicon photomultipliers (SiPM) are used as light receivers. As a result, we can decrease energy consumption and cost.

4. Two sets of gamma-ray selection systems placed on upper and lower calorimeter butt ends (Fig. 2) are used. In this case, geometric factor of the telescope is doubled with the slight increase of telescope weight.

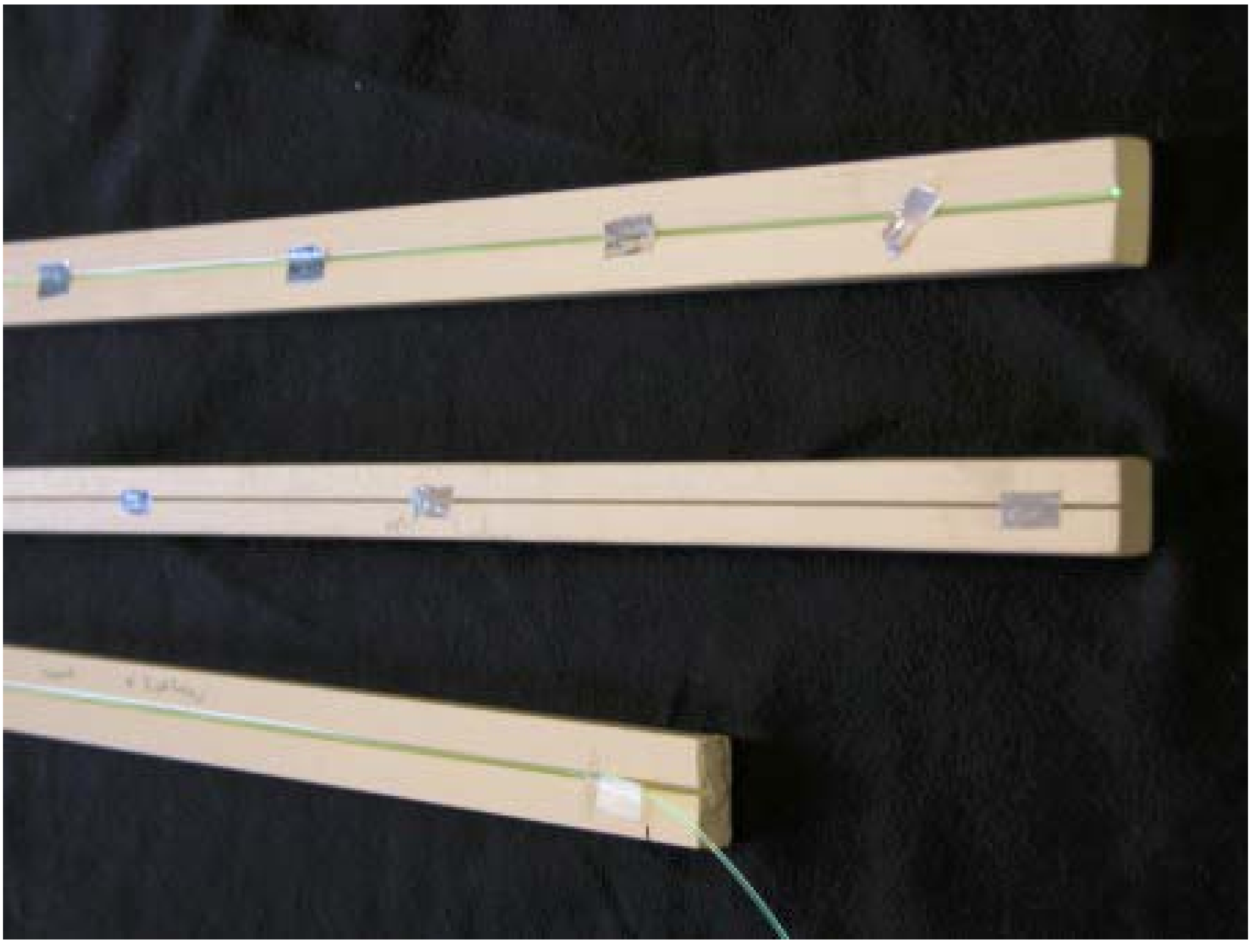

Fig. 2. Photograph of scintillation strips with wavelength shifter fibers

5. Calorimeter is assembled from 25 separate modules (Fig. 3). Every sampling type module consists of alternate layers of lead (thickness 0.55 mm) and scintillator (thickness 1.5 mm). Total calorimeter thickness is 18 radiation lengths (200 layers of lead and scintillators). Scintillation light is collected by 144 WLS fibers, transpiercing all scintillation layers, and is transported to vacuum photomultiplier (Fig. 4, 5).

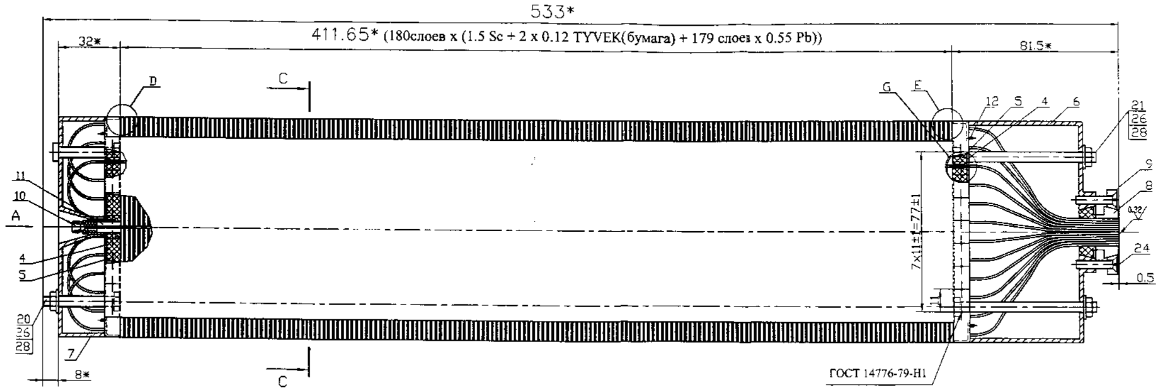

Fig. 3. Scheme of one calorimeter module

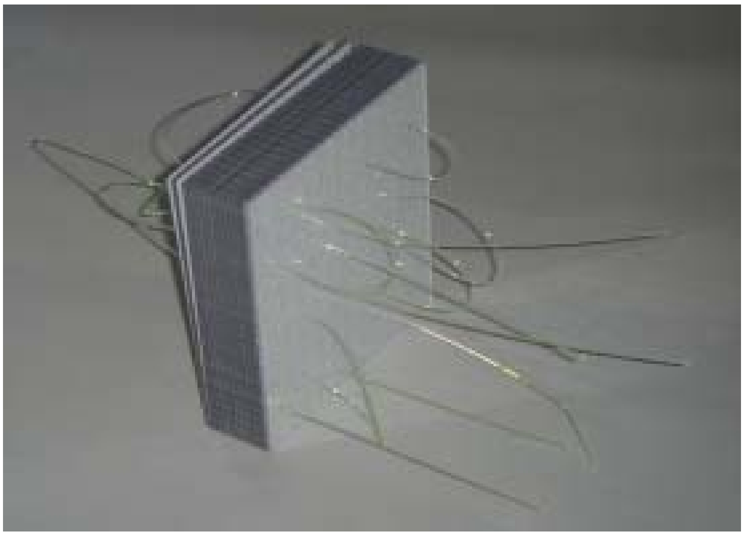

Fig. 4. Element of calorimeter

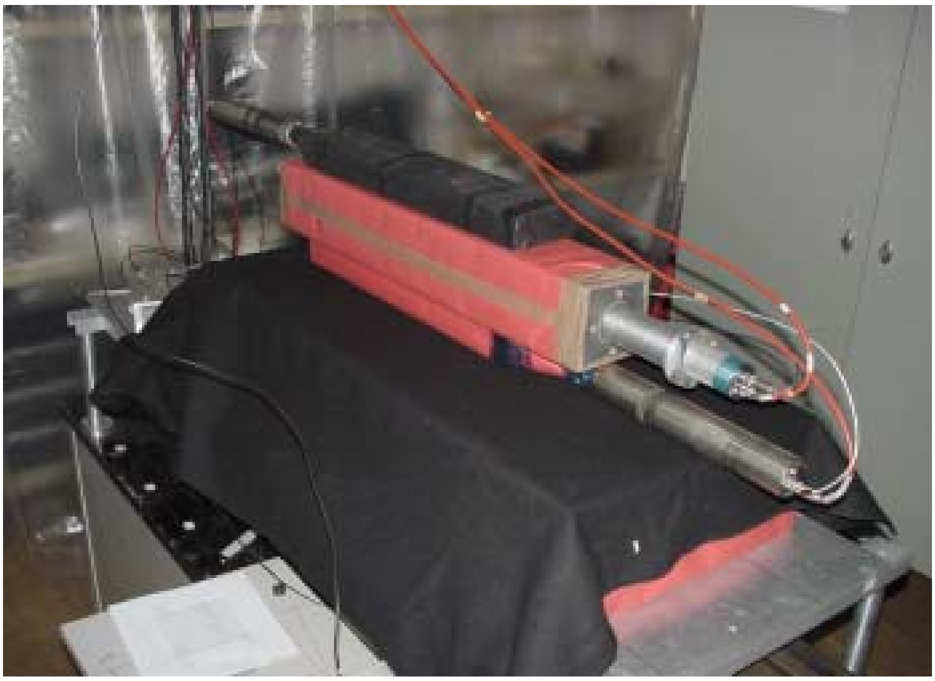

Fig. 5. Measurement of the module performances by means of cosmic rays

GAMMA-400 performances

Geometrical factor .... 1 m^2sr
Conversion efficiency 0,7
Measurement accuracy of gamma-ray direction (Eg = 1 TeV) .... 1°
Angular resolution for point gamma-ray sources .... 0,1°
Energy resolution (Eg = 1 TeV) .... 1.8 %
Telescope weight .... 800 kg

Si-PM performances

Telescope weight .... 800 kg
Supply voltage .... 20–50 V
Gain... 10^6
Time resolution .... 30 ps

3.6.1.3. Present status of the GAMMA-400 project

1. Monte-Carlo simulations of the telescope performances are carried out.
2. Block-schemes of separate electronic telescope systems are developed.
3. Solid-state silicon photomultiplier performances are investigated.
4. Laboratory version of calorimeter consisting of 9 modules is manufactured and now is prepared for measurements with cosmic-ray particles (Fig. 6).
5. Model of coordinate system is under construction and manufacture.
6. We begun consultations with Lavochkin Construction Office, which creates scientific satellites, on the realization of the GAMMA-400 experiment.

Fig. 6. Laboratory version of calorimeter

3.6.2. ASTROPHYSICS

3.6.2.1. Several important astrophysical studies were made by Russian astrophysicist during two years of observations of INTEGRAL — joint ESA, Russia and NASA gamma-ray observatory

Detailed study of positron annihilation spectra at central part of Galaxy according to INTEGRAL measurements

The most important of the recent INTEGRAL finding is that the central part of our Galaxy is a site of copious production of positrons. INTEGRAL observatory is now making the most precise measurements of the positron annihilation spectrum of the Galaxy.

The observed flux implies that of order 10^{43} positrons per second are annihilating in the inner part of our Galaxy. An important and unsolved problem is the origin of these positrons. In astrophysical conditions positrons can be born during nuclear decay of radioactive elements, produced in supernovae and nova explosions. They can also appear in the vicinity of rapidly rotating neutron stars or black holes, be produced by interaction of cosmic rays with ordinary matter or by gamma-ray bursts. But the most fascinating is a possible link between positron production and the "dark matter" particles. Some versions of the modern theory allow dark matter particles to annihilate with each other, albeit very rarely, and to give rise to positrons along with other particles.

