A&A 411, L357–L361 (2003)
DOI: 10.1051/0004-6361:20031481

Astronomy & Astrophysics

Letter to the Editor

First results from TOO observations of the Aql X-1 field with INTEGRAL⋆

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Received 28 July 2003 / Accepted 20 September 2003

Abstract. We present results of observations of the Aql X-1 field performed in March-April 2003 with the INTEGRAL observatory. This TOO (Target Of Opportunity) INTEGRAL observations was initiated upon receiving an indication from the ASM/RXTE that the source started an outburst. Thirteen X-ray sources were detected by the INTEGRAL imagers, JEM-X and IBIS, during these observations. We present a preliminary spectral and timing analysis for several bright sources in the field, Aql X-1, X1901+03, 4U1907+097, XTE J1908+094 and X1908+075. We also detected two X-ray bursts from Aql X-1 near the end of the general outburst episode.

Key words. stars: binaries: general – X-rays: general – X-rays: stars

1. Introduction

The hard X-ray emission has long been considered to be a unique property of the Black Hole (BH) binaries. Later, however, it was found that X-ray bursters can also be detected in the hard X-ray band (Barret & Vedrenne 1994; Churazov et al. 1995; Pavlinsky et al. 2001). Moreover, some Neutron Star (NS) binaries are often found in the spectral state with the enhanced X-ray flux (e.g. Zhang et al. 1996), which is similar to the so-called low spectral state of Cyg X-1 (Hasinger & van der Klis 1989; Yoshida et al. 1993). The presence of the hard X-ray emission can be plausibly associated with the low accretion rates. Therefore, one can expect transitions between the spectral states in X-ray transients at the beginning of outbursts when the accretion rate increases and at the end of outburst when it decreases until it falls below detectable level (Barret et al. 1996).

The Low Mass X-ray Binary (LMXB) Aql X-1 is ideally suitable for the study of such spectral transitions. It is a well known soft X-ray transient which demonstrates transitions from low to high flux states approximately once a year (see the historical light curve shown in the bottom panel of Fig. 1).

The sky region around Aql X-1 contains several other bright X-ray sources because it is projected on the Scutum arm of the Galaxy. One of the most interesting sources in this field is the transient X1901+03, which showed an outburst in January 2003 (Galloway et al. 2003a) for only the second time since 1971 (Forman et al. 1976). During the 2003 outburst, X1901+03 showed coherent pulsations with a period of 2.763 s (Galloway et al. 2003a), therefore this source is an accreting X-ray pulsar in a binary system. Most of remaining sources are either pulsars or black-hole candidates (4U1907+097, XTE J1908+094, X1908+075, SS433, GRS1915+105, etc.) and are likely to be high-mass binaries (Grimm et al. 2002).

In this paper, we present preliminary scientific results from the INTEGRAL observations of the Aql X-1 field in March–April 2003.

2. Observations and data reduction

The present dataset was obtained in a campaign of TOO observations of Aql X-1 during its outburst. Six approximately equally spaced (one per five-six days, see Fig. 1) observations were carried out from Mar 10 to Apr 13, 2003. Each observation consists of 25 pointings with a ∼2 ksec exposure, forming a 5×5 dithering pattern. The total integration time during this campaign was approximately 300 ks. In this work, we present only results from the Joint European X-ray Monitor (JEM-X, module 2; see Lund et al. 2003) and the upper layer of the Imager on Board INTEGRAL (ISGRI/IBIS; Ubertini et al. 2003). The detailed description of the instruments can be found in these papers, but several main parameters like a field of view (FOV), fully coded field of view (FCFOV), collecting area and energy range are pointed here: 13.2° in a diameter, 4.8° in a diameter, 500 cm^2 and 3–35 keV for JEM-X, and $25° \times 25°$, $9° \times 9°$, 2600 cm^2 and 15–300 keV for ISGRI/IBIS, respectively.

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⋆ Based on observations with INTEGRAL, an ESA project with instruments and science data centre funded by ESA member states (especially the PI countries: Denmark, France, Germany, Italy, Switzerland, Spain), Czech Republic and Poland, and with the participation of Russia and the USA.

