X-ray and $\gamma$-ray spectra of Cyg X-1 in the soft state

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Abstract.
We present X-ray/$\gamma$-ray observations of Cyg X-1 in the soft state during 1996 May–June. We analyze ASCA, RXTE and OSSE data. The spectrum consists of soft X-ray blackbody emission of an optically thick accretion disk in the vicinity of a black hole and a power law with an energy index $\alpha \sim 1.2–1.5$ extending to at least several hundred keV. In the spectra, we find the presence of strong Compton reflection, which probably comes from the disk.

INTRODUCTION

Cyg X-1, the primary black-hole candidate, undergoes transitions between two spectral states: the hard (‘low’) state in which its X-ray spectrum is hard ($\alpha \sim 0.6$) and extends up to several hundred keV, and the soft (‘high’) state dominated by a strong soft X-ray emission together with a much softer power law ($\alpha \sim 1.5$) tail. Usually, Cyg X-1 remains in the hard state. The last transition to the soft state began around 1996 May 16 when the soft X-ray flux started to increase. The source remained in the soft state until about August 11 (Zhang et al. 1997).

THE DATA

In this paper, we analyze three groups of observations of Cyg X-1 in 1996. An RXTE observation on May 23 shows the object still undergoing a transition between the states (Fig. 1). The remaining data sets are from a simultaneous ASCA/RXTE observation on May 30 and from six simultaneous

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Figure 1. The spectral states of Cyg X-1. The solid curve is a fit to the soft state observed by RXTE and OSSE on 1996 June 17. The dashed curve is a fit to an intermediate state observed by RXTE on 1996 May 23. For comparison, we also show a Ginga/OSSE spectrum in the hard state (on 1991 June 6) with the model represented by the dotted curve (see Gierliński et al. 1997). The data have been rebinned for clarity.

RXTE/OSSE observations on June 17-18, when the object was in the soft state.

The RXTE data come from the public archive. A 2% systematic error has been added to each PCA channel to represent calibration uncertainties. Since dead-time effects of the HEXTE clusters are not yet fully understood, we allowed a free relative normalization of the HEXTE data with respect to the PCA data.

The CGRO/OSSE observation in the soft state on June 14–25 (from 50 keV to 1 MeV) overlaps with the RXTE observations on June 17 and 18. We have extracted six OSSE data sets near-simultaneous with the RXTE observations. In order to get better statistics, we have increased each OSSE data interval to include 30 minutes on either side of the corresponding RXTE interval. The spectrum is shown in Fig. 1, which also shows a spectrum from the hard state for comparison.

ASCA observed Cyg X-1 from May 30 5:30 (UT) through May 31 3:20 (Dotani et al. 1997, hereafter D97). The GIS observation was made in the standard PH mode. The SIS data suffer from heavy photon pile-up and thus are not usable. We have selected 1488 live seconds of the ASCA data near-simultaneous with the corresponding RXTE observation.
RESULTS

First, we fit the simultaneous RXTE/OSSE soft-state data of June 17–18. At soft X-rays, the spectra are dominated by a black-body component. The OSSE data show the emission extending up to at least 800 keV. Our basic model consists of a soft X-ray blackbody disk model and a power law. The power-law energy index, $\alpha$, varies between $\sim 1.3$ and $\sim 1.5$. We do not observe any high-energy cutoff in the power law, which suggests a non-thermal origin of the emission. We note that the power-law component comes probably from Comptonization of the soft photons and should be therefore cut off at low energies. However, this cutoff would occur only well below 1 keV and its neglect in the model does not affect our conclusions.

Between $\sim 10–200$ keV, the observed spectrum systematically departs from the power law and forms a smooth hump. There is also a broad absorption feature above 7 keV, which can be attributed to an Fe Kα absorption edge. Considering both effects, we conclude that Compton reflection from cold matter takes place in the soft state of Cyg X-1. The covering factor of the reflector, $\Omega/2\pi$, varies in the range 0.6-0.7. The reflector can be identified with the optically thick disk also responsible for the soft blackbody.

The iron edge is smeared, which we attribute to Doppler and strong-gravity effects in the vicinity of the black hole. Therefore, we consider models in the Schwartzschild metric with the accretion disk inclined at angle 35° and reflection taking place between $R_{\text{in}} = 3R_g$ and $R_{\text{out}} = 15R_g$ (where $R_g = 2GM/c^2$). In this paper, we use a model of angle-dependent Compton reflection (Magdziarz & Zdziarski 1995) convolved with the relativistic line profile (Fabian et al. 1989). We note that this is only an approximation of the real disk reflection and does not take into account all angular effects near the black hole.

