INTEGRAL'S VIEW OF EMISSION PROCESSES INVOLVED IN THE HARD X/γ-RAY EMISSION OF GALACTIC AND EXTRAGALACTIC COMPACT OBJECTS

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ABSTRACT

Most compact objects, in particular X-ray Binaries (XRBs) and Active Galactic Nuclei (AGN), are characterized by X and γ-ray radiation, leading to investigate and compare the physical processes occurring in their high energy emission. We perform various studies on the hard X/γ ray emission of several Galactic and Extragalactic compact objects. In particular, with the spectrometer SPI (20 keV-8 MeV), we detect in three observations an emission extending above 200 keV and for the first time even up to 350 keV for a neutron star LMXRB, GS 1826-24. The 25-150 keV spectra are well fitted by a classical thermal model, however an excess is clearly observed above 200 keV in the two broadest spectra. They are best fitted by a hybrid model instead of a pure thermal one. The additional component above 200 keV is most probably of non-thermal origin. This non-thermal feature reminds the one found in some black hole candidates and AGNs. In particular, studying with SPI the microquasar XTE J1550-564 during the Low/Hard State (LHS) of its 2003 outburst, we emphasize for the first time various spectral states within the LHS. We discover the presence of a non-thermal additional component up to 500 keV in the first plateau phase of the LHS while its disappeared in the ending plateau part whereas the source had a similar flux and was within the same plateau phase. Through the example of several XRBs and AGNs, we propose that both thermal ("disk+corona" system) and non-thermal (e.g. jet or non-thermal electrons within the corona) emission processes could be involved ubiquitously in the high energy emission of Galactic and extragalactic compact objects.

Key words: compact objects; hard-X rays; Gamma rays; emission processes.

1. GALACTIC COMPACT OBJECTS: LMXRBS

1.1. The Neutron Star LMXRB GS 1826-24 with INTEGRAL/SPI: discovery of a hard tail up to ~350 keV with a probable hybrid origin

X-ray binaries present an emission extending up to X/γ rays making them ideal candidates for the INTEGRAL satellite. We analysed two years of Galactic Centre Deep Exposure (GCDE) by INTEGRAL/SPI (20 keV-8 MeV, Vedrenne et al. [16]) to study the hard X/γ ray emission of X-ray bursters like the Neutron Star XRBs **4U 1812-12** and **GS 1826-24**. The detection limit of these objects was set to ~150 keV with the *Beppo*SAX satellite [7]. We reveal with SPI a hard tail up to 220 keV for 4U 1812-12 (Figure 1) and even up to ~350 keV for GS 1826-24 (Figure 2), representing the hardest emission ever detected for a Neutron Star LMXRB. The hard X-ray emission of LMXRBs systems is generally explained by a thermal comptonisation of soft photons (kT_{seed}) in a hot region (corona defined by the electrons temperature kT_e and the optical depth τ) probably placed between the neutron star and the accretion disk. The SPI spectrum of 4U 1812-12 is well reproduced by a pure thermal component, modeled by the Titarchuck thermal Comptonisation (*Comptt*) model [13], with kT_{seed}=0.20, kT_e=$36.8^{+88.9}_{-11.1}$ keV and τ=$0.97^{+0.6}_{-0.9}$, compatible with IBIS results obtained by [11].

