DISC-JET COUPLING IN THE LMXB 4U 1636–53 FROM INTEGRAL OBSERVATION

MARIATERESA FIOCCI, ANGELA BAZZANO, PIETRO UBERTINI
Istituto di Astrofisica Spaziale e Fisica Cosmica di Roma (INAF)
Via Fosso del Cavaliere 100, Roma, I-00133, Italy

PIERRE JEAN
CESR, CNRS/Universit Paul Sabatier Toulouse 3, BP 4346, 31028 Toulouse Cedex 4, France

ABSTRACT

We report on the spectral analysis results of the neutron star, atoll type, low mass X-ray Binary 4U 1636–53 observed by INTEGRAL and BeppoSAX satellites. Spectral behavior in three different epochs corresponding to three different spectral states has been deeply investigated. Two data set spectra show a continuum well described by one or two soft blackbody plus a Comptonized components with changes in the Comptonizing electrons and black body temperature and the accretion rates, which are typical of the spectral transitions from high to low state. In one occasion INTEGRAL spectrum shows, for first time in this source, a hard tail dominating the emission above 30 keV. The total spectrum is fitted as the sum of a Comptonized component similar to soft state and a power-law component ($\Gamma = 2.76$), indicating the presence of a non thermal electron distribution of velocities. In this case, a comparison with hard tails detected in soft states from neutron stars systems and some black hole binaries suggests that a similar mechanism could originate these components in both cases.

Subject headings: accretion, accretion disks – gamma rays: observations – radiation mechanisms: non-thermal – stars: individual: 4U 1636–53 – stars: neutron – X-rays: binaries

1. INTRODUCTION

4U 1636–53 is a neutron star low mass X-ray binary (LMXB) classified as a atoll source (Hasinger & van der Klis 1989), with an orbital period of 3.8 hr derived from the optical variability of its companion V801 Arae (Pedersen, van Paradijs & Lewin 1984) and at distance of 3.7–6.5 kpc (Fujimoto et al. 1988, Smale & Lochner 1992, Augusteijn et al. 1998).

While the X-ray burst properties and timing signatures have been analyzed extensively (see Jonker et al. 2005, Belloni et al. 2005 and references therein) the spectral characteristics have been studied only at low energy with Einstein, EXOSAT, Temma and ASCA. In general, the spectrum was acceptably fitted by a Comptonization model plus a black body component. A coronal temperature of 2.3-2.6 keV, an optical depth of 13, and a soft black body temperature of 0.55 keV were the best fit parameter for the Einstein data (Christian and Swank 1997). EXOSAT data reveal two different source intensity: for the maximum intensity the coronal temperature was $\sim 0.55$ keV were the best fit parameter for the Einstein data (Christian and Swank 1997). A coronal temperature of 2.3-2.6 keV , an optical depth of 13, and a soft black body temperature of 0.55 keV were the best fit parameter for the Einstein data (Christian and Swank 1997).

2. OBSERVATIONS AND DATA ANALYSIS

Table I summarizes the log of INTEGRAL and BeppoSAX observations of 4U 1636–53. BeppoSAX observed the source on three occasions: February and March 1998 and February 2000. LECS, MECS and PDS event files and spectra, available from the ASI Scientific Data Center, were generated by means of the Supervised Standard Science Analysis [Fiore et al. 1999]. Both LECS and MECS spectra were accumulated in circular regions of 8’ radius. The PDS spectra were obtained with the background rejection method based on fixed rise time thresholds. Publicly available matrices were used for all the instruments. The cross-calibration constant values were taken in agreement with the indications given in Fiore et al. 1999. Fits are performed in the following energy band: 0.5–3.5 keV for LECS, 1.5–10.0 keV for MECS and 15–70 keV for PDS. The analyzed INTEGRAL (Winkler et al. 2003) data set consists of all observations in which 4U 1636-53 was within the high-energy detectors field of view. Observations are organized into uninterrupted 2000 s long science pointing, windows (scw): light curves and spectra are extracted for each individual scw. Wideband spectra (from 5 to 150 keV) of the source are obtained using data from the two high-energy instruments JEM-X [Lund et al. 2003] and IBIS.
Data were processed using the Off-line Scientific Analysis (OSA version 5.1) software released by the INTEGRAL Scientific Data Centre. While IBIS provide a very large FOV (~ 30°), JEM-X has a narrower FOV (~ 10°), thus providing only a partial overlap with the high-energy detectors. Data from the Fully Coded field of view only for both instrument have been used. The angular resolution of IBIS instrument is 12 arcmin, any source at a distance larger than the instrument angular resolution do not contribute at all to the observed source spectrum and flux (Ubertini et al. 2003) due to the coded mask intrinsic characteristics.