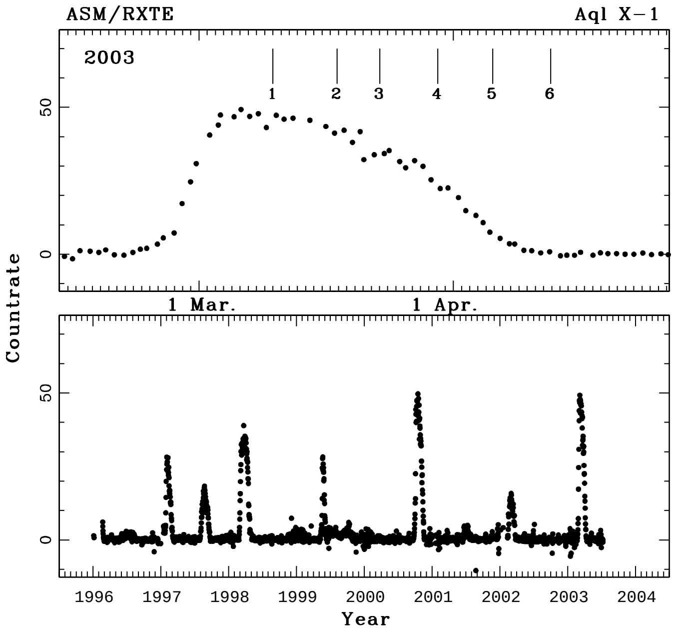

Fig. 1. Bottom: historical light curve of Aql X-1 in the 2−12 keV energy band, obtained by RXTE (data averaged over 1-day intervals). Top: detailed profile of the March, 2003 outburst. Vertical lines indicate moments of the INTEGRAL observations.

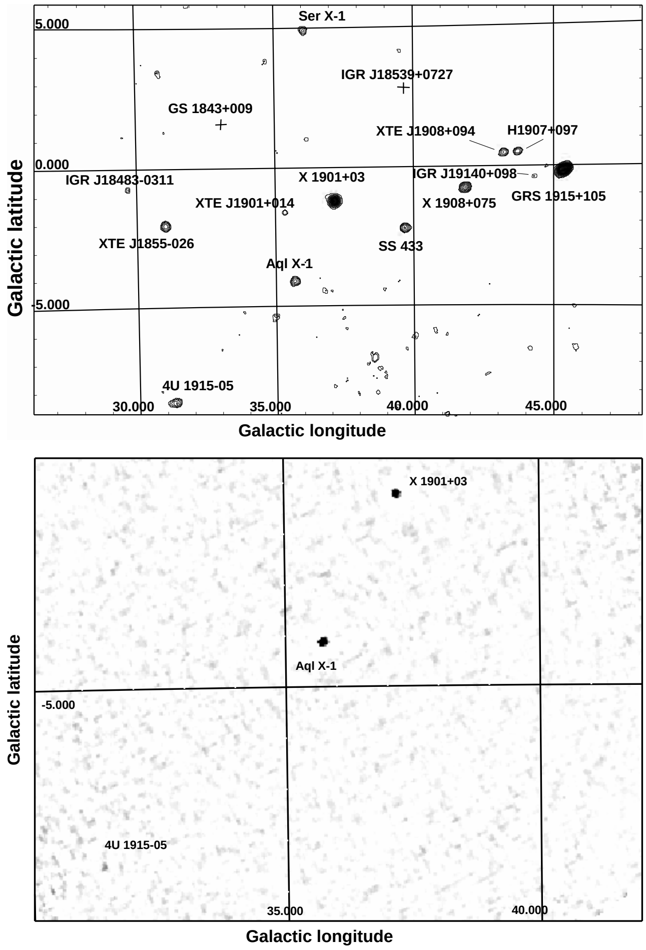

Fig. 2. X-ray images of the Aql X-1 sky region, obtained with ISGRI/IBIS in the 25−50 keV energy band (upper panel) and JEM-X in the 3−10 keV energy band (bottom panel) in March–April 2003. Contours on the ISGRI/IBIS map are given at the signal-to-noise levels of 2, 2.5, 3.3, 4.5, 6.2,... 42σ (for the brightest sources GRS 1915+105 and X1901+03 contours begin from 4.5σ).

Data reduction was performed using the IDAS 1.0 software distributed by the INTEGRAL Science Data Center. This software package at present does not allow one to carry out detailed spectral analysis of the ISGRI data. Therefore, the spectral information for sources in the IBIS field of view (FOV) was obtained from a comparison of their observed pulse height spectra with that of the Crab nebula as measured by INTEGRAL in February, 2003. The analysis of a set of the Crab observations and preliminary analysis of hard X-ray emission from SAX J2103.5+4545 (Lutovinov et al. 2003) have shown that this method provides satisfactory reconstruction of the source spectra and allows one to estimate the main spectral parameters.