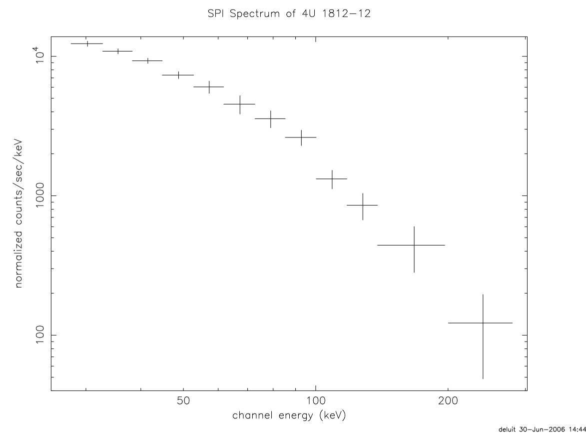

Figure 1. SPI Spectrum of 4U 1812-12

For GS 1826-24, analysing 5 GCDE periods from 2003 to 2005, the source reveals the presence of a hard tail in three observations, respectively up to 240, 320 and 360 keV. All spectra can be correctly reproduced by a pure thermal model (Comptt). However, for the two broadest spectra a clear excess is observed above ~200 keV, indicating the presence of an additional component. To identify the nature of this excess, we add to the previous model either a power law (PL) to test a non-thermal origin or a second thermal component ("Comptt+Comptt" model) to test a thermal one. Even if a thermal origin

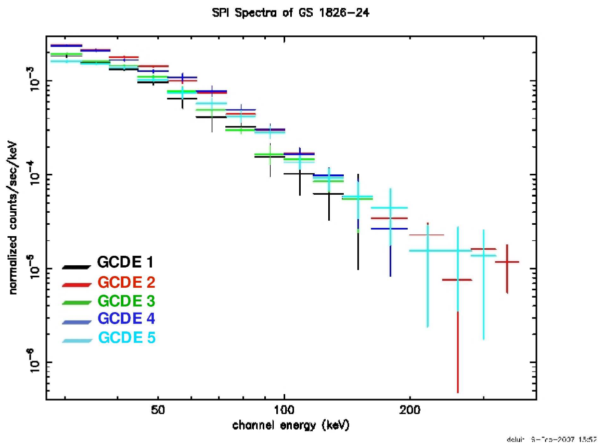

Figure 2. SPI Spectra of GS 1826-24

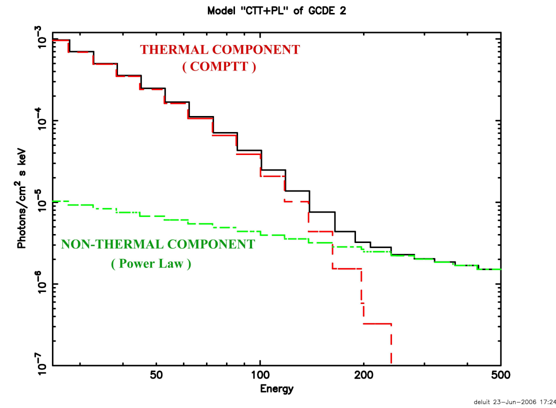

Figure 3. Model "Comptt+PL" reproducing the best the SPI Spectrum of GS 1826-24

cannot be definitively rule out, the hybrid model (Figure 3) is clearly statistically favored (adding a PL gives a F-test probability of 10^{-4}). The thermal component of the most extended spectrum is characterized by a soft seed photons temperature of kT_{seed}=0.4 keV, an electron plasma temperature of $kT_e\sim$20 keV and an optical depth of $\tau\sim$1.9. The index of the non-thermal additional component is $\Gamma_{nt}\sim$1.40 (Deluit, 2007, submitted).

The hard tails present in the two broadest spectra have very similar spectral characteristics and are found in the highest flux observations. The flux increase does not seem to be due to an accretion rate modification since that would inevitably entail a change in the burst recurrence time of GS 1826-24, that has not been observed [12]. We propose that the flux change is mainly due to the occurrence of the non-thermal component since even below 200 keV, it contributes to the observed global emission. Furthermore, the thermal component below 150 keV is similar for all 5 observations, leading to the conclusion that two distinct regions would be involved in the generation of the thermal and non-thermal components.
Whether the origin of the hard tail is non-thermal, the involved photons could be generated either via non-thermal electrons present in the corona, magnetic reconnections or directly from a jet. No radio observation of GS 1826-24 has ever been performed to date, preventing us to claim any correlation/relation between the occurrence of the additional non-thermal component to the presence of a jet. A multi-wavelength campaign would be of great benefit to definitively identify the region generating the non-thermal hard tail of GS 1826-24 discovered by SPI and the conditions of its triggering.