3. SPECTRAL ANALYSIS RESULTS

The whole data set was carefully fitted with several physical models, while trying to keep the number of free parameters as low as possible. Each time a new component was added to the model, a F-test was performed. We assumed that a F probability larger than 95% implies a significative improvement of the fit. The uncertainties are at 90% confidence level for one parameter of interest ($\Delta \chi^2 = 2.71$). When spectra are from more than one detector, we allow the relative normalization to be free with respect to the MECS and IBIS data, for BeppoSAX and INTEGRAL respectively. XSPEC v. 11.3.1. has been used.

Spectral behavior has been studied separately in three epochs consisting of the following data:

1st epoch: all three BeppoSAX observations available from February 1998 to February 2000. During these periods the source was always in a soft/high state.

2nd epoch: JEM-X and IBIS data available from 52644 MJD to 53644 MJD with count rate < 5 counts s$^{-1}$ in the 20–40 keV energy band. For the chosen period the source was in a hard/low state.

3rd epoch: JEM-X and IBIS data available from 52644 MJD to 53644 MJD with count rate > 5 counts s$^{-1}$ in the 20–40 keV energy band. This epoch does not correspond to either the soft or the hard state and here we call it peculiar state as will be explained in detail later on.

The most simple model which provides a good fit to each BeppoSAX spectrum in the energy band 0.5–70 keV consist of a thermal Comptonized component modeled in XSPEC by COMPTT (a spherical geometry was assumed) plus a soft component which we modeled with two temperature blackbody. The simplest model consisting of multicolor DISKKBB (Makishima et al. 1986) plus a COMPTT component do not give a good fit, with a $\chi^2_{\text{red}} \sim 2.5$ for each observations. The black body and thermal Comptonized component parameters were left free in order to determine the blackbody temperature $T_{bb}$, the electron temperature $T_e$, the optical depth $\tau$ and seed photon temperature $T_0$. Results from these fits are reported in Table 2. Figure 4 shows three BeppoSAX spectra and the residuals with respect to the corresponding best fits. The column density $N_H$ towards the source was left free and its value measured by the LECS and MECS instrument is always close to the galactic column density ($N_H \text{ galactic} = 3.58 \times 10^{21} \text{cm}^{-2}$, estimated from the 21 cm measurement of Dickey & Lockman 1990). The seed photon temperature is always $T_0 = 1.3 \pm 0.2$ keV, and all parameters did not significantly vary from one observation to another.

In order to achieve the highest signal to noise ratio we build the BeppoSAX average spectrum arranging all three observations. This procedure can, in principle, be risky since the source can change its spectrum from one observation to another. However in our case, the previous analysis showed no significant shape changes for the three observations. We thus can take advantage of the high quality of the average spectrum up to about 70 keV. We fit the average BeppoSAX spectrum with the model used for the single observations. $N_H$ has been fixed to the value for the galactic column density. Spectral fit results are given in Table 3 the average spectrum is shown in Fig. 2.

