SPECTRAL ANALYSIS OF X-RAY PULSARS WITH THE INTEGRAL OBSERVATORY

E.V. Filippova, S.S. Tsygankov, A.A. Lutovinov, and R.A. Sunyaev

Space Research Institute, Profsoyuznaya str. 84/32, Moscow 117997, Russia

ABSTRACT

We studied 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). 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 analyze the evolution of spectral parameters as a function of the intensity of the sources and compare these with the results of previous studies.

Key words: X-ray pulsars, spectra.

1. INTRODUCTION

There are about 100 accretion-powered X-ray pulsars known to date and many papers have been devoted to studies of individual sources as well on to review them. Reference [1] was the first to summarize the spectra and pulse profiles for X-ray pulsars and proposed an empirical model to describe their spectra. Subsequently, reference [2] gave an overview of accretion-powered pulsars. GRANAT ([3]) and ComptonGRO ([4]) data were used to investigate the pulse profiles and the evolution of the pulse periods. Reference [5] used the RXTE data to analyze the pulsars whose spectra exhibited cyclotron lines.

Here we shortly report results of the broad-band spectral analysis of the X-ray pulsars observed by the INTEGRAL observatory ([6]). The full review with detailed description of results for individual sources with corresponding references can be found in [7].

2. OBSERVATIONS

In this work we used the INTEGRAL observations from orbit 23 (MJD 52629, December 21, 2002) to orbit 239 (MJD 53276, September 28, 2004); these were the then publicly available data and the data of the Russian quota obtained as part of the Galactic plane scans (GPS), the Galactic center deep exposure (GCDE), and the observations in the Guest observers program. The publicly available observations of the X-ray pulsar V0332+53, performed from orbit 272 (MJD 53376, January 6, 2005) to orbit 278 (MJD 53394, January 24, 2005) were used as an exception. Data from the ISGRI detector of the IBIS telescope and from the JEM-X monitor were used for the analysis.

3. DATA ANALYSIS

For all of the detected X-ray pulsars we constructed light curves in the energy range $18 - 60$ keV and analyzed their variability. We constructed average spectra for persistent sources and analyzed the dependence of the spectrum on the source's state for pulsars with variable fluxes: if the spectrum did not change, we also provided an average spectrum; otherwise, we gave the spectra of different states. To fit the spectra, we used a standard (for pulsars) empirical model that includes a power law with a high-energy cutoff ([1]). In certain cases, the standard model did not describe the pulsar's spectral shape quite accurately. Therefore, we introduced some additional components when fitting the spectra: low-energy photoelectron absorption, an iron emission line described by a Gaussian profile, a resonance cyclotron scattering feature.

4. RESULTS

As mentioned above, we constructed and studied spectra of 35 sources. The list of detected pulsars with best fit parameters of their spectra is presented in Table 1. A sample of broadband spectra ($\sim 4 - 100$ keV) for 18 pulsars is shown in Fig.1. Below we briefly dwell on the most interesting results.

First detection of hard X-ray emission from several sources. Hard X-ray spectra for X-ray pulsars RX J0146.9+6121, AX J1820.5-1434 and AX J1841.0-0535 have been obtained for the first time. The pulsar RX J0146.9+6121 is a faint source with a 18 – 60 keV flux of 3 mCrab. The pulsar AX J1841.0-0535 was registered only during two outbursts, when its 18 – 60 keV flux

Table 1. List of X-ray pulsars detected with INTEGRAL and their best-fit spectral parameters