2. BLACK HOLE CANDIDATES

The spectrum of GS 1826 revealed by SPI, for which several components seem to be present, naturally reminds the one found for BHCs in the hard X/γ ray domain. As an example, **Cyg X-1** [9], presents following its state a global emission decomposed of a thermal and non-thermal component extending up to the MeV domain. We analysed the 2003 outburst of XTE J1550-564 with SPI [6]. The outburst evolution as recorded by RXTE/ASM (Fig. 4), shows relatively simple profile and evolution: a rise phase, then the source reaches a plateau lasting $\sim$20 days before to decline. The RXTE/ASM hardness ratio clearly indicates that the source was in the Low Hard State during the whole duration of the outburst.
Studying for the first time the LHS of the source above 300 keV, we emphasize an unforeseen spectro-temporal evolution in hard X-rays. Indeed, during the rising phase (Rev. 55), the spectrum reaches 360 keV and is well reproduced by a pure thermal model (Comptt [13] or Compps [10]) (but with the suspicion of the presence of a hard tail), while during the first plateau phase of the LHS (Rev. 57), the SPI spectrum reaches 500 keV and then the emission drops to 320 keV in the ending plateau phase (Rev. 60, Figure 5). That constitutes the hardest emission detected for the LHS of XTE J1550-564. The most extended spectrum is best reproduced by a hybrid ("Compps+PL") model. The addition of a PL is required with a F-test probability of 10^{-5}. The thermal component is defined by a soft seed photons temperature of $kT_{seed}\sim$0.4 keV, an electrons temperature of $kT_e\sim$40 keV and an optical depth of $\tau\sim$5.4, whereas the non-thermal component is defined by $\Gamma_{nt}\sim$1.50. The additional component is absent in the ending plateau phase while the source is in the same state and the exposure time is almost two times greater than for the Rev. 57 observation. We thus emphasize for the first time various spectral states within the Low Hard State. We propose that the non-thermal feature is related to the presence of a compact jet and that the density of the Corona could play a key role in the triggering of the hard tail.
The presence of a jet in XTE J1550-564 and Cyg X-1 systems makes it the ideal candidate to produce the non-thermal emission observed in the γ-ray domain. Furthermore, a clear correlation is found between the radio and hard X-ray/γ domain in the low/hard state where the jet is dominant.

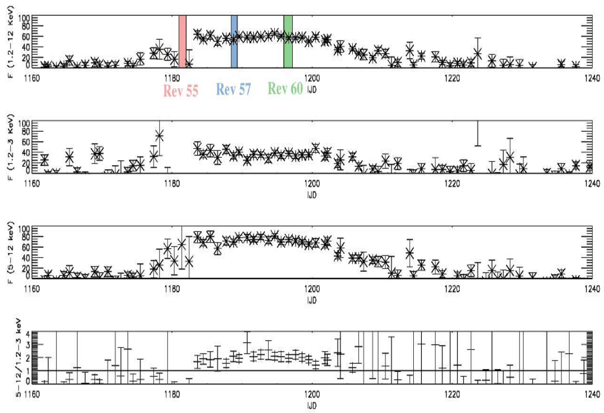

Figure 4. RXTE/ASM lightcurves (from top: 1.2-12 keV, 1.2-3 keV and 5-12 keV fluxes in mCrab unity) and the hardness ratio (5-12 keV)/(1.2-3 keV) of XTE J1550-564 during the 2003 outburst. From Deluit [6].

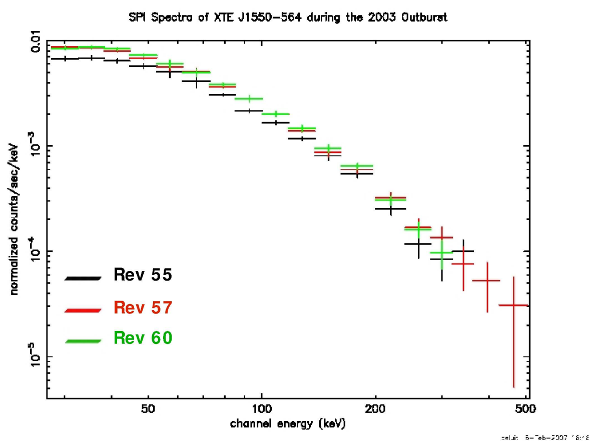

Figure 5. Comparison of XTE J1550-564 SPI spectra at different epochs of the 2003 outburst: rising phase (black), first plateau phase (red) and ending plateau phase (green). From Deluit [6].