Our analysis of the Crab observations has shown a strong dependence of the reconstructed source intensity on the off-axis angle. To reduce this potential source of systematic errors, the spectral analysis of our sources was performed using only the data from the fully coded part of FOV (FCFOV) in the case if at least 20 suitable pointings were available for the source of interest. We estimate the systematic uncertainty of the flux for such data selection to be ~10−20% at all energies. The instrumental teams independently estimate this uncertainty as at least ~10%. For the image reconstruction, we used the entire FOV of the IBIS telescope.

We note that at present, systematic uncertainties in the spectral reconstruction dominate the statistical noise. Therefore, the usual reduced χ^2 is not a correct measure of the quality of the applied models. We generally avoid quoting reduced χ^2 for our spectral models.

Examination of the JEM-X data for Crab nebula shows that the current calibration of the instrument response matrix is satisfactory in the 5−20 keV energy range. It was found, however, that while the spectral shape is recovered well, the absolute source fluxes are systematically underestimated. To correct this problem, we renormalized our JEM-X spectra using the absolute fluxes in the 5−12 keV energy band provided by the RXTE All-Sky Monitor simultaneously with the INTEGRAL observations.

3. Results

The JEM-X and ISGRI mosaic images reconstructed in the 5−12 and 25−50 keV energy bands for the entire set of the Aql X-1 observations are presented in Fig. 2. These images show that 13 sources were significantly detected in the IBIS FOV, and three of them were also covered by JEM-X. Below, we briefly discuss the properties of some of the observed sources.

3.1. Aql X-1

The Aql X-1 sky region was not accessible for observations with INTEGRAL in the beginning of March, 2003, and

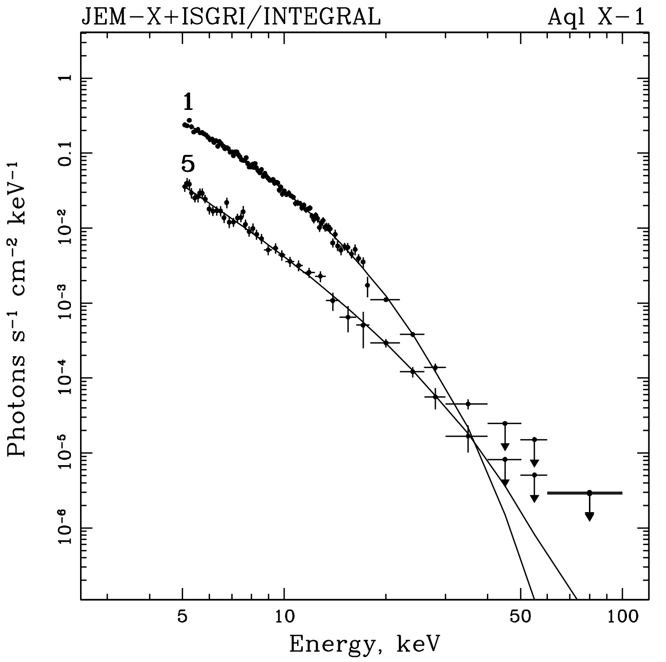

Fig. 3. The photon spectra of Aql X-1 observed with INTEGRAL on March 10 (the 1st set of observations) and on April 5 (the 5th set). The best fit thermal bremsstrahlung models are shown by solid lines.

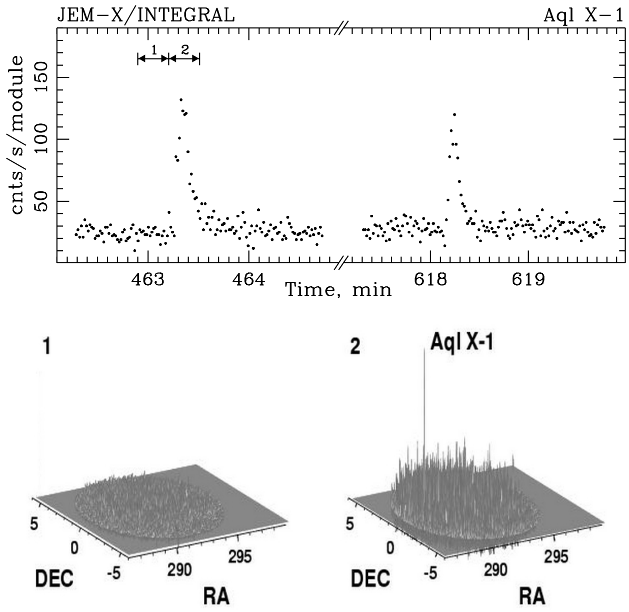

Fig. 4. Top: JEM-X light curves containing two X-ray bursts from Aql X-1. Time resolution is 1 s. The zero time on the horizontal axis corresponds to Apr. 5.00 2003 UT. Bottom: image reconstruction of the Aql X-1 field before the burst (1) and during the burst (2).