In most scenarios positrons are born hot, i.e. their kinetic energy is at least of the order of their rest mass. Once the positrons cool down via collisions with electrons and protons they can capture electron and form so-called positronium atoms. Positronium appears in two flavors (depending on the total spin of the atom): para and ortho-positronium, with the former accounting for about 75 % of all positronium atoms and the latter making up the remaining 25 %. Ortho-positronium annihilation produces two photons with energy equal to the rest mass of the electron or the positron — 511 keV, which can be observed by telescopes as a narrow gamma-ray line. Para-positronium decays into 3 photons and instead of a narrow line a broad continuum is observed. These are exactly the signatures which INTEGRAL sees coming from the central region of the Galaxy. The position of the line center is found to coincide with the rest energy of the electron or positron to an accuracy better than one part out of 10 000. Both the width of the line and ratio of the fluxes in the narrow line and low energy continuum are consistent with the annihilation of positrons in a warm (T ~ 8000K) slightly ionized gas which is one of the widespread phases of the interstellar medium in the Galaxy.

The innermost region of the Galaxy is especially bright in the annihilation radiation. This can be considered as an argument against association of the annihilation radiation with the positrons produced by young massive stars, which are predominantly found in the disk of the Galaxy, rather then in the bulge. Type I supernovae — the "standard" candidate for positrons production could be the primary source, but to account for the bulk of the Galactic positrons they have to escape from a dense supernova remnant. Production of positrons by dark matter particles therefore remains an attractive option. A crucial test would be provided by comparing the exact morphology of the annihilation line intensity distribution with the distribution of potential sources of positrons, including compact sources, supernova remnants and dark matter. INTEGRAL is now making a detailed map of annihilation radiation to finally resolve this problem.

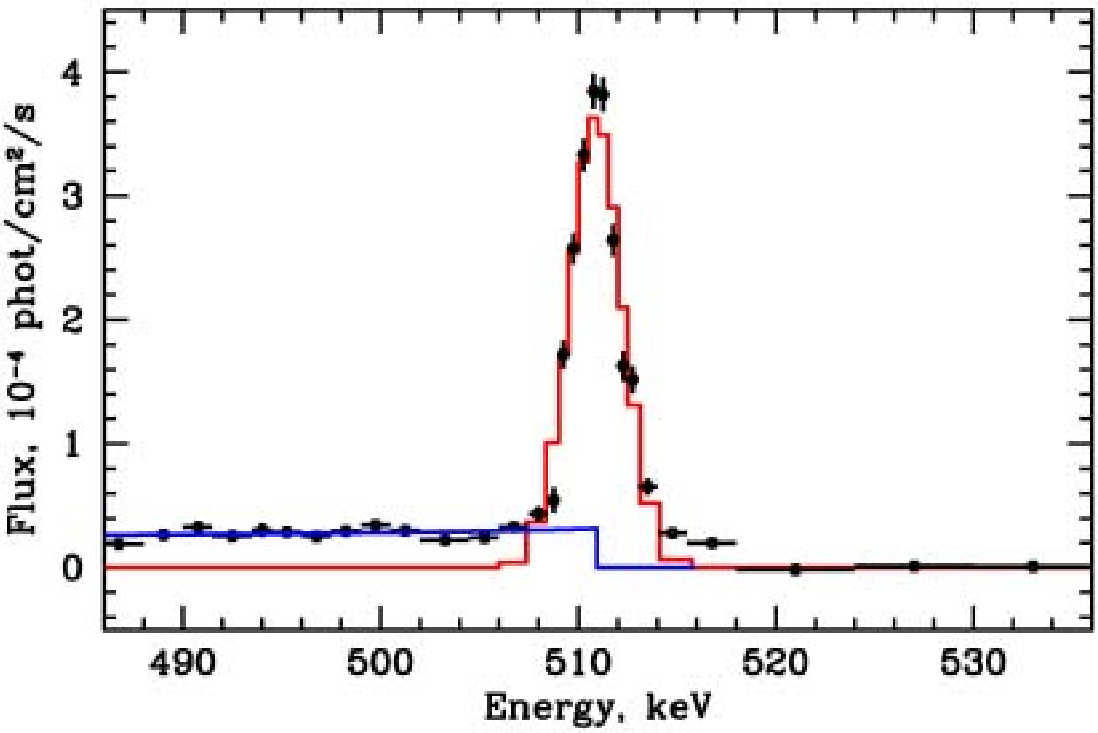

Fig. 7. Spectrum of the e+e- annihilation radiation measured by INTEGRAL from the GC region after 3.5 million seconds exposure. The red line shows the positron annihilation line, while blue line shows the continuum spectrum associated with the three photon ortho-positronium decay

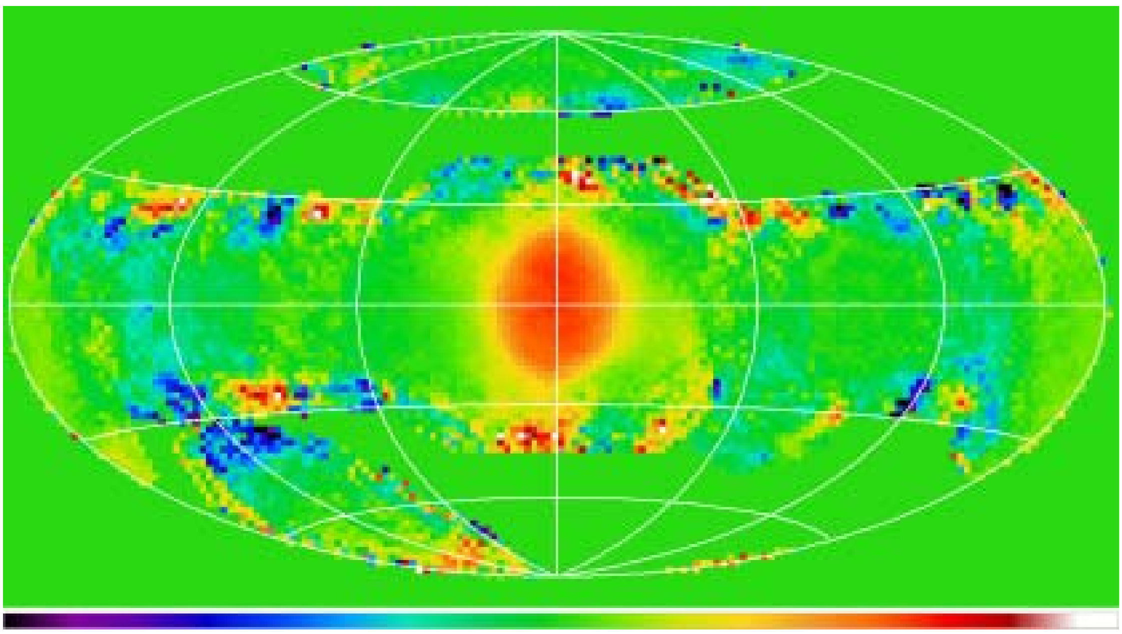

Fig. 8. Heavily smoothed image of the Milky Way emission in the electron-positron annihilation line. Central bright spot corresponds to the Galactic Center region

GRB 031203: unusually underluminous gamma-ray burst

INTEGRAL detects an underluminous gamma-ray burst. On 2003 December 3 the hard X-ray imager IBIS on INTEGRAL detected a gamma-ray burst, GRB 031203. It went off in a galaxy at a redshift of $z = 0.105$. With a duration of 40 s and rest-frame spectral peak energy of >200 keV this event appears to be a typical GRB, even though its isotropic gamma-ray energy, $\sim 10^{50}$ erg, is about three orders of magnitude smaller than typically found for distant GRBs. This burst as well as GRB 980425 are clear outliers for the much discussed isotropic-energy peak-energy relation and luminosity spectral-lag relations.

This discovery suggests the existence of a new population of GRBs that are much less energetic than the majority of those known so far. Such under-luminous bursts may occur very frequently in the Universe, and the bulk of this population has probably escaped our attention simply owing to its intrinsic faintness. GRB 980425 and GRB 031203 can be just the tip of the iceberg and the recently launched NASA's SWIFT spacecraft should find more sub-energetic GRBs.

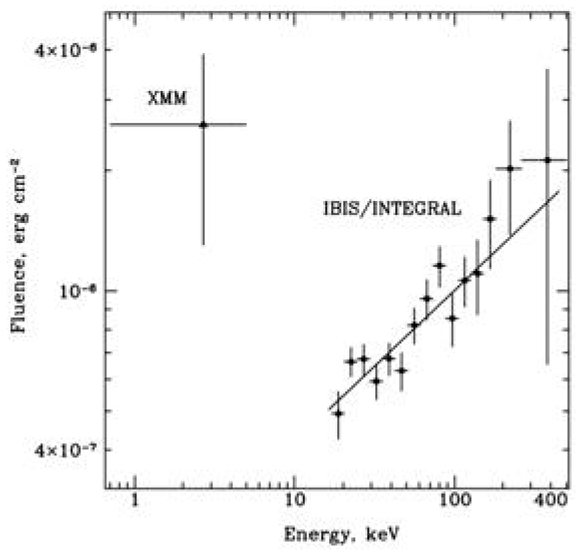

Fig. 9. Energy spectrum of underluminous gamma-ray burst GRB 031203 discovered by INTEGRAL

Extragalactic Source Counts in the 20-50 keV Energy Band from the Deep Observation of the Coma Region by INTEGRAL/IBIS

The Coma Cluster was observed by INTEGRAL observatory with a deep, 500 ks exposure. In addition to the Coma cluster itself, the final 20–50 keV image contains serendipitous sources which have been used to extend the extragalactic source counts in the 20–50 keV energy band down to a limiting flux of 10^{-11} erg/s/cm^2 (~1 mCrab). This is a more than a factor of 10 improvement in sensitivity compared to the previous results in this energy band obtained with the HEAO-1 observatory. The derived source counts are consistent with the Euclidean relation, $N(>f) \sim f^{-1.5}$. A large fraction of identified serendipitous sources are low-redshift, $z < 0.02$ AGNs, mostly of Seyfert 1 type. These sources directly account for 3 % of the cosmic X-ray background in the 20–50 keV energy band. Given the low redshift depth of that sample, one can expect that similar sources at higher redshifts account for a significant fraction of the hard X-ray background.

