INTEGRAL-RXTE OBSERVATIONS OF CYGNUS X-1

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ABSTRACT

The canonical black hole binary Cygnus X-1 has been extensively observed during *INTEGRAL*'s performance verification phase in 2002 November and December. The source was found to be in the hard state. About 50 ks of (quasi-)simultaneous *RXTE* observations have been obtained in order to support calibration efforts. Together these observations provide some of the highest quality broad band spectra available for this source. The campaign is also supported by radio data obtained with the *Ryle* telescope. We present an analysis of the broad band spectra using several Comptonization models. Compared to our earlier presentations of this data set, a new *RXTE-PCA* calibration and a much improved *INTEGRAL-SPI* response have been used. This allows to better constrain important physical parameters of the accretion process such as the temperature and optical depth of the corona as well as the reflection fraction.

Key words: black hole physics — stars: individual (Cygnus X-1) — Gamma-rays: observations — X-rays: binaries — X-rays: general.

1. INTRODUCTION

Broad band studies are of special importance for understanding the physical processes at work near galactic and extragalactic black holes, which emit an appreciable fraction of their overall luminosity in this energy regime. *INTEGRAL* used most of its performance verification (PV) phase in 2002 November/December to observe the prototype black hole binary Cygnus X-1 (Bazzano et al., 2003; Bouchet et al., 2003; Pottschmidt et al., 2003). Since several (quasi-)simultaneous *RXTE* pointings have been obtained, this data set provides a unique opportunity for testing physical Comptonization models for black holes. The 15 GHz *Ryle* radio and the 2–12 keV *RXTE-ASM* lightcurves displayed in Fig. 1 put the PV phase observations into context (dashed lines denote *RXTE* pointings): In summer 2002 a soft state was observed showing high *ASM* rates and quenched radio emission followed by an intermediate state with typical radio flaring and decaying *ASM* rates marking the transition into the canonical hard state characterized by moderate but steady radio emission and low soft X-ray flux. This scenario is confirmed by evaluating broad band spectra and timing statistics like the X-ray time lags, see Fig. 1 of Gleissner et al. (2004). During *INTEGRAL*'s PV phase the source was thus found in its Comptonization dominated spectral hard state, although not too long after one of the recent soft episodes. With the exception of failed state transitions, states in Cyg X-1 are known to evolve over weeks rather than days. The consideration of spectra summed over subsets from the same revolution of *INTEGRAL* ($\sim 3\,\mathrm{d}$), has proven to be a good choice to evaluate this spectral variability of Cyg X-1. This includes the *RXTE* data in the analyzed broad band spectra coming from the same revolution as the *INTEGRAL* data and thus being (quasi-)simultaneous. We presented first results of modeling the *RXTE-INTEGRAL* broad band spectra in Pottschmidt et al. (2003) and Wilms et al. (2004). See those references for more details on data selection and models. Here we focus on recent improvements and additions to our analyses, results, and conclusions.

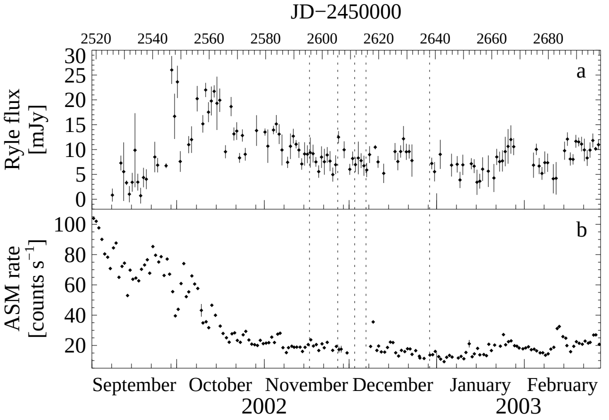

Figure 1. Ryle radio flux (15 GHz) and RXTE-ASM count rate (2–12 keV) of Cyg X-1 from 2002 September to 2003 February. Dashed lines indicate pointed RXTE observations which were performed (quasi-)simultaneously with INTEGRAL PV phase observations.

2. DATA ANALYSIS

All *ISGRI* and *SPI* spectra have been re-extracted using the new OSA 3.0 extraction software. A much improved *SPI* redistribution matrix compared to the one used by Pottschmidt et al. (2003) is available now (post-OSA 3.0). This allows us to extend the upper limit of the energy range under consideration from 200 keV to 550 keV for the *SPI* spectra, which were again obtained over one revolution. `COMPTT`, `EQPAIR`, and `2COMPTT` (see below) fits including the new *INTEGRAL* data have been performed for revolutions 11 and 25, which are especially suited to obtain *SPI* spectra (99.2 ks in rev. 11 and 63.7 ks in rev. 25, dithering).