Name	N_H,10^{22} cm^{-2}	Photon index, Γ	E_{cut},keV	E_{fold}, keV	χ^2
A 0114+650	–	2.3±0.4	–	–	0.42(6)
SMC X-1	–	1.48±0.02	$20.5^{+1.0}_{-1.8}$	$12.9^{+0.6}_{-0.7}$	0.98(124)
RX J0146.9+6121	–	$2.9^{+1.1}_{-0.8}$	–	–	0.31(3)
V0332+53	4[a]	0.77 ± 0.02	$24.3^{+0.5}_{-0.7}$	$14.0^{+0.5}_{-0.7}$	0.35(127)
4U 0352+309	–	1.92±0.19	50±16	77±27	0.36(9)
LMC X-4	–	0.2±0.15	9.1±0.8	11.0±0.6	0.93(117)
A 0535+26	–	1.2[a]	24[a]	$13.8^{+4.5}_{-3.2}$	0.07(5)
Vela X-1(eclipse)	–	3.1±0.3	–	–	0.83(7)
Vela X-1(outside eclipse)	–	0.88±0.01	25.5±0.2	13.0±0.1	0.34(131)
CEN X-3(quiescent state)	–	0.87±0.06	16.4±0.6	7.1±0.2	1.5(120)
CEN X-3(outbursts)	–	1.16±0.04	15.3±0.2	7.8±0.2	1.4(116)
4U 1145-619	–	1.5±0.1	6.7±1.4	30±4	1(142)
1E 1145.1-614	3.3[a]	1.08±0.07	8±1	$21.9^{+1.8}_{-0.8}$	0.98(139)
GX 301-2 (high state)	–	$0.74^{+0.32}_{-0.09}$	$23.3^{+0.3}_{-0.5}$	8.3±0.7	0.74(8)
GX 301-2 (low state)	10.6±2.5	0.30±0.06	17.8±0.2	9.7±0.7	0.9(118)
2RXP130159.6-635806	2.56[a]	0.69[a]	24.3±3.4	$8.5^{+0.2}_{-0.1}$	[c]
4U 1538-52	1.63[a]	1.37±0.06	28.7±0.8	9.9±0.7	0.94(119)
4U 1626-67	–	0.87[a]	$23.9^{+1.0}_{-1.4}$	7±1	1.25(5)
IGR/AX J16320-4752[b]	18[a]	0.7±0.2	–	13±1	[d]
IGR J16358-4726[b]	40[a]	0.7±0.5	–	16±5	[d]
AX J163904-4642[b]	58[a]	1.3±1.0	–	11±1	[d]
IGR J16465-4507[b]	72[a]	1.0±0.5	–	30[a]	[d]
OAO 1657-415	$15.2^{+0.7}_{-1.4}$	1.57±0.02	$26.3^{+0.7}_{-1.8}$	$29.2^{+1.2}_{-0.5}$	0.73(119)
EXO 1722-363	–	3.5[a]	–	–	2.7(5)
GX 1+4 (low state)	–	$2.24^{+0.06}_{-0.12}$	–	–	0.93(126)
GX 1+4 (intermediate state)	–	$1.54^{+0.35}_{-0.22}$	$24.8^{+5.8}_{-3.0}$	$47.0^{+15.2}_{-10.7}$	1.16(125)
GX 1+4 (high state)	–	$0.93^{+0.12}_{-0.14}$	$25.1^{+1.1}_{-1.7}$	30.4 ± 2.4	1.19(136)
IGR/SAX J18027-2017[b]	–	0.1[a]	–	∼10	–
XTE J1807-294	–	1.96[a]	$48.1^{+7.6}_{-9.9}$	$75.7^{+58.1}_{-24.5}$	0.92(7)
AX J1820.5-1434	–	0.9[a]	25±3	17.0±2.7	0.37(9)
AX J1841.0-0535	–	2.2 ± 0.3	–	–	0.42(5)
GS 1843+009	–	0.34[a]	5.95[a]	17.4±1.4	1.2(8)
A 1845-024	–	2.62±0.19	–	–	0.46(7)
XTE J1855-026	–	1.69±0.23	$23.99^{+2.88}_{-6.73}$	$38.49^{+10.35}_{-7.38}$	1.08(112)
XTE J1858+034	14.3±0.7	1.38±0.02	25.16±0.33	7.92±0.22	0.95(144)
X 1901+031	–	2.035±0.015	11.27±0.19	13.22±0.11	0.82(127)
4U 1907+097	–	1.26±0.07	7.0±0.3	$9.0^{+0.3}_{-0.6}$	0.75(131)
KS 1947+300	–	$1.07^{+0.24}_{-0.13}$	$8.6^{+3.4}_{-1.2}$	$23.6^{+5.3}_{-2.3}$	1.18(104)
EXO 2030+375	–	1.71±0.09	$25.2^{+2.5}_{-3.7}$	33^{+6}_{-4}	1.06(137)
SAX J2103.5+4545	0.9[a]	1.04±0.15	8.5±2.4	21.37±2.75	1.21(120)

[a] The parameter is fixed

[b] The cutoffpl model was used to fit the spectrum

[c] The pulsar's spectrum was fitted over a wide energy range together with data from the XMM observatory [8] .

[d] The pulsar's spectrum was fitted over a wide energy range together with data from the XMM observatory [9].