therefore the rising phase of the source outburst was not covered by INTEGRAL. The observing campaign started on March 10, thus INTEGRAL monitored the outburst from its maximum to decay (Fig. 1). The maximum observed fluxes from Aql X-1 were ~600 and ~55 mCrab in the 5−12 keV and 25−50 keV energy bands, respectively.

Figure 3 shows two combined JEM-X+ISGRI spectra obtained during the first set of observations when the Aql X-1 flux was highest and during the fifth set of observations when the outburst was near its end. The observed spectra can be fitted with a thermal bremsstrahlung model with temperatures 4.2 and 5.1 keV for the 1st and 5th sets, respectively. The source was undetectable in the 50−100 keV energy band, with an upper limit of 4 mCrab at the 68% confidence level. However, we cannot fully rule out a presence of a faint hard tail in the source spectrum because of the limitations of the current data analysis discussed above. Our estimations on the flux in tail are consist with the source spectrum of an early stage of fast outburst decline measured by BeppoSAX (Campana et al. 1998).

The JEM-X monitor has detected 2 X-ray bursts of type I from the source. The light curve taken from the entire JEM-X detector around the moments of the bursts is shown in the upper panel of Fig. 4. The image reconstruction during ~15 s time intervals covering the burst shows unambiguously (localization accuracy is ~4′) that the the bursts originated from Aql X-1 (bottom panel of Fig. 4). Both the bursts have light curves typical of the type I X-ray bursts which are considered to be manifestations of the thermonuclear explosions on the surface of a neutron star. Interestingly, both the bursts were detected during the 5th set of observations when source outburst was near its end.

3.2. X1901+03

During all the Aql X-1 observations, the High-Mass X-ray Binary pulsar X1901+03 was detected both in the soft (JEM-X) and hard (ISGRI/IBIS) energy bands. The preliminary source position determined with both the telescopes agrees well with the RXTE location (Galloway et al. 2003b).

During our set of observations, the X1901+03 flux in the 25−50 keV energy band decreased gradually from 110 mCrab to 90 mCrab. The combined JEM-X and ISGRI/IBIS source spectrum averaged over the entire set of observations is presented in Fig. 5. The spectrum can be fited with a power law + high energy cutoff model, with the photon index $\Gamma \sim 1.95$ and the cutoff parameters $E_{\rm cut} \sim 12$ keV, $E_{\rm fold} \sim 13.5$ keV. These values are typical for X-ray pulsars. In addition to our observations, there is a long set of observations of this source carried out in May, 2003, kindly made available to us by the PIs of INTEGRAL observations of GRS 1915+105, SS 433 and Ser X-1. The source flux in May 2003 decreased by a factor of 2 relative to that in March, 2003. It would be interesting to trace the spectral evolution of the source during the outburst decay and this analysis is now in progress.

We performed a timing analysis of the X1901+03 JEM-X data. Fourier transforms were computed for those periods in which X1901+03 was in the FCFOV of JEM-X. The coherent pulsations with a frequency of 0.362 Hz were clearly detected along with the second harmonic. This period is consistent with that obtained with RXTE (Galloway et al. 2003a). The period slightly changes from the observation to observation, which may be explained by the orbital motion of the compact object in the binary system. The light curve obtained from the whole JEM-X detector in the 5−15 keV energy band folded with the above pulse period is presented in Fig. 6. Unfortunately,