BHCs have often been compared to AGNs, and in the last decade, an AGNs/BHCs paradigm has even emerged (Figure 6).

3. EXTRAGALACTIC COMPACT OBJECTS: ACTIVE GALACTIC NUCLEI

AGNs are composed of several classes, mainly radio quiet (e.g. Seyfert) and radio loud (e.g. blazar) objects. Their emission extension differs following the class considered, in particular if a jet is present. The Seyfert galaxies emission is presumed to be due to a pure thermal process with a cutoff detected between 100-300 keV, whereas for blazars, the presence of a dominant non-thermal emission from the jet reaches MeV or GeV

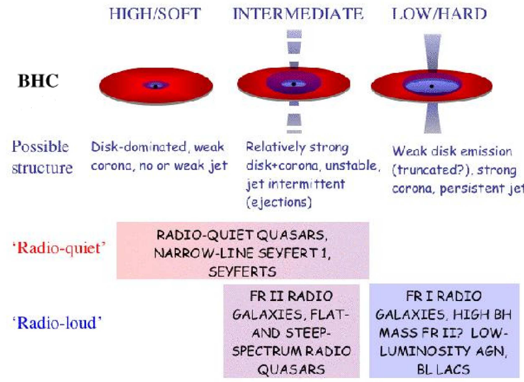

Figure 6. Schematic view of the Grand Black Hole Unification Paradigm (from Uttley P. [15])

domains.

We analysed 2 years of IBIS data of the Compton thick Sy 2 **NGC 4945** and the Radio/Sy 2 galaxy **Cen A** (Figure 7). We firmly constrain for the first time a cutoff in the NGC 4945 galaxy found at $E_c=62.2^{+32.4}_{-16.9}$ keV with a F-test probability of $1.7 \cdot 10^{-4}$ (Figure 8). That confirms its occurrence that the BeppoSAX satellite evoked but did not well constrain, letting subsist a doubt of its presence. That represents the archetypical thermal emission found in Seyfert galaxies. The cutoff is found at a relatively low energy, which is most similar to the one found for Sy 1 galaxies.
Analysing Cen A data, which clearly presents a jet unlike the major part of Sy 2 galaxies, the spectrum presenting the highest flux is best reproduced by a broken power law model with $\Gamma_1=1.87^{+0.05}_{-0.06}$, $E_b=79.6^{+138.0}_{-36.1}$ keV and $\Gamma_2=2.06_{-0.11}$ with a F-test probability of $8 \cdot 10^{-3}$ compared with a PL model. That constitutes a new detection of the break in hard X-rays since OSSE measurement of the break in Cen A high (Eb$\sim$120 keV) and low (Eb$\sim$150 keV) states. In the three observations analysed, an energy break is clearly favored compared to a cutoff as the origin of the curvature observed by several satellites. Cen A thus presents a hard X-ray emission characteristics of a dominant non-thermal process, unlike classical Sy 2 galaxies.

Is non-thermal process always absent from the hard X-ray emission of basic Sy 2 ?
In Deluit et al. [2] and Deluit [3], we show that Sy 1 and Sy 2 with Polarized Broad Lines (PBLs hereafter) present common properties with in particular a clear detection of a cutoff. On the contrary, Sy 2 without PBLs detected do not seem to exhibit a cutoff, leading us the hypothesis that another emission process, probably non-thermal, could occur in this kind of Sy 2 and possibly within the Seyfert galaxies class in general but in lower proportions.