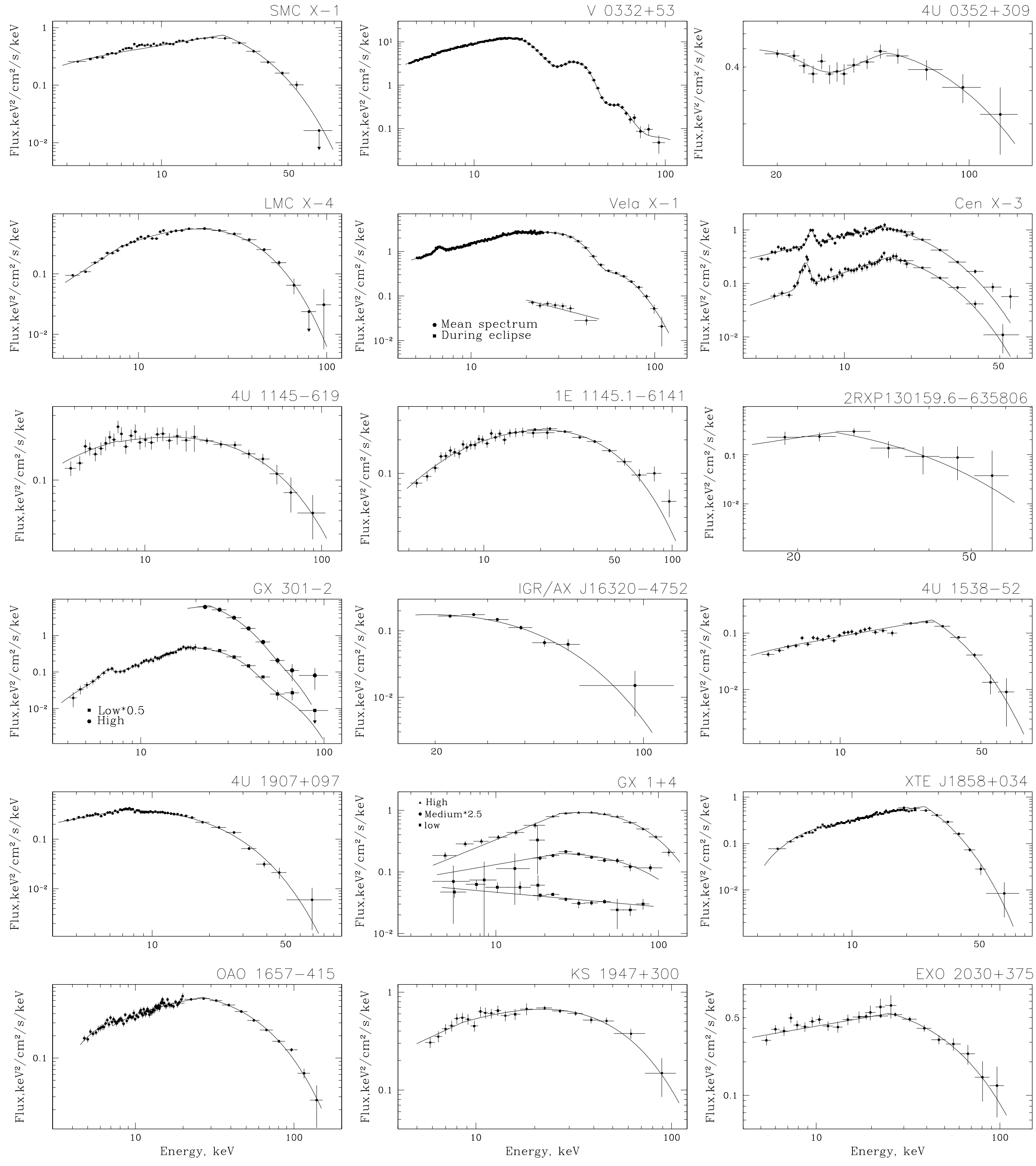

Figure 1. INTEGRAL energy spectra for 18 X-ray pulsars. The solid lines represent the best fit to the spectrum. The errors correspond to one standard deviation.

was increasing to $\sim 10-40$ mCrab. Because of the low-statistics data for these pulsars we used a simple power law with photon index $\Gamma = 2.9^{+1.1}_{-0.8}$ and $\Gamma = 2.2\pm0.3$, respectively, to fit their spectra. For the pulsar AX J1820.5-1434 the statistics were relatively good (the source was detected at a statistically significant level up to ~ 70 keV), therefore we used the model of a powerlaw with a high-energy cutoff to fit its spectrum. The photon index was fixed at 0.9 taken from previous studies ([10]).
We detected for the first time at a statistically significant level the 18 – 60 keV flux of $\sim$ 7 mCrab from the pulsar Vela X-1 during its eclipse by the optical companion. Since the source was not detected by the JEM-X instrument during the eclipse, we were able to construct its spectrum only in the hard X-ray energy range. The spectrum was fitted by a simple power law with the index of 3.1±0.3 (Fig.1).

