INTEGRAL Broadband X-ray spectrum of the intermediate polar V709 Cas

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Abstract. We present the hard X-ray time-averaged spectrum of the intermediate polar V709 Cas observed with INTEGRAL. We performed the observation using data from the IBIS/ISGRI instrument in the 20–100 keV energy band and from JEM-X at lower energy (5–20 keV). Using different multi-temperature and density X-ray post-shock models we measured an improved post-shock temperature of ∼ 40 keV and estimated the V709 Cas mass to be 0.82⁺0.12₋0.25 M⊙. We compare the resulting spectral parameters with previously reported BeppoSAX and RXTE observations.

Key words. accretion, binaries: close – stars: individual (V709 Cas) – X–rays: stars

1. Introduction

V709 Cas (RX J0028+5917) is a member of the intermediate polars (IP) systems, a sub-class of magnetic cataclysmic variables. This system consists of an accreting white dwarf (WD) and a low-mass late type main sequence companion star. The accretion onto V709 Cas is believed to be driven through the Roche-lobe overflow, where the accretion flow from the secondary proceeds towards the IP through an accretion disk, until it reaches the magnetospheric radius. Here the material attaches to the magnetic field lines and follows them almost radially at free-fall velocity towards the magnetic poles of the IP surface. At some distance from this surface, the accretion flow undergoes a strong shock, below which material settles onto the IP, releasing X-ray as it cools by thermal bremsstrahlung processes (see reviews Aizu, 1973; Cropper, 1990; Patterson, 1994). According to this standard model the spectra of the X-ray post-shock emitting region has a multi-temperature and density structure (e.g., Cropper et al., 1999). In order to measure the maximal shock temperature, hight energy observatories like INTEGRAL are needed. In the most case the temperature of the post-shock region of the accretion column of IPs are in the order of ∼ 10–60 keV. A hard X-ray study can also be used to estimate the IP mass by measuring the maximum temperature of the post-shock plasma (Suleimanov, Revnivtsev & Ritter, 2005). Using the INTEGRAL/RXTE data on the IP V1223 Sgr (Revnivtsev et al., 2004) studied such a broadband X-ray spectrum to determine the shock parameters and the IP mass.

The X-ray V709 Cas source was discovered and identified as a IP from the ROSAT All sky Survey (Haberl & Motch, 1995) and has been extensively studied with ROSAT (Haberl & Motch, 1995; Motch et al., 1996; Norton et al., 1994), with a joint RXTE/BeppoSAX X-ray observation (De Martino et al., 2001) and using optical spectroscopy and photometry (Bonnet-Bidaud et al., 2001; Kozhevnikov, 2001), respectively. The pulse period was found to be 312.8 s (Haberl & Motch, 1995; Norton et al., 1994) and a detailed spectroscopic study finally concluded to a 5.34 h orbital period after a previous ambiguity between 5.4 hr and 4.5 hr (Bonnet-Bidaud et al., 2001).

We present here a first INTEGRAL results of a broadband spectrum study, from 5–100 keV, where the energies above 20 keV are based on hard X-ray IBIS/ISGRI observations of V709 Cas.

2. Observations and Data Analysis

The present dataset was obtained during the Target of Opportunity (ToO) A02 INTEGRAL Winkler et al.

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observation of the Cas A region performed from 5–6 and 7–9 December 2004 (53345.6–53346.8 and 53347.8–53349.8 MJD), i.e. from part of INTEGRAL satellite revolutions 262 and 263. We use data from the IBIS/ISGRI (20–100 keV) coded mask imager (Ubertini et al., 2003; Lebrun et al., 2003) for a total exposure of 181.9 ks and from the JEM-X (5–20 keV) monitor (Land et al., 2003) for a total exposure time of 82 ks. For ISGRI, the data were extracted for all pointings with a source position offset ≤ 7", and for JEM-X with an offset ≤ 3.5". The spectrometer (SPI) (Roques et al., 2003) was not used to extract the hard X-ray spectrum due to the lower sensitivity of this instrument with respect to IBIS/ISGRI for a weak source below 100 keV. Above 90 keV, V709 Cas was not consistently detected in a single exposure and in the total exposure time. Data reduction was performed using the standard Offline Science Analysis (OSA) version 4.2 (Courvoisier et al., 2003). The algorithms used in the spatial and spectral analysis are described in Goldwurm et al. (2003).