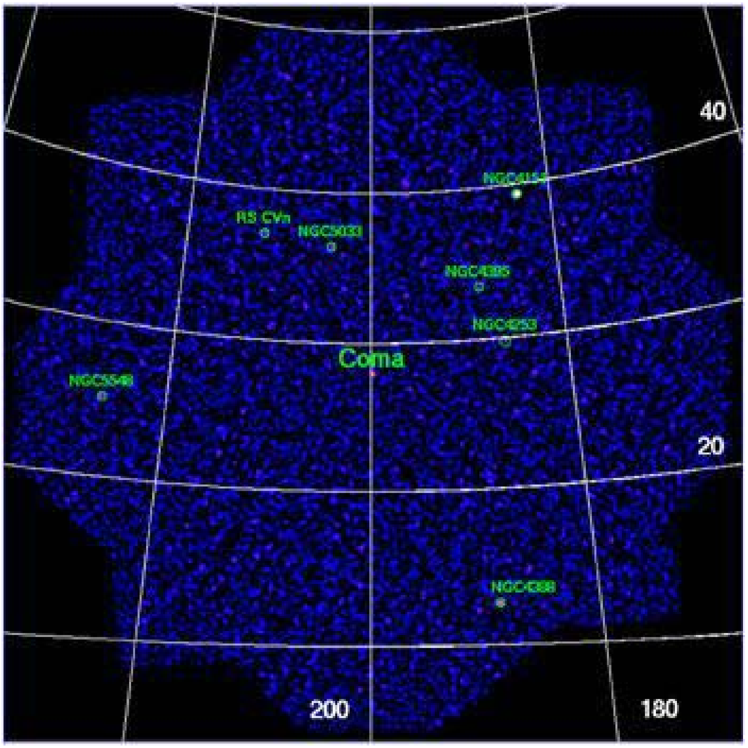

Fig. 10. Image of Coma Region by INTEGRAL/IBIS

Hard X-ray bursts observed with IBIS telescope onboard INTEGRAL in 2003–2004

Here presented the results of the search for X-ray bursts in the archived data of the first one and a half years of IBIS/INTEGRAL work on the orbit (10.02.2003–02.07.2004). Scaning of the 15–25 keV lightcurves measured with the IBIS/ISGRI detector have revealed 1077 bursts with durations ranging from ~5 to ~500 s. All the events passed quite a high statistical criterion, allowing only a 20 % chance for a fake burst to be detected as a true one in the whole time series. In total 115 bursts were localized and all of them but one were identified with known persistant or transient X-ray sources (96 — with the known X-ray bursters). Among the rest of detected events some were related to cosmic gamma-ray bursts and solar flares passing through a telescope cover. One of the localized bursts was related to none of the known sources, but originated from a new burster with a very low persistent luminosity. We named it IGRJ17364-2711. All the information on the localized bursts observed from X-ray bursters is collected in a burst catalogue. It is worth mentioning that 61 of the observed bursts originated from one X-ray burster — GX354-0. This fact allowed us to build and investigate statistical distributions of bursts from this source on its duration, peak flux and reccurence period. Some of the identified bursts were also observed with the JEM-X/INTEGRAL X-ray monitor allowing us to build lightcurves for these bursts in the standard X-ray band — 3–20 keV.

INTEGRAL insight into the inner parts of the Galaxy.

High mass X-ray binaries

A new large sample of high mass X-ray binaries in the inner part of the Galaxy from the Norma spiral arm region to the Sagittarius spiral arm region (-35 grad. < l < 50 grad.) is obtained with the INTEGRAL observatory. This sample is significantly larger than the HMXBs sample in the same region of the sky, based on RXTE/ASM data, used early. The main reason for this is the hard X-ray energy band (18–60 keV) used in the present observations which helped to reveal a considerable population of absorbed HMXBs. The majority of HMXB sources in our sample are significantly photoabsorbed. We performed for the first time a spectral analysis for 8 strongly absorbed sources of our sample. Based on the spectral approximations we argue that the majority of these sources should be neutron star binaries with a high mass companion. We detected pulsations in the hard X-ray flux (18–60 keV) from IGR J16358-4726 with the period $P = 5980 \pm 22$ s and discovered pulsations with the period $P = 228 \pm 6$ s in the X-ray flux of IGR J16465-4507 using the data of XMM-Newton. We constructed the angular distribution of high mass X-ray binaries in the inner part of the Galaxy (see Fig.5) and showed that this distribution differs from the distribution of LMXBs, which are concentrated in the Galactic Center. A small offset of the density peak of detected high mass X-ray binaries from spiral arms tangents was found. Such a displacement can be connected with the delay between the star formation epoch and the time when the number of HMXBs reach its maximum, the proper motion of stars and spiral waves, etc. Its statistical significance is not enough at the moment to make final conclusions and more observations are needed.

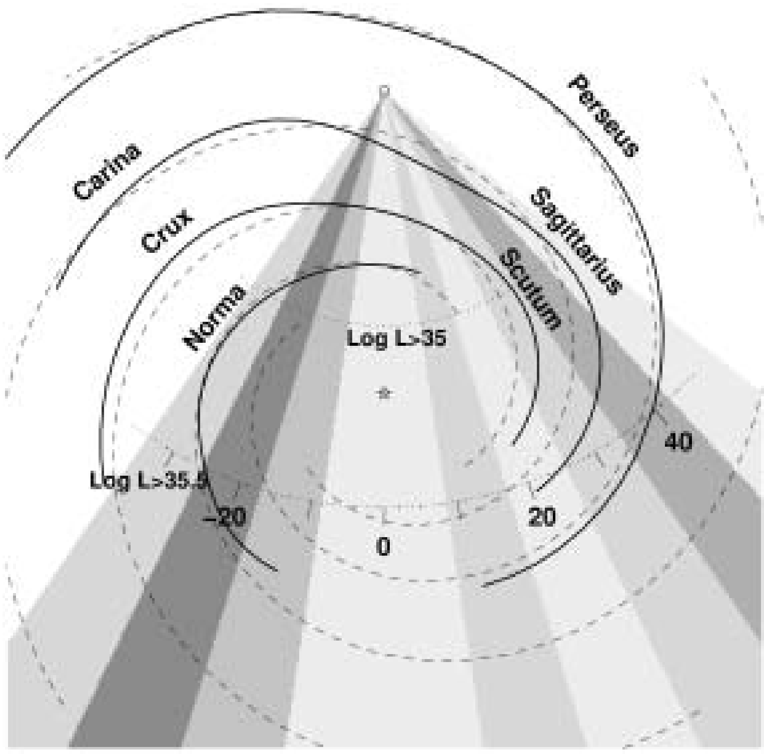

Fig. 11. Map of Our Galaxy with relative HMXB distribution

Hard Spectra of X-ray Pulsars from INTEGRAL Data

Spectra for 34 accretion-powered X-ray and one millisecond pulsars that were within the field of view of the INTEGRAL observatory over two years (December 2002 – January 2005) of its in-orbit operation and that were detected by its instruments at a statistically significant level (> 8 sigma in the energy range 18–60 keV) were measured. There are seven recently discovered objects of this class among the pulsars studied: 2RXP J130159.6-635806, IGR/AX J16320-4751, IGR J16358-4726, AX J163904-4642, IGR J16465-4507, SAX/IGR J18027-2017 and AX J1841.0-0535. We have also obtained hard X-ray (> 20 keV) spectra for the accretion-powered pulsars RX J0146.9+6121, AX J1820.5-1434 and AX J1841.0-0535 for the first time. We analyze the evolution of spectral parameters as a function of the intensity of the sources and compare these with the results of previous studies.

Long-Term INTEGRAL and RXTE Observations of the X-Ray Pulsar LMC X-4

We analyze the observations of the X-ray pulsar LMC X-4 performed by the INTEGRAL observatory and the All-Sky Monitor (ASM) of the RXTE observatory over a wide energy range. The observed hard X-ray flux from the source is shown to change by more than a factor of 50 (from ~70 mCrab in the high state to ~1.3 mCrab in the low state) on the time scale of the accretion-disk precession period,whose mean value for 1996—2004 was determined with a high accuracy, P_{prec} = 30.275±0.004 days. In the low state, a flare about 10 h in duration was detected from the source; the flux from the source increased by more than a factor of 4 during this flare. The shape of the pulsar’s broadband spectrum is essentially invariable with its intensity; no statistically significant features associated with the possible resonance cyclotron absorption line were found in the spectrum of the source.

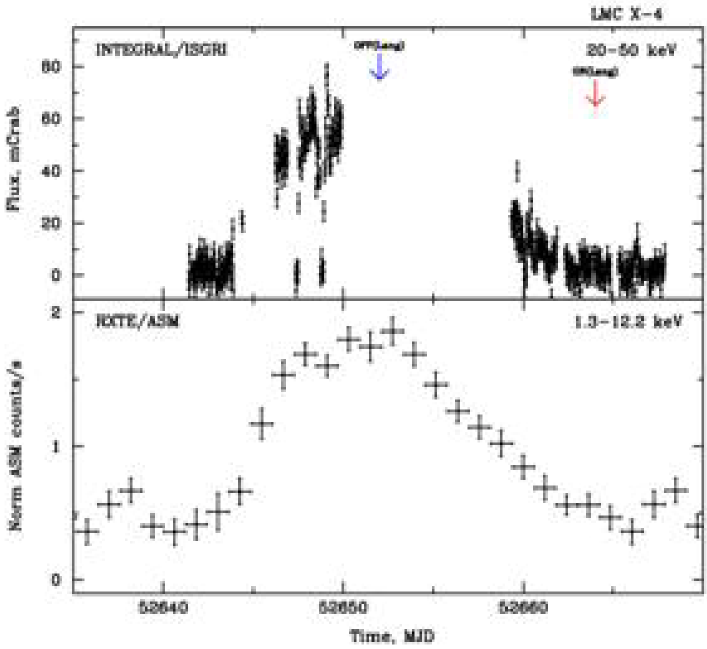

Fig. 12. Results of observations of LMC X-4 pulsar by INTEGRAL and ASM/RXTE

Observations of the Transient X-ray Pulsar KS 1947+300 by the INTEGRAL and RXTE observatories

The observations of the X-ray pulsar KS 1947+300 performed by the INTEGRAL and RXTE observatories over a wide (3-100 keV) X-ray energy range have been analyzed. The shape of the pulse profile was found to depend on the luminosity of the source. Based on the model of a magnetized neutron star, the characteristics of the pulsar using the change in its spin-up rate were stuted. The magnetic field strength of the pulsar and the distance to the binary have been estimated.

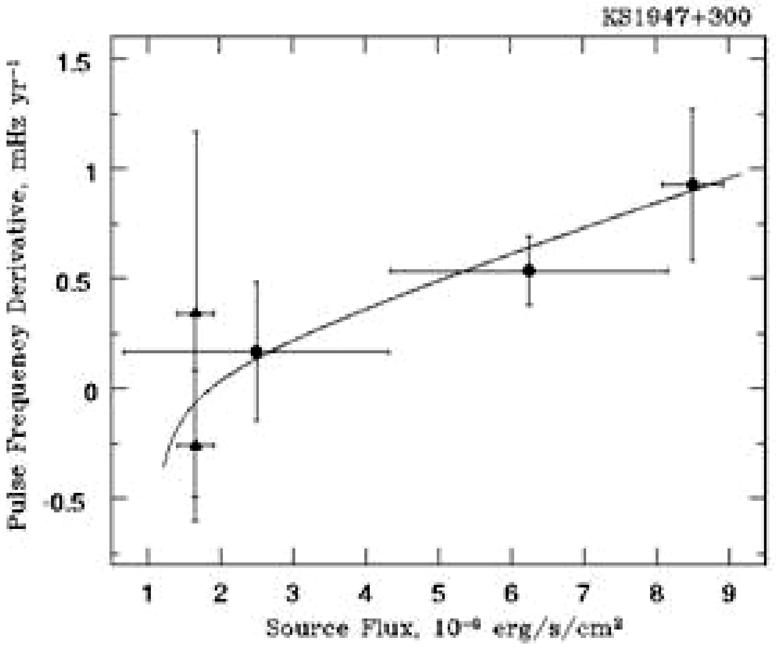

Fig. 13. Pulse profile dependence on KS 1947+300 flux

3.6.2.2. Theoretical and experimental researches at high energy astrophysics

The analysis of the archival data from several X-ray observatories has allowed of making break through at extragalactic astronomy. Not only the formation of X-ray binaries, but mechanisms of generation of X-ray at binary system have been studied in more details. Cosmology results and theoretical result as co-evolution of supermassive black holes and elliptical galaxies role of radiative ad mechanical feedback are presented.

Populations of X-ray binaries in galaxies as a new star formation rate and stellar mass indicator

Depending on the mass of the optical companion, X-ray binaries are subdivided in to two classes — low- and high-mass, having significantly different evolutionary time scale, millions and billions years respectively. The nearly prompt emission of HMXBs makes them a potentially good tracer of the recent star formation activity in the host galaxy. The LMXBs, on the other hand, have no relation to the present star formation, but, rather, are related to the stellar content of the host galaxy. Chandra and XMM-Newton observations of the nearby galaxies presented a possibility to confirm this simple picture and to calibrate the HMXB-SFR and LMXB-M* relations.