For the summed *ISGRI* spectra the constraint of achieving greatest possible simultaneity with the *RXTE* data has been dropped in favor of gaining higher total exposure. However, due to the known dependence of the flux normalization provided by OSA 3.0 on the source's off-axis angle, an angle selection has been performed before summing spectra: For rev. 11 two specra were produced, one for on-axis pointings of Cyg X-1, the other for offsets $\leq 2°$, for rev. 25 all pointings with the source in the fully coded field of view were considered. For rev. 25 this results in the same exposure as before (8 ks). For rev. 11 the second option allows for a 3.4 times longer exposure than the on-axis data (11.9 ks), however the typical sawtooth systematics due to OSA 3.0 calibration uncertainties are rather pronounced in both selections. Since the associated underestimation of the flux above 100 keV significantly influences the fit for the longer exposure data we only present the results for the on-axis selection in the following. As recommended we again apply systematics of 10%, thus the influence of the "sawtooth" on the fit results is low for the spectra presented in Fig. 2.

All *PCA* spectra have been re-extracted using the new *RXTE/PCA* calibration of HEASOFT 5.3 (Jahoda, 2004). The *PCA* and *HEXTE* flux normalizations and slopes are now consistent and the former has been frozen to unity in the fits presented here. All `COMPTT` and `EQPAIR` fits presented by Pottschmidt et al. (2003) have been re-done for this new *PCA* calibration. Preliminary results have already been presented by Wilms et al. (2004). An energy independent systematic uncertainty of 0.5% has been added to all *PCA* spectra. Due to the high *RXTE* SNR in rev. 25, the systematics introduced by the Xenon K-edge at ~ 30 keV dominate. We therefore fit the *PCA* to 20 keV, only.

It is generally useful to apply and compare several of the different Comptonization models available to see whether any trends in the evolution of spectral fit parameters are stable against their intrinsic limitations (Nowak et al., 2002, for GX 339−4). In addition to updating the `COMPTT` (Hua & Titarchuk, 1995) and thermal `EQPAIR` (Coppi, 1999) modeling already presented by Pottschmidt et al. (2003) we now also applied a model with two Comptonization components (`2COMPTT`) in order to evaluate the possible presence of a complex soft excess in our data set: Recently the presence of such an emission component in the hard state has been suggested by several authors, e.g., for *BeppoSAX* spectra of Cyg X-1 by Di Salvo et al. (2001, $\tau \sim 8$, $kT \sim 3$ keV) or Frontera et al. (2001, $\tau \sim 0.5$, $kT \sim 40$ keV, influence mainly below 1.5 keV).

3. RESULTS

`COMPTT`: As before, thermal Comptonization with reflection provides an adequate description of the Cyg X-1 broad band spectrum (Fig. 2). Inclusion of the reflection component results in a clear improvement of the fit. The χ^2_{red} is still rather high due to the systematic uncertainties associated which each instrument: $\chi^2_{\text{red}} = 1.58$ and 1.81 for rev. 11 and rev. 25, respectively. The degeneracy of the results obtained with and without including the *SPI* data set (Pottschmidt et al., 2003) has been resolved. The Comptonization parameters of rev. 11 and rev. 25 are in better agreement now. The best fit parameters for rev. 11 are $\tau = 0.71^{+0.05}_{-0.07}$, $kT = 82^{+16}_{-5}$ keV, and $\Omega/2\pi = 0.11^{+0.01}_{-0.01}$, where τ is the electron optical depth, kT is the electron temperature, and $\Omega/2\pi$ is the reflection fraction. All uncertainties are at the 90% level. For rev. 25 we now find $\tau = 1.01^{+0.08}_{-0.12}$, $kT = 65^{+8}_{-5}$ keV and $\Omega/2\pi = 0.14^{+0.00}_{-0.01}$. Compared to the `COMPTT` results presented by Pottschmidt et al. (2003), $\Omega/2\pi$ is $\sim 5\%$ lower.