The source was in the soft/high state with an un-absorbed luminosity of $L_{0.1-200\text{keV}} \approx 2.0 \times 10^{37}$ erg s$^{-1}$, assuming a distance of 5.9 kpc (Cornelisse et al. 2003). As in the case of the Einstein observation (Christian and Swank 1997),
peculiar spectra are shown in Fig. 3. In this component becomes negligible and it is not necessary to best fit the data. Spectral fit results are given in Table 3, and blackbody (Makishima et al. 1986) instead of Comptonization halo; nevertheless the temperature is extremely high. BeppoSAX state, a possible interpretation of this state is that 4U 1636–53 was in a similar soft/high state as during and perhaps unphysical. Since the spectral parameters in the BeppoSAX the measured by the BeppoSAX observations. During this period, the source has a luminosity of \( L \) erg s\(^{-1}\). The disk components seem to originate from two different parts of the disk, corresponding to two different temperature. The thermal Comptonization of the optically thick plasma corona with a quite low electron temperature is dominating. The most simple model which provides a good fit to the INTEGRAL hard state consist of a thermal Comptonized component modeled in XSPEC by \texttt{COMPTT} (Titarchuk 1994) (a spherical geometry was assumed) plus a soft component which we modeled by a single temperature blackbody. Because of the very good low energy BeppoSAX coverage, we used the average value of input soft photon temperature and column density (\( T_0 = 1.3\) keV and \( N_H = N_H \) Galactic) measured by the BeppoSAX observations. During this period, the source has a luminosity of \( L_0,1–200\) keV \( \simeq 4 \times 10^{37} \) erg s\(^{-1}\), lower than the one in the soft state, in agreement with the usual ranking of the luminosity in atoll sources (e.g., Hasinger & van der Klis 1989; van der Klis 2000; Gierliński & Done 2002). The electron temperature is now substantially higher than in the soft state, \( T_e \sim 23 \) keV, and the Comptonization component extends well above \( \sim 100 \) keV.

The same model was been applied to the 2\(^{nd}\) INTEGRAL data set but resulted in a poor fit with a \( \chi^2/d.o.f = 97/57\) and clear residuals above 60 keV. Adding a power law improves the fit significantly (\( \chi^2/d.o.f \) becomes 64/55). A simple model with the single temperature blackbody and power law do not fit our data (\( \chi^2_{red} \approx 5\)). The disk component becomes negligible and it is not necessary to best fit the data. Spectral fit results are given in Table 3 and spectra are shown in Fig. 3. In this peculiar state, the spectrum is also compatible with a power-law and multiple blackbody (Makishima et al. 1986) instead of Comptonization halo; nevertheless the temperature is extremely high and perhaps unphysical. Since the spectral parameters in the peculiar state are similar to those in the soft/high BeppoSAX state, a possible interpretation of this state is that 4U 1636–53 was in a similar soft/high state as during the BeppoSAX observations, but with a new overlapped component at high energies simultaneously present. The un-absorbed luminosity is \( L_0,1–200\) keV \( \simeq 7 \times 10^{37} \) erg s\(^{-1}\). Comparison between the models in the three different spectral states are shown in Fig. 4. Spectral state transitions are evident, with the hard INTEGRAL state extended up well above 100 keV and, in the peculiar state, a steep power-law component detected with high statistical significance up to 100 keV.

4. DISCUSSION AND CONCLUSIONS

According to our present understanding, the black-body component in the soft states could originate at both the neutron star surface and the surface of an optically-thick accretion disk. In our observations the two black body components seems to originate from two different parts of the disk, corresponding to two different temperature. The
TABLE 3

Results of the fit of 4U 1636–53 spectra in the energy band 0.5 – 70 keV and 5 – 150 keV for BeppoSAX and INTEGRAL observations respectively, for three different spectral states. For each state we report the best fit model. The black body equivalent radius is computed using a distance of 5.9 kpc (Cornelisse et al. 2003). Uncertainties are at the 90% confidence level for a single parameter variation.

