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SPECTRAL PROPERTIES OF GALACTIC AND EXTRAGALACTIC BLACK HOLE CANDIDATES

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ABSTRACT

We review current theoretical understanding of the spectral properties (low and high states, transition of states, quasi-periodic oscillations etc.) of the low mass as well as supermassive black hole candidates.

Key Words : Accretion, Advective disks, Shock Waves, Comptonization

Galactic black hole candidates show very interesting spectral properties: the emitted power is sometimes in the softer energy (soft-state) and in other times it is in harder energy (hard state). In the low or the hard state, the soft bump is almost absent, and the energy spectral index is $\alpha \sim 0.5 - 0.8$ in the range $2 - 50$kev ($F(\nu) \sim \nu^{-\alpha}$). In the high or soft state the power-law (hard) component is very weak, with a spectral slope of $\alpha \sim 1.5 - 1.8$. (See, Ebisawa, Titarchuk & Chakrabarti, 1996 for a list of black hole candidates and their typical spectral indices.).

Simplistic spherical symmetric models of Bondi flow of the 1950s (Bondi, 1952) or predominantly rotating flow models of the 1970s (Shakura & Sunyeav, 1973) or their other variations cannot explain these strange properties. It is recognized that the entire disk model has to be revised with complete advection, heating and cooling effects so that one could explain these spectra without invoking any external components such as Compton cloud or corona etc. First such attempt was made by Chakrabarti & Titarchuk (1995, hereafter CT95; see, also Chakrabarti, 1996 for a review) where concepts from the earlier solution on advective disks (Chakrabarti, 1990; Chakrabarti & Molteni, 1995) were used. Here, it was pointed out that flows must deviate from a Keplerian disk close to the horizon to satisfy inner boundary condition on the horizon (radial velocity of matter equals to the velocity of light and the corotating condition on the horizon). Disks on the equatorial plane may remain Keplerian until very close to the black hole depending on accretion rate and viscosity parameter (the flow is bound with specific energy $\mathcal{E} < 0$ everywhere) while away from the plane, the flow could have standing or oscillating shock waves (see, Chakrabarti et al., this volume). This is possible either because of lower viscosity, or because of weaker gravity away from the plane, or because of energy deposition from the Keplerian disk on the advecting corona, or in the wind-fed systems where supersonic flow is deposited, or any combination of above. Thus the flow essentially has two components, one Keplerian and the other sub-Keplerian.

This is required, since in many systems, the soft and the hard components vary independently. If the Keplerian component rate is very small compared to the sub-Keplerian rate, (typically, less than $0.1\dot{M}_{Edd}$ for a sub-Keplerian rate of $1.0\dot{M}_{Edd}$), the number of soft photons from the Keplerian disk intercepted by the standing shocks is unable to cool the post-shock region and the object remains in a hard state. For higher Keplerian rate, the post-shock region cools dramatically and the object goes to the soft state. (Here, the phrase 'post-shock' really means the enhanced density region behind the centrifugal barrier experience by the inflow.) Even then, a weak hard tail is produced not because of thermal Comptonization, but because of bulk motion Comptonization as the relativistic matter rushes to the horizon and transfers bulk momentum to soft photons. Thus, the weak hard tail is unique to black hole candidates and neutron star candidates must not show this component. CT95 showed that for high enough rate ($\dot{M} \gtrsim 3$) the spectral slope is roughly -1.5 while below that rate the power law is broken, since the hard component consists of contributions from thermal and bulk motion Comptonizations.

Figs. 1(a-b) show results of different versions of CT95 solutions of two component accretion. In Fig. 1(a), the disk rate is changed while keeping the halo rate ($\dot{m}_h = \dot{m}_{Edd}$) fixed. The density enhancement close to the black hole due to the centrifugal barrier may or may not produce shock waves in the sub-Keplerian component. The solid, long-dashed and dotted curves are for strong-shock, weak-shock and no-shock cases. It is seen that the no-shock solutions mostly produce softer states since the electron density is lower near the hole. In Fig. 1b, a hard-state to soft-state transition is achieved by changing the location where the disk component deviates from a Keplerian disk, while keeping the halo component fixed. This behavior (achievable by increasing viscosity in the disk) is expected to be important during the rising phase of a novae outburst.

Fig. 2a, drawn using data from Tanaka (1991), shows the spectral evolution of a typical X-ray novae GS2000+25 and its rough fit using two component advective disk model (TCAF) of Chakrabarti & Titarchuk (1995) in the presence of a strong shock. Only parameters varied were the two mass accretion rates (for the

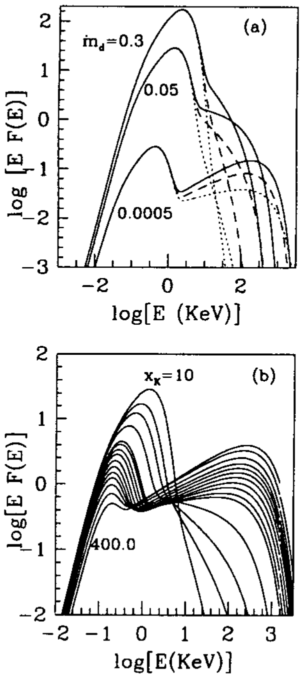

Fig. 1.— Model dependence of spectral properties. (a) Solid, long-dashed and short-dashed curves are for strong-shock, weak-shock and no-shock cases respectively. Strong shock cases produce harder spectra. (b) Result of no-shock solution ($\dot{m}_{disk} = 0.05$, $\dot{m}_{halo} = 1.0$). Spectrum changes from hard state to soft state as the Keplerian disk approaches the black hole due to increase in α and $\dot{m}_d$ (as probably in the rising phase of a novae outburst).

disk and the halo components). The light curve (2-20keV) derived from these fitted rates is shown in Fig. 2b. Linear-linear (solid) or linear-log (dotted) interpolations of the rates were used. Squares and crosses are the light curves from the observed data and fitted plots respectively. Mass of the black hole (in Figs. 1ab and 2ab) was chosen to be $1 M_\odot$ which after correction due to spectral hardening factor ($f \sim 1.9$, see, Shimura & Takahara, 1995) corresponds to a mass of $3.6 M_\odot$. The results remain similar when supermassive black holes are chosen. The bumps after $\sim 60 - 70$d and after ~ 200d of the outburst are clearly reproduced. A single component model will have difficulty to explain such variations as explain. Note that the light shows a decay time scale of about 30 days.