It has been demonstrated that the number and/or the collective X-ray luminosity of X-ray binaries in a galaxy can be used as a new and independent star formation rate (HMXBs) and stellar mass (LMXBs) indicator. High redshift (up to $z \sim 1.2$) starburst galaxies observed by Chandra in the Hubble Deep Field North showed that the calibration of the HMXB Lx-SFR relation based on the local sample is valid at cosmological redshifts as well.

The luminosity distributions of low and high mass X-ray binaries in nearby galaxies can be described by the respective “universal” luminosity functions, whose shapes do not vary significantly from a galaxy to a galaxy and the normalizations are proportional to the SFR (HMXBs) and stellar mass (LMXBs) of the host galaxy. There is a qualitative difference between XLFs of high and low mass X-ray binaries, reflecting the difference in the accretion regimes in these two types of X-ray binaries.

The high luminosity cut-off is by an order of magnitude larger for HMXBs – although bright sources, $\log(L_X) \geq 39$, are observed in both young and old galaxies, the truly ultraluminous ones, with $\log(L_X) \sim 40$–40.5, are associated with the regions of intense star formation and have not been detected so far in old stellar populations of elliptical and S0 galaxies. The L_X-SFR relations for distant galaxies in the HDF-N indicates that ULXs at redshifts of $z \sim 0.2$–1.3 were not significantly more luminous than those observed in nearby galaxies.

Dynamical formation of X-ray binaries in bulges of spiral galaxies may be important channel of X-ray binary production

In the high stellar density environment X-ray binaries can be formed ynamically, via tidal captures, collisions of neutron stars with red giants and through various exchange interactions involving binary stars and isolated compact objects. These processes may play the dominant role in the centers of galaxies. In particular, they explain the origin of the “surplus” X-ray binaries recently discovered in the inner bulge of the Andromeda galaxy. Overall, about a half of X-ray binaries in the inner ~3 kpc of Andromeda are formed dynamically, either in its center or in globular clusters, rather than are of primordial origin. The efficiencies of different formation channels depend critically on the relative velocities of the stars. As the same mechanisms operate in globular clusters, having a factor of ~100 lower velocity dispersion, this opens the possibility to validate microphysics of the stellar interactions and populations synthesis models in general.

Boundary layer emission in accreting neutron stars

The modern picture of accretion onto neutron stars in low mass X-ray binaries (LMXB) has two main ingredients - the accretion disk and the boundary layer. While in the disk matter rotates with nearly Keplerian velocities, in the boundary layer it decelerates down to the spin frequency of the neutron star and settles onto its surface. For the typical neutron star spin, comparable amounts of energy are released in these two regions.

Based on the method of Fourier-frequency resolved spectroscopy, it has been shown that aperiodic and quasi-periodic variability of bright LMXBs — atoll and Z-sources, on ~ s – ms time scales is caused primarily by variations of the luminosity of the boundary layer. The emission of the accretion disk is less variable on these time scales and its power density spectrum follows $P_{disk}(f) \sim 1/f$ law, contributing to observed flux variation at low frequencies and low energies only. The kHz QPOs have the same origin as variability at lower frequencies, i.e. independent of the nature of the "clock", the actual luminosity modulation takes place on the neutron star surface. The boundary layer spectrum remains nearly constant in the course of the luminosity variations and is represented to certain accuracy by the Fourier frequency resolved spectrum. Therefore it can be directly determined from observations.

In the investigated range of Mdot ~ 0.1–1Mdot$_{Edd}$ it depends weakly on the global mass accretion rate and in the limit Mdot ~ Mdot$_{Edd}$ is close to Wien spectrum with kT ~ 2.4 keV. Its independence on the global value of Mdot lends support to the theoretical suggestions that the boundary layer is radiation pressure supported. With this assumption we constrain the gravity on the neutron star surface and its mass and radius.

The properties of the accretion disk and the boundary/spreading layer in accreting neutron star binary systems

Having analyzed all available data of the RXTE observatory on bright accreting neutron star binary systems, made with needed spectral and timing resolution, they have shown that independently on the mass accretion rate in the binary system the emission of the accretion disk boundary layer might be well described by a diluted blackbody model, which parameters are determined practically only by the gravity of the neutron star. The measured spectral parameters of the neutron star boundary layer emission allowed them to put constrains on the ratio of mass to radius of the studied neutron stars. Assuming masses of the neutron stars approximately 1.4 M Sun the constrains on the radii are ~9–14 km. Analysis of a large number of observations of different systems at different instant mass accretion rate allowed to trace the behavior of the accretion disk in the binary system. It was shown that approximately at the Eddington mass accretion rate the structure of the accretion disk strongly changes, it is likely that the accretion flow near the neutron star becomes puffed up. Proposed model of the behavior of the whole accretion flow in the systems reasonably well describes the so-called "Z-track" of the bright neutron star X-ray binaries.

The finding of the origin of the Galactic ridge X-ray emission

The utilization data of the scanning and slewing observations of the RXTE observatory has shown that the origin of the Galactic ridge X-ray emission, which was a long standing problem in Galactic X-ray astronomy since the discovery of this emission in late seventies, is a superposition of a large number of known type of Galactic X-ray sources. First of all it was shown that the intensity distribution of the Galactic ridge X-ray emission very closely follows the intensity distribution of the near infrared emission of the Galaxy which is in turn very closely traces the Galactic stellar mass distribution. Then, analyzing the results of all sky surveys performed by the RXTE and ROSAT observatories the luminosity function of weak Galactic X-ray sources was constructed which covered very broad luminosity range 10^{27}-10^{34} erg/s. Comparison of the unit stellar mass X-ray emissivity obtained from the constructed luminosity function with that obtained from the Galactic ridge X-ray emission showed that they give compatible values. It confirms that the majority of the Galactic ridge X-ray emission consists of known type of Galactic X-ray point sources and not of truly diffuse emission. Comparison of composite spectrum of weak X-ray point sources which make contribution to the unit stellar mass Galactic emissivity with that of the Galactic ridge emission also confirmed the abovementioned conclusion.

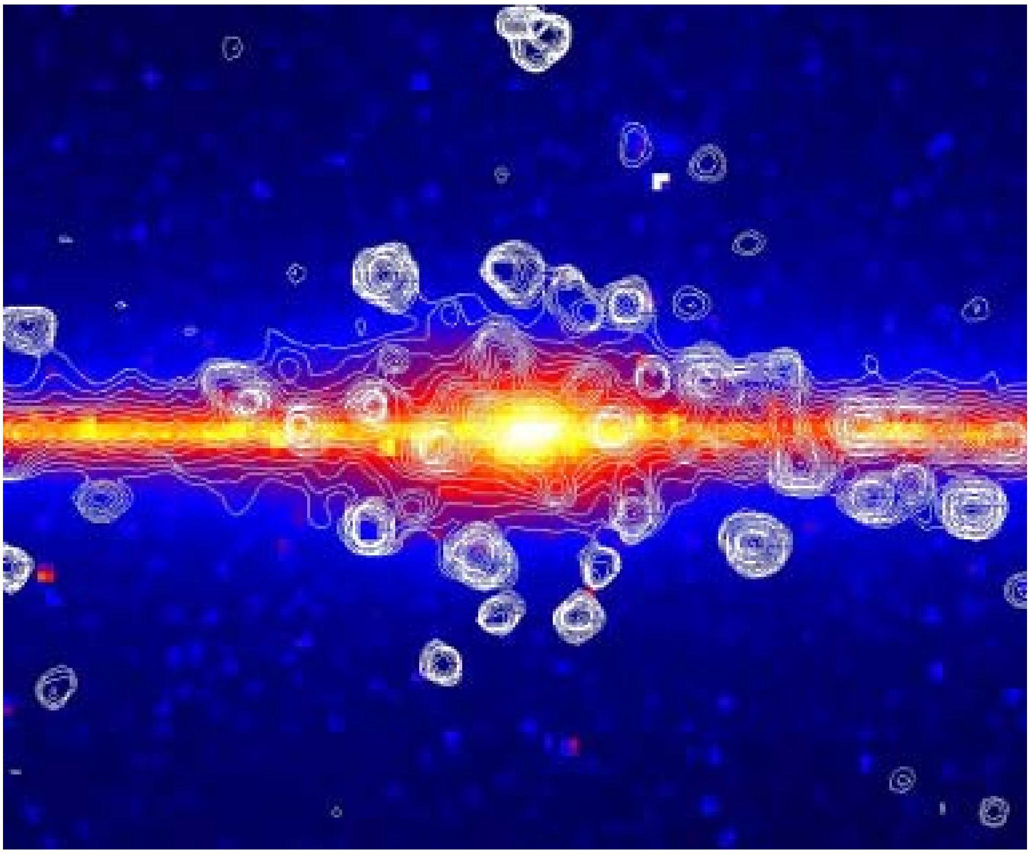

Fig. 14. It is shown that the intensity distribution of the Galactic ridge X-ray emission (lines) very closely follows the intensity distribution of the near infrared emission of the Galaxy (colored data COBE mission) which is in turn very closely traces the Galactic stellar mass distribution

Determination of cosmology parameters with X-ray clusters

The 400 deg^2 ROSAT survey, derived earlier has been used for the cosmological work. The survey is completely identified in the optical 95 % of the X-ray candidates are confirmed as clusters. This is the largest available sample. It contains 43 high flux clusters at $z > 0.35$ and the volume covered is 3 times the volume of the entire local Universe (within z < 0.1). All distant clusters from the 400d are followed up with Chandra.

The mass function measurements at z = 0.05 (local sample) and z = 0.5 (160d sample) shows that the factor of x10 change in the cluster number density at the given mass threshold reflects growth of matter density perturbations since z = 0.5. This growth is our primary cosmological observable. The observed change in the cluster number density is predicted only for certain combinations of Omega_M and Omega_Lambda. Lines show example of model fits to these data. The "concordant" model, Omega_M = 0.27, Omega_Lambda = 0.73 describes both the local and the distant data. For Omega_M = 1, one predicts a very different slope for the local mass function, inconsistent with the data.

The confidence regions from the full maximum likelihood analysis of the cluster data allowed combinations of Omega_M and Omega_Lambda — only those that are consistent with both the shape of the local mass function and the observed change in the cluster number density. They are in good comparison with results from SN Ia (c.2003) and from WMAP-only. With the entire 400d sample, we should be able to constrain the Dark Energy equation of state parameter, w, to approximately ±0.15 from a single experiment.

Gas heating by quasar emission

Data on cosmic backgrounds, composite spectra of active galactic nuclei, and the local mass density of supermassive black holes (SMBHs) were combined to determine the spectral energy distribution of the average quasar in the Universe. Radiation from such sources can photoionize and heat interstellar medium up to $2{\cdot}10^7$ K, i.e. above the virial temperatures of giant elliptical galaxies. Radiative feedback of central SMBHs in elliptical galaxies could lead to the observed orrelation between black hole mass and stellar velocity dispersion (Magorrian relation).

