Disk–corona interactions in soft spectral states of black hole binaries

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**Abstract.** Re-analysis of some archival X–ray data of black hole binaries in soft spectral states is presented. Results of detailed spectral fitting, including proper physical description of the X–ray reprocessed component, indicate that in most cases the soft, thermal disk emission cannot be described by a simple multi-color blackbody model. Additional Comptonization of those seed photons provides an acceptable description of the soft component, implying a presence of a warm ($kT_e \sim 1$ keV), mildly optically thick ($\tau \sim 10$) phase of accreting plasma.

Combined spectral/temporal analysis of GS 1124-68 during 'flip-flop' transitions in VHS suggests that the optically thick accretion flow can proceed in (at least) two modes giving the same time-integrated behaviour (i.e. energy spectra) but very different timing behaviour.

**Keywords:** black holes, accretion disk, X-rays

1. The Comptonized soft component

Accreting black holes, both stellar (including the Galactic $\mu$–quasars) and supermassive, show strong, soft, thermal components in their EUV–X-ray spectra, when accreting above certain fraction of Eddington rate. This component is thought to come from an optically thick accretion disk, and its spectrum is usually modeled as a simple, multi-color blackbody. For re-examining a number of such spectra, I will use the spectral models described in Zycki et al. (1998).

1.1. The Intermediate State

An example of IS is the May 18th observation of GS 1124-68 (Nova Muscae 1991). Using first the frequently employed but unphysical model, \texttt{diskbb + smedge(powerlaw)}, gives an unacceptable fit, $\chi^2_{\nu} = 38/25$. Adding a Gaussian line at 6.4 keV does not improve the fit, unless the line width is $\sim 10$ keV ($\chi^2_{\nu} = 28/23$). Allowing the line energy to be free gives $\chi^2_{\nu} = 21/23$ for $E = 4\pm 0.5$ keV. These values have little to do with Fe spectral features, but rather indicate that it is the continuum shape that is not properly modeled. Using now the \texttt{diskbb + thcomp + rel-repr} model gives very bad fit, $\chi^2_{\nu} = 308/24$. Replacing the \texttt{diskbb}
component with a Comptonized blackbody (COMPTT) results in a dramatic improvement, $\chi^2_\nu = 13/22$. Thus the best fit is obtained for the proper physical description of X–ray reprocessing and the Comptonized blackbody model for the soft component. The same effect is observed in GRO J1655-40, GS 2000+25 and XTE J1550-564 (Życki et al., in preparation).

1.2. The High State

Nova Muscae 1991 was in the High State when observed on Mar 18th. The spectrum shows a strong soft component, and the hard component is negligible (Ebisawa et al., 1994). Modeling the spectrum with the DISKBB + THCOMP model gives $\chi^2_\nu = 27/24$ (see Fig. 1). The Comptonized component is steep and makes a significant contribution to the soft component. Again, the soft component has to be described by a model broader than the multi-color disk blackbody.

1.3. The Very High State

On Jan 11th, while still on the rise to the peak of the outburst, Nova Muscae 1991, showed a spectrum consisting of two Comptonized components: the softer one again cannot be described by the DISKBB model. It can be modeled as Comptonization of $\approx 0.3$ keV blackbody by a warm, $kT_e \approx 3$ keV, optically thick, $\tau \sim 7$, plasma.

1.4. Physical Origin of the Comptonization

The additional Comptonization seems to be a common feature of disk-dominated spectral states of accreting black holes. There are two possible scenarios to explain it. The first one is Comptonization in a “hot skin” on top of the accretion disk. Such a hot layer could not be heated by X–ray irradiation (as postulated for the low/hard state), but it
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would require enhanced viscous energy dissipation compared to the bulk of the disk. The second possibility is that the electron energy distribution in the Comptonizing plasma is a hybrid, thermal–non-thermal one, rather than a pure thermal (Maxwellian) distribution. In fact, the COMPS model (J. Poutanen, private communication) using the hybrid distribution gives very good fits to the HS and IS data sets: $\chi^2_\nu = 17/24$ for IS, $\chi^2_\nu = 16/23$ for HS, but it fails for VHS.

2. Inner disk oscillations in GS 1124-68 in VHS?

Shortly before reaching the peak of outburst Nova Muscae 1991 showed 'flip-flop' transitions (Takizawa et al., 1997): the flux in the 2–20 keV band changed by $\approx 20\%$. Spectral and timing analysis during this period suggests that the source were undergoing re-structuring of the inner accretion disk.

2.1. Spectral analysis

Energy spectra both in the high- and low-flux state can be adequately described by the \texttt{diskbb + thComp + rel-repr} models (no additional Comptonization of the soft component is required). The best-fit model spectra differ most at energies 5–10 keV: the differences are small both at the lowest and highest energies (Fig. 2). The difference spectrum can be described as Comptonization of single blackbody emission, but it cannot be described as Comptonized disk blackbody.

2.2. Timing analysis

X–ray power density spectra show both energy and flux dependence. The soft X–rays ($E < 4$ keV) PDS is very different in the two flux states.

![Figure 2](image-url)  
*Figure 2. Energy and power spectra of Nova Muscae 1991 on Jan 14th (VHS), when the source showed 'flip-flop' transitions, probably related to re-structuring of the accretion disk. Two spectra in each panel are for two flux states.*
states (Fig. 2). In the high flux state the PDS resembles that of typical HS, i.e. a power law \( f^{-\alpha} \) with \( \alpha \approx 1.2 \), although there is also a narrow QPO at \( \approx 8 \) Hz. However, in the low flux state the PSD has a Lorenzian shape peaking (in the \( f \times Power \) representation) at \( \approx 2 \) Hz.

The PDS of the hard X–ray component \( (E > 8.5 \text{ keV}) \) is similar in both flux states except for the QPO energy which is higher in the low flux state.

3. Discussion

Interactions between accretion disk and corona in the soft spectral states of accreting black holes are clearly complex. One outcome of those interactions is a presence of warm, mildly optically thick plasma modifying the disk thermal emission. Proper modeling of the resulting spectra is important e.g. for correct determination of system parameters.

The 'flip-flop' transitions observed in VHS of GS 1124-68 close to the peak of its outburst suggest that the optically thick accretion flow can proceed in two modes giving the same time-integrated characteristics. One mode, usually observed in HS, shows the \( f^{-1} \)-like PDS, i.e. a scale-invariant behaviour, perhaps realized in magnetic turbulence (Kawaguchi et al., 2000). The other mode clearly possesses certain spatial/temporal scale, since the PDS is described by a Lorenzian, i.e. it corresponds to exponential shots of a single time scale.

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