This is due to the better consistency of the *PCA* and *HEXTE* calibration and the new values therefore represent a more reliable constraint. The relative flux normalizations are the following: *PCA* and *HEXTE* are consistent and set to unity, *SPI* is found at 1.33 and 1.22, *ISGRI* at 0.65 and 0.71, for rev. 11 and 25, respectively. Above 300 keV the *SPI* data points deviate systematically from the cut-off described by thermal Comptonization, however, those deviations are of low statistical significance. They are most probably due to uncertainties in the background subtraction, but at this point the presence of a hard tail (McConnell et al., 2002), e.g., due to non-thermal

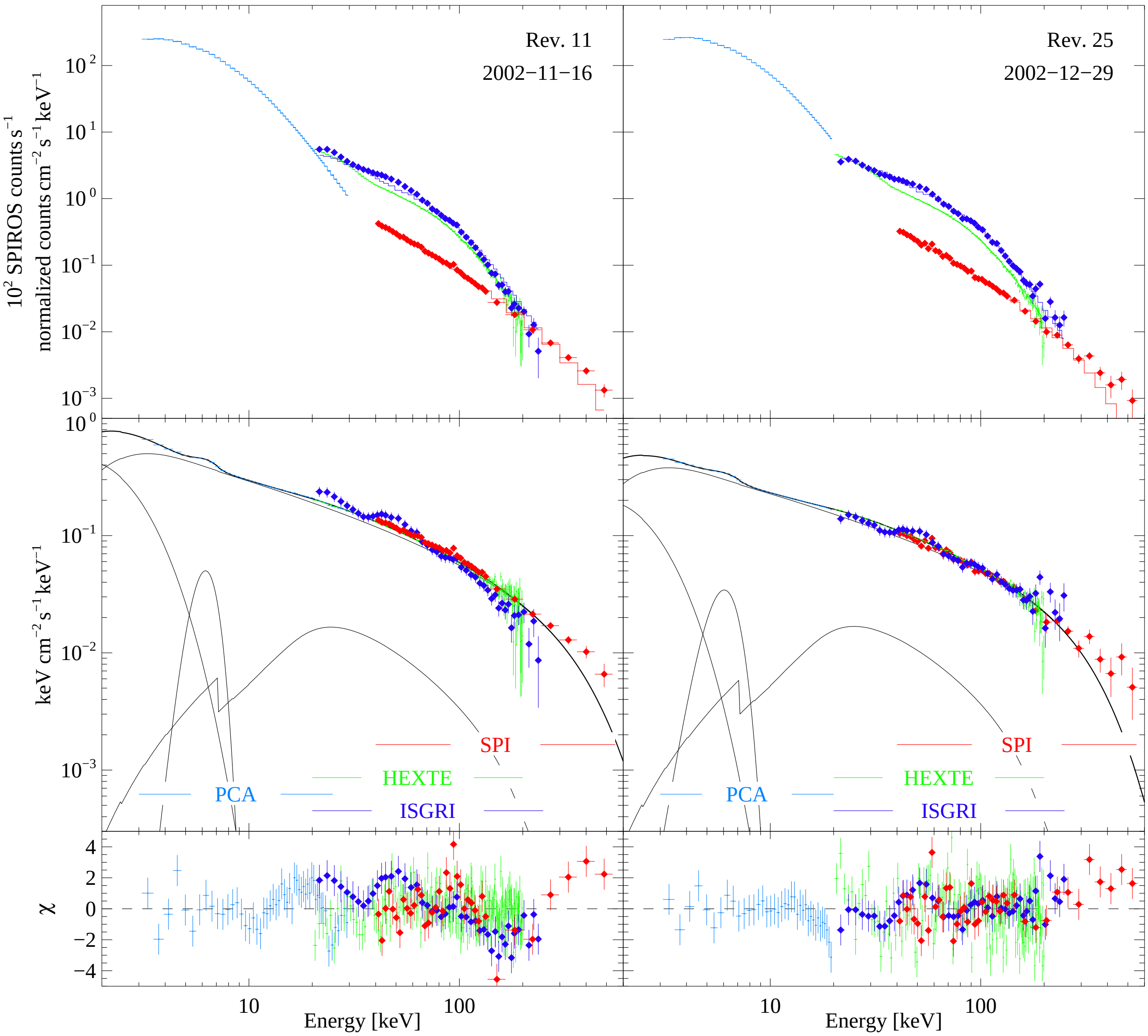

Figure 2. Combined INTEGRAL-RXTE spectra of Cyg X-1. The counts spectra (upper panels) as well as the unfolded spectra (middle panels) for rev. 11 and rev. 25 are shown together with their best fit `COMPTT` *models* [`const`×`phabs`×`(diskbb+gaussian+compTT+reflect(compTT))`]. *The residuals are also displayed (lower panels).*

Comptonization, cannot be ruled out. Note, however, that the source-inherent variability should be carefully studied before modeling spectra which were summed over an even longer time basis. Unfortunately, the *ISGRI* calibration does not yet allow to further refine the models. The comparatively strong black body emission in the earlier observation is due to the preceeding flaring episode (Fig. 1).