Furthermore, in Deluit [4] and Deluit, Stuhlinger & Staubert [5], studying the 1996-2004 X-ray emission of

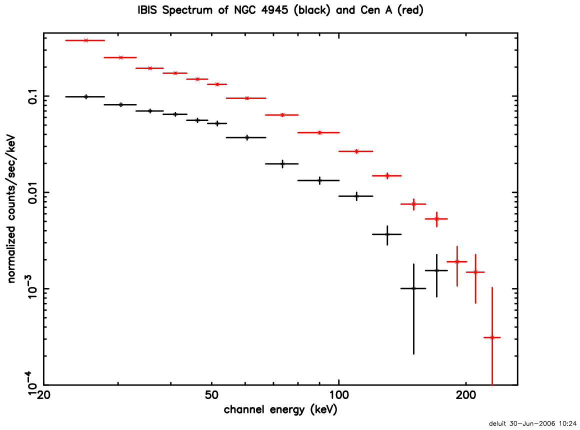

Figure 7. IBIS spectrum of NGC 4945 (black) and Cen A (red)

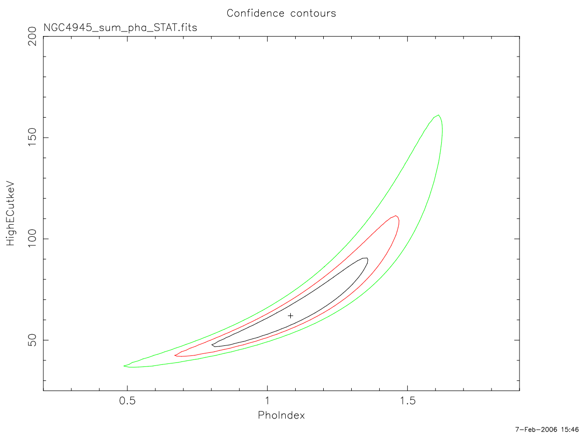

Figure 8. Confidence Contour of Ec versus Γ *for NGC 4945*

the quasar **3C 273** with BeppoSAX and XMM-Newton satellites, usually largely dominated by the non-thermal emission from the jet, we revealed different hard X-ray flux states correlated with the radio domain. We also emphasized the lowest X-ray flux states ever observed in the 3C 273 history (corresponding to low states of the jet activity) in June 2000, 2001 and 2004. In particular for June 2000 and 2001 observations, the hard X-ray emission observed by BeppoSAX/PDS lets appear for the first time cutoffs in the 150-300 keV domain. We then deduced that the non-thermal emission from the jet is dominant most of the time, and when its activity becomes fainter thus the contribution from the jet to the global emission is less dominant, it lets appear thermal features like a cutoff. These results were in agreement with a phenomenological study [8].

Considering the case of 3C 273, Cen A, NGC 4945 and other Seyfert galaxies, a thermal+non-thermal origin of the high energy emission of radio-quiet and loud AGNs could be drawn, like for X-ray binaries.

4. DISCUSSION

Studying the high energy emission of different compact objects like neutron star and black hole candidate binaries or AGNs, we emphasise the emergence of a more complex picture of their emission, but also great similarities between all these classes of compact objects. Indeed, it appears that both thermal and non-thermal processes could occur universally in their high energy emission. The thermal component is well explained by the ”accretion disk+hot corona” system. The non-thermal component is natural in the case of a jet presence, like e.g. for Cyg X-1, 3C 273 and Cen A.
However, what is the explanation for Seyfert galaxies and neutron star binaries for which no jets are observed ? Either non-thermal electrons are present in the corona or we evoke the possibility that jets extended in small distance scale (i.e. “mini-jet”) could be omni-present in radio-quiet AGNs and X-ray binaries presenting an emission above 200 keV.

To confirm that, a statistical study on a sample of NS and BHC sources first and secondly extended to a sample of AGNs is required to test the ubiquity of a “thermal+non-thermal” origin to the hard X/γ ray emission of such Galactic and Extragalactic Compact Objects. We thus started a statistical study with INTEGRAL/SPI to investigate this hypothesis, allowing us to identify the emitting regions and obtain crucial information about accretion/ejection processes.

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