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On the Geometry of Accretion Flow in Soft X-ray Transients from Modeling the X-ray Reprocessing

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Abstract. We perform detailed spectral analysis of archival *Ginga* data of a number of Soft X-ray Transient sources. Our models include thorough description of the X-ray reflected/reprocessed component. We derive constraints on geometry of accretion and physical state of the reprocessor, and compare them with prediction of theoretical models.

1. Introduction

Accretion flow around black holes in compact objects (both active galaxies and stellar sources) clearly proceeds through at least two phases: optically thick, cooler plasma producing a soft thermal component, and optically thin, hot plasma where hard X-rays/γ-rays are produced (see Mushotzky, Done & Pounds 1993 and Tanaka & Lewin 1995 for reviews).

The geometrical configuration of the two phases is still uncertain. Simple possibilities include pure radial and pure vertical stratification of the flow, but more complicated geometries, with partial overlap are also considered.

The commonly made assumption that the observed hard X-ray spectra are due to the inverse Compton process requires an input of soft photons from the optically thick plasma to the optically thin one. The reverse interaction must then also take place: the hard X-rays will illuminate the optically thick plasma (Guilbert & Rees 1988) and they will be reflected and reprocessed. As a result, a continuum spectral component is formed by Compton reflection, with spectral features due to emission/absorption by heavy elements (primarily iron) superimposed on it.

Studying the effects of such reprocessing can be extremely useful as a tool for constraining the spatial distribution of the two phases of accreting plasma. The amplitude of the reflected component constrains the solid angle subtended by the optically thick plasma from the X-ray source. The shape of the reflected continuum below ~ 10 keV, and the energy and strength of iron spectral features around 7 keV give information about ionization state of the reflecting plasma.

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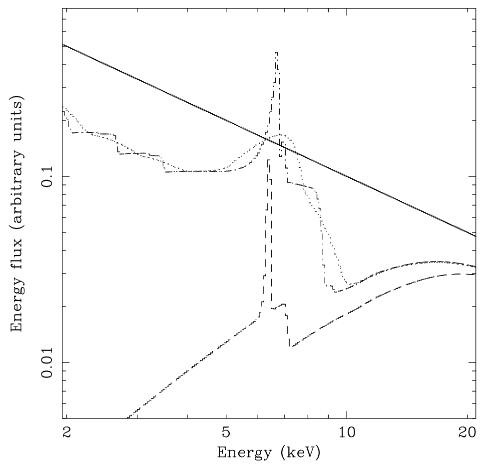

Figure 1. X-ray reprocessed spectra showing effects of ionization (dashed vs. dot-dashed curves) and relativistic smearing (dotted vs. dot-dashed curves)

Possible broadening/smearing of spectral features can constrain the plasma velocity field if it can be distinguished from e.g. broadening due to Comptonization.

Black hole Soft X-ray Transients (SXT) are particularly suited to this kind of analysis. Those are a sub-class of X-ray binaries that undergo occasional, dramatic outbursts (Tanaka & Shibazaki 1996 for review). During the subsequent decline phase the mass accretion rate, which is thought to be the most important parameter, decreases roughly exponentially, with a typical e-folding time scale of $30 - 60$ days. During the decline they go through a sequence of well defined states characterized by distinct spectral and timing properties.

2. Data

For our analysis we use archival *Ginga* data of a number of SXT. The data combine broad band (1 to 20–30 keV) with moderate spectral resolution (18% at 6 keV), very good statistics due to large effective area of the LAC detector ($\sim 4000\,\mathrm{cm}^{-2}$) and systematic uncertainties of the instrument below 1%. Background subtraction can pose a problem for bright sources, due to the contamination of the background monitors by source counts. We have developed a method to estimate the background, described in some detail in Życki, Done & Smith (1998b).

