THE INTEGRAL LMXRB MONITORING PROGRAMME

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ABSTRACT

Our collaboration is responsible for the study of a sample of 72 low mass X-ray binaries (LMXRB) using the INTEGRAL Core Programme data. In this paper we describe the monitoring programme we have started and the current variability and spectral results on a sample of 8 persistently bright LMXRBs hosting a neutron star (Z and Atoll sources). Current results show that among our sample of sources there seems to be no important difference in the variability of Z sources with respect to Atolls and the first colour-colour and hardness intensity diagrams built in the “traditional” energy bands display the expected patterns.

Z sources seem to be harder than the bright Atolls of our sample (above 20 keV) and present no evident cut-off until about 50 keV. A hint of a non-thermal hard tail is seen in Sco X-1 with ISGRI and SPI, similarly to what was previously detected by D’Amico et al. (2001) with RXTE. These results, even if preliminary, show the importance of such a programme and the potential underlying it to understand these sources as a class.

Key words: stars: neutron – binaries: close – X-rays: binaries –INTEGRAL sources.

1. INTRODUCTION

The International Gamma-Ray Astrophysics Laboratory, INTEGRAL (Winkler et al. 2003), has been launched in October 2002. Since then, it has been providing a large amount of interesting data. The combination of two wide field of view (FOV) instruments, the imager IBIS (15 keV – 10 MeV, $29^\circ \times 29^\circ$ partially coded FOV, Ubertini et al. 2003) and the spectrometer SPI (20 keV – 8 MeV, $35^\circ \times 35^\circ$ partially coded hexagonal FOV, Vedrenne et al. 2003) coaligned with the JEM–X (Lund et al. 2003) and OMC (Mas-Hesse et al. 2003) monitors, allows large areas of the sky to be observed and monitored simultaneously in a wide energy range from the optical to the $\gamma$-ray domain. Such a capability is fully exploited during the INTEGRAL Core Programme (Winkler et al. 2003b), a series of successive scans of the Galactic Plane (GPS) and Galactic Centre (GCDE), which is regularly producing large amounts of data, in particular on persistently bright sources.

Our collaboration is responsible for the monitoring of a sample of low mass X-ray binaries (LMXRBs). In this paper we describe the current results of this programme, showing the importance of this study and the potential underlying such a long term monitoring.