|                  | BeppoSAX average high/soft state spectrum |                  |                  |                  |                  |                  |                  |
|------------------|------------------------------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| model            | bbody + bbody + comptt                    |                  |                  |                  |                  |                  |                  |
| $T_{BB1}$ keV    | 0.24 ± 0.01                               |                  |                  |                  |                  |                  |                  |
| $T_{BB2}$ keV    | 0.58 ± 0.02                               |                  |                  |                  |                  |                  |                  |
| $T_e$ keV        | 1.3 ± 0.1                                 |                  |                  |                  |                  |                  |                  |
| $T_0$ keV        | 3.4 ± 0.3                                 |                  |                  |                  |                  |                  |                  |
| $\tau$           | 3.8 ± 0.4                                 |                  |                  |                  |                  |                  |                  |
| $R_{BB1}$ km     | 79 ± 6                                    |                  |                  |                  |                  |                  |                  |
| $R_{BB2}$ km     | 25 ± 1                                    |                  |                  |                  |                  |                  |                  |
| $n_{COMP}$       | 0.19 ± 0.02                               |                  |                  |                  |                  |                  |                  |
| $\chi^2$/d.o.f  | 235/190                                   |                  |                  |                  |                  |                  |                  |

|                  | INTEGRAL low/hard state spectrum         |                  |                  |                  |                  |                  |                  |
| model            | bbody + comptt                            |                  |                  |                  |                  |                  |                  |
| $T_{BB2}$ keV    | 0.24 ± 0.02                               |                  |                  |                  |                  |                  |                  |
| $T_0$ keV        | 0.58 ± 0.02                               |                  |                  |                  |                  |                  |                  |
| $T_e$ keV        | 1.3 fixed                                 |                  |                  |                  |                  |                  |                  |
| $\tau$           | 5.3 ± 3                                   |                  |                  |                  |                  |                  |                  |
| $R_{BB2}$ km     | 25 ± 1                                    |                  |                  |                  |                  |                  |                  |
| $n_{COMP}$       | 0.19 ± 0.02                               |                  |                  |                  |                  |                  |                  |
| $\chi^2$/d.o.f  | 235/190                                   |                  |                  |                  |                  |                  |                  |

|                  | INTEGRAL peculiar state spectrum          |                  |                  |                  |                  |                  |                  |
| model            | comptt + powerlaw                         |                  |                  |                  |                  |                  |                  |
| $T_0$ keV        | 1.3 fixed                                 |                  |                  |                  |                  |                  |                  |
| $T_e$ keV        | 3.2 ± 0.2                                 |                  |                  |                  |                  |                  |                  |
| $\tau$           | 2.6 ± 0.1                                 |                  |                  |                  |                  |                  |                  |
| $\Gamma$         | 5.3 ± 5                                   |                  |                  |                  |                  |                  |                  |
| $n_{COMP}$       | 0.19 ± 0.02                               |                  |                  |                  |                  |                  |                  |
| $n_{powerlaw}$   | 25 ± 5                                    |                  |                  |                  |                  |                  |                  |
| $\chi^2$/d.o.f  | 57/59                                     |                  |                  |                  |                  |                  |                  |

Fig. 2.— The BeppoSAX average spectrum in the soft state (epochs 1), shown together with the total model and its components: the total, two blackbody and the Comptonization components are shown in green, red, magenta and blue, respectively. Residuals with respect to the corresponding best fits are also showed.