We then study the ASCA/RXTE data of May 30. We apply a conservative lower limit of 4 keV to the PCA data, and use the ASCA data in the range of 0.7–10 keV. First, we use a blackbody disk emission model taking into account general relativity (Hanawa 1989) together with a power law with relativistic reflection (as for the June data above). This, however, yields an unacceptable $\chi^2$ of about 1100/577 d.o.f. (see the residuals in the upper panel of Fig. 2). The fit can be significantly improved by an additional weak high-energy tail on top of the disk spectrum. We model this tail as due to thermal Comptonization of a 300 eV blackbody in a plasma with $kT \approx 5$ keV and $\tau \approx 3$ (shown by the long-dashed curve on Figure 3). The resulting $\chi^2$ is 680/575 d.o.f. The additional component can be interpreted as Compton radiation of an intermediate layer between the optically thick disk and an optically thin corona. We note that a similar reduction of $\chi^2$ can be (instead of adding the Comptonization tail) obtained by breaking the power law to a softer one below a few keV. A similar softening of the power law at low energies was observed by ASCA in the hard state (Ebisawa et al. 1996).
FIGURE 2. The data-to-model ratios for the 1996 May 30 observation. The upper panel corresponds to the model including power law, reflection and disk emission, the middle panel includes a Comptonization tail to the disk emission, and the lower panel includes the tail and an Fe line.

FIGURE 3. The model spectrum of Cyg X-1 in the soft state based on the simultaneous ASCA/RXTE observations of 1996 May 30. The short-dashed, dotted, dash-dotted, and long-dashed curves show the power law, the Compton reflection, the blackbody-disk emission, and the thermal Comptonization components, respectively. Solid line is the sum of all components. In order to show the details of the soft X-ray emission, the interstellar absorption was removed from the model.

The fit can be further improved by adding an Fe Kα line. For that, we use a relativistic disk line (Fabian at al. 1989) with the same parameters as for
the Compton reflection. The obtained $\chi^2$ is 641/573 d.o.f., i.e., the presence of line is statistically significant at a very high confidence level. Figure 2 shows the residuals corresponding to the above models. The model spectrum is presented in Fig. 3.

The spectrum is absorbed by $N_H = 0.47 \pm 0.01$. The fitted power-law index is $\alpha = 1.23 \pm 0.03$. We assume no cutoff in the power law (as implied by the June 14–25 OSSE data). The covering factor of the reflector is $\Omega/2\pi = 0.55 \pm 0.1$, and the reflecting medium is ionized with ionization parameter $\xi \equiv L/nr^2 = 430^{+160}_{-130}$ erg cm s$^{-1}$, corresponding to Fe xxii-xxiv as the most abundant species.

The best fit value of the rest-frame line energy, $E_{Fe} = 6.54^{+0.11}_{-0.15}$ keV, strongly depends on the assumed disk inclination angle. Since the Auger resonant destruction strongly suppresses Kα emission following photoionization of Fe xvii-xxiii, we should expect fluorescence from lithium-like Fe xxiv at $\sim 6.7$ keV. On the basis of our model, this line energy is consistent with the disk inclination angle of $30^\circ$. Notwithstanding, we stress that due to approximate character of the model and uncertainties in the PCA response matrices, the line parameters obtained here might be inaccurate.

If we use the same blackbody disk model as D97 assuming $T_{col}/T_{eff} = 1.7$, we obtain a black hole mass of $21 \pm 2$ M$_\odot$ and an accretion rate of $6.5 \pm 0.4 \times 10^{17}$ g s$^{-1}$. That mass is significantly higher than $12^{+3}_{-1}$ M$_\odot$ found by D97. The discrepancy is explained by influence of the additional Comptonization component used here. On the other hand, we obtain $M_\delta \approx 16$ M$_\odot$ by assuming $T_{col}/T_{eff} = 1.5$. We stress that the ratio of $T_{col}/T_{eff}$ is very uncertain due to theoretical difficulties. In particular, the standard Shakura-Sunyaev solution is unstable at $\dot{m} \equiv Mc^2/L_{Edd} \sim 1$. In Cyg X-1 the total disk luminosity in the soft state is $L_{\text{disk}} \approx 5 \times 10^{37}$ erg s$^{-1}$ (about 5 times higher than in the hard state), which corresponds to $\sim 0.05L_{Edd}$. Assuming the emission efficiency of 0.08, we find $\dot{m} \sim 1$.

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