3. Results

3.1. ISGRI Imaging

Fig. 1 shows a significance map around the source V709 Cas in the 20–40 keV energy range. Single pointings were deconvolved and analyzed separately, and then combined in mosaic images. Two sources are clearly detected at a significance level of respectively 12.6σ for V709 Cas and 82.8σ for IGR J00291+5934, a newly discovered millisecond pulsar in outburst (Falanga et al., 2003). In the energy band 40–80 keV, the confidence level was 5σ for V709 Cas and 46σ for IGR J00291+5934. At higher energies above 100 keV V709 Cas was not detected at a statistically significant level either in single exposures or in the total exposure time. To obtain precise source locations we simultaneously fitted the ISGRI point spread function to the two close sources. We obtained a position for V709 Cas at $\alpha_{2000} = 00^h28^m55.29^s$ and $\delta_{2000} = 59^\circ16'14''.0$. The position of IGR J00291+5934 is given by $\alpha_{2000} = 00^h29^m02.92^s$ and $\delta_{2000} = 59^\circ34'06''.4$. The source position offsets with respect to the optical catalog positions (Downes, Webbink & Shara, 1997; Fox & Kulkarni, 2004) are 1'4 for V709 Cas and 0'2 for IGR J00291+5934. The errors are 1'5 and 0'2 for V709 Cas and IGR J00291+5934, respectively. These are within the 90% confidence level assuming the source location error given by Gros et al. (2003). The derived angular distance between the two sources is ~ 20''. Due to the fact that INTEGRAL is able to image the sky at high angular resolution (12'' for ISGRI and 3' for JEM-X), we were able to clearly distinguish and isolate the high-energy fluxes from the two sources separately. This allows us to isolate and study the X-ray emission of V709 Cas during the outburst of the IGR J00291+5934 pulsar. The lack of contamination by the pulsar outburst was verified by building V709 Cas light curves in different energy ranges. While during the observation, the pulsar showed a significant decay with an e-folding time of ~ 6.6 day (Falanga et al., 2003), the V709 Cas (20-80 keV) light curve remains stable with a constant mean counting rate of ~ 0.6 ± 0.09.

3.2. Spectral Analysis

The spectral analysis was done using XSPEC version 11.3 (Arnaud, 1996), combining the 20–100 keV ISGRI data with the simultaneous 5–20 keV JEM-X data. Due to the short exposure time of JEM-X, and therefore lower statistics, we rebinned this data in a 5 channel energy response.
matrix. A constant factor was included in the fit to take into account the uncertainty in the cross-calibration of the instruments. A systematic error of 2% was applied to the JEM-X/ISGRI spectra which corresponds to the current uncertainty in the response matrix. All spectral uncertainties in the results are given at a 90% confidence level for single parameters.

The joint JEM-X/ISGRI (5–100 keV) broadband spectrum was first fitted with a simple optically thin thermal bremsstrahlung. The data fitted with $\chi^2$/dof=5/12, and the plasma temperature was found around 27 keV. In order to compare with previously reported measurements (e.g., De Martino et al. 2001), we also fit the plasma emission model MEKAL. We found a consistent plasma temperature value with the previous thermal bremsstrahlung fit, where the flux in the 5-100 keV energy range is $1.2 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ (see Table 1). During our INTEGRAL observation the source flux in the 3–100 keV was ~ 1.4 times smaller than that observed in July 1998 by BeppoSAX and ~ 2 times smaller by RXTE (De Martino et al. 2001). Suleimanov, Revnivtsev & Ritter (2005). The obtained value of the temperature parameter (26 keV) is significantly smaller than that obtained by De Martino et al. (2001) from BeppoSAX data (42 keV) and RXTE data (36 keV) using the same model. De Martino et al. (2001) found the same plasma temperature ~ 26 keV, only by including a reflection model in the fit. We attempted to test the hypothesis of a Compton reflection in the spectrum including the reflection model from Magdziarz & Zdziarski (1995). The lack of statistics in the low energy part of the JEM-X data prevent us to determine significant reflection parameters. The best fit parameters using only the high energy ISGRI data alone agree with the value from the joint JEM-X/ISGRI spectrum. This confirm the importance of the high energy observation to determine the post-shock temperature above 20 keV.

However, from the standard accretion shock model, when the matter falls onto the WD, the X-ray post-shock emission region is expected to show a multi-temperature and multi-density structure. To fit the spectrum we therefore use a more physically motivated model where the X-ray emission is determined through a density and temperature gradient along the emission region. The broadband time-averaged spectrum is then given by summing local bremsstrahlung spectra in the region between the WD surface and the shock distance, $z_0$. We use the same geometrical model described by Suleimanov, Revnivtsev & Ritter (2005), where the observed flux is given by Zombeck (1990):

$$F_E = 9.52 \times 10^{-38} \int_{R_{wd}}^{z_0} \left( \frac{\rho(z)}{n m_H} \right)^2 T(z)^{-1/2} \left( \frac{E}{k T(z)} \right)^{-0.4} \exp \left( -\frac{E}{k T(z)} \right) dz, \quad (1)$$

