Cygnus X-1: shedding light on the spectral variability and polarization of black holes

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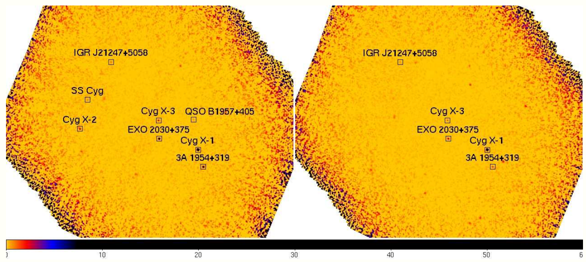
Abstract

We present an analysis of extensive recent monitoring observations of the black hole HMXB Cygnus X-1 obtained as part of the 2007 to 2011 Key Programme (KP) observations of the *INTEGRAL* mission. Cyg X-1 is one of only three persistent black hole binaries in our galaxy that spend most of their time in the hard spectral state. After spending 3 years in the hardest regime of its parameter space, the source displayed a softening and flaring episode in mid 2009, entered a soft state in early 2010 and entered a transitional phase in April 2011. While the hard X-ray spectrum of Cyg X-1 is one of the best studied examples of its kind, e.g. through our monitoring campaign with *RXTE* and coordinated radio observations with AMI (formerly: Ryle) telescope, the *INTEGRAL* monitoring allows us to study the spectral evolution from about half an hour over a few days to weeks, timescales that have been only sparsely sampled so far. The parameter ranges for the hard and soft states as well as the transitional phases are constrained. These measurements are of special importance for understanding the physics of the hot plasma of the jet base and/or the corona, but typically difficult to obtain for transient source. Additionally, we report on polarization studies which have been conducted using a larger *INTEGRAL*/IBIS dataset and led to the discovery of gamma-ray polarization in Cyg X-1.

Cyg X-1 Region



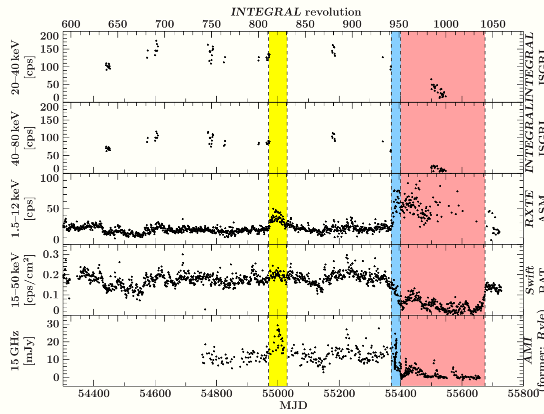
Cyg X-1 has been observed as part of the ongoing *INTEGRAL* KP since 2007. Above we present the mosaic (left: 20–40 keV energy band; right: 40–80 keV) of the revolution 744 containing 101 Science Windows (ScWs) as an example of a typical observation. Sources with $\sigma_{\rm det} \geq 5$ are shown.

During the KP we serendipitously discovered outbursts of 3A 1954+319, which belongs to the rare class of symbiotic X-ray binaries; the preliminary analysis of the source has been presented by Fürst et al. (2010), and further work is in progress (Marcu et al., 2011).

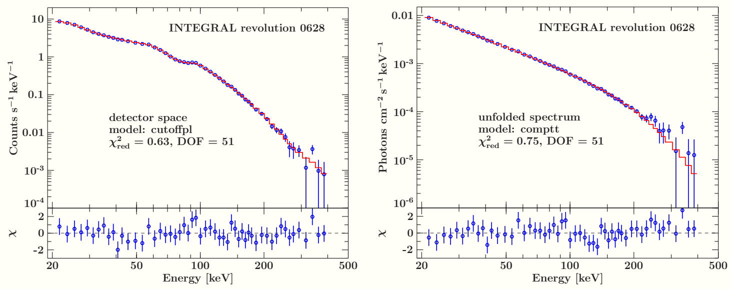
Cyg X-1 Long Term Behaviour

The source spent the first three years of the KP in an extraordinarily hard state (see Nowak et al., 2011), interrupted only by a radio flaring episode in mid 2009, which was not seen in the BAT lightcurve. In June 2010 it entered the soft state (Grinberg et al., 2010), which continued until April 2011 (Grinberg et al., 2011). In the figure, the radio flare is indicated in yellow, the hard to soft state transition in blue and the soft state in red.

Since December 2009 (revolution 877 and after) the Cyg X-1 KP is carried out with a random dither pattern instead of the standard hexagonal one. This means a better coverage with the JEM-X instrumend onboard *INTEGRAL*, as the source is in the JEM-X field of view in every KP ScW, as well as fewer artificial features (ghosts, visible as square pattern on the mosaic in the previous box) during the image reconstruction for ISGRI.



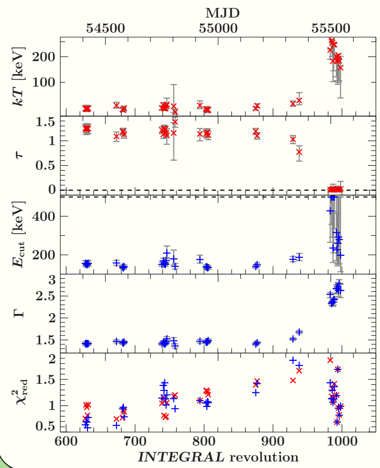
Spectral Models



We extracted ISGRI spectra for all ScWs during the Cyg X-1 KP using OSA 9. We added spectra for every revolution ($\sim$3 days) to achieve a better signal to noise ratio and used a 2% systematic error for fitting as recommended in the cookbook.