3. Models

Our model of X-ray reprocessing combines the model for Compton–reflected continuum of Magdziarz & Zdziarski (1995) and the iron Kα line computations of Życki & Czerny (1994), with photo–electric opacities computed by the photo–ionization code described in Done et al. (1992). This is parameterized by the ionization parameter, $\xi \equiv 4\pi F/n$, where F is the illuminating flux and n electron density. The reflected continuum and the Fe line (i.e. its energy and normalization) are thus computed consistently rather than being modeled as two separate components. Single ionization computations can then be combined, weighted by a suitable spatial dependencies of illumination emissivity and ξ, in order to

Table 1. Fits of the reprocessing model

sp.st.	Source	obs. date	Γ^a	f	ξ	$R_{\rm in}$ ($R_{\rm g}$)	χ^2/dof
LS	GS 1124	23/07/91	1.72 ± 0.02	$0.24^{+0.11}_{-0.08}$	17^{+40}_{-16}	$50^{+\infty}_{-35}$	15.3/24
LS	GS 2023	19/06/89	1.72 ± 0.03	$0.66^{+0.11}_{-0.07}$	0^{+1}	18^{+13}_{-7}	23.1/23
LS	GS 2000	16/12/88	$1.93^{+0.14}_{-0.08}$	$0.24^{+0.80}_{-0.21}$	$100^{+5\times10^4}_{-100}$	–	20/24
HS	GS 1124	18/05/91	$2.29^{+0.05}_{-0.03}$	$0.64^{+0.40}_{-0.10}$	$(3.5^{+9.5}_{-3.0}) \times 10^4$	18^{+22}_{-6}	13.5/22
HS	GS 2000	18/10/88	$2.00^{+0.26}_{-0.03}$	$0.45^{+0.45}_{-0.11}$	$(15^{+45}_{-14.6}) \times 10^3$	7^{+2}_{-1}	15/21
VHS	GS 1124	11/01/91	$2.02^{+0.16}_{-0.21}$	$0.35^{+0.25}_{-0.09}$	$(10^{+10}_{-8}) \times 10^3$	13^{+6}_{-3}	26.6/31
VHS(?)	GS 2023	30/05/89	1.70 ± 0.01	$0.17^{+0.16}_{-0.04}$	$(6^{+18}_{-4}) \times 10^3$	6^{+2}	25.7/27

[a] Photon spectral index

describe reflection from an accretion disk. The amplitude of the component is expressed as a solid angle of the reflector, normalized to 2π, $f \equiv \Omega/2\pi$. The effects of relativistic smearing are computed convolving the total reprocessed spectrum with relativistic line profiles of Fabian et al. (1989), implemented in XSPEC as the "diskline" model. The main parameter here is the inner disk radius in units of $R_{\rm g} \equiv GM/c^2$, assuming a fixed illumination emissivity (we assume $F_{\rm irr}(r) \propto r^{-3}$). Figure 1 shows typical model spectra.

4. Results

We will present results of spectral modeling of data of GS 1124-68 (Nova Muscae 1991), GS 2023+338 (optical counterpart: V404 Cyg) and GS 2000+25.

4.1. Low/Hard State

The results are shown in Table 1. The reprocessed component is significantly present in the spectra. Its amplitude is significantly smaller than 1, typical values being 0.3 – 0.7. It is rather weakly ionized, $\xi \lesssim 50$ corresponding to mean ionization level of iron <FeXVII i.e. only M-shell electrons removed. Relativistic smearing of the reprocessed component is significant in some of the spectra, and is consistent with decreasing in time, as the sources progressed through the decline phase. Even at the beginning of decline in GS 2023+338 the smearing is less than expected from a disk extending down to the last stable orbit at $r_{\rm ms} = 6\,R_{\rm g}$, typical values being $R_{\rm in} \sim 20 - 30\,R_{\rm g}$ (see Figure 1 and Życki, Done & Smith 1997), although $R_{\rm in}$ is compatible with $r_{\rm ms}$ in Nova Muscae (Życki, Done & Smith 1998a)

4.2. High/Soft State

In the high state spectra the major difference in the reprocessed component is its strong ionization (Table 1). Dominant iron ions are usually helium- and hydrogen-like ones. Consequently, the Kα line and absorption edges are much stronger in the composite spectra. The amplitude f is also larger, close to 1.