allowing the density profile, $\rho(z)$, and temperature profile, $T(z)$, to vary in the post-shock region (e.g., see Suleimanov, Revnivtsev & Ritter 2005; Cropper et al. 1999). In the flux equation, $\mu = 0.62$ is the mean molecular weight of fully ionized accreting matter, $m_H$ is the hydrogen mass and $k$ is the Boltzmann constant. The only two parameters in this model is now the WD mass, $M_{wd}$, and the accretion rate by unit of surface $a$. From the best fit, using a standard local accretion rate of $a = 1.0 \text{ g cm}^{-2} \text{ s}^{-1}$, we found $M_{wd} = 0.82 \text{ M}_\odot$, corresponding to a shock temperature of 39 keV (Table 1). The $\chi^2$ value is comparable with one of the simple bremsstrahlung model, however the post-shock model represent in more detail the physical processes in the WD emission region. Absorption by neutral hydrogen and partial absorber have not been included in these models since they have no significant effect above 5 keV. Table 1 gives the best fit parameters of this column model, for the ISGRI and combined JEM-X/ISGRI data sets. In Fig. 2 we present the $\nu F_\nu$ spectrum of the entire observation, plotted together with the residuals in units of $\sigma$ with respect to the best fit post-shock model.

3.2.1. Spectral Analysis: Models

Different models for the structure of accretion column have been put forward based on assumptions of constant pressure (Frank et al. 2002), influence of the magnetic field (Wu, Chanmugam & Shaviv 1994) or gravitational potential (Cropper et al. 1999). In an effort to also evaluate the influence of these different assumptions, a phenomenonological fit with a variable emission measure can be performed. Each model is indeed characterized by a power-law type density and temperature profiles along the accretion column. Assuming profiles with $(T/T_{shock})^\alpha$ and $(\rho/\rho_{shock}) = (x/x_{shock})^\beta$, it can be shown that the emission measure $EM = \int_{R_{wd}}^{z_0} \rho(z)^2 A dz$ is defined as:

$$EM = (T/T_{shock})^\Gamma \Gamma = \frac{(2\beta+1)}{\alpha}. \quad (2)$$

The $EM$ therefore also follows a power-law in temperature with an index $\Gamma$ and the column spectrum can be described with a power-law multi-temperature plasma emission model such as the XSPEC-CMKL. The parameters $\alpha$ and $\beta$ have been determined by fitting the published profiles of the different accretion shock structure models and are reported in table 2. To determine the post-shock temperature, the JEM-X/ISGRI spectrum have been then fitted using CMKL and fixing the model dependent power-law index, $\Gamma$, and the results are reported also in table 2.

4. Conclusions

A first broadband spectrum result on V709 Cas was already studied by De Martino et al. 2001 using BeppoSAX and RXTE data. We report here the first 5–100 keV high energy INTEGRAL spectrum result of V709 Cas. We found a bremsstrahlung temperature around 26 keV which is in agreement of a post-shock temperature around 40 keV (see Fig. 3). The theoretical spectrum of the post-shock model shown in Fig. 3 is calculated using equation (1), where the bremsstrahlung spectrum is...
Table 2. Best fit parameters from the JEM-X/ISGRI data in the 5–100 keV energy range.

| Model          | $\alpha$ | $\beta$ | $\Gamma$ | B-Field (MG) | $kT_{\text{shock}}$ (keV) | $\chi^2$/dof | $F_x$ (erg cm$^{-2}$ s$^{-1}$) |
|----------------|----------|---------|----------|--------------|---------------------------|-------------|-------------------------------|
| Frank et al. 2002 | 0.4      | -0.4    | 0.5      | -            | 39.9$^{+12.3}_{-12.1}$    | 4.91/12     | 1.36$\times 10^{-10}$        |
| Wu et al. 1994  | 0.341    | -0.399  | 0.592    | -            | 39.02$^{+11.8}_{-12.4}$   | 4.8/12      | 1.35$\times 10^{-10}$        |
| Wu et al. 1994  | 0.389    | -0.452  | 0.247    | 30           | 42.9$^{+13.8}_{-13.4}$    | 5.07/12     | 1.4$\times 10^{-10}$         |
| Suleimanov et al. 2005 | 0.312  | -0.433  | 0.430    | -            | 40.6$^{+12.6}_{-13.1}$    | 4.95/12     | 1.37$\times 10^{-10}$        |

Table 1. Best fit parameters of the phase-averaged X-ray spectra.

