Geometry of accretion in Soft X-ray Transients

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Abstract.
We present results of modelling Ginga data of a number of Soft X-ray Transient sources performed with the aim of constraining the geometry of accretion during various stages of the sources’ evolution. Assuming a generic geometry of a central, extended X-ray source with an external, optically thick accretion disk, we use consistent models of X-ray reprocessing to constrain the inner radius of the accretion disk and its ionization state. We show that the evolution of GS 1124-68 (Nova Muscae 1991) and GS 2000+25 agree qualitatively with the recent ideas linking the high/low state transition with changing radius of the optically thick disk, but the case of GS 2023+33 (V404 Cyg) poses a problem for any model.

INTRODUCTION

Black hole binary systems give one of the most direct ways in which to study the physics of accretion disks since there is no surface boundary layer or strong central magnetic field to disrupt the flow and the parameters of the systems are often very well known. Additionally, many of these systems (the Soft X–ray Transients, hereafter SXT’s) show dramatic outbursts where the luminosity rises rapidly to close to the Eddington limit, and then declines over a period of months, giving a clear sequence of spectra as a function of mass accretion rate. Usually, the outburst spectrum is dominated by a soft component of temperature \( \sim 1 \text{ keV} \), with or without a power law tail, while the later stages of the decline show much harder power law spectra, extending out to \( 100-200 \text{ keV} \) [1]. The same bimodal spectral states are seen in the persistent black hole candidates, showing that they are a general outcome of an accretion flow.

The “standard”” accretion disk model [2] (hereafter SS) gives temperatures of order 1 keV for galactic black hole candidates (GBHC) at high accretion rates but it is unable to explain the presence of the power law tail to high energies, possibly indicating the presence of an additional, optically thin phase of accretion flow.

Recently there has been much excitement about the possibility that advection dominated accretion flows (ADAF; see [3] for review) may explain the hard X–ray
data. These flows can exist only below a critical accretion rate, $\dot{m} \leq \dot{m}_{\text{crit}}$ and, by assumption, their radiative efficiency is very low. Since ADAFs are hot and optically thin, they lack any strong source of soft seed photons for Comptonization which means that the resulting X–ray spectra are hard. Such flows were proposed to explain the hard and very faint X–ray spectra seen from SXT in quiescence [4], and then extended in [5] (hereafter EMN) to cover the whole range of luminosity seen in SXT’s. As $\dot{m}$ increases to $\dot{m} \sim \dot{m}_{\text{crit}}$ the radiative efficiency of the flow increases, but above $\dot{m} = \dot{m}_{\text{crit}}$ the advective flow collapses into an SS disk. This change from a hot ADAF to a cool SS disk is proposed to be the origin of the hard/soft spectral transition seen in GBHC (see Fig. 1 in EMN).

The changing geometry of EMN’s model is testable from the X–ray spectral data. Wherever hard X–rays illuminate optically thick material they can be reflected back through electron scattering. The reflected spectrum is harder than the intrinsic spectrum, with photo–electric edge features and the associated fluorescence lines imprinted on it, most prominently from iron [6]. It is a function of the ionization state and elemental abundances of the reflecting gas [7].

Furthermore, the sharp spectral features can be broadened and smeared by the Doppler effect due to high orbital velocities and gravitational redshift if the reflection is from an accretion disk orbiting a black hole [8]. Therefore, the reprocessed component gives us a strong diagnostic of the geometry: the amount of reflection indicates the solid angle subtended by the optically thick material, while the relativistic smearing reveals its velocity field. In particular, reflected features can only be seen if there is optically thick material that subtends a substantial solid angle to the X–ray source, unlike the ADAF–based geometry proposed for the low and quiescence state SXT’s.

### DATA MODELLING AND THE GEOMETRY

First, we used Ginga data of Nova Muscae 1991 to look for the effects of reprocessing, since it is the source used by EMN to illustrate their model, and it shows the full sequence of spectral evolution from Very High State (VHS) to Low State (LS). We fit these data with a self–consistent model of the reflected continuum and Fe K$\alpha$ line, including relativistic smearing [9].