Section 2 of this paper describes the aim of the monitoring programme with a basic overview of the source characteristics. Section 3 contains the data reduction and analysis description while in Section 4 the current results are given. In the last Section we present our conclusions and future plans.
sources have weaker magnetic fields (as well. Many differences, however, remain: Atoll source, ADC=Accretion Disc Corona. The nature of the sources in our list is very rich, containing black hole (BH) as well as weakly magnetised neutron star (NS) binaries with very different variability. Monitoring these sources through the years will give an overview of the hard energy (> 10 keV) behaviour of the Galactic Plane and Centre LMXRBs as a class: outburst frequency, variability level, type I X-ray burst frequency, persistent emission etc, all in the poorly studied hard energy domain. Among all the sources of our sample, in this paper we focus on the 8 persistently bright LMXRBs listed in Table 1. They all host a neutron star. The current classification of NS LMXRBs is based on the pattern displayed by individual sources in the X-ray colour-colour (CC) and hardness-intensity (HI) diagrams (Hasinger & van der Klis, 1989 and van der Klis, 1995). It comprises the so-called Z sources (that display a "Z" pattern in the diagrams) and the Atoll sources (that display an upwardly curved branch in the diagrams). More recent studies (Muno et al. 2002, Gierliński & Done 2002 and Done & Gierliński 2003) suggest that the clear Z/Atoll distinction in the CC diagram is an artifact due to incomplete sampling: Atoll sources, if observed long enough, do exhibit a Z shape in the CC as well. Many differences, however, remain: Atoll sources have weaker magnetic fields (<10^9–10^{10} G versus ~10^9–10^{10} G of Z sources), are generally fainter (0.01–0.3L_{Edd} versus ~ L_{Edd}), can exhibit harder spectra, trace out the Z shape on longer time scales than typical Z sources and have a different correlated timing behaviour along with the position on the Z. Thus the distinction, at least from a practical point of view, still makes sense. Our sample of sources includes both Z and Atoll sources. Thanks to the INTEGRAL monitoring programme we (will) have a long term coverage of all these sources. For the first time they will be studied in a regular and unbiased way in the energy band in which they are poorly known, hard X/γ rays, where they display an interesting behaviour. Thermal comptonisation is dominant both in soft and hard spectral states of NS LMXRBs and in most cases it is a good representation of the spectra below 20 keV. In this range, LMXRB with a weakly magnetised NS (i.e. non pulsating) can be well described by two competing models. On one side, there is the so-called "western" model in which the spectrum is composed of the sum of unsaturated Comptonised spectrum (produced by an inner disc corona) plus a blackbody originating from a region close to the neutron star surface or from the boundary layer between the disc and the neutron star (White et al. 1986, 1988). On the other hand, in the "eastern" model the spectrum consists of the sum of an optically thick multi-temperature disc-model (locally emitting like a pure blackbody) plus a comptised blackbody again originating from the neutron star or boundary layers (Mitsuda et al. 1984; Mitsuda et al. 1989). Hard X-ray components extending up to several hundred keV have been revealed in about 20 NS LMXRBs of the Atoll class (Di Salvo & Stella 2002 and references therein). In these systems a power-law like component (with photon index Γ ~ 1.5 – 2.5) is followed by an exponential cutoff between ~20 and many tens of keV. This is explained in terms of unsaturated thermal Comptonisation. But there are cases in which no evidence for a cutoff is found up to 100-200 keV. This is the so-called "hard state" of Atoll sources and occurs especially in the lower luminosity systems (note that the Atolls of our sample are among the brightest). On the other hand, broad band studies have shown that also many Z sources display a variable hard power-law (Γ ~ 1.9–3.3) component dominating the spectra above ~ 30 keV. The origin of these hard tails is still debated. Radio observations of some Z sources (Fender & Hendry 2000) seem to show a general trend in which the highest radio fluxes (thought to be originating in jets) are associated to the hardest state of the sources. This could mean that the non thermal, high-energy electrons responsible for the hard tails in Z sources could be accelerated in jets (Di Salvo et al. 2000). The long term X-ray variability of LMXRBs has been extensively studied in the 2–12 keV band with the RXTE All Sky Monitor. At higher energies, the information gathered from the sources has been obtained mainly via dedicated pointings (RXTE, BeppoSAX etc). The combination of regular monitoring in the hard X-rays and γ-rays has not been done before and this is where INTEGRAL will give a major contribution to understand the behaviour of bright LMXRBs from 5 keV up to ~ 200 keV (see also Paizis et al. 2003). By focusing on the sources presented in this paper, we intend to try to understand the differences between Z and Atoll sources via their (less explored) high-energy emission (hard tails, CC diagrams, different variability, etc). In collaboration with the accreting pulsars collaboration,
we intend to put the extracted light-curves and hardness intensity diagrams on the web\textsuperscript{1}. In this way, the high-energy history of these sources will be easily accessible, enabling also multiwavelength comparisons. In this respect, our collaboration has coordinated RXTE observations to the INTEGRAL ones in order to have a better coverage of the soft X-ray domain\textsuperscript{2}. Similarly, we have access to Radio (RATAN/MOST/VLA) and Optical (La Palma, La Silla) telescopes.

3. DATA REDUCTION AND ANALYSIS

INTEGRAL performs a GPS about every 12 days and the GCDEs are performed according to the Galactic Centre visibility. At the time of writing the first year of core programme has been completed and we have analysed all the data from revolution 26 (January 2003) until revolution 142 (December 2003) for a total of 3078 science windows corresponding to about 5.7 Msec. Version 3.0 of ISDC’s (Courvoisier et al. 2003) Offline Science Analysis (OSA) software has been used for analysing the data.

Given the type of sources involved (rather steep spectra with about hundred of mCrabs in the 2–10 keV band, Liu et al. 2001) and the pointing exposures of about 2000 s, for the analysis we have chosen JEM-X for soft photons (5–20 keV) and the low energy IBIS detector, ISGRI (Lebrun et al. 2003) for harder photons (20–200keV). We have not used PICSIT, the hard photon IBIS detector (Di Cocco et al. 2003), as its peak sensitivity is above 200 keV, where LMXRBs have fluxes below PICSIT detectability. The spectrometer SPI and the imager ISGRI have been used to extract the hard energy spectra (20–200 keV) averaged on longer time scales. To increase the detectability. The spectrometer SPI and the imager ISGRI have been used to extract the hard energy spectra (20–200 keV) averaged on longer time scales. To increase the detectability.