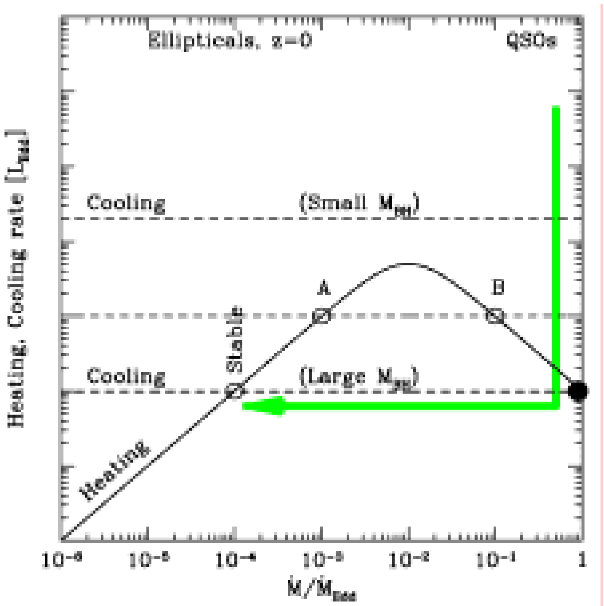

Fig. 15. Simple evolutionary model for elliptical galaxy

Evolution of black holes at elliptical galaxies

Relativistic outflows are a characteristic feature of both Galactic stellar mass black holes and SMBHs. The outflow is strong at low accretion rates but weakens dramatically at high accretion rates. Elliptical galaxies could then evolve through two stages. Early on, the central SMBH rapidly grows by accreting cooling gas at a near-Eddington rate with high radiative efficiency but with weak feedback. This stage terminates when the SMBH has grown to a sufficiently large mass that its feedback (radiative and/or mechanical) suppresses gas cooling. The system switches to the stable state of a passively evolving elliptical, with the accretion rate is low but the energy input from a relativistic outflow keeps the surrounding gas hot.

Magnetorotational supernovae, jets formation

New results of the simulations of the magetorotational mechanism of core collapse supernova explosion are represented. The magnetorotational mechanism was suggested by G.S. Bisnovaty-Kogan in 1970. The idea of the magnetorotstional mechanism is to transfer rotational energy of the star to t explosion energy by magnetic field. The magnetic field is frozen into the matter of the star, during the collapse a differential rotation appears, what leads to the amplification of the magnetic field and hence to the growths of the magnetic pressure. The increased magnetic pressure leads to the formation of compression wave, which moves from the center of the star. This compression wave is moving along steeply decreasing density profile and in a short time it transforms to the fast MHD shock wave, what produces supernova explosion. For 2D non-stationary simualations we have used implicit Lagrangian method on dynamically adapted triangular grid. This numerical method was specially developed for the simulations of the astrophysical MHD flows with huge difference of the flow parameters (up to 10 orders) and for the flows with significantly different time scales. This mechanism today is practically the only mechanism, which allows getting core collapse supernova explosion in self-consistent numerical simulations. Our simulations show that supernova explosion takes place for the different initial configurations of magnetic field and explosion energy is 0.5–0.6 1051 эрг. The shape of the supernova explosion significantly depends on the configuration of the initial magnetic field (magnetic field symmetry type). The initial quadrupole-like magnetic field leads to the supernova explosion, developing mainly near equatorial plane. The initial dipole like magnetic field leads for the supernova explosion with mildly collimated jet. The simulations have been done for the wide range of the initial magnetic energy.

It was shown that during the evolution of the magnetic field the magnetorotational instability (MRI) is developing. The MRI leads to the exponential grows of the toroidal and poloidal components of the magnetic field. Due to the MRI the evolution time of the magnetic field until the magnetorotational supernova explosion is significantly reduced. 2D simulations show that due to the MRI appearance, the time of the magnetorotational explosion is weakly depends on the relation of the initial magnetic and gravitational energies and can be approximately expressed by the frollowing formula t~-log(Emag/Egrav). The numerical simulations show that for the realistic values of the magnetic field the magnetorotational supernova explosion appears not later that 1 second after start of the evolution of the magnetic field.

We have estimated timescale for the reconnection of the magnetic field. It was shown that the reconnection of the magnetic field cold take place significantly after formation of the supernova shock wave.

The mechanism of the mirror symmetry violation in magnetorotational supernova explosion was suggested. It allows to explain formation of the asymmetric jets and formation of the rapidly moving radio pulsars.

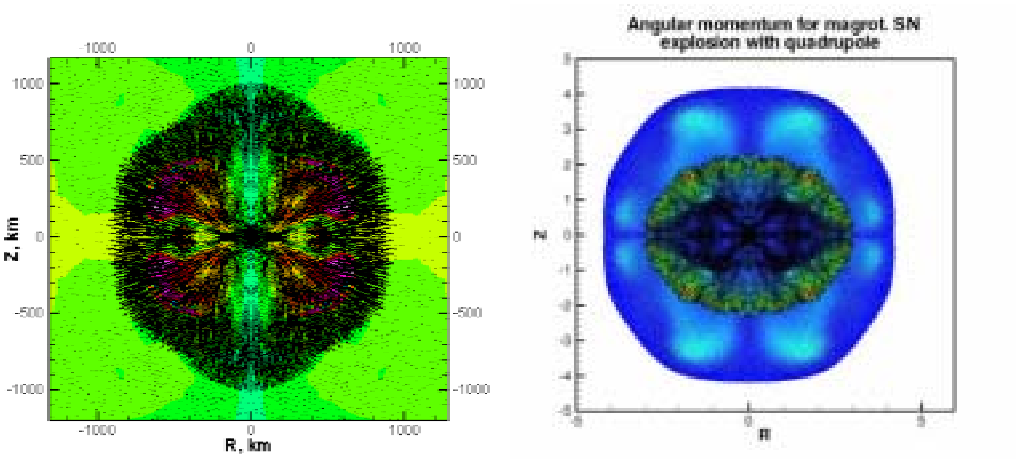

Fig. 16

At the Fig. 16 the velocity field at the developed stage of the magnetorotstional supernova explosion for the initial dipole (left plot) and initial quadrupole (right plot) magnetic field is represented. The color is the distribution of the specific angular momentum distribution.

3.6.3. STUDIES OF COSMIC GAMMA-RAY BURSTSAND TRANSIENT SOURCES IN THE KONUS AND HELICON EXPERIMENTS

The nature of cosmic gamma-ray bursts and the generation mechanism of giant fluences of electromagnetic radiation in their sources are among the most topical problems of the fundamental space research. A number of experimental data on the nature of this astrophysical phenomenon has been obtained in the Russian-American experiment Konus-Wind, successfully performed by a Russian scientific instrument Konus on board of an American spacecraft Wind since November 1994. The diversity of the temporal profiles of bursts, including the initial stages of the events and the fine temporal structure of sharp high-intensity peaks in the temporal profiles of the bursts have been analyzed in detail on a vast statistical material. New data on the fast spectral variability of the radiation in the bursts on time intervals up to 2 ms have been obtained. The first catalogue of short gamma-ray bursts with hard energy spectra, whose unusual properties attract interest and are being widely discussed, has been compiled.

The recording of the inverse Compton scattering of the initial pulse of the giant burst of SGR1806-20 from the Moon by the Helicon instrument on board the solar astrophysical observatory Coronas-F made it possible, for the first time, to reconstruct with high reliability the intensity, temporal history, and energy spectrum of the giant burst. It has been shown, on the basis of the results of the Konus-Wind experiment that the soft spectra of the pulsing tail of the giant burst from this source contain a hard component extending as far as 10 MeV. A weak decaying afterglow of SGR1806-20 is observed during several hours in the energy range below 1 MeV. The general pattern of the activity of SGR1806-20 in emission of repeated bursts before and after the giant burst has been obtained.

The Konus-Wind experiment is a unique source of information about the temporal and spectral characteristics of gamma-ray bursts in the energy range from 20 keV to 10 MeV. These data constitute an integral part of present-day multi-wavelength studies of the sources of gamma-ray bursts by spacecraft and a network of ground-based optical and radio telescopes and are in great demand. Studies in this area have been markedly extended owing to a new NASA mission Swift, and the Konus-Wind experiment efficiently complements them in a wide range of X-rays and gamma-ray energies.

3.6.3.1. Experimental procedure

The Russian-American experiment designed to study of cosmic gamma-ray bursts has been performed on board the American spacecraft Wind since November 1994, using the scientific instrument Konus manufactured at the Ioffe Physico-Technical Institute of the Russian Academy of Sciences. The orbit and conditions of gamma-ray bursts observation in the experiment are exceedingly favorable. The detectors of the instrument permanently inspect the whole celestial sphere under the optimal conditions of the interplanetary space at a stable radiation background in the absence of interference from the radiation belts or shadowing by the Earth. Owing to these circumstances, the observational database of the Konus-Wind experiment is presently the most complete.

The Konus-Wind instrument is a scintillation gamma-ray spectrometer comprising two identical gamma-ray detectors and an electronic unit for recording and preprocessing of the detector signals. Each detector contains a NaI(Tl) crystal 130 mm in diameter and 75 mm high, placed in a thin-walled aluminum container with a beryllium input window and a highly transparent lead glass that serves to protect the detector from the background generated by the spacecraft in the soft spectral range. A detector of this kind provides a low energy threshold in recording of the 10–12 keV radiation, records gamma photons with energy of up to 10 MeV with an energy resolution of 8.5–9.0 % at the Cs^{137} line, and a sensitivity of burst detection on the order of 10^{-7} erg°cm^{-2}. The detectors are mounted in a rotation-stabilized spacecraft in such a way that they continuously observe the northern and southern celestial hemispheres, respectively.

The instrument permanently operates in the burst-waiting mode and starts to record with high temporal resolution the information about a gamma-ray burst when a statistically significant increase in the counting rate of gamma photons is recognized by the burst detection cell. The temporal profiles of burst are presently recorded in the following energy ranges: 20–70, 70–300, and 300–1100 keV with a temporal resolution of 2 ms to 0.25 s and the total record duration of 230 s. The standard program for recording of event profiles provides a temporal resolution of 2 ms during the first 0.5 s of a burst and 0.5 s of its “prehistory”. The instrument also has two special temporal analyzers, the so-called temporal verniers, which make it possible to record with a high temporal resolution of 2 ms any part of an event profile in which there are clearly pronounced rises in the counting rate of gamma photons.

The energy spectra of events are measured with two multichannel amplitude analyzers with a quasilogarithmic scale in two energy ranges 20–1100 keV and 770 keV to 10 MeV. A special adaptive system automatically adjusts the spectrum accumulation time, depending on the burst intensity. This makes it possible to obtain data on fast spectral variability even for weak events under conditions of limited statistical information.

The instrument operates in two basic modes: burst recording and burst waiting. In the second mode, the background X-ray and gamma radiation is measured also in three energy ranges: 20–70, 70–300, and 300–1100 keV and the counting rate of charged particles with energy release in the detectors exceeding 10 MeV is recorded. The rated value of the lower energy thresholds of the detectors was 12 keV at the beginning of an experiment. The detector gain of the detectors gradually decreased in the course of many-year uninterrupted operation. The capacity for their correction by commands from the Earth was exhausted in 1997. At the end of 2005, the lower threshold was 21.5 keV for the detector inspecting the southern celestial hemisphere and 18.5 keV for that inspecting the northern hemisphere. For convenience of comparison, the data are reduced in processing to a threshold value of 20 keV.

The Konus-Wind experiment has the following advantages over other instruments presently used to cosmic gamma-ray bursts study:

1. The instrument observes gamma-ray bursts in exceedingly favorable conditions. The spacecraft spends most of time outside the Earth's magnetosphere, which provides a stable radiation background and absence of interference with the radiation belts or shadowing by the Earth and enables permanent observations.

2. The two detectors of the instrument continuously monitor the whole celestial sphere and make it possible to record with the same sensitivity gamma-ray bursts arriving from different directions.

An additional essential advantage of the Konus-Wind instrument, which became especially important after the Swift mission started to observe gamma-ray bursts at the end of 2004, is its ability to analyze the temporal and spectral characteristics of the bursts in a wide energy range from 20 keV to 10 MeV.

The Helicon gamma-ray spectrometer is one of the instruments of the solar space observatory Coronas-F, which operated on a near-Earth polar orbit at a height of 500 km from July 2001 till December 2005. The spacecraft was stabilized by rotation about an axis directed to the Sun with an accuracy of 10'. One of the detectors of the Helicon instrument is oriented to the Sun, and the second observes the antisolar hemisphere. The Helicon spectrometer is virtually identical to the Konus spectrometer in the characteristics of its two detectors and in the structure of information presentation.