In the VHS the reflector is highly ionised and strongly relativistically smeared. The power law component is too weak to examine for reflected features in the High State (HS), but at the start of the Intermediate State (IS) the reflector is still highly ionised and strongly smeared. It seems probable that during all of this time the disk extends down to the last stable orbit, and that it is ionised by the strong soft component. As source fades through the IS and LS, importance of the soft component declines, the ionization of the reflector drops, the power law hardens by $\Delta \Gamma \sim 0.4$, and the solid angle subtended by the reflector decreases. Figure 1a shows the derived confidence contours for the innermost radius of the disk (from constraints on relativistic smearing) and amount of reflection ($f = 1$ corresponds to
FIGURE 1. (a) - confidence contours as functions of amplitude of reflection and inner radius of the reflecting disk, for a sequence of spectra of Nova Muscae 1991; (b), (c) - best fit model spectra for GS 2000+25: (b) - soft/high state, (c) - hard/low state.

the amount of reflection expected from a reprocessor which covers $2\pi$ solid angle) during the IS and LS.

Similar results are obtained for another source, GS 2000+25. When a strong, soft component is present, the power law tail is soft, the reflector is strongly ionized and the relativistic smearing is significant. The disappearance of the soft component is accompanied by hardening of the power law, a drop in ionization and the smearing effects becoming insignificant (Figure 1bc).

Thus, in both objects all the observed spectral changes during the the HS/LS transition can be explained in a model where the inner radius of the optically thick flow progressively increases: this would trivially explain the decrease in solid angle subtended by the disk to the inner X-ray source. Also, as the luminosity and

FIGURE 2. Confidence contours as functions of the amplitude of reflection and photon spectral index for a sequence of spectra; (a) – Nova Muscae 1991, (b) – GS 2023+338.
temperature of the disk declines (since most of the energy is released in the inner radii) so the ionization state of the disk decreases, and there are fewer seed photons for Compton scattering giving a harder power law, as shown in Figure 2a.

However, no such clear trend was shown by GS 2023+338. First, the source never showed “classical” soft state spectrum, even though it clearly reached almost Eddington luminosity [1]. During subsequent decline phase, the reprocessed component was present in the spectrum, its amplitude correlated with the amount of smearing as expected, but this had no influence on the spectral index, except that the latter increased (i.e. spectrum became softer) sometime between 1 and 6 months after the outburst while the amplitude of reflection decreased! (Figure 2b)

Summarizing, the observed transition from high (soft) to low (hard) state in Nova Muscae 1991 and GS 2000+25 does seem to involve a retreat of the optically thick disk, as in the EMN model. However, quantitatively, the inner disk radius we infer is much smaller than the values postulated by EMN in their IS and LS. Their concept of accretion occurring via an optically thin flow from very large radii (10^4 R_s) for the low state spectra cannot be sustained as such models produce negligible reflected features. Instead we see reflection at a level which is lower than expected from a complete disk, but is nonetheless significant. Similar covering fractions for the reflector are seen in other GBHC hard state spectra, showing that it is a general property of these sources [10,11,9]. While the EMN treatment of the transition radius is assumed rather than calculated, nonetheless a major facet of their model is the sudden switching of all the accretion flow into an optically thin state over a very small range in m. This is clearly inconsistent with the observed behavior of GBHC in general and Nova Muscae 1991 in particular, where a composite optically thin/optically thick flow is required.

Ironically, GS 2023+338 – the object on which the ADAF model for SXT’s quiescent states was based [4] – does not follow the extended scenario in a quite spectacular way.

REFERENCES

1. Tanaka, Y., & Shibazaki, N. 1996, ARAA, 34, 607
2. Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
3. Narayan, R. 1997, in Proc. IAU Colloq. 163 on Accretion Phenomena & Related Outflows, ASP Conf. Series, eds. D. T. Wickramasinghe et al., 75
4. Narayan, R., McClintock, J. E., & Yi, I. 1996, ApJ, 457, 821
5. Esin, A. A., McClintock, J. E., & Narayan, R. 1997, ApJ, 489, 865
6. George, I. M., & Fabian, A. C. 1991, MNRAS, 249, 352
7. Ross, R. R., & Fabian, A. C. 1993, MNRAS, 261, 74
8. Fabian, A. C., Rees, M. J., Stella, L., & White, N. E. 1989, MNRAS, 238, 729
9. Życki, P. T., Done, C., & Smith, D. A. 1997, ApJ, 488, L113
10. Done, C., Mulchaey, J. S., Mushotzky, R. F., & Arnaud, K. A. 1992, ApJ, 395, 275
11. Ueda, Y., Ebisawa, K., & Done, C. 1994, PASJ, 46, 107