INTEGRAL/*RXTE* Observations of Cygnus X-1

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Abstract. We present results from simultaneous observations of Cyg X-1 with *INTEGRAL* and *RXTE* in 2002 November and December, employing the new *RXTE* calibration from *HEASOFT* 5.3. The broad-band X-ray/γ-ray spectrum is well described by Comptonization spectra with an additional reflection component. The temperature of the Comptonizing plasma is $kT_{\mathrm{e}} \sim 60$–80 keV and its optical depth is $\tau \sim 0.8$–1.2. The covering factor of the reflector is $\Omega/2\pi \sim 0.1$. There is a possible soft excess below 10 keV, interpreted as emission from the accretion disk. The spectral parameters are slightly different from those obtained by us earlier due to the different *RXTE*-PCA calibration.

INTRODUCTION

One of the major advances in observational X-ray and gamma-ray astronomy of the past decade has been the availability of broad band, 2–200 keV studies of X-ray sources through the instruments on board the Rossi X-ray Timing Explorer (*RXTE*) and the *BeppoSAX* satellites. Such broad band studies are of special importance for the understanding of the physical processes at work in galactic and extragalactic black holes (BHs), which emit an appreciable fraction of their overall luminosity in this energy regime.

As has been outlined by Mike Nowak elsewhere in this volume, current belief is that the 2–200 keV spectrum of BHs is caused by three major physical components: 1. soft photons from an accretion disk with a $r^{-3/4}$ temperature profile and typical inner disk temperatures of a few 100 eV, 2. a hard power-law continuum with an exponential cutoff above ~100 keV, probably caused by Comptonization of accretion disk photons or soft photons from another source, and 3. X-rays produced from a jet. The relative contribution of these three components obviously depends on the spectral state of the source, with Comptonization and jet dominating in the "hard state", and with the soft accretion disk photons dominating during the "soft state" [see,e.g., 1, 2, 3].

With the launch of Europe's newest X-ray and γ-ray satellite, the *International Gamma-Ray Astrophysics Laboratory* (*INTEGRAL*), another opportunity to measure spectra above ~5 keV has become available. Simultaneous *RXTE* and *INTEGRAL* measurements will help in determining the above spectral components in greater detail than what was possible with *RXTE* alone: Simultaneous *RXTE* and *INTEGRAL* observations approximately double the available collecting area above 20 keV, which is important for constraining the parameters of the Comptonizing medium, of the jet, and also the strength of the reflection hump. The SPI instrument on *INTEGRAL* also adds very high spectral resolution capabilities that are not available with *RXTE*'s HEXTE instrument. At the same time, *INTEGRAL* alone lacks *RXTE*'s capability of performing high time resolution studies, especially below 20 keV, where the collecting area of *INTEGRAL*-JEM-X is only a small fraction of what is available with the Proportional Counter Array (PCA) on *RXTE.*

In this contribution we describe the results of modeling simultaneous *RXTE* and *INTEGRAL* observations of the black hole Cygnus X-1 performed during the performance verification (PV) and calibration phase of *INTEGRAL* in the fall of 2002. We update the earlier results presented by Pottschmidt et al. [4] by including the newer *RXTE* PCA calibration available in the newest release of the *RXTE* data analysis software, *HEASOFT 5.3*, which is described by Keith Jahoda elsewhere in this volume.

DATA ANALYSIS AND OBSERVATIONS

There are a total of five observations during *INTEGRAL*'s PV phase for which we were able to secure strictly simultaneous RXTE observations. These observations happened during the fall of 2002, shortly after the end of the 2002 soft state of Cyg X-1. See Pottschmidt et al. [4] for a detailed description of the data. In summary, our observations consist of roughly 5–10 ksec long *RXTE* observations simultaneously to similarly long observations with the Imager on-board *INTEGRAL* [IBIS, 40–250 keV; 5]. During three observations, one of the two cameras of the Joint European X-ray Monitor [JEM-X, 10–40 keV; 6] was switched on for a similar time, while for the other two observations we were able to also use data from the Spectrometer on-board *INTEGRAL* [SPI, 50–200 keV; 7]. The *INTEGRAL* data were extracted with the *INTEGRAL* off-line scientific analysis software, version 1.1, with fixes available up to 2003 June 15 and are the same that we have already used before [4]. Due to calibration issues, we used the energy ranges given above for the spectral analysis and add a 10% systematic uncertainty to the IBIS data (Ubertini, priv. comm.). Preliminary studies using a newer version of the *INTEGRAL* software show that it will be possible to extend the SPI spectrum out to at least 500 keV, however, these studies were not yet finished at the time of writing.