High optical thickness of the plasma rules out the black body component as originates from the neutron star cap regions. Anyway, independently from the optical thickness of the plasma, it is very improbable to have emission from the polar caps of the neutron star for this source. In fact the magnetic field of the LMXBs is $\sim 10^8$ Gauss implying that the accretion onto the neutron star is not magnetically dominated and the matter accretes onto the whole NS surface. The Comptonization component may arise from a corona above the disk and/or between the disk and the neutron star surface. In the hard states, accretion probably assumes the form of a truncated outer accretion disk and a hot inner flow, joining the disk and the stellar surface as previously reported by Barret & Olive (2002) for LMXB 4U 1705-44. The spectral transitions are generally, but not necessarily, coupled with changes in luminosity, indicating they are driven by variability of the accretion rate or change of the geometry of the system as for Black Hole hard/soft transition at constant luminosity (Belloni et al. 2005). For 4U 1636–53 the accretion rate is lower in the hard state than in the soft state: for an accretion efficiency of $\eta = 0.2$ (corresponding, e.g., to $M_{NS} = 1.4M_\odot$ and $R_{NS} = 10$ km ) and using our model luminosities, $L_{0.1–200\text{keV}}$, we get $\dot{M}_{\text{soft}} \approx 7.3 \times 10^{-9}M_\odot \text{yr}^{-1}$ and $\dot{M}_{\text{hard}} \approx 4.0 \times 10^{-9}M_\odot$.
Transitions are apparently accompanied by changing in the geometry of the flow, and in the relative contribution of the blackbody-like and Comptonization components. In the peculiar state the accretion rate becomes very high ($\dot{M}_{\text{peculiar}} \simeq 2.1 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$), but this value can be influenced by the steep power law that dominates the energy spectrum at low energies. The emission is best described by Comptonization from a complex electron distribution due to a low temperature ($\sim 3 - 4$ keV) thermal electron distribution together with non-thermal power-law electrons. This two-component electron distribution could arise from non-thermal electron acceleration regions powered by magnetic reconnections above a disc. Low-energy electrons cool preferentially by Coulomb collisions leading to a thermal distribution while the high-energy electrons cool by Compton scattering, preserving a non-thermal distribution (Coppi 1999). Alternatively, the thermal and non-thermal electrons could be spatially distinct, e.g. magnetic reconnection above the disc can produce a non-thermal electron distribution, while overheating of the inner disc produces the thermal Comptonization (Kubota et al. 2001).

LMXBs exhibit hard X-ray states which are very similar to the Black Hole Candidates ones and investigating the possible disc-jet coupling is very interesting and still matter of discussion. The power-law component could be produced by Comptonization by synchrotron emission in the jet (Bosch-Ramon et al. 2005, Fender 2004) as proposed for others...
LMXBs: the power law component in Cir X-1 is explained by Iaria et al. (2002) as jet emission that has been resolved using radio interferometry by Fender & Kuulkers (2001); a significant correlation between radio and X-ray flux has been detected for 4U 1728-34 (Migliari et al. 2003), indicating a clear signature of disc-jet coupling. In our source, this hypothesis is strengthened by radio detection: Sydney University Molonglo Sky Survey catalog gives a flux of 7.5 mJy at 843 GHz (Mauch et al. 2003). Assuming a radio spectral index of -0.5 to estimate the flux density at 5 GHz based on other observations, we found a radio loudness $P_R/P_X$ (as defined in Fender & Kuulkers 2001) in the range 1.1-2.2 Jy/Crab, where $P_R$ is the radio flux density at 5 GHz and $P_X$ is the peak X-ray flux measured in the soft band ($<12$ keV), even though the two data set are not simultaneous. The radio loudness value is consistent with the one for Cir X-1 (Fender & Kuulkers 2001) and it is very high respect to other LMXBs and quite similar to that of Back Hole Candidates. These founding are in favour of the jet hypothesis as origin of the power-law observed for 4U 1636–53 similarly to GX 5-1, Cir X-1 and GX 17+2 being all of them associated with variable radio sources (Fender & Hendry 2000, and reference therein).

Simultaneous high energy and radio observations during spectral transition are crucial to disentangle the power law emission in the LMXBs containing a neutron star.

Finally, Laurent & Titarchuk (1999) suggest the detection of a power-law component at high energy to be a signature of presence black hole in an X-ray binary system. Our data are supporting result on GX 17+2 by Di Salvo et al. (2000), clearly showing this criterion proposed to distinguish black hole versus neutron star binaries is inadequate.

We acknowledge the ASI financial/programmatic support via contracts ASI-IR 046/04. A special thank to M. Federici and G. De Cesare for supervising the INTEGRAL data archive and software respectively. A very particular thank to K. Kretschmer for making data available before becoming public.