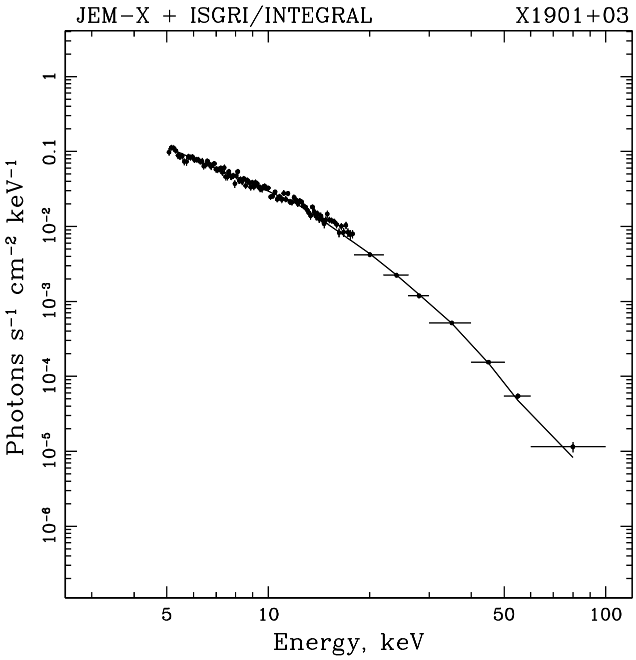

Fig. 5. Average photon spectrum of X1901+03 measured with JEM-X and IBIS/ISGRI over the entire set of observations. Solid line shows the approximation by a power law with the high energy cutoff.

Table 1. Hard X-ray fluxes for sources in the Aql X-1 field.

XTE J1855-026	∼13 mCrab
4U1907+097	∼12 mCrab
X1908+075	∼17 mCrab
XTE J1908+094	∼9.5 mCrab
X1916-053	∼8 mCrab
IGR J18483-0311	∼13 mCrab

we cannot estimate the source pulse fraction because of a lack of accurate measurements of the JEM-X background.

3.3. Other sources

As was mentioned above, 13 X-ray sources were detected by the INTEGRAL instruments during the observations of the Aql X-1 field on March–April, 2003 (Fig. 2). Several of these sources (GRS1915+105, SS443, Ser X-1, and IGR J19140+098) are subjects of other INTEGRAL proposals and therefore are not discussed here. We present the averaged hard (20−50 keV) X-ray fluxes for the remaining sources in IBIS FOV (Table 1).

Several points are noteworthy: 1) sources fluxes are variable by a factor of a few, but here we quote only the average values; 2) the fluxes were derived assuming that the Crab intensity in the 25−50 keV energy band of ISGRI detector is 130 counts/s; 3) the new transient source IGR J18483-0311 was formally discovered with INTEGRAL on Apr. 23–28, 2003 (Chernyakova et al. 2003), but it is also detectable in one of our observations (Apr. 5, 2003) with a signal to noise ratio of $S/N \sim 10$ in the 25−50 keV energy band.

A detailed analysis of the sources in the Aql X-1 field is beyond the scope of this paper. Here we discuss only the preliminary spectral analysis for three sources of different classes – 4U1907+097, XTE J1908+094, and X1908+075. The first of them is a typical X-ray pulsar with the energy spectrum described by a power law with a high energy cutoff. The cyclotron absorption line with several harmonics was detected in the spectrum of this source (Coburn et al. 2002). The second source is a likely black hole candidate with a relatively hard, power law spectrum ($\Gamma \sim 2$) without any indication for a high energy cutoff. No pulsations or type I X-ray bursts were observed from XTE J1908+094 (in't Zand et al. 2002). The nature of the third source, X1908+075, is not yet determined.

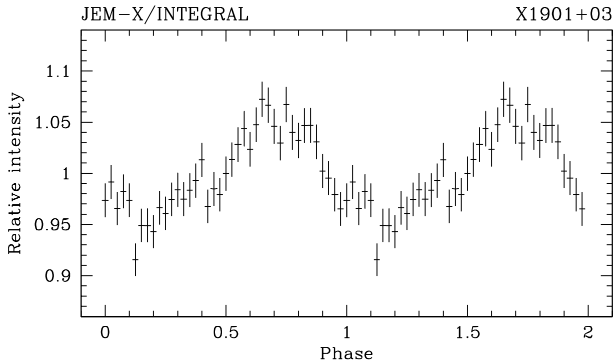

Fig. 6. The pulse profile of X1901+03 in the 5−15 keV energy band.