Figs. 3(a-b) shows CT95 strong shock solutions for variation in the disk accretion rate $\dot{m}_{disk}$. The mass (uncorrected for spectral hardening) of the black hole and the shock location were chosen to be $5 M_\odot$, and $x_s = 10 x_g$ (typical values) respectively. For higher mass (QSOs and AGNs) black holes, the result is similar, though much cooler (electron temperature $T_e \propto$

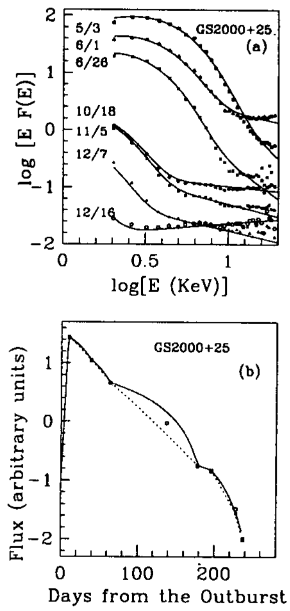

Fig. 2.— Rough fits of spectral evolution of X-ray novae GS2000-25 using two component advective flow model and (b) comparison of derived light curve with the observed light curve.

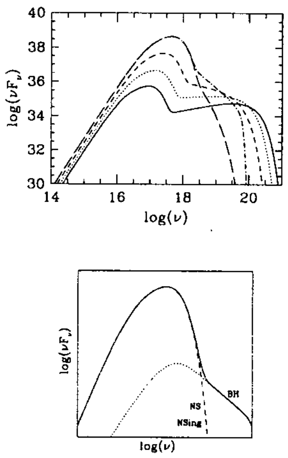

Fig. 3.— Hard to soft state transition of a black hole candidate of mass $5 M_\odot$ as the Keplerian accretion rate is increased. (a) $\dot{m}_{disk} = 0.001$ (solid), 0.01 (long dashed), 0.1 (short dashed) and 1 (dotted) Dot-dashed curve is drawn after including the bulk motion Comptonization. (b) Comparison of soft states of black hole (BH), neutron stars (NS) and naked singularities (NSing). Black holes always show weak hard tail even in the soft state, while other compact bodies do not.

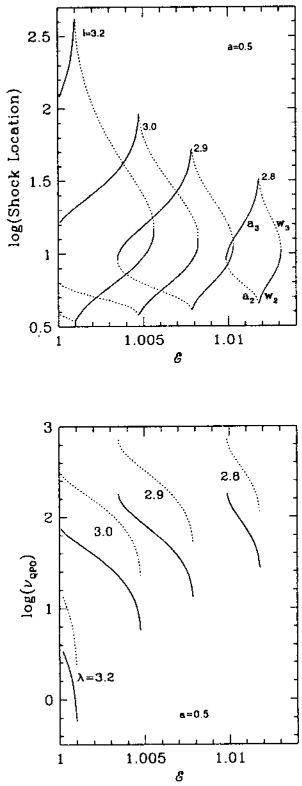

Fig. 4.— Variation of (a) shock locations (solid curves a_3 and w_2 are stable in accretion and winds) and (b) quasi-periodic oscillation frequencies as functions of the angular momentum and energy of the flow. Kerr parameter $a = 0.5$ is chosen. Solid curves in (b) are drawn for a_3 and dotted curves are drawn assuming that the shocks are absent but Keplerian disk joins with sub-Keplerian flow at a_3.

$M^{0.04-0.1}$). $\nu F(\nu)$ is plotted against ν. In Fig. 3a, the object goes from hard to soft states, as the Keplerian accretion rate is increased from 0.001 to 1.0 while keeping the sub-Keplerian rate fixed at $1 M_{Edd}$. In Fig. 3b, we show the spectral shape in soft states. The weak hard tail of slope $\alpha \sim -1.5$ is formed due to relativistic radial motion of the flow outside the horizon of a black hole (marked as BH). The neutron stars (NS) or naked singularities (NSing) should not have this hard tail (CT95).

Many of the black hole candidates also show the so-called quasi-periodic oscillations in the range of several millihertz to some kilohertz range (e.g., van der Hooft et al. 1996; Grebenev et al., 1993) with the hard X-rays modulated by 10-30% or more. As shown by Ryu et al. (1996) and Molteni et al (1996), these oscillations could be well understood by the resonance oscillation or the dynamic oscillation of the high density region near the centrifugal barrier (see Chakrabarti et al. this volume). Typically, the frequency of oscillation $f \sim 4x_s^{3/2}(2GM/c^3)$ s. In Fig. 4a, we show the shock location (Kerr black hole parameter $a = 0.5$) for angular momentum of matter $\lambda = 3.2, 3.0, 2.9, 2.8$ respectively (Chakrabarti, 1996b). In Fig. 4b, we show the corresponding QPO frequencies. Solid lines are for shock oscillations and dashed lines are for oscillation of the same flow if shocks were absent (shock free solutions) and the Keplerian disk joined the sub-Keplerian at $x_{tr} = x_s$ instead.

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