All the above-mentioned factors, combined with the high sensitivity and information output of the Konus-Wind and Helicon instruments, made it possible to obtain in 2002–2005 a number of priority fundamental results in studies of cosmic gamma-ray bursts, gamma repeaters, and unusual transient phenomena in the cosmic X-ray and gamma radiation.

3.6.3.2. Studies of temporal profiles, energy spectra, and spectral variability of cosmic gamma-ray bursts

More than 2500 gamma-ray bursts have been recorded and studied during 11 years of observation in the Konus-Wind experiment. The diversity of the temporal structures of the bursts, including the initial phases of the events and the fine temporal structure of sharp high-intensity peaks in the temporal profiles of the bursts, was analyzed in detail on a vast statistical material. Multichannel measurements of energy spectra cover a wide range of energies from 20 keV to 10 MeV. A special procedure has been developed for studying the fast spectral variability of the burst on a temporal scale up to 2 ms. This procedure enables use for these purposes of temporal analyzers data in three energy windows. This makes it possible to obtain for gamma-ray bursts a dependence of the instantaneous radiation fluence of a burst on its peak energy, which is a measure of the hardness of radiation from a burst. The procedure developed was used to analyze the spectral variability of 30 gamma-ray bursts recorded in the Konus-Wind experiment, for which the cosmology redshifts are known. The advantage of this approach is that all the spectral measurements are made by the same instrument. The results of this analysis are presented in Fig. 17 as a dependence of the maximum spectral luminosity of the burst source on the maximum peak energy in the rest frame of the source.

The results of the Konus-Wind experiment were used to compile the first Internet-accessible catalogue of short gamma-ray bursts. The existence of a separate class of short gamma-ray bursts with duration of less than 2 s was first revealed in the Konus experiments on board Venera space station and was later confirmed in the BATSE experiment on the Compton Gamma Ray Observatory. The catalogue contains the temporal histories, energy spectra, spectral parameters, and a number of other emission characteristics of 130 short bursts. The existence of a statistically significant fluence of early afterglow of the sources of short bursts in the region of hard X-rays and gamma radiation has been demonstrated for a number of events included in the catalogue. An important advantage of the Konus-Wind experiment in observation of this afterglow is the stable radiation background. The effect of the early afterglow of short bursts is important for understanding of the nature of the bursts, and its intensive discussion is continued. The data contained in the catalogue are used in analysis of events of this class, including that aimed to compare the characteristics of short bursts recorded in different experiments.

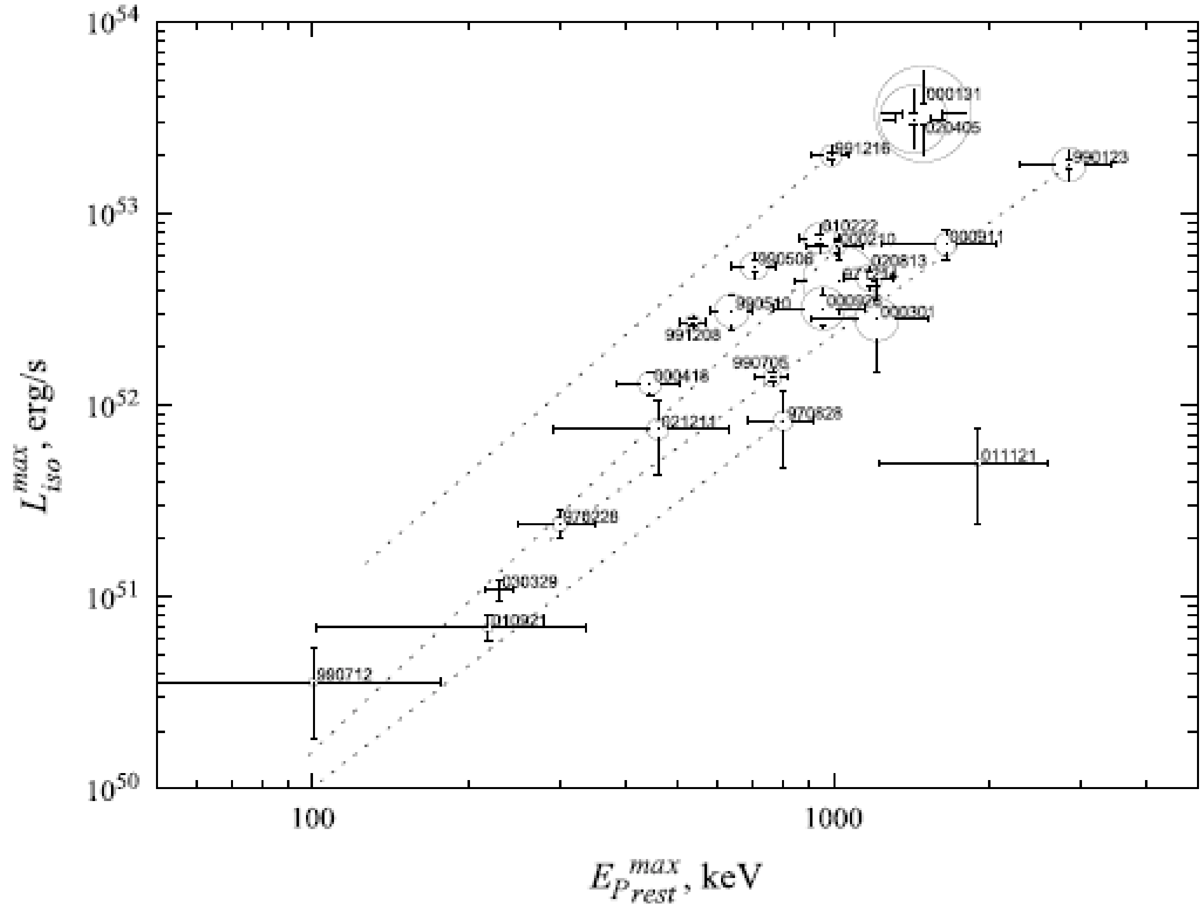

Fig. 17. Maximum isotropic luminosity vs. maximum peak energy in the rest frame of the burst source for gamma-ray bursts with a known cosmological redshift. The circle radii are proportional to the bursts redshifts. The dashed lines show several correlation tracks for separate bursts

3.6.3.3. The role of the Konus-Wind experiment in multi-wavelength studies of cosmic gamma-ray bursts

Studies of sources of gamma-ray bursts by ground-based and space-based telescopes in order to identify these sources with the known astrophysical objects and to analyze in detail their characteristics in a wide range of wavelengths play the key role in understanding of the nature of the phenomenon. The first success in these studies was achieved in 1997 with the Italian-Dutch satellite Beppo-SAX, owing to which the afterglow of the burst source in the optical and X-ray spectral ranges was discovered and the cosmological origin of, at least a part of, gamma-ray bursts was established. These studies also widely used the results obtained in triangulation measurements of the coordinates of sources of gamma-ray bursts with the use of the data obtained by the interplanetary network (IPN) of spacecraft with burst detectors. Owing to its high sensitivity and the optimal observing conditions, the Konus-Wind experiment is a basic vertex of this network. In 2002–2004, the IPN rapidly localized several tens of burst sources with high accuracy. These data were used to discover and study in detail the optical and X-ray afterglow for a number of sources, to determine their red shift, and to obtain results important for the physics of gamma-ray bursts, which confirmed the cosmological origin of the phenomenon. At present, the Konus-Wind experiment is the only source of temporal and spectral characteristics of gamma radiation in a wide energy range from 20 keV to 10 MeV for multi-wavelength studies of bursts. The most important results have been obtained for the following events.

GRB020410. One of gamma-ray bursts with record-breaking length (more than 1500 s) with X-ray and optical afterglow. A comparison of the data obtained by the X-ray chamber of the Beppo-SAX satellite and Konus-Wind instrument yielded a spectrum of the X-ray and gamma radiation of the burst in the energy range from 2 keV to 1270 keV.

GRB001025A. This is a gamma-ray burst with a bright X-ray afterglow, but no optical afterglow, the so-called "dark" burst. Its source was observed during 2.5 years. The Konus-Wind data were used to obtain detailed temporal profiles and energy spectra in the energy range 18–1150 keV, with evidences of a strong spectral evolution.

GRB000911. This is one of the bursts the most accurately localized by the IPN, for which an afterglow in the optical and radio wavelength ranges was revealed. Temporal profiles and energy spectra of the burst in the energy range from 15 keV to 8 MeV were obtained for this burst in the Konus-Wind experiment.

As the NASA mission Swift started to operate, the multi-wavelength studies of sources of gamma-ray bursts went into a fundamentally new phase. The Swift Burst Alert Telescope (BAT) determines the burst position to within several arcminutes and transmits the data obtained to the Earth in the online mode. The Internet network transports these data to ground-based optical and radio telescopes. Multi-wavelength studies of burst sources are now commenced immediately, in several seconds or tens of seconds, after an event is discovered. Simultaneously, the Swift spacecraft slew to the burst position and the Swift X-ray Telescope (XRT) and UV/optical telescope (UVOT) start to observe the burst source, too. The Swift BAT can perform spectral analysis of gamma radiation in a limited energy range 15–150 kV, which gives no way of determining such highly important parameters of gamma-ray bursts as the full integral fluence and the energy of peak energy release, E_{peak}, for most of gamma-ray bursts, because the main region of energy release lies above 150 keV. Therefore, the data obtained by the Konus-Wind experiment have become the integral part of these studies as a unique source of information about the temporal, spectral, and energy parameters of radiation in a wide energy range from 20 keV to 10 MeV. Below, use of these data in analysis of a number of gamma-ray bursts that occurred in 2005 and 2006 is considered.

GRB 060124. The Swift BAT localized this burst on the basis of a weak precursor and, owing to this circumstance, the X-ray and optical telescopes of the Swift mission were already directed to the radiation source before the beginning of the main phase of the event. The Konus-Wind instrument recorded in detail this burst, whose main phase is represented by three sharp peaks (Fig. 18). The event was observed by quite a number of ground-based telescopes, which made it possible to determine the redshift $Z = 2.297$ and to trace the behavior of the afterglow during a long period of time. A comprehensive analysis of the spectral characteristics of the burst in a wide energy range from 0.5 to 2000 keV was made using the data obtained by the XRT and the BAT instruments of the Swift mission and by the Konus-Wind gamma-ray spectrometer. This analysis enabled a detailed study of the strong spectral evolution in the main phase of the burst and yields an isotropic energy release $4.2 \cdot 10^{53}$ erg.