| Dataset       | JEM-X/ISGRI | ISGRI         |
|---------------|-------------|---------------|
| Energy range  | (5–100) keV | (20–100) keV  |
| Model         | BREMSSTRAHLUNG |
| $kT_{\text{Brems}}$ (keV) | 26.7$^{+6.7}_{-10.4}$ | 25.5$^{+9.3}_{-6.1}$ |
| $\chi^2$/dof | 5.3/12      | 5.8/9         |
| $F_x$ (erg cm$^{-2}$ s$^{-1}$) | 1.2$\times 10^{-10}$ | 0.52$\times 10^{-10}$ |
| Model         | MEKAL       |
| $kT_{\text{Max}}$ (keV) | 25.7$^{+6.7}_{-6.4}$ | 24.6$^{+5.6}_{-5.8}$ |
| $\chi^2$/dof | 5/12        | 5.8/9         |
| $F_x$ (erg cm$^{-2}$ s$^{-1}$) | 1.3$\times 10^{-10}$ | 0.57$\times 10^{-10}$ |
| Model         | POST-SHOCK  |
| $M_{\text{wd}}$ ($M_\odot$) | 0.82$^{+0.12}_{-0.25}$ | 0.85$^{+0.18}_{-0.15}$ |
| $kT_{\text{shock}}$ (keV) | 39.38      | 41.3          |
| $\chi^2$/dof | 5/12        | 6.3/9         |
| $F_x$ (erg cm$^{-2}$ s$^{-1}$) | 1.2$\times 10^{-10}$ | 0.95$\times 10^{-10}$ |

\[ \frac{1}{8} \frac{\mu m_H}{k R_{\text{wd}}} \]

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Fig. 3. The figure shows the agreement between the found value of the shock temperature from the post-shock model (see Sec. 3.2) with the best fit value using equation (1) as a Bremsstrahlung model.

References

Aizu, K. 1973, Prog Theoret. Phys., 49, 1184
Arnaud, K. A. 1996, in Astronomical Data Analysis Software and Systems V. ed. G. H. Jacoby, & J. Barnes, ASP Conf. Series 101, (San Francisco: ASP), 17
Bonnet-Bidaud, J. M., Mouchet, M., de Martino, D., Matt, G., Motch, C. 2001, A&A, 374, 1003
Courvoisier, T. J.-L., Walter, R., Beckmann, V., et al. 2003, A&A, 411, L57
Cropper, M., Wu, K., Ramsay, G., Kocabiyik, A. 1999, MNRAS, 306, 684
Cropper, M. 1990, Space Sci. Rev., 54, 195
Downes, R., Webbink, R., Shara, M., M., 1997, PASP, 109, 345
Eckert, D., Walter, R., Kretschmar, P., et al. 2004, Astr. Tel., 352
Falanga, M., Kuiper L., Poutanen J. et al., 2005, A&A, in press, astroph[0508613]
Fox, D. B., & Kulkarni, S. R., 2004, Astr. Tel., 354
Frank, J., King A., Raine D., 2002, in Accretion Power in Astrophysics, Camb. Univ. Press
Goldwurm, A., David, P., Foschini, L., et al. 2003, A&A, 411, L223
Gros, A., Goldwurm, A., Cadolle-Bel M., et al. 2003, A&A, 411, L179
Haberl, F., & Motch, C. 1995, A&A, 297, L37
Kozhevnikov, V. P. 2001, A&A, 366, 891
Lebrun F., Leray J.-P., Lavocate, Ph., et al. 2003, A&A, 411, L141
Lund, N., Budtz-Jørgensen, C., Westergaard, N. J., et al. 2003, A&A, 411, L231
Magdziarz, P., & Zdziarski, A. A. 1995, MNRAS, 273, 837
Motch, C., Haberl, F. & Guillout, P. et al. 1996, A&A, 307, 459
Nauenberg, M 1972, ApJ, 175, 417
Norton, A. J., Beardmore, A. P. Allan, A., Hellier, C. 1999, A&A 347, 203
Patterson, J 1994, PASP, 106, 209
Revnivtsev, M, Lutovinov, A., Suleimanov, V., A&A, 246, 253
Roques, J. P., Schanne, S., von Kienlin, A., et al. 2003, A&A, 411, L91
Suleimanov, V., Revnivtsev, M., & Ritter, H. 2005, A&A, 435, 191
Ubertini, P., Lebrun, F., Di Cocco, G., et al. 2003, A&A, 411, L131
Warner, B. 1995, Cataclysmic variable stars (Cambridge University Press)
Winkler, C., Courvoisier, T. J.-L., Di Cocco, G., et al. 2003, A&A, 411, L1
Wu, K., Chanmugam, G., & Shaviv, G. 1994, ApJ, 426, 664
Zombeck, M. V., 1990, Handbook of Astronomy & Astrophysics, Cambridge Univ. Press, Cambridge