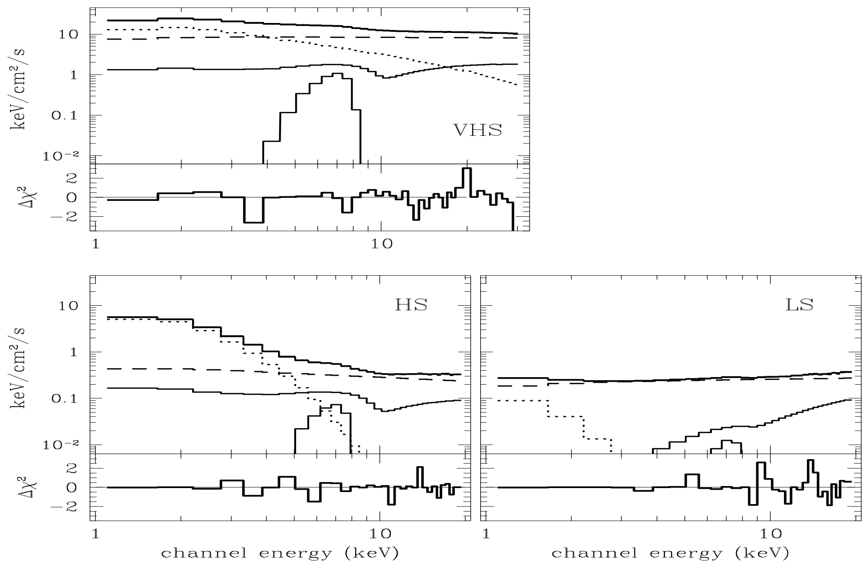

Figure 1. Spectra of Nova Muscae in low, high and very high states (upper panels) and χ^2 contributions (lower panels). Lower solid histograms show the iron Kα line and the reflected continuum, dotted histograms show the soft thermal component and the dashed histograms show the primary power law.

Relativistic smearing is significant, but the values of $R_{\rm in}$ differ between different objects. The fact that, for GS 2000+25, $R_{\rm in} \approx 6$ (which is not expected given the assumed $F_{\rm irr} \propto r^{-3}$ i.e. without the boundary condition term; Shakura & Sunyaev 1973) may suggest that an additional broadening of that component (e.g. due to Comptonization) takes place.

We find that the soft component of the continuum spectrum cannot be described by either pure black body or multi-temperature (disk) blackbody spectrum. Additional power law tail is required, which can be modeled as additional Comptonization of a (disk) black body. This differs from results of Ebisawa et al. (1994) who were able to fit the disk blackbody to the spectra but they were using the smeared edge model with a narrow gaussian to model the iron spectral features, rather than a reprocessing model.

4.3. Very High State

Here, we show two examples (Table 1): Nova Muscae 1991 showed an example of Very High State spectrum at the beginning of its decline. The soft continuum component again cannot be modeled as a (disk) blackbody, so we assume a Comptonized blackbody instead. The presence of the reprocessed component is then again highly statistically significant although its amplitude is not well constrained from above, in particular if radial distribution of ionization is allowed for. The reflection is strongly ionized and smeared, similarly to high state spectra.

As the second example of spectrum at very high luminosity we show GS 2023 at the peak of its outburst on 30th May 1989. Its spectral and timing properties are not the same as those of Nova Muscae so it is necessarily another example of the VHS. Properties of the reprocessed component are nevertheless quite similar: best fit amplitude is less than 1, reprocessing material has to be strongly ionized, and strong additional smearing is required, although in this case it may rather be Comptonization than relativistic smearing (see Zycki, Done & Smith 1998c)

5. Discussion

The results presented in previous Section clearly suggest that the geometry of accretion and the physical state of reprocessing material change as sources make transition between hard and soft states. The most significant changes to the reprocessing are those of ionization of the reflector and the amplitude of reflection. In the low/hard state the solid angle of the reprocessor from the X-ray source is smaller and the reprocessor is colder than in the high/soft state. The amount of relativistic smearing does not show clear, statistically significant changes between the transitions, but $R_{\rm in}$ is consistent with increasing as the amplitude f decreases.

We can compare the above results with predictions of models proposed for the spectral transitions.

The observed changes are qualitatively expected in the model of Esin, McClintock & Narayan (1997). This model assumes predominantly radial stratification of the flow, with optically thick disk extending only outside certain transition radius. The central, hot solution derives from advection dominated accretion flow solutions although when applied to typical low state, it has radiative efficiency of ~ 0.35. The transition radius (which can be identified with our $R_{\rm in}$) has to decrease with increasing $\dot{m}$ to explain softer spectra when sources are brighter, and this also explains larger amplitude of the reprocessed component and its strong ionization in high state. The behavior of $R_{\rm in}$ we find from relativistic smearing is also consistent with that prediction. Thermal radiation emitted by the disk can be Comptonized by hot upper layer of the disk, giving rise to the observed steep power law tail.

