Relativistic smearing of the reflection spectrum in Galactic Black Hole Candidates

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We identify the reflected component in the GINGA spectra of Nova Muscae, a Black Hole transient system which has been used as the prototype for the recent advection dominated disk models. We see that the reflected spectrum is generally significantly relativistically smeared, and use this and the amount of reflection to track the innermost extent of the accretion disk. We see that the optically thick disk does retreat during the decline, but more slowly than predicted by the advective models, posing problems for this description of the accretion flow.

1. INTRODUCTION

Black hole binary systems give one of the most direct ways in which to study the physics of accretion disks. There is no surface boundary layer or strong central magnetic field to disrupt the flow, and the orbital parameters are often well studied so that the inclination, mass and distance of the system are tightly constrained. Additionally, many of these systems (the Soft X–ray Transients, hereafter SXT’s) show dramatic outbursts where the luminosity rises rapidly from a very faint quiescent state to one which is close to the Eddington limit, and then declines again over a period of months, giving a clear sequence of spectra as a function of mass accretion rate. The usual pattern for such objects is for the outburst to be dominated by a soft component of temperature $\sim 1$ keV, with or without a (rather steep) power law tail, while the later stages of the decline show much harder power law spectra, extending out to 100–200 keV (see e.g. [1]). The same bimodal spectral states are seen in the persistent black hole candidates (such as Cyg X–1), showing that they are a general outcome of an accretion flow.

The “standard” accretion disk model developed by \textsuperscript{2}; hereafter SS, derives the accretion flow structure in the limit when the gravitational energy released is radiated locally in a geometrically thin disk. Such models give temperatures of order 1 keV for galactic black hole candidates (hereafter GBHC) at high accretion rates but are unable to explain the presence of a (hard or soft) power law tail to high energies. Either there are parts of the disk flow in a different configuration to that of SS, or there is some non–disk structure such as a corona powered by magnetic reconnection (e.g. \textsuperscript{3}), for which there is little physical justification as yet.

Recently there has been much excitement about the possibility that another solution of the accretion flow may explain the hard X–ray data without having recourse to such \textit{ad hoc} structures. Below a critical accretion rate, $\dot{m} \leq \dot{m}_{\text{crit}}$, a stable, hot, optically thin, geometrically thick solution can be found if radial energy transport (advection) is included (see e.g. the review by \textsuperscript{3}). The key assumption of these models is that the protons gain the energy from the viscous processes, while the electrons only acquire energy through interactions (electron-ion coupling) with the protons. This coupling timescale can be rather slow compared to the accretion timescale, so protons can be accreted into the black hole, taking some of the energy with them. The energy that the electrons do manage to obtain is radiated away via cyclotron/synchrotron emission (on an internally generated magnetic field), bremsstrahlung, or Compton scattering of the resultant spectra of these two processes. In contrast to the SS accretion flow models, there is no cold disk, so no strong source of soft seed photons for
Compton scattering, hence 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 (e.g. [6]), and then extended by [4] to cover the whole range of luminosity seen in SXT’s. As the mass accretion rate increases from \( \dot{m} < < \dot{m}_{\text{crit}} \) to \( \dot{m} \sim \dot{m}_{\text{crit}} \) the flow density increases, so the electron–ion coupling becomes more efficient and the fraction of energy the electrons can drain from the protons increases. This increase in radiative efficiency continues to \( \dot{m} = \dot{m}_{\text{crit}} \), where only \( \sim 35 \% \) of the heat energy is advected. At higher \( \dot{m} > \dot{m}_{\text{crit}} \) the advective flow collapses into an SS disk. This change from a hot advective flow to a cool SS disk is postulated as the origin of the hard / soft spectral transition seen in GBHC [4]. Their scenario for the SXT spectral evolution is shown in Figure 1.

**2. TESTING THE ADVECTIVE FLOW MODELS**

The changing geometry shown in Figure 1 is testable from the X–ray spectral data. Whenever hard X–rays illuminate optically thick material, such as a cool SS disk, there is the possibility that the X–rays can be reflected back through electron scattering. The reflection prob-

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**Figure 1.** Schematic view of the evolution of the accretion flow in an SXT outburst proposed by [4] as a function of mass accretion. Typical spectra for each state are shown also, with the solid line and dashed lines indicating the SS disk and advective flow emission, respectively.
Figure 2. Reflected continuum and associated iron line from power law illumination of optically thick, cosmic abundance material subtending a solid angle of $2\pi$ and viewed at an angle of $60^\circ$. The thick solid line shows the reprocessed spectrum from neutral material while the thin solid line shows the spectrum from highly ionised material. The thick and thin dotted lines show the expected distortions from relativistic smearing if the material forms a disk extending from infinity to $6R_g$, where $R_g = GM/c^2$.

ability is given by a trade-off between the importance of electron scattering and photo-electric absorption. Higher energy photons are then preferentially reflected due to the smaller photo-electric opacity of the material, and there is associated fluorescence line emission from the recombining photo-ionised species. The dependence on photo-electric absorption means that the reflected spectrum is a function of the ionisation state and elemental abundances of the reflecting gas. The thick solid line in Figure 2 shows the characteristic 1–20 keV reflected spectral shape from neutral material, while the thin solid line shows the resulting reflected spectrum from highly ionised material, assuming a power law illuminating spectrum (dashed line in figure 2) [7–9].