REFERENCES

Asai, K., Dotani, T., Mitsuda, K., Inone, H., Tanaka, Y., Lewin, W. H. G., 1998, IAUS, 188, 354
Augusteijn, T., van der Hooft, F., de Jong, J. A., van Kerkwijk, M. H., van Paradijs, J., 1998, A&A 332, 501
Barret, D., & Olive, J. F. 2002, ApJ, 576, 391
Belloni T., Mendez M. & Homan J., 2005, A&A, 437, 209
Bosch-Ramon, V., Romero, G. E. and Paredes, J. M., 2005, A&A, 429, 267
Christian D. J. & Swank J. H., 1997, ApJ, 109, 177
Coppi P. S., 1999, in ASP Conf. Ser. 161, High Energy Processes in Accreting Black Holes, ed. J. Poutanen & R. Svensson (San Francisco: ASP), 375
Cornelisse, R. et al., 2003, A&A, 405, 1033
D’Amico, F., Heindl, W.A., Rothschild, R.E., Gruber, D.E., 2001, ApJ, 547, 147
Dickey & Lockman, 1990, Ann. Rev. Astron. Astrophys. 28, 2
Di Salvo, T., et al., 2000, ApJ, 544, 119
Di Salvo, T., Robba, N. R., Iaria, R., Stella, L., Burderi, L., Israel, G. L., 2001, ApJ, 554, 49
Fender, R. P. & Hendry M. A., 2000, MNRAS, 317, 1
Fender, R. P. & Kuulkers, E., 2001, MNRAS, 324, 923
Fender, R. P., 2004, Compact Stellar X-Ray Sources’, eds. W.H.G. Lewin and M. van der Klis, Cambridge University.
---

Fiore, F., Guainazzi, M., & Grandi, P. 1999, Cookbook for BeppoSAX NFI Spectral Analysis (www.asdc.asi.it/bepposax/software/cookbook)
Fujimoto, M. Y., Sztajno, M., Lewin, W. H. G., van Paradijs, J., 1988, A&A, 199, 9
Gierlinski, M., & Done, C., 2002, MNRAS, 337, 1373
Hasinger, G., & van der Klis, M. 1989, A&A, 225, 79
Jonker P. G., Mendez M., van der Klis M., 2005, MNRAS, 360, 921
Kubota A., Makishima K., Ebisawa K., 2001, ApJ, 560, L147
Iaria, R., Di Salvo, T., Burderi, L., Robba, N. R., 2001, ApJ, 548, 883
Iaria, R., Di Salvo, T., Robba, N. R., Burderi, L., 2002, ApJ, 567, 503
Laurent, P. & Titarchuk, L., 1999, ApJ, 511, 289
Lund, N., et al., 2003, A&A, 411, L231
Makishima, K., Maejima, Y., Mitsuda, K., Bradt, H. V., Remillard, R. A., Tuohy, I. R., Hoshi, R., Nakagawa, M., 1986, ApJ, 308, 635
Mauch, T., Murphy, T., Buttery, H. J., Curran, J., Hunstead, R. W., Piestrzynski, B., Robertson, J. G., Sadler, E. M., 2003, MNRAS, 342, 1117
Migliari, S., Fender, R. P., Rupen, M., Jonker, P. G., Klein-Wolt, M., Hjellming, R. M., van der Klis, M., 2003, MNRAS, 342, 67
Pedersen, H. van Paradijs, J. Lewin, W. H. G. 1984, IAUC, 3952, 3
Piraino, S., Santangelo, A., Ford, E. C., Kaaret, P., 1999, A&A, 349, 77
Smale, Alan P., & Lochner, James C., 1992, ApJ, 395, 582
Titarchuk, L. 1994, ApJ, 434, 570
Ubertini, R., Lebrun, F., di Cocco, G. et al. 2003, A&A, 411, 131
Vacca, W. D., Sztajno, M., Lewin, W. H. G., Truemper, J., van Paradijs, J., Smith, A. 1987, A&A, 172, 143
van der Klis, M., 2000, ARA&A, 38, 717
Waki, I., et al., 1984, PASJ, 36, 819
White N. E., Stella L. & Parmar A. N. 1988, ApJ, 324, 363
Winkler, C., Gehrels, N., Schnfelder, V., Roques, J.-P., Strong, A. W., Wunderer, C., Ubertini, P., 2003, A&A, 411, 349
Zhang, S. N., et al., 1996, A&A, 120, 279