Good fits are achieved using both the empirical `cutoffpl` model (left panel) and the simple Comptonization model `comptt` (right panel). Both models have been used in the literature (see Cadolle Bel et al., 2006, for *INTEGRAL* data and Wilms et al., 2006, for *RXTE* data) and result in fits of comparable quality (see next box). For `comptt` the seed photon temperature has been shown to lie in the range of $\sim$1 keV (e.g. Wilms et al., 2006), so it cannot be constrained in ISGRI spectra and has therefore been frozen to 1 keV.

Spectral Evolution

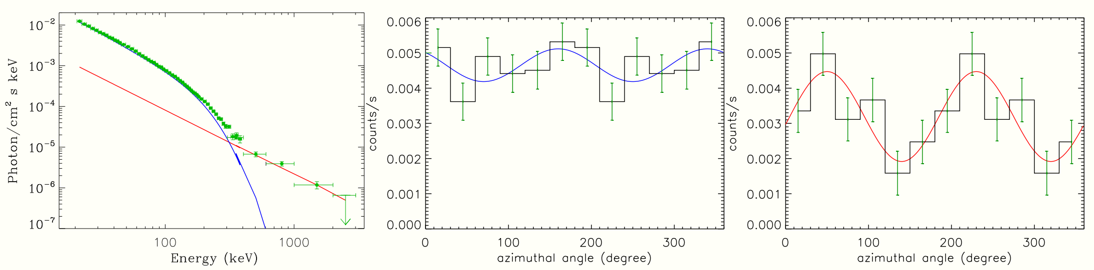


We present an overview of the evolution of spectral parameters on the timescale of single revolutions for the `cutoffpl` and `comptt` models. The rising trend in $\chi^2_{\rm red}$ in both models during the hard state can be attributed to problems with the current response. The low $\chi^2_{\rm red}$ values for the soft state are due to the reduced brightness of the source in the ISGRI band.

The fit parameters are stable during the hard state and clearly differ during the soft: for `cutoffpl`, the folding energy $E_{\rm cut}$ is badly constrained. A simple power law can in fact describe these data satisfactorily. For `comptt` the optical depth decreases while the electron temperature increases. Cyg X-1 shows self-similar spectral variability on timescales of $\sim$3 days, weeks (see Wilms et al., 2006, *RXTE*) and hours (see Böck et al., 2011, *RXTE*).

Interestingly, revolutions 929 and 938 already show changes in the spectral parameters in the hard X-ray, while the state transition is not yet clearly visible in the soft X-rays (ASM) and radio (Ryle) (see box above).

Polarization



Cyg X-1 data from the whole mission have been used for the polarization studies conducted by Laurent et. al. (2011), which led to the discovery of polarized gamma-ray emission from the source. Overall, 5 Ms observations of Cyg X-1 between 2003 and 2009, when the source was mostly in the hard state, yield the standard *INTEGRAL*/IBIS spectrum presented in the left panel. The spectrum clearly shows a thermal Comptonization component as well as a high energy component of disputed origin, which can be described with a power law with a photon index of 1.6 ± 0.2. Cadolle Bel et al. (2006) observed this component with the SPI instrument onboad *INTEGRAL*. The existence of two distinct components implies the presence of different emission processes.

Using *INTEGRAL*/IBIS as a Compton polarimeter (e.g. Forot et al., 2007) the polarization signal of the two spectral components, i.e. the polarization signal in the 250–400 keV (middle panel) and the 400 keV to 2 MeV (right panel) band, can be measured.

The results obtained by Laurent et al. (2011) show that the emission in the 250–400 keV region is not significantly polarized with an upper limit of 20% for the polarization fraction, as expected for a Comptonization region. The emission in the 400 keV to 2 MeV region on the other hand is polarized with a polarization fraction of 67 ± 30 %. Such a high degree of polarization can only be achieved if the magnetic field is stable over a large fraction of the emission site, which in turn can be indicative for a jet origin of the gamma rays in this energy range, consistent with results of recent studies of Cyg X-1 in the mid-infrared band (Rahoui et al., 2011).

Outlook

- The low count rates in the soft state prevent us from constraining the spectral parameters in revolution-wise summed data well. We are therefore investigating the stability of the source on longer timescales to be able to increase the exposure of the analysed spectra.
- The inclusion of JEM-X (with a better coverage due to the random pointing strategy) and SPI data will enable us to extend the analysis both to lower and higher energies and therefore to investigate the behaviour below the spectral break at $\sim$10keV, which has been seen e.g. in *RXTE* and *Suzaku* data (Wilms et al., 2006; Nowak et al., 2011) and of the hard tail.
- As steady jets are not present in the soft state of the source, state resolved polarization analysis will allow us to confirm the origin of the polarized high energy emission.
- Using simultaneous *RXTE* and *INTEGRAL* observations we will be able to better constrain the spectral parameters and to extend the X-ray timing analysis for Cyg X-1 to the energy range above 20 keV.

References

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