Quantitatively, however, the values of $R_{\rm in}$ we derive are rather smaller than those postulated by Esin et al. In particular, in the low state we derive $R_{\rm in} \sim 20 - 50\,R_{\rm g}$, while they assume $2 \times 10^4\,R_{\rm g}$. Esin et al. (1998) argue that the smaller values are still compatible with their model but this claim has not been verified by actual data modeling.

Relatively small values of $R_{\rm in}$ we derive indicate that there must exist significant overlap between the central hot X-ray source and external cool disk i.e. the hot source has to extend much further out than $R_{\rm in}$: otherwise the energy release within the source would be much too small to account for the overall energetics and spectral shape (Poutanen, Krolik & Ryde 1997; Poutanen 1998; Gierliński et al. 1997). Perhaps the hot plasma forms a corona at large distances. The transition between the disk and the corona at large distances could result from e.g. the thermal instability of X-ray irradiated plasma, as considered by Witt, Czerny & Życki (1997) and Czerny et al. (1999)

An alternative geometry was proposed by Di Matteo, Celotti & Fabian (1998). They suggest that magnetic flares above the disk produce the hard X-ray radiation, the disk itself always extends to the last stable orbit, and the hard/low – soft/high transition is due to changes in characteristic height of the flares. In order to account for harder spectra in the low state they postulate that the flares are higher in this state. This however does not naturally explain why the reflection amplitude is smaller in the hard state unless the flares are strongly concentrated towards the inner edge of the disk, so a significant fraction of photons is lost within the central hole (see Życki, Done & Smith 1997). Alternative explanation, that the inner disk is strongly ionized and so the iron spectral features are weak, does not seem to be supported by data analysis, at least in Cyg X-1 (Done & Życki 1998).

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References

Czerny B., Janiuk A., Różańska A., Życki P. T., 1999, these proceedings

Di Matteo T., Celotti A., Fabian A. C., 1998, MNRAS, submitted (astro-ph/9805345)

Done C., Mulchaey J. S., Mushotzky R. F., Arnaud K. A., 1992, ApJ, 395, 275

Done C., Życki P. T., 1998, MNRAS, submitted

Ebisawa, K. et al., 1994, PASJ, 46, 375

Esin A. A., McClintock J. E., Narayan R., 1997a, ApJ, 489, 865

Esin A. A., Narayan R., Cui W., Grove J. E., Zhang S.-N., 1998, ApJ, 505, 854

Fabian A. C., Rees M. J., Stella L., White, N. E., 1989, MNRAS, 238, 729

Gierliński M. et al. 1997, MNRAS, 288, 958

Guilbert P. W., Rees M. J., 1988, MNRAS, 233, 475

Magdziarz P., Zdziarski A. A., 1995, MNRAS, 273, 837

Mushotzky R. F., Done C., Pounds K. A., 1993 ARA&A, 31, 717

Poutanen J., 1998, in Theory of Black Hole Accretion Discs, Abramowicz M. A., Björnsson G., Pringle J. E., Cambridge: Cambridge Univ. Press, 100 (astro-ph/9805025)

Poutanen J., Krolik J. H., Ryde F., 1997, MNRAS, 292, L21

Shakura N. I., Sunyaev R. A., 1973, A&A, 24, 337

Tanaka Y., Lewin W. H. G., 1995, in X–Ray Binaries, Lewin W. H. G., van Paradijs J., van den Heuvel E., Cambridge: Cambridge Univ. Press, 126

Tanaka Y., Shibazaki N., 1996, ARA&A, 34, 607

Witt H. J., Czerny B., Życki P. T., 1997, MNRAS, 288, 848

Życki P. T., Czerny B., 1994, MNRAS, 266, 653

Życki P. T., Done C., Smith D. A., 1997, ApJ, 488, L113

Życki P. T., Done C., Smith D. A., 1998a, ApJ, 496, L25

Życki P. T., Done C., Smith D. A., 1998b, MNRAS, submitted

Życki P. T., Done C., Smith D. A., 1998c, in preparation