The average ISGRI photon spectra of 4U1907+097, XTE J1908+094 and X1908+075 in the 18−100 keV energy band are presented in Fig. 7. In all three cases, the spectra can be described well by a power law model with the photon index $\Gamma \sim 2.1$ for XTE J1908+094, ∼2.9 for X1908+075, and ∼3.9 for 4U1907+097. The spectral slope of XTE J1908+094 is similar to that of other accreting BHs in the low/hard state and the value of its photon index Γ is in agreement with the previous results of the BeppoSAX observatory (in't Zand et al. 2002). The photon index for 4U1907+097 is typical of X-ray pulsars spectra in the hard energy band. We note that this spectrum can be equally well described by the power law + high energy cutoff model. The power law and cutoff parameters cannot be derived independently from the INTEGRAL data due to lack of data below 18 keV. Therefore, we fixed some of the parameters (the photon index Γ and cutoff energy $E_{\rm cut}$) at the values obtained by the RXTE observatory and then derived $E_{\rm fold} \simeq 10$ keV, in agreement with the RXTE results $E_{\rm fold} = 9.8 \pm 0.6$ keV (Coburn et al. 2002).

The spectrum of X1908+075 has the intermediate value of the photon index with respect to typical black hole binaries (e.g., XTE J1908+094) and the X-ray pulsars (4U1907+097). No obvious cyclotron features are present in the source spectrum, but they cannot be strongly ruled out because of the limited spectral resolution of the ISGRI instrument. Therefore, the question about the nature of X1908+075 is still open.

4. Conclusions

The transient X-ray source Aql X-1 was observed with INTEGRAL during the source outburst in March–April 2003. The observing strategy allowed us to cover almost the entire outburst episode, and therefore investigate the source in the

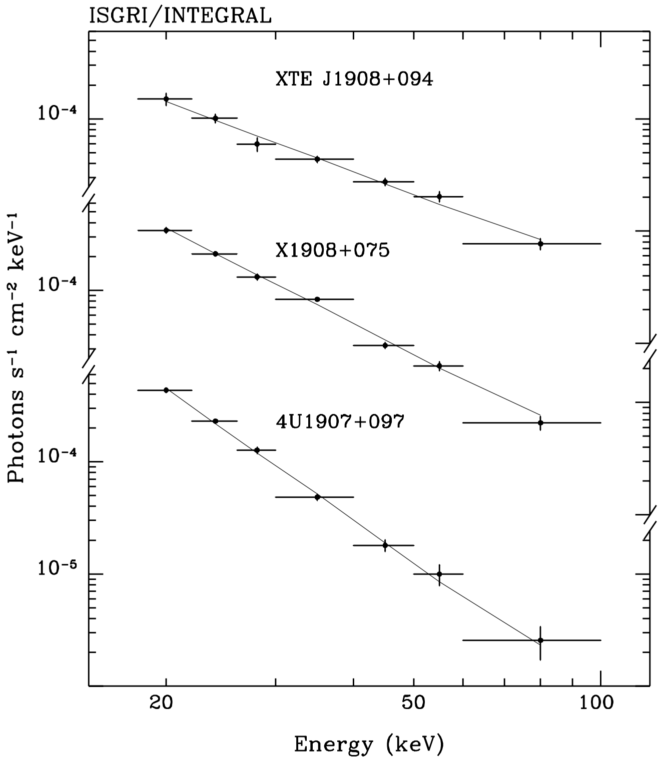

Fig. 7. Average photon spectra of XTE J1908+094, X1908+075 and 4U1907+097 obtained with the ISGRI instrument. Solid lines show the power law approximations.

states with different luminosity. The preliminary spectral analysis indicates that the spectrum in the 3−40 keV energy band can be described by a thermal bremsstrahlung model. The source was undetectable in the harder energy band. We observed two X-ray bursts of type I from Aql X-1.

Dozen other sources were detected in the INTEGRAL field of view. We reconstructed the pulse profile and average spectrum of one of the most interesting of these sources, the pulsar X1901+03 (indentified as a pulsar only one month before our observations, see above). The 18−100 keV energy spectra of three other bright sources, XTE J1908+094, X1908+075, and 4U1907+097 can be described by a simple power law model with photon indices of 2−3.9.

A more detailed analysis of the sources in the Aql X-1 field is in progress.

Acknowledgements. We would like to thank Mike Revnivtsev and Alexey Vikhlinin for very useful discussions and comments. This research has made by using of data obtained through the INTEGRAL Science Data Center (ISDC). This work was supported by RFBR grant 03-02-06772, grants of Minpromnauka NSH-2083.2003.2 and 40.022.1.1.1102, and the program of the Russian Academy of Sciences "Nonstationar phenomena in astronomy".

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