Light-curves similar to Fig. 2 and Fig. 3 are being extracted also with JEM-X. In this case, due to the smaller size of the FOV, the resulting data set is smaller than for ISGRI. On the other hand, JEM-X covers a softer part of the X-ray spectrum and thus has more statistics. This allows the extraction of smaller time-bin light-curves like the one showed in Fig. 4 where 1 pointing (science window) is further sampled into 100 second bins. Starting from this data base of light-curves (1 pointing bin for ISGRI and 100 seconds bin for JEM-X) we have produced, per source, the count rate distributions in different energy bands. The distributions for GX5-1 (Z source) and GX3+1 (Atoll) are shown in Fig. 5 and Fig. 6 respectively, while Table 2 summarises the results we obtain for all the Z and Atoll sources of our sample. Only the pointings where both ISGRI and JEM-X data were available have been considered. The spread of the distributions is most likely mainly due to the source variability: the poissonian spread accounts for a few % and the vignetting factor (more difficult to quantify) seems to play a minor role since the dependency of the count rate on the off-axis angle has been studied and shows no evident trend for the different sources. What can be seen from the current data set is that Z sources are brighter than Atoll sources (as expected) and there seems to be no important difference in the long-term (> 100 sec) variability of these sources as a class. Apart from GX5-1, that shows an important variability increase when moving from soft to hard range, the remaining Z and Atoll sources do not seem to have evident differences\textsuperscript{5}.

4. RESULTS

In this section we go through the main results that we have obtained during our monitoring programme up to now. They can be mainly split into two parts: the variability study of our sources and the (average) spectral study. Fig. 7 shows the distribution of the Galaxy of the sample of sources studied in this paper (with the exception of Sco X-1 and Cyg X-2\textsuperscript{3}). The total exposure time is about 5.7 Msec while the final exposure time per source depends on its position with respect to the Galactic Centre; the closer to the Centre the higher the exposure.

4.1. Variability study

4.1.1. Light-curves

As already stated, one of the main aims of the monitoring programme is to extract light-curves for the sources in different energy bands. The richness of the light-curve depends on the position of the source in the sky. Fig. 7 (left panel) is an example of an ISGRI light-curve for GX5-1 (quite close to the Centre of the Galaxy). The points with larger error bars correspond to pointings where the source was more off-axis.

For comparison the right panel shows the RXTE/ASM light-curve for the same period (7 months). The ASM coverage is of course more extensive (INTEGRAL has no all sky monitor programme) but with INTEGRAL/ISGRI we will have a coverage of the sources in the harder energy bands, completing the ASM. A hard-energy (20 keV – 1 MeV) sky survey has been performed by the BATSE mission aboard CGRO covering the period from April 1991 until June 2000 (Shaw et al. 2004). The INTEGRAL high-energy survey will achieve a much better angular resolution and sensitivity\textsuperscript{4}.

Fig. 8 shows a zoom in a 5-day ISGRI light-curve of GX5-1 and GX17+2. Light-curves similar to Fig. 2 and Fig. 3 are being extracted also with JEM-X. In this case, due to the smaller size of the FOV, the resulting data set is smaller than for ISGRI. On the other hand, JEM-X covers a softer part of the X-ray spectrum and thus has more statistics. This allows the extraction of smaller time-bin light-curves like the one showed in Fig. 4 where 1 pointing (science window) is further sampled into 100 second bins. Starting from this data base of light-curves (1 pointing bin for ISGRI and 100 seconds bin for JEM-X) we have produced, per source, the count rate distributions in different energy bands. The distributions for GX5-1 (Z source) and GX3+1 (Atoll) are shown in Fig. 5 and Fig. 6 respectively, while Table 2 summarises the results we obtain for all the Z and Atoll sources of our sample. Only the pointings where both ISGRI and JEM-X data were available have been considered. The spread of the distributions is most likely mainly due to the source variability: the poissonian spread accounts for a few % and the vignetting factor (more difficult to quantify) seems to play a minor role since the dependency of the count rate on the off-axis angle has been studied and shows no evident trend for the different sources. What can be seen from the current data set is that Z sources are brighter than Atoll sources (as expected) and there seems to be no important difference in the long-term (> 100 sec) variability of these sources as a class. Apart from GX5-1, that shows an important variability increase when moving from soft to hard range, the remaining Z and Atoll sources do not seem to have evident differences\textsuperscript{5}.

\textsuperscript{1}The results will thus be publically available, similarly to what the RXTE/All Sky Monitor has been doing in the softer X-ray band.

\textsuperscript{2}In fact, due to the GPS and GCDE dithering patterns, the sources are very often only in the partially coded FOV of JEM-X and sometimes even not covered at all.

\textsuperscript{3}Sco X-1 and Cyg X-2 are far away from the galactic plane and actually are never covered by JEM-X during the scans. This makes our simultaneous RXTE coverage even more important.