The sharp spectral features shown in Figure 2 are what we expect to see from hard X-ray illumination of a slab of material. For material around a black hole, the conditions are somewhat different! The high orbital velocities give relativistic Doppler shifts, and gravitational redshift is also important. The expected reflected line profiles are broad and skewed rather than narrow atomic transitions [10]. The effect of these relativistic processes on the total reflected spectrum from both neutral and ionised material is shown as the thick and thin dotted lines in figure 2. The sharp line features are almost entirely lost, while the edge is only slightly broadened.

These reprocessed spectral features give us a strong diagnostic of the geometry. The amount of reflection and line indicate the solid angle subtended by the optically thick material, while the relativistic smearing shows where this material is in the gravitational potential. Together this means that the structure of the accretion flow can be assessed from high quality hard X-ray data, giving a clear test of the theoretical accretion models discussed above. 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 advective source geometry for the low and quiescence state SXTs [11].

We used the GINGA data on the SXT Nova Muscae (GS 1124–68) to look for these effects, since it is the source used by [1] to illustrate their model, and shows the full sequence of spectral evolution from Very High to Low state shown in Figure 1. We fit these data with self-consistent reflected continuum plus line models, including relativistic smearing (see Figure 2 and [11]).

In the Very High State 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, but at the start of the Intermediate State the reflector is still highly ionised and strongly relativistically 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 Intermediate and Low states, the importance of the soft component declines, the ionisation of the reflector drops, the power law hardens by $\Delta\Gamma \sim 0.4$, and the solid angle $f$ subtended by the reflector decreases (see table 1).
3. CONCLUSIONS

All the observed spectral changes during the Intermediate and Low State 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 temperature of the disk declines (since most of the energy is released in the inner radii) so the ionisation state of the disk decreases, and there are fewer seed photons for Compton scattering, giving a harder power law.

Thus, the observed transition from high (soft) to low (hard) state does seem to involve a retreat of the optically thick material, as proposed by [4]. However, quantitatively, the inner disk radius we infer is much smaller than that of their models for the intermediate and low states [4]. Their concept of accretion occuring via an optically thin flow from very large radii ($10^4$ $R_s$) so the ionisation state of the disk decreases, and there are fewer seed photons for Compton scattering, giving a harder power law.

| Data       | $\Gamma$  | $f$       | $\xi$         | $R_{in}/R_g$ | $\chi^2$/dof |
|------------|-----------|-----------|---------------|--------------|--------------|
| Jan 11, VHS | 2.03 ± 0.16 | 0.30$^{+0.13}_{-0.04}$ | $(1.0^{+1.0}_{-0.7}) \times 10^4$ | $13^{+8}_{-5}$ | 26.1/31      |
| May 18, HS/IS 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      |
| June 13, IS  | 1.91 ± 0.03 | 0.5$^{+0.23}_{-0.17}$ | $10^{+22}_{-10}$ | $10^{+19}_{-4}$ | 20.9/24      |
| June 21, IS  | 1.83 ± 0.03 | 0.46 ± 0.12 | $4^{+12}_{-3}$ | $13^{+25}_{-16}$ | 11.9/24      |
| July 23, LS  | 1.72 ± 0.02 | 0.24$^{+0.11}_{-0.08}$ | $17^{+40}_{-16}$ | $50^{+18}_{-35}$ | 15.3/24      |
| Sept 3, LS   | 1.95 ± 0.11 | 0$^{+1.1}$          | 0(f)           | –             | 26.9/26      |

REFERENCES

1. Tanaka, Y., & Shibazaki, N. Ann. Rev. Astron. Astrophys., 34, (1996) 607
2. Shakura, N. I., & Sunyaev, R. A. A& A, 24 (1973) 337
3. Haardt, F., Maraschi, L., & Ghisellini, G. ApJL 432 (1994) L95
4. Esin, A. A., McClintock, J. E., & Narayan, R. ApJ. 489 (1997) 865
5. Narayan, R. in Proc. IAU Colloq. 163 on Accretion Phonomena & Related Outflows, ASP Conf. Series, (1997) eds. D. T. Wickramasinghr et al., in press
6. Narayan, R., McClintock, J. E., & Yi., I ApJ 457 (1996) 821
7. Lightman, A. P., & White, T. R., ApJ 335 (1988) 57
8. George, I. M., & Fabian, A. C. MNRAS 249 (1991) 352
9. Matt, G., Perola, G. C., & Piro, L. A&A 247 (1991) 25
10. Fabian, A. C., Rees, M. J., Stella, L., & White, N. E., MNRAS 238 (1989) 729
11. Zycki, P.T., Done C., & Smith D.A., ApJL 488 (1997) 113
12. Done, C., Mulchaey, J. S., Mushotzky, R. F., & Arnaud, K. A., ApJ 395 (1992) 275
13. Ueda, Y., Ebisawa, K., & Done C. PASJ 46 (1994) 107
14. Ebisawa, K., Ueda, Y., Inoue, H., Tanaka, Y., & White, N. E. ApJ 467 (1996) 419
15. Gierliński, M., Zdziarski, A. A., Done, C., Johnson, W. N., Ebisawa, K., Ueda, Y., & Phillips, F. MNRAS 288 (1997) 958
16. Dove, J. B., Wilms, J., Maisack, M., & Begelman, M. C. ApJ 487 (1997) 759
17. Poutanen, J., Krolik, J. H., & Ryde, F. MNRAS 292 (1997) 21p