As mentioned above, we use the newest PCA response from *HEASOFT 5.2.* Compared to earlier releases of the PCA calibration, this matrix has been adjusted to give a flux level from the Crab that is consistent with measurements by other instruments, including the HEXTE (Arnaud, these proceedings). As a result, PCA fluxes are now found at about 85% of the values reported previously. The matrix has also been adjusted to give a slope that is consistent with other instruments. We have confirmed these claims by modeling RXTE observations of the Crab nebula and thus normalize all fluxes mentioned in this contribution to that measured by the RXTE by including a multiplicative constant in the spectral models that is set to unity for both, the PCA and the HEXTE, and is allowed to vary freely for the *INTEGRAL* measurements. Since fitting the PCA data from the Crab show the presence of further systematic deviations from a power law, we add an energy independent uncertainty of 0.5% to all PCA spectra. In future work, energy dependent systematic errors will have to be assumed, especially in the regime around 6 keV where the residuals still show deviations larger than 0.5%. As a result the χ^2 values quoted below are generally $\chi^2_{\rm red} > 1$ and we will not quote formal uncertainties for the best fit parameters, despite the fact that the residuals show that the continuum is rather well described by the spectral model. We are currently working on improving these issues, by including energy dependent systematics and updating the *INTEGRAL* spectra with those extracted using more recent software.

MODELING THE *RXTE*/*INTEGRAL* SPECTRUM OF CYGNUS X-1

We model the joint data with two kinds of Comptonization models. This approach allows us to gauge the influence of the implicit assumptions entering these models on the possible variation of physical parameters between the observations [8]. The models used are the Comptonization model of Hua and Titarchuk [`compTT`; 9], which is partly reflected off a cold accretion disk [10]. The second Comptonization model is that of Coppi [`eqpair`; 11], which includes reflection off a possible ionized disk [12]. For both models, a disk black body [13] is used to describe the soft excess and a Gaussian function models the Fe Kα emission line. The absorbing column to the black hole is fixed at $N_{\rm H} = 6\times10^{21}\,{\rm cm}^{-2}$ [14]. Examples for our spectral fits are shown in Fig. 1.

Both models describe the data equally well. For the `compTT` model, the Comptonization parameters are in principle consistent with earlier observations during the hard state [15, 16]. The electron temperature, $kT_{\rm e}$, is between 60 and 80 keV, and the optical depth of the corona, $\tau_{\rm e}$, is between 0.8 and 1.2. The covering factor of the reflecting slab is measured to be $0.08 < \Omega/2\pi < 0.12$. Compared to our earlier results [4], the corona is hotter, $\tau_{\rm e}$ is slightly lower, and $\Omega/2\pi$ changed from around $\Omega/2\pi \sim 0.18$ to $\Omega/2\pi \sim 0.1$. These changes are a consequence of the now better agreement between the spectral slopes of the PCA and HEXTE. When modeling the PCA and HEXTE separately with power laws, the difference in the power law slopes measured with these two instru-

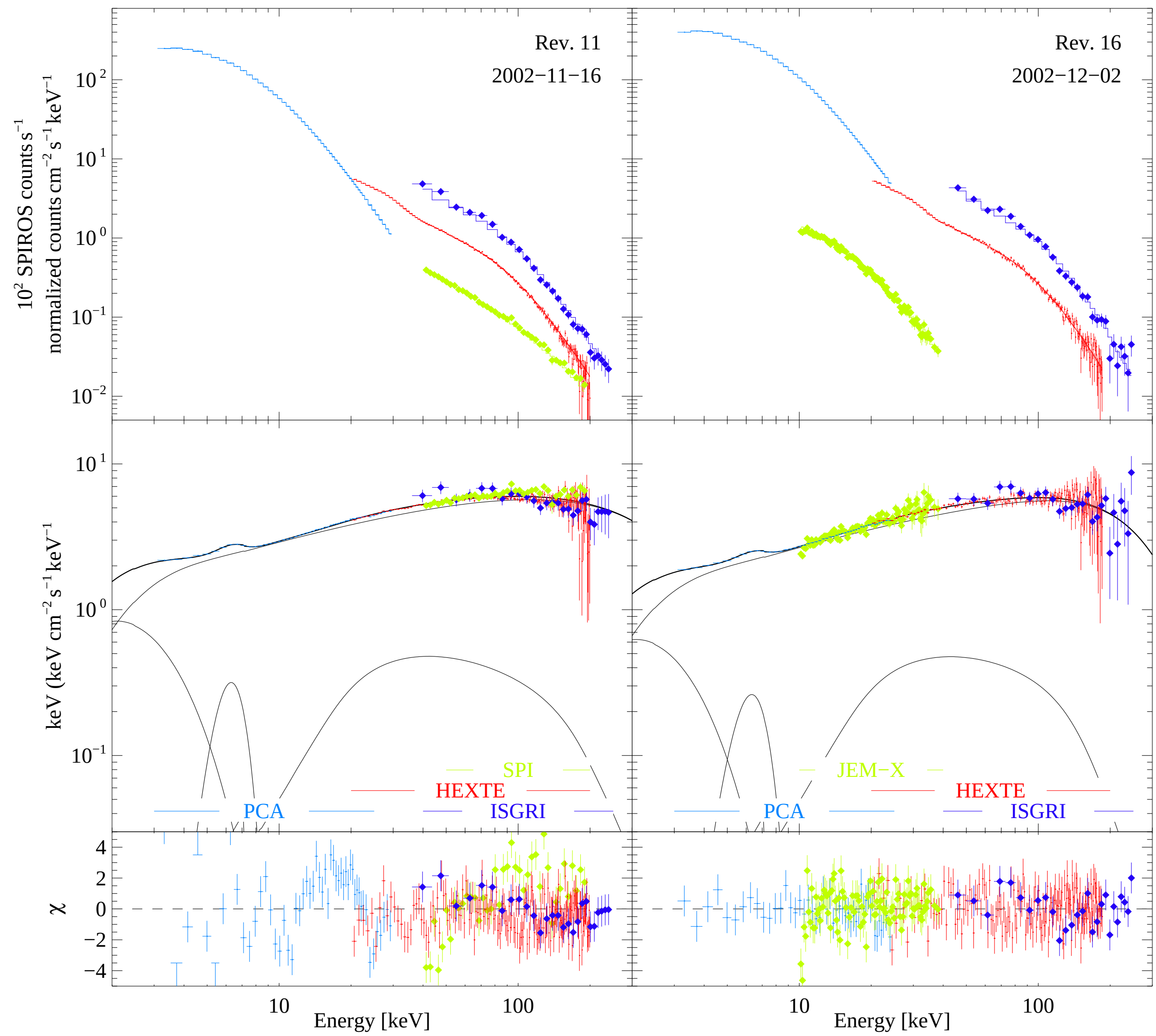

Figure 1. Typical fits of a Comptonization plus reflection model to the joint *RXTE* and *INTEGRAL* data from *INTEGRAL* revolutions 11 and 16. Top: Count rate spectrum. For SPI, we show the spectrum as provided by the SPI spectral extractor, SPIROS, for the other instruments the measured count rate is normalized by the detector effective area. Middle: Unfolded spectrum. Due to the uncertainty of the flux calibration of *INTEGRAL*'s instruments, the measured fluxes have been renormalized to the flux determined with *RXTE*. Bottom: residuals in terms of the contribution to χ^2. We urge readers of the book version of this paper to print this figure in color, using the files available on the AIP web page.

ments was $\sim$0.05, with HEXTE being harder than the PCA. This small systematic difference could be compensated by increasing the strength of the reflecting medium, since the Compton reflection hump peaks at $\sim$30 keV and becomes important right around in the overlap of the PCA and the high energy instruments. In the new data, such a compensation is not necessary anymore and as a consequence a larger fraction of the $>$20 keV spectrum can be attributed to the Comptonization continuum. In agreement with our earlier fits, the `eqpair` model again gives qualitatively similar results. Compared to the best fit `compTT` models, the reflection fractions found in the `eqpair` fits is larger by a factor of $\sim$2, with typical values of $\Omega/2\pi \sim 0.2$. This trend of a generally larger $\Omega/2\pi$ in the `eqpair` fits is consistent with our earlier results [2].

At the soft end of the spectrum we see clear influence from the accretion disk. Our new fits confirm our earlier conclusions that the strength of the disk decreases with time, an effect attributed to the final stages of the soft state to hard state transition of Cyg X-1 in the fall of 2002 [2]. Again in agreement with the earlier results, the inner disk temperature is found to be higher in the `compTT` models ($kT_{\mathrm{in}} \sim 700$ eV) than in the `eqpair` models ($kT_{\mathrm{in}} \sim 200$ eV; almost too small to be detectable with the PCA). The residuals shown in Fig. 1 show definitive structure that is not fully consistent with the systematic uncertainty of the PCA. Furthermore, the Fe Kα line found in the fits is broad, with a width exceeding 500 eV.

One possible explanation for the spectral parameters of the line and the accretion disk, and for the residuals seen in the PCA is that the seed photon spectra assumed in the `compTT` and the `eqpair` models are different: while `compTT` assumes a Wien spectrum, `eqpair` uses an accretion disk spectrum. Since the latter is probably a better description of the real continuum, the broad Fe Kα line found in the `compTT` fits is likely to be an attempt to compensate for the difference in the spectral continuum. See Maccarone et al. [17] for a discussion of these issues.

Finally, we comment on the comparison between the *INTEGRAL* and the *RXTE* data. As shown in Fig. 1, there is overall agreement between the spectral shapes determined with the two satellites. The remaining differences are mainly in the flux calibration, while the spectral redistribution seems to be well understood. This agreement shows that in the near future, as the calibration of *INTEGRAL*'s calibration improves over the next months, it will be possible to test more advanced Comptonization and jet models with our measurements, and to further constrain the parameters of the medium responsible for generating the X-ray and γ-ray spectrum of Galactic black holes.

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