\textsuperscript{4}Integrating over the full nine year database of BATSE observations and over 7 energy channels (25 – 160 keV), the 5\textsigma sensitivity to a persistent source is \textasciitilde 2mCrab while the angular resolution achieved with BATSE is about half a degree.

\textsuperscript{5}The soft (JEM-X) Sco X-1 variability is missing because JEM-X FOV is too small to cover it during the scans. Our RXTE observations of this source will provide a simultaneous soft (RXTE) hard (INTEGRAL) variability. The same holds for Cyg X-2 (not covered by JEM-X) for which we currently have too few ISGRI points for the count rate distri-
Figure 1. IBIS/ISGRI (20–40 keV) mosaic of the Galactic Centre (5.7 Msec, about 20° x 40° centred on the Galactic Centre). Only a few sources are labelled for clarity. Most of the sources of this paper are visible in the image (GX9+9 is labelled here as 1728-169).

Figure 2. GX5-1 light-curves from March 2003 until October 2003. Left panel: ISGRI results in the 20-40 keV band (about 2000 sec time-bin). In this energy band 1 Crab corresponds to about 100 counts/sec. Right panel: quick-look results provided by the RXTE/ASM team in the 2-10 keV band (1 day time-bin).
Figure 3. 5-day ISGRI light-curve for GX5-1 (left panel) and GX17+2 (right panel).

Table 2. Variability properties of the sources. \( J_{\text{Mean}} \): mean counts/sec in the 5–12 keV JEM-X band. \( J_{\text{Var}} \): standard deviation of the distribution normalised to the mean in the 5–12 keV JEM-X band in %. \( I_{\text{Mean}} \): mean counts/sec in the 20–40 keV ISGRI band. \( I_{\text{Var}} \): standard deviation of the distribution normalised to the mean in the 20–40 keV ISGRI band in %.

| Source     | \( J_{\text{Mean}} \) | \( J_{\text{Var}} \) | \( I_{\text{Mean}} \) | \( I_{\text{Var}} \) |
|------------|------------------------|------------------------|------------------------|------------------------|
| Z          | 56.96                  | 39%                    | 4.46                   | 64%                    |
| GX 5–1     | 40.30                  | 35%                    | 5.82                   | 42%                    |
| Sco X–1    | -                      | -                      | 78.20                  | 32%                    |
| ATOLL      |                        |                        |                        |                        |
| GX 3+1     | 23.04                  | 42%                    | 1.65                   | 44%                    |
| GX 9+9     | 14.77                  | 36%                    | 1.35                   | 42%                    |
| GX 9+1     | 32.41                  | 41%                    | 1.72                   | 41%                    |
| ADC        | 1822–371               | 1.34                   | 87%                    | 3.35                   | 26%                    |

On the contrary, the ADC source 4U1822-371 displays a very high flux change in the softer energy range. This result is most likely due to the nature of this source that is known (e.g. Parmar et al. 2000) to display deep variations in the form of regular dips and coronal partial eclipses (hence the name of accretion disc corona source).

4.1.2. Colour-colour and hardness-intensity diagrams

The changes in X-ray spectra of Z and Atoll sources are very subtle and not easy to spot and describe with proper model fitting. Alternative tools are often used to study the spectral variability of these sources and are the ab-

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Figure 5. Count rate distribution for GX5-1. The solid line is the 20-40 keV ISGRI distribution while the remaining three curves are the distributions in the three different JEM-X bands used in our analysis.

Figure 6. Count rate distribution for GX3+1 in the same energy bands of Fig. 5.

Figure 7. Hardness intensity diagram for GX5-1 obtained with JEM-X (one year data, 5 minute bins).

Figure 8. Hardness intensity diagram for GX5-1 obtained with Ginga-All Sky Monitor (three years data). The Ginga-ASM hardness ratio is built with counts in the 6–20 keV/1–6 keV bands while the intensity is the overall count rate in the 1–20 keV band (van der Klis et al. 1991).

4.2. Spectral study

Starting from the ISGRI imaging results, we have built several mosaics, one per energy band, and then extracted the spectra for each source. Fig. 9 and 10 show the resulting ISGRI (average) spectra. The spectra have been normalised to the Crab spectrum (extracted in the same energy bands).
Figure 9. ISGRI spectra extracted from a mosaic of 1 year of core programme data. Atoll sources plus the ADC source.

way): a zero slope in the graphs means a source as hard as Crab (i.e. effective photon index of 2) while a positive slope means a source softer than Crab.