Spectral variability of X-ray pulsars. The pulsar Cen X-3 is an eclipsing system; it demonstrates outbursts with a flux of $\sim$ 90 mCrab, that is about 5 times higher than the source flux in the quiet state, $\sim$17 mCrab (in the 18 – 60 keV energy range). We constructed the pulsar's radiation spectrum averaged over all outbursts and an average persistent spectrum outside the eclipses and found that the spectrum becomes softer during outbursts: the photon index increases from 0.87 ± 0.06 to 1.16 ± 0.04.
Our analysis confirmed ([11]) that the spectral parameters of pulsar GX 1+4 strongly depend on its flux. Despite significant statistical errors (Fig.1) it is clear that as the intensity of the radiation from the object under study decreases, its spectrum becomes slightly softer.
Also we detected a statistically significant increase in photon index of pulsar GX 301-2 during its transition from the low to the high state (Table 1).

Absorption and emission features. For several pulsars line features of different natures were observed in their spectra. We found three harmonics of the cyclotron absorption line in the spectrum of V 0332+53 at energies E_{cycl1}=24.25$^{+0.07}_{-0.14}$ keV, E_{cycl2}=46.8$^{+0.2}_{-0.1}$ keV, E_{cycl3}=67.9$^{+3.2}_{-4.3}$ keV; two harmonics in the spectrum of Vela X-1 at energies 24.0±0.3 keV and 50.2 ± 0.5 keV; one harmonic in the spectra of 4U 0352+309 and GX 301-2 at energies 28.8±2.5 keV and $\sim$ 49 keV, respectively. Furthermore for pulsar V 0332+53 the cyclotron line energy is not constant but changes significantly with luminosity ([12])
Fe line emission was detected in the spectra of Vela X-1 and GX 301-2 (low state) at energies 6.64±0.10 keV and 6.54$^{+0.17}_{-0.11}$ keV, respectively. Note that there are a number of features near energies $5-7$ keV in spectra reconstructed from the JEM-X data that are attributable to flaws in the current response matrix of the instrument, making it difficult to identify the iron emission line and to determine its parameters.

5. SUMMARY

– We constructed a catalog of spectra for 34 accretion-powered and one millisecond X-ray pulsars. Some of them were detected in hard X-rays for the first time. For 18 of the 35 sources, we were able to reconstruct their broadband spectra. For variable sources, we analyzed the flux dependence of the spectral shape.
– A hard X-ray spectrum was obtained for the first time for the pulsar Vela X-1 during an eclipse of the source by its optical companion.
– Cyclotron lines and their harmonics were detected in the spectra of several pulsars: one harmonic in 4U 0352+309, one harmonic in both low and high states in GX 301-2, two harmonics in Vela X-1, and three harmonics in V 0332+53.

6. AKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research (project no. 04-02-17276), the Russian Academy of Sciences (The Origins and evolution of stars and galaxies program) and grant of President of RF (NSh-1100.2006.2). AL acknowledges the financial support from the Russian Science Support Foundation.

REFERENCES

[1] N. White, J. Swank, and S. Holt, *Astrophys. J.* 270, 771 (1983).

[2] F. Nagase, *Publ. Astron. Soc. Jpn.* 41, 1 (1989).

[3] A. A. Lutovinov, S. A. Grebenev, R. A. Sunyaev, and M. N. Pavlinsky, *Astron. Lett.* 20, 538 (1994).

[4] L. Bildsten, D. Chakrabarty, J. Chiu, *et al.*, *Astrophys. J., Suppl. Ser.* 113, 367 (1997).

[5] W. Coburn, W. Heindl , R. Rothschild *et al.*, *Astroph. Journal* 580, 394 (2002).

[6] C. Winkler, T. J.-L. Courvoisier, G. Di Cocco, et al., *Astron. Astrophys.* 411, L1 (2003).

[7] E. Filippova, S. Tsygankov, A. Lutovinov, R. Sunyaev, *Astron. Letters* 31, 729 (2005).

[8] M. Chernyakova, A. Lutovinov, J. Rodriguez, and M. Revnivtsev, *Mon. Not. R. Astro. Soc.* 364, 455 (2005).

[9] A. Lutovinov, M. Revnivtsev, M. Gilfanov, *et al.*, *Astron. Astrophys.* 448, 82 (2005).

[10] K. Kinugasa, K. Torii, Y. Hashimoto, *et al.*, *Astrophys. J.* 495, 435 (1998).

[11] B. Paul, P. C. Agrawal, V. R. Chitnis, *et al.*, *Bull.Astron. Soc. India* 23, 478 (1995).

[12] Tsygankov S., Lutovinov A., Churazov E., Sunyaev R., 2006, *MNRAS*, 371, 19.