Spectral Properties of Black Holes in Gamma Rays

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Abstract. Black holes are the most compact objects in the universe. Therefore, matter accreting onto is likely to radiate photons of energy comparable to very high gravitational potential energy. We discuss the nature of the emitted radiation in X-rays and gamma-rays from black hole candidates. We present theoretical solutions which comprise both Keplerian and sub-Keplerian components and suggest that shocks in accretion and outflows may play a major role in producing this spectra.

Keywords: Black hole physics — shocks — hydrodynamics — spectral properties: γ-rays, X-rays

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1. Introduction

It is well known that the black holes themselves do not emit any radiation, but the matter which accretes on to them does. There are three distinct ways one could study the spectral properties: the first is through direct observation of the radiation. Here, one has to use separate instruments, either ground based (IR, optical, UV, very high energy gamma rays) or space based (optical, X-rays, gamma-rays). The goal would be to find if there are fast variabilities or spectral signatures of high velocity (which may point to massive compact objects at the core or some spectral signatures especially predicted for black holes.). A second method which is really the other extreme, is to solve equations which govern the motion of matter around a black hole and produce the most likely solutions which explain both the steady and non-steady behaviour of the radiation. A third way is intermediate between the other two approaches: here, one assimilates the gist of the theoretical results and gives models and fits the observational results with these models using several free parameters. (The reverse may also be appropriate sometimes: theoreticians may get clues from ‘models’ to select the best solution out of many possible ones.) Very often, this third approach requires separate models for separate objects.
In the present paper, I will present the theoretical reasonings behind the most accurate solution of the black hole accretion of today in order to assist the observers to more fruitfully plan their observations and perhaps to provide hints to the model builders so that they may fine tune their present models accordingly. Historically, in the present subject, tentative models came first (such as disks with corona, see, e.g., Galeev, Rosner & Viana, 1979) and as the theoreticians sharpened their tools through viscous transonic solutions with heating, cooling, steady and oscillating shocks (Chakrabarti 1990; 1996a), both theoretically and through numerical simulations, new models started emerging (a good example being Something or the Other Dominated Accretion Flow [SODAF] models; dynamical corona models etc.) which converge to the outcome similar to these theoretical solutions. Consequently, these models do not throw any new insights into the problem.

Because correct theoretical works incorporates proper boundary conditions (such as entering through the black hole with velocity of light, or hitting the hard surface of a neutron star with zero radial velocity) the solutions got to be correct beyond doubt. However, in certain situations (such as inclusion of all the components of the magnetic field self-consistently) it may not be possible to obtain solutions in the first place. In such cases ‘patch-up’ works are done (such as putting toroidal field or radial field on the top of hydrodynamics solutions) which are often satisfactory.

2. The advective disk paradigm

A cartoon diagram of the flow geometry which comes out of extensive analytical and numerical works (see, e.g., Chakrabarti, 1990, Chakrabarti 1993, Chakrabarti, 1996ab) is shown in Fig. 1. The Keplerian disk, because of its low energy, resides at the equatorial plane, while matter with lower angular momentum flows above and below it (Chakrabarti, 1995; Chakrabarti & Titarchuk, 1995 [CT95]; Ebisawa, Titarchuk & Chakrabarti 1996; Chakrabarti, Titarchuk, Kazanas & Ebisawa, 1996; Chakrabarti, 1997 [C97]). The wind is predominantly produced from the CENBOL area or the CENtrifugal barrier supported BOundary Layer of the black hole, which is the post-shock region. A transient shock may be present just outside the inner sonic point. The inner edge of the Keplerian disk is terminated at the transition radius as dictated by the viscosity of the flow. The wind may be variable because of shock-oscillation and every supersonic puff of wind is expected to produce a propagating shock in the jet. It is to be noted that all the components in this diagram could be variable (see, Chakrabarti & Nandi, 2000).
Not surprisingly, this paradigm, created almost a decade ago, is now vindicated by most of the observations. Indeed, the cartoon diagrams (see, e.g., Esin et al, 1998; Zdziarski and Gerlinski, 2004; Novak, 2003, Fender et al, 1999) are slowly, but surely, converging to those predicted by our exact approach. Whereas our exact approach identifies the reason of the movement of the inner edge of the disk with viscosity and accretion rate, other models merely take these as facts and proceed fitting with observations assuming such behaviours a priori.

The advective paradigm, which requires two component advective flows (TCAF) has been tested for a varied range of observational facts. It is the only solution which explains QPOs and their variations quite naturally as manifestations of the shock oscillations (Chakrabarti, Acharyya & Molteni, 2004 and references therein). Hence it is worthy to look at the high energy predictions within this paradigm in order to find an interpretation of recent gamma-ray observations.

3. Spectral properties at soft and hard X-rays

Detailed properties of the spectrum coming out of TCAF solution have been discussed in CT95 and C97. The soft radiation coming from the Keplerian disk is intercepted by the sub-Keplerian hot flows in the CENBOL region and is re-radiated as the hard radiation. Depending on the relative importance of the Keplerian disk rate $\dot{M}_d$ in comparison to the sub-Keplerian halo rate $\dot{M}_h$, the electrons in the sub-Keplerian disk may or may not be cooled down. If not, then the system is in the...