In Fig. 9 the 3 Atoll sources (GX9+1, GX9+9 and GX3+1) have a similar soft spectrum until about 50 keV. Above 50 keV, GX3+1 shows a hardening comparable to the hardness of the Crab with a $4.5\sigma$ significance in the last 3 bins. Such hardening can be described by a comptonised black-body component and (with the current systematics) no additional power-law component (hard tail) is needed. It is also important to note that the source brightness above 60 keV (where the hardening is more evident) is around a few mCrab i.e. comparable to the background fluctuations at these energies (Bodaghee et al. 2004). It is currently difficult to disentangle among source and background contribution and a complete calibration of the instrument is needed to derive more firm conclusions.

Fig. 10 shows the spectra of the Z sources of our sample. Z sources are brighter than Atolls (as expected) and seem also to be harder with no evident cut-off until about 50 keV. Sco X-1 shows a hardening above 50 keV. In this case the hardening is more significant than for GX3+1 ($10\sigma$ detection in the 55 keV centred bin and $5.3\sigma$ detection in the 70 keV centred bin) and starts well above the aforementioned background limit. Triggered by this, we have performed a deeper spectral study. Fig. 11 shows ISGRI and SPI spectra of Sco X-1. We fitted the data with the best fit model that D’Amico et al. (2001) used to describe the non-thermal hard tail detected in Sco X-1 with RXTE/HEXTE instrument. We get comparable results for the bremsstrahlung component (temperature of about 4.5 keV) and a slightly steeper power-law slope (2.9 instead of their maximum 2.37). In our case the slope of the power-law component is difficult to determine accurately given that it strongly depends on the softer bremsstrahlung component which, in turn, depends on the softer ($<20$ keV) part of the spectrum currently missing (the source is not covered by JEM-X and the simultaneous RXTE data have not been triggered yet). Our detection confirms the non-thermal hard tail detection of RXTE/HEXTE by D’Amico et al. (2001). Nevertheless,
such a result should be taken with caution: ISGRI calibration is not optimised yet and a hard tail as the one we detect on a ∼260 ksec averaged spectrum would mean that the tail is either steadily there (which does not seem the case from previous observations on Sco X-1) or indeed is variable but very strong when present. The latter could be the case and we will extract spectra at a (few) science window(s) level to have the answer.

5. CONCLUSIONS

We have analysed about 1 year of INTEGRAL Core Programme data and built a LMXRB data base that will be made publicly available via the web. In our monitoring program we plan to study in a systematic way the high-energy emission of a sample of 72 LMXRBs. Among these are 8 persistently bright neutron star LMXRBs (4 Z sources, 3 Atolls and 1 ADC source). In this paper we have shown the current results from this sample of 8 LMXRBs (all hosting a weakly magnetised neutron star).

The variability study (light-curves and CC-HI diagrams) has shown that the INTEGRAL core programme coverage is enough to study the high-energy history and evolution of the sources. Z sources are brighter than Atolls (as expected) and, with the current data set, there seems not to be an important difference in the variability of the sources as a class. The CC-HI diagrams built in the “traditional” energy bands already display the expected patterns which is an encouraging result for exploring new, INTEGRAL defined, diagram energy bands.

The spectral study of the sources of our sample has shown that Z sources seem to be harder than Atolls (> 20 keV) and present no evident cut-off until about 50 keV. Atoll sources in general, as previously stated, can be much harder than Z sources but this is mainly true for the low luminosity ones whereas the Atolls of our sample are soft-high state bright systems.

In our averaged ISGRI spectra, a hardening in GX3+1 data is visible (well described by the traditional comptonised black-body model, i.e. no additional power-law component needed) and a hint of a non-thermal hard tail in Sco X-1 ISGRI and SPI data is seen, similarly to what was previously detected by D’Amico et al. (2001) with RXTE.

The hunt for such hard tails in NS LMXRBs is a key goal of our monitoring with INTEGRAL. They add one more piece to a mosaic that places neutron star binaries next to black holes, for which non-thermal emission was thought to be a prerogative.

In the results presented here, variability and spectral studies have been carried out separately and the next step will be to merge these two aspects, extracting only spectra for a given branch in the CC-HI diagrams, i.e. for well defined spectral states. The coordinated observations will show the presence (or absence) of multiwavelength emission in the different states.

Using all this we are able to build a huge data base that will offer a unique long-term, regular and energy-wide study of a sample of (intrinsically different) LMXRBs. We expect this to be a step forward in the understanding of the physics and geometry of X-ray binaries.

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