# RXTE/PCA Observations: Spectral Variability in Black Hole Candidate Cygnus X-1

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**Abstract—** RXTE observations of more than 500 have been analyzed for Cygnus X-1. In spectrum, the relative strength, width of iron line and the reflection parameter are in general correlated into the high energy photon spectral index for hard state geometry of hot inner comptonizing region surrounded by a truncated cold disk. Further reflection parameter shows non monotonic behavior suggesting a complex state of the reflector. In the soft state, the flux of the comptonized component is always similar to the disk which rules out ultra soft state in Cygnus X-1. Present study provides more detailed and sophisticated broadband understanding for physical state of black hole Cygnus X-1

**Index Terms—** accretion – accretion disks – X-rays: Stars – Black hole, Individual: Cygnus X-1.

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## 1 INTRODUCTION

During the past forty decade's, it was found by the most of the generation of the X-ray satellites, that Cygnus X-1 is X-1 is the best studied black hole system. It is a well known

Source that undergoes spectral state transitions between a hard/low state and a soft/high state. Historically, the source is found in the hard state most of the times, which can be characterized approximately as a hard power-law emission with a high energy cutoff at ~100 keV. A truncated cold standard accretion disk model invoked to explain the hard state with a hot inner region [14]. In this model, geometry photons from the outer truncated disk impinge into the hot inner region and produces the observed Comptonization spectrum. This generic model has been refined theoretically by the formulation, found more consistent and stable for hot inner disks [12] & [3] and by more detailed spectral modeling, which include the effect of reflection and possible non-thermal emission [4]. For hard state, an alternate interpretation is that there is an extended transition region where the temperature increases rapidly and the emergent spectrum is the sum of the local spectra of each radii [9] & [10].

A steep hard X-ray emission extending to at least several hundred keV while the soft state is dominated by a thermal emission. A cold accretion disk extending to the last stable orbit with a hot corona on top [6] is the the basic model for the soft state, in analogy with the solar corona. It is theoretically more consistent modeling comprising of active regions or blobs on top of the cold disk have been formulated [5] and detailed spectral modeling of this state including reflection and non-thermal emission have been undertaken.

The transitions between two spectral states is shown by Cyg X-1, which are sometimes referred to as an intermediate state [8]. The GRS 1915+105 and many other black holes systems whose classification also depends on the temporal property of the source [1], [2], [13] & [15] shows a myriad of spectral states. Conspicuous with its absence for Cygnus X-1 seems to be the very high or ultra-soft state where the spectrum is dominated by the thermal emission and the power-law emission is weak. In general the simpler spectral behavior of Cygnus X-1 pave the way for a better understanding of black hole systems and its systematic analysis than other black hole systems.

## 2 RXTE SAMPLE

In this work, to fit the spectra of each observation with a uniform model, we analyze 504 pointed RXTE observations of Cygnus X-1. We show that all the spectral shapes of Cygnus X-1 is represented by these large number of observations. Our motivation is to verify the standard paradigms of the geometry of the hard and soft states, by studying the correlation between different spectral components and to bring out any discrepancies or complexities in the spectral evolution. Thus the entire range of spectral variability of Cygnus X-1 is covered in this work by the analysis of sample of pointed observations.

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## 3 SPECTRAL ANALYSIS

We used a generic model consisting of a multi colour disk black body and a hot thermal plasma which Comptonizes the disk photons to fit all 504 RXTE pointed observations. The model includes reflection and an Iron line. In terms of XSPEC routines the model is described as wabs (diskbb + reflect(nthcomp) + Gaussian). Since the PCA energy band is >3 keV, the column density of the absorption component (wabs) cannot be constrained and hence was fixed at a negligible value of $10^{21}$ cm$^{-2}$. The disk black body emission (diskbb) is parameterized by the inner disk temperature, kTin. In the thermal Comptonization model,nthcomp [17], the input photon spectrum is taken to be the disk black body shape and its temperature is tied to kTin. The thermal Comptonized spectrum is parameterized by the electron temperature kTe and the high energy spectral index, $\Gamma$. The temperature was fixed at kTe = 100 keV as HEXTE is not sensitive enough to detect the high energy turnover in the spectrum. We have checked that our results are insensitive as long as kTe > 50 keV. The Iron line was represented by a variable width Gaussian with centroid energy fixed at 6:4 keV. Finally, a convolution model (reflect) produces the reflected component of the incident X-ray photons from the accretion disk. Apart from the three normalization factors for the additive models, the parameters of this generic model are the inner disk temperature kTin, the high energy photon spectral index $\Gamma$, the reflection fraction R and the width of the Gaussian line, σ . The model was fit to all the observations and errors ($\Delta\chi^2$=2.7) on these parameters were computed.