`EQPAIR`: The best fit parameters for the thermal `EQPAIR` model are $\tau = 1.3$, $kT = 82\,\mathrm{keV}$, $\Omega/2\pi = 0.21$ for rev. 11 and $\tau = 1.4$, $kT = 85\,\mathrm{keV}$, $\Omega/2\pi = 0.22$ for rev. 25, with $\chi^2_{\mathrm{red}} = 1.37$ and 1.95, respectively. This confirms the trend of lower reflection of a few $\%$ and of more consistency between the data sets as compared to the results of Pottschmidt et al. (2003). The disk temperatures are now comparable to the `COMPTT` fits (600–700 eV). The disk emission is again stronger in rev. 11 and not detected in rev. 25.

`2COMPTT`: While our `2COMPTT` model is not in all details comparable to either the one of Frontera et al. (2001, `2COMPPS`) or the one of Di Salvo et al. (2001, `COMPTT+THCOMP`), they show similar tendencies. We employ the strategy of Frontera et al. (2001) by coupling $\Omega/2\pi$ for both Comptonization components. We find reflection factors of 17% (rev. 11) and 28% (rev. 25) for the harder component, comparable to the *BeppoSAX* results. The softer Comptonized component is optically thick and has an electron temperature $\sim 2.8\,\mathrm{keV}$, similar to Di Salvo et al. (2001). The harder component, however, is hotter ($kT \sim 155\,\mathrm{keV}$) and much more transparent ($\tau \sim 0.4$). In this case, *SPI* is well described up to 550 keV. As Di Salvo et al. (2001), but in contrast to Frontera et al. (2001), we find that a non-Comptonized disk emission component is still required. Consistent with the single `COMPTT` fits, the strength of the disk emission in rev. 11 is about two times that of rev. 25.

4. CONCLUSIONS

Thermal Comptonization with reflection provides an adequate description of the broad band hard state spectrum of Cyg X-1 as measured with *RXTE* and *INTEGRAL*. The Comptonizing plasma is of moderate optical depth and temperature. The new *SPI* and *PCA* calibrations allow to better constrain the model parameters, e.g., the reflection fraction was found to be $\sim 5\%$ lower than before. The presence of a second and optically thick Comptonization cloud also remains an interesting possibility, giving fits of comparable statistical quality as the single `COMPTT` model. However, these fits might alternatively indicate complexity of a different origin at low energies.

In order to distinguish between the different Comptonization models, the broad band calibration of the *INTEGRAL* instruments has to be further improved. Solving the question about the existence of a hard tail additionally requires to sum spectra over longer exposure times — after closer evaluation of the variability on those time scales. Also, no absolute flux measurement is possible at the moment, especially for *ISGRI*. The relative normalization between *SPI* and *ISGRI* reported above, however, is comparable to the values found for Crab observations reduced with OSA 3.0 (Lubiński et al., 2004).

Finally, there has been some question of whether or not the high energy spectrum of Cyg X-1 uniquely requires a Comptonization description. Solely considering the 10–200 keV spectrum in a first approach, we have found that synchrotron X-rays from a jet (when properly folded through the detector response) can provide a very good description of the data (Markoff & Nowak, 2004). Additional work is required to determine if such models can be extended to the whole 2–550 keV range.

ACKNOWLEDGEMENTS

This work has been financed by Deutsches Zentrum für Luft- und Raumfahrt grants 50 OG 95030 and 50 OG 9601, Deutsche Forschungsgemeinschaft grant Sta 173/25-3, National Science Foundation grant INT-0233441, National Aeronautics and Space Administration grant NAS8-01129, Deutscher Akademischer Austauschdienst grant D/0247203, KBN grants 5P03D00821, 2P03C00619p1,2, and PBZ-054/P03/2001, as well as the French Space Agency (CNES) and the Foundation for Polish Science. We thank all people involved in building and calibrating *INTEGRAL* for their efforts, and E. Smith and J. Swank for the very smooth scheduling of the *RXTE* observations.

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