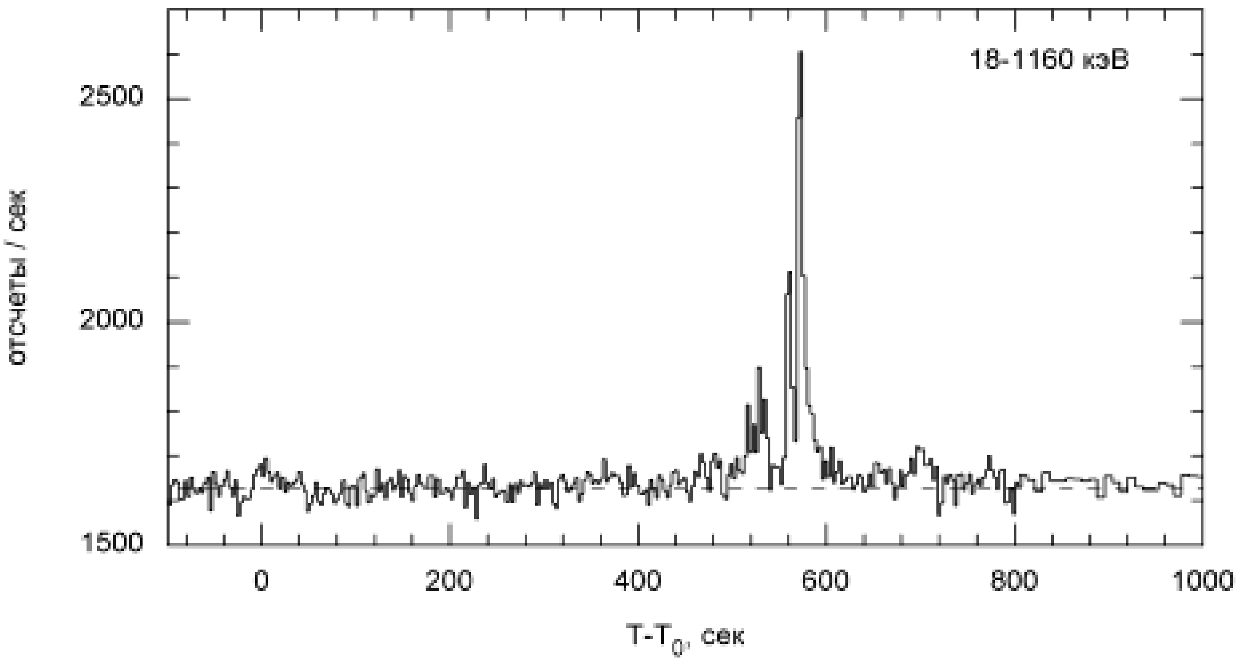

Fig. 18. Temporal profile of GRB060124 according to the Konus-Wind data

GRB 050713A. This is one of the rare bursts simultaneously observed in the ranges of soft X-rays (by Swift XRT), hard X-rays (by Swift BAT), and gamma-rays (by Konus-Wind). The results of a joint spectral analysis of the radiation in the main phase of the burst on the basis of the BAT-Swift and Konus-Wind data are shown in Fig. 19.

GRB 050820A. The observations of this burst by the RAPTOR ground-based telescope were commenced 5.5 s after information from the Swift mission was received. However, after that, Swift entered the zone of the South-Atlantic anomaly and data on the temporal profile of the event, obtained in gamma rays, are available only from the Konus-Wind experiment. This is the third occasion in the whole history of observations, in which the optical emission was observed simultaneously with the gamma- adiation of the burst. Owing to the exceptional duration of the gamma-ray burst (~800 s) and brightness of the optical source, unique data on various components of the optical emission and their relationship with the gamma radiation were obtained.

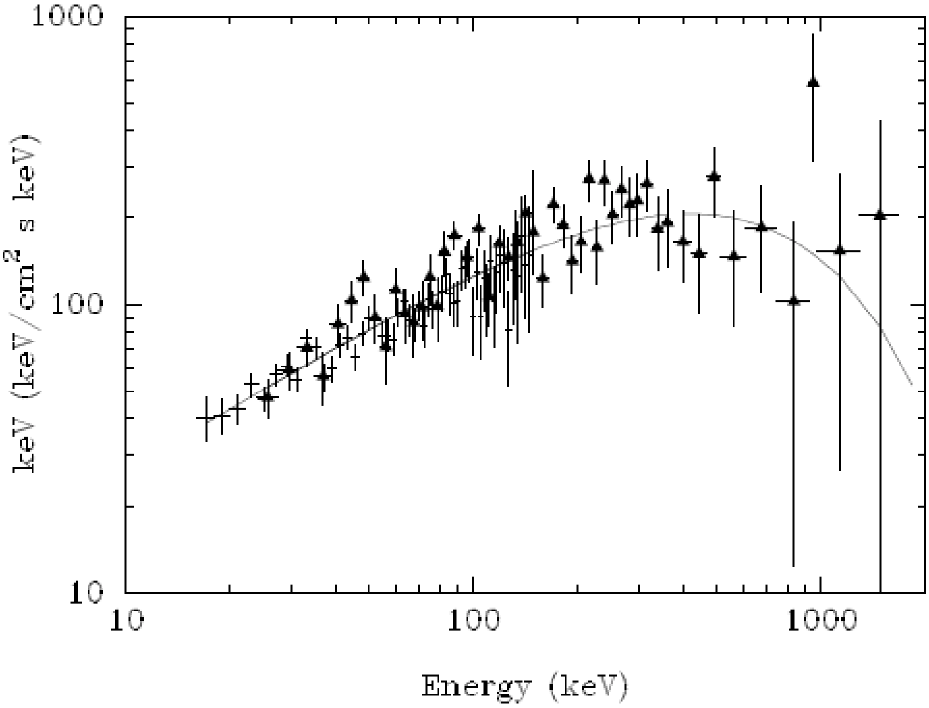

Fig. 19. Joint spectral energy distribution of Konus-Wind and BAT data on GRB 050713A during burst prompt emission, showing E_{peak} at ~440 keV. Points from the BAT spectrum are shown as crosses, those from the Konus spectrum are shown as filled triangles

3.6.3.4. Studies of soft gamma repeaters. giant burst from SGR1806-20 repeater and its compton backscattering from the Moon

A study of soft gamma repeaters is one of the most important tasks to be accomplished in the observational program of the Konus and Helicon experiments. The very phenomenon of recurrence of sources of soft repeated burst and the first two gamma repeaters were discovered in Konus experiments on board Venera interplanetary stations. The results of prolonged observations of gamma repeaters are summarized in the first catalogue of sources of soft repeated gamma-ray bursts, which is accessible via the Internet.

In the Konus-Wind and Helicon experiments performed in 2002–2005, new activity manifestations by two gamma repeaters SGR1900+14 and SGR1806-20 were observed both in the form of separate repeated bursts and as intense series of these events. The results of these observations were regularly published as GCN (Gamma-Ray Burst Coordinate Network) circulars. One of these circulars is, in fact, a brief electronic catalogue of the activity of SGR1806-20 in the middle of 2004. Figure 20 shows the series of repeated bursts from SGR1806-20, observed in 2004.

On December 27, 2004, the Konus-Wind instrument performed, simultaneously with the Helicon instrument, unique observations of a giant burst from SGR1806-20 gamma repeater (Fig. 21). The giant burst from the gamma repeater is a short, exceedingly intense initial pulse of gamma radiation, followed by a weaker tail decaying in ~500 s and pulsating with the rotation period of the neutron star. The detectors are completely overloaded by the initial pulse and “go off-scale”. Precise measurement of the energy parameters of the initial pulse becomes a virtually impracticable task because only rough estimates are possible. The unique feature of the observation on December 27, 2004, is that the Coronas-F spacecraft was occulted from the radiation source by the Earth, but its instruments were illuminated by a full Moon (Fig. 22).

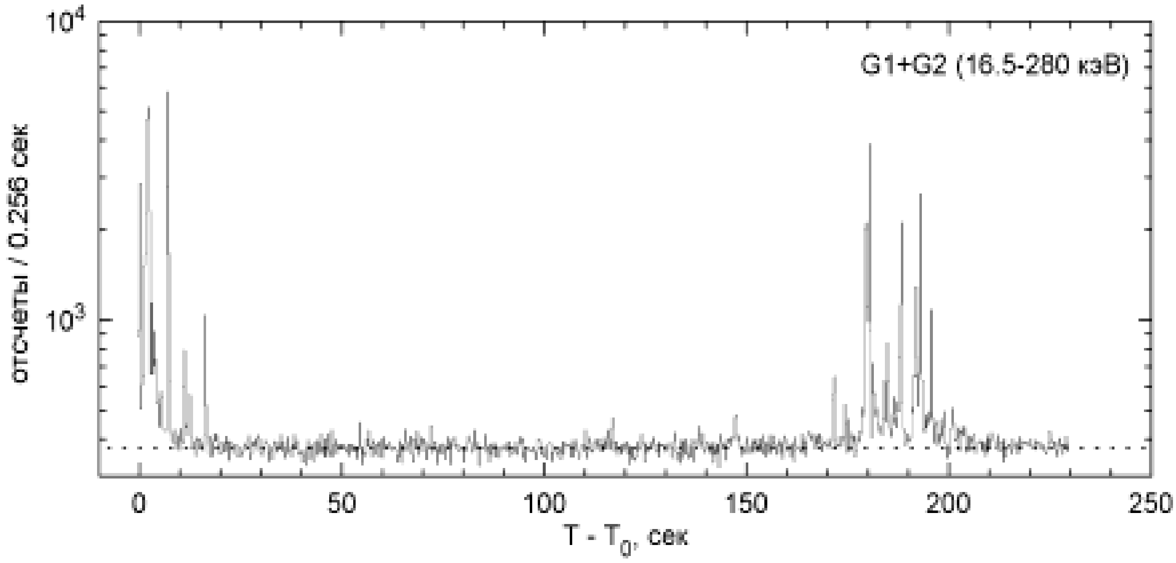

Fig. 20. Series of repeated bursts from the SGR1806-20 gamma repeater, recorded on October 5, 2004 by the Konus-Wind experiment

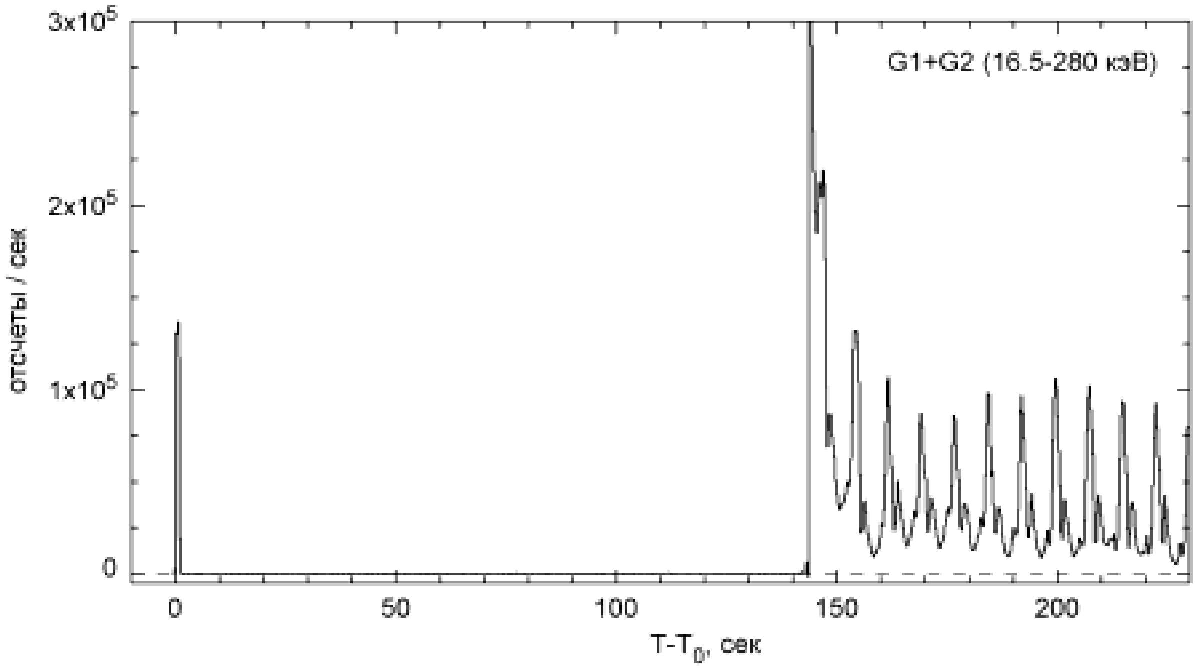

Fig. 21. General temporal pattern of the event on December 27, 2004, according to the results of the Konus-Wind experiment. The trigger recording was initiated by the arrival of a short soft burst (“precursor”). This burst was followed in 143 s by a giant radiation pulse, which caused a total saturation of the detector. After the end of the initial pulse, the radiation intensity rapidly falls and turns into a slowly decaying pulsating “tail”

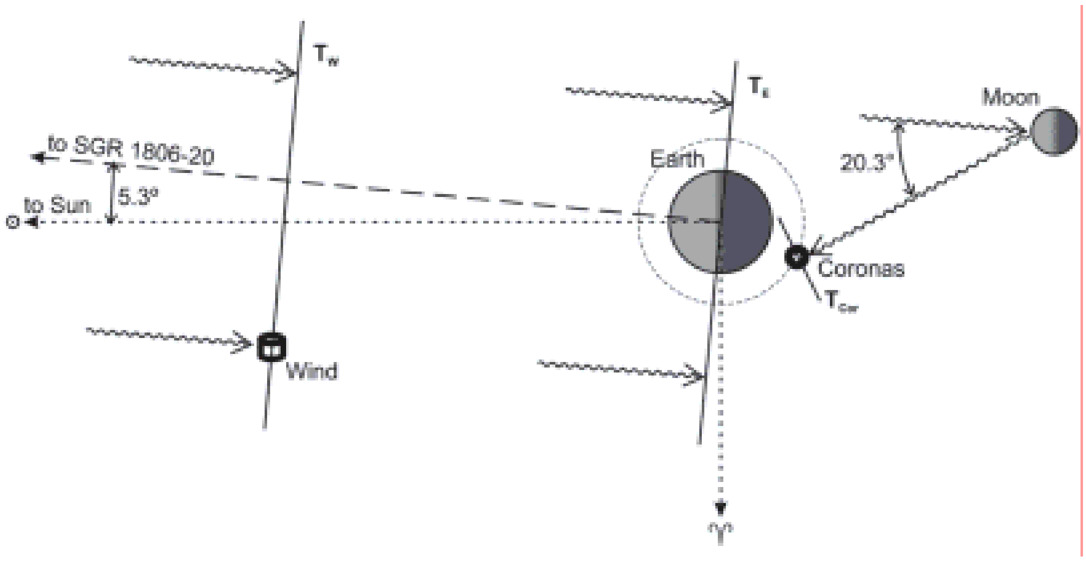

Fig. 22. Schematic of the observation of the giant flare from SGR1806-20 on December 27, 2004, by the Konus-Wind and Helicon instruments. The leading front of the flare arrives to Wind at instant of time T_W, passes the Earth at $T_E = T_W + 5.086$ s, reaches the Moon and is reflected from its surface, and, finally, the reflected radiation reaches the Helicon detector on board Coronas-F at the instant of time $T_{Cor} = T_W + 7.69$ s

The detector of the Helicon instrument, whose characteristics are identical to those of the detectors carried by Wind, clearly recorded the Compton backscattering of the giant pulse from the Moon and measured the temporal profile and its energy spectrum. This made it possible to reliably determine for the first time the temporal profile of the initial pulse (Fig. 23) and the energy parameters of the giant burst in the soft gamma repeater. These data are the first observation of reflection of a gamma-ray burst from a celestial body, or, in other words, the first example of natural pulsed location of a celestial body with gamma-rays. The data obtained in the Konus-Wind experiment were used to determine the temporal and spectral characteristics of the pulsating tail of the giant burst. It was found that its soft spectra also contain a hard power-law component extending as far as 10 MeV. A weak afterglow of the source, observed in the range below 1 MeV, decays during several hours. Also, the general activity pattern of SGR1806-20 in emission of repeated bursts before and after the giant burst was subjected to a detailed analysis.

One more result of importance is also related to the problem of what is the origin of gamma repeaters. On November 3, 2005, the Konus-Wind experiment recorded and analyzed in detail an exceedingly strong short burst. It possessed a rather hard spectrum with a peak energy of 2 MeV, steep rise (~2 ms) and a gradual decay at a total duration of less than 200 ms (Fig. 24). The burst was recorded by several instruments of the IPN and localized by the triangulation method. Its position coincides with a nearby galaxy M81 situated at a distance of 3.6 Mpc (Fig. 25). On the assumption that the burst source is associated with the M81 galaxy, the isotropic energy release can be estimated to be $\sim 4.5 \cdot 10^{45}$ erg, which is consistent with the energy released in the giant flare from SGR 1806-20 on December 27, 2004. The data obtained confirm the hypothesis that part of short bursts with a hard spectrum are initial pulses of giant flares in sources situated at substantially larger distances in neighboring galaxies. This hypothesis was first put forward by the authors of the Konus experiment in 1982 and its wide discussion was commenced after a giant burst from the SGR 1806-20 gamma repeater was recorded.

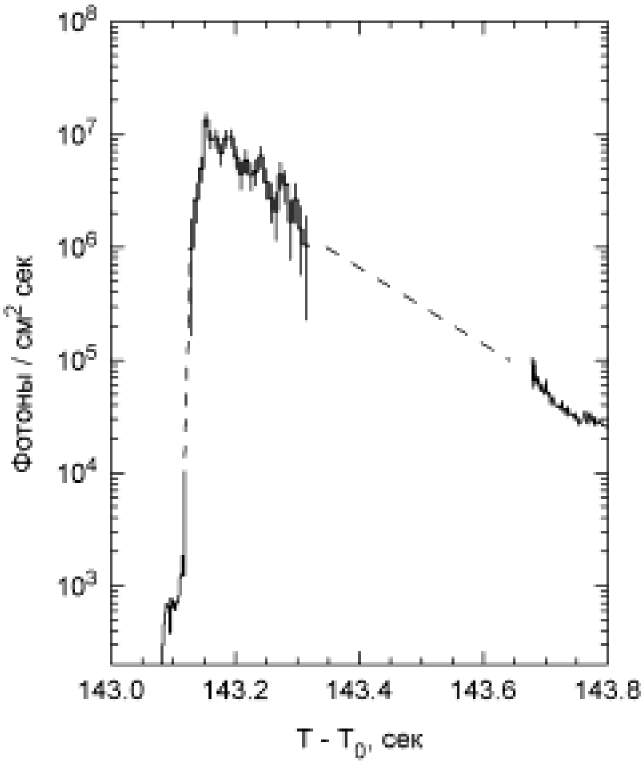

Fig. 23. Reconstructed time history of the initial pulse of the giant flare on December 27, 2004. The upper part of the curve is reconstructed using Helicon data, and the lower part, using Konus-Wind data

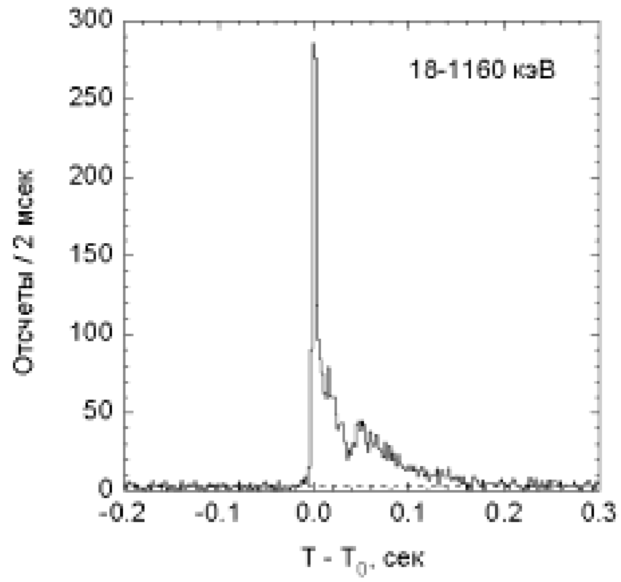

Fig. 24. Light curve of a short high-intensity hard burst on November 3, 2005, a probable giant burst from a soft gamma repeater in a nearby galaxy

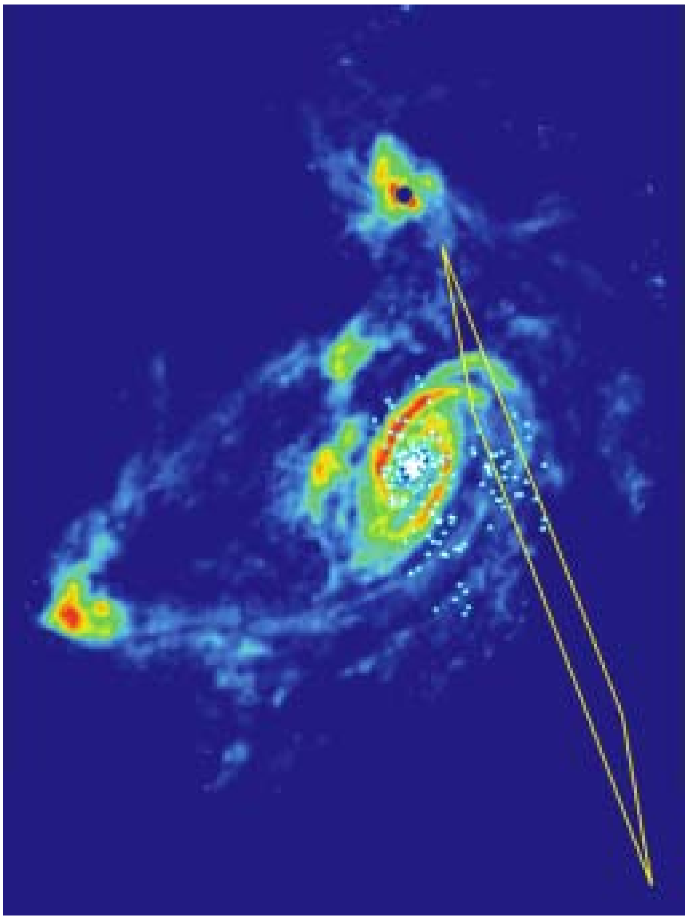

Fig. 25. IPN localization of the event on November 3, 2005, on the map of the M81 galaxy group, plotted using the HI 21 cm line. The blue asterisks denote the X-ray sources belonging to the M81 galaxy (at the center), according to the data obtained by the Chandra observatory

3.6.3.5. A new kind of activity of the Cygnus X-1 source

The Konus-Wind experiment, carried out together with the burst experiment on board the Ulysses space probe, revealed an unusual activity of the Cygnus X-1 source. The first candidate for a black hole, Cygnus X-1 is among the brightest galactic X-ray sources. It is observed in two activity states: occasionally, in the "soft" state, with predominant emission in the 2–10 keV range, and, more frequently, in the "hard" state with emission energy in the 10–200 keV range. In 1995-2002, high-intensity gamma-ray bursts with duration of 10000 to 20 000 s were recorded from this source in the energy range from 15 keV to 1 MeV. The maximum fluences exceeded by an order of magnitude those observed previously. The integral fluences of these bursts were as high as $8{\cdot}10^{-4}$ erg/cm^2, which corresponds to energy release in the source equal to $5{\cdot}10^{41}$ erg. A total of six events of this kind were recorded. Detailed temporal and spectral characteristics were obtained in the Konus-Wind experiment for these events. The hard energy spectra of these burst give reason to believe that the events observed represent a new kind of activity for the Cygnus X-1 source, with a spectrum close to that for the "hard" state.

3.6.3.6. Conclusion

The Konus-Wind experiment and the synchronous Helicon experiment obtained new priority data on the nature of cosmic gamma-ray bursts and of a special class of repeated soft-spectrum bursts from gamma repeaters. The recording of the Compton backscattering of a giant flare from the SGR 1806-20 by the Moon surface made it possible to reliably determine for the first time the temporal profile of the initial pulse and its energy parameters. Owing to the high sensitivity of the detectors of the Konus-Wind instrument in a wide range of gamma-ray energies and to the optimal observing conditions in the interplanetary space, the data obtained by the experiment are in high demand in present-day multi-wavelength studies of sources of cosmic gamma-ray bursts.