## 4 RESULTS

We use the high energy photon index $\Gamma$, of the thermal Comptonized component which was the best constrained parameter as a basis and hence to study its correlation with other parameters. The width σ, the relative strength of the Iron line and the reflection parameter R has been plotted versus $\Gamma$ in Figure 1. The relative strength of the Iron line (i.e. the Equivalent Width) correlates tightly with $\Gamma$ for $\Gamma$< 2.0. There is a sharp change of behavior at $\Gamma$ ~ 2 and for larger values the Equivalent Width is uncorrelated and has a larger dispersion. The width of the line shows a similar behavior being correlated at low $\Gamma$ < 1.8 and is uncorrelated for larger values. There is a hint of double valued solutions for the width versus $\Gamma$ but given the errors it is difficult to make any concrete statements. If the Iron line emission and the reflection component are from the same physical component, they should be correlated and indeed the reflection parameter R is also broadly correlated with $\Gamma$ as expected. However, the dependence is more complex with R having a non-monotonic behavior i.e. there seems to be anti-correlation when 1.8 < $\Gamma$ < 2.1.

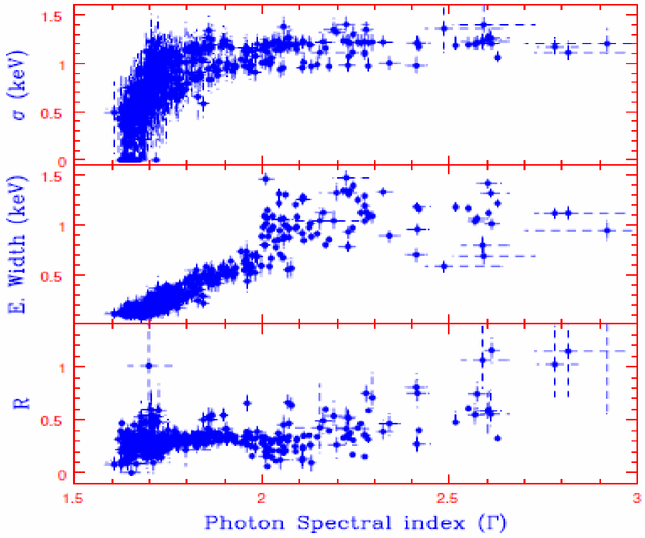

**Fig. 1** The width $\sigma$ (top panel), the Equivalent Width (middle panel) of the Iron line and the reflection parameter $R$ versus the photons spectral index $\Gamma$. For three observations $R > 2$ and hence are not plotted in the bottom panel.

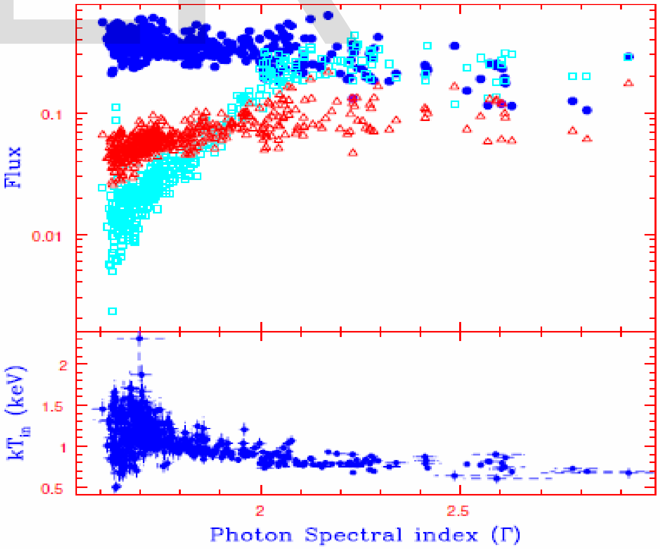

**Fig. 2** Top panel: The bolo-metric flux ($10^{-7}$ ergs/cm$^2$/sec) versus the photons spectral index $\Gamma$. The circles represent the flux of the Comptonization component, $F_c$ while the squares represent the flux of the disk black body component, $F_{DBB}$. The triangles represent the flux of the input photons entering the Comptonizing region, $F_{in}$. Bottom panel: The inner disk temperature, $kT_{in}$ versus $\Gamma$.

The top panel of Figure 2 shows the unabsorbed bolometric flux of the Comptonization component, Fc (filled circles), disk black body component, FDBB (open squares) and that of the input photons entering the Comptonizing region, Fin (open triangles). As expected, the Comptonization component dominates during the hard state, while in the soft state, its flux is comparable with that of the disk black body. It is interesting to note that the flux of the disk blackbody photons entering the Comptonization region is smaller than the observed disk black body flux in the soft state, but is larger in the hard state. This may indicate changes in the geometry of the system as discussed in the next section. The variation of the inner disk temperature kTin is shown in the bottom panel of Figure 2. The temperature is nearly constant with a hint of an increase in the hard state.

## 5 DISCUSSION

Geometrical model for Cygnus X-1 is an attractive and more or less standard model where for the hard state, there is a truncated disk surrounding a hot Comptonizing region in contrast to the soft state and the disk extends to the inner regions and a hot corona on top Comptonizes its photons. The inner radius of the truncated disk moves inwards, while the inner Comptonizing region shrinks during a state transition. As the cold disk fills the inner regions, a hot corona (or more specifically several active regions) arise on top of it and Comptonize its photons. The results presented here are broadly consistent with this general scenario, although there are some specific inconsistencies or complexities.

As a consequence of this results the inner radius of the disk moves inwards, the relative energy released between the inner hot region and the disk decreases. Hence the required Compton amplification decreases which translates into an increase in the spectral index $\Gamma$ . At the same time, the reflection parameter (and consequently the equivalent width of the Iron line) should increase and hence there should be a positive correltion between these quantities and $\Gamma$. Furthermore, as the disk moves inwards, the increased relativistic effects should broaden the Iron line and hence the width of the line should also be correlated with $\Gamma$ . As the disk fills the inner regions, the reflection and the line width should saturate to their maximum values and hence in the soft state they should not be correlated with $\Gamma$. These predictions are broadly consistent with the results shown in the top and middle panels of Figure 1. Both the relative strength (i.e. the Equivalent width) and the width of the Iron line increase with $\Gamma$ and then saturate. However, the value of $\Gamma$ for which this saturation occurs is different. Given the spectral resolution of the PCA and the approximate Gaussian model used for the skewed broad Iron line, one may expect that the Equivalent Width is a better measured quantity than the width of the line. It is interesting to note that there is a rather sharp discontinuity in the Equivalent Width variation at $\Gamma = 2$. As the disk extends to the innermost region, the geometry of the Comptonization region changes from being a hot inner disk with $\Gamma < 2$ to a patchy corona on top of the disk with $\Gamma > 2$. This geometrical transformation at $\Gamma \sim 2$ could be the cause of the rather sharp discontinuity. The reflection parameter R has a complex non-monotonic behavior with $\Gamma$ (Bottom panel of Figure 1). It is correlated for $\Gamma < 1.8$, inversely correlated for $1.8 < \Gamma < 2.1$ and correlated for larger values. This suggests that as the standard disk extends to the innermost radii, the geometry and nature of the active coronal regions becomes more complex and the disk maybe getting ionized, an effect which is not taken into account here.

The expected result is shown by the top panel of Figure 2, that the flux of the Comptonizing components (filled circles) decreases with increasing $\Gamma$ while the disk black body flux increases (open squares). The flux of each of these components is single valued for a given $\Gamma$ which shows that source never undergoes any hysteresis effect, conforming results obtained from a single transition [15]. Such an effect has been observed in some black hole systems (e.g. GX 339-4) where the variation of $\Gamma$ with flux depends on whether the source is transiting from low to hard or from hard to low [15]. It is interesting to note that for the entire soft state ($\Gamma > 2.0$) the disk emission is nearly equal to the Comptonizing one which implies that the fraction of energy dissipated in the corona is ~ 0.5 independent of $\Gamma$.

Here we demonstrate the universality of this result for different epochs of the soft state. It is also clear the Cygnus X-1 never exhibits an ultra-soft state spectrum where the disk emission dominates the Comptonized one. The input flux of soft photons entering the Comptonized region are marked as open triangles in the top panel of Figure 2. For $\Gamma > 2.0$, this flux is less than the disk emission, which suggests that the in the soft state the corona is a patchy one, covering a fraction of the surface area of the disk. These patchy active regions Comptonize only a fraction of the disk photons while the rest are observed directly. For the hard state ($\Gamma < 1.8$), it is surprising to note that the input photons have significantly more flux than the disk emission.

## 6 CONCLUSION

In brief we can conclude that the comprehensive spectral analysis of Cygnus X-1 using 504 pointed observations is broadly consistent with the picture that in the hard state there is a truncated disk and a hot inner region. As the system moves to the soft state, the inner radius of the disk moves inwards. Finally in the soft state the hot inner region disappears, with the appearance of active coronal regions on top of the cold disk. This scenario is supported by the increase of the relative strength and width of the Iron line with spectral slope $\Gamma$ for small values of $\Gamma < 2$ of the hard state and their saturation for large $\Gamma > 2$ values of the soft state. However, the reflection parameter R shows non-monotonic behavior with $\Gamma$, indicating complexities in the geometry or in the ionization state of the reflector. The analysis conforms that in the soft state the disk flux is similar to the Comptonized component for a large range of $2 < \Gamma < 2.9$ and the source never goes into a ultra-soft state. Overall, with its relative simplicity compared to other black hole systems, especially transient ones, Cygnus X-1 remains a promising source to understand the nature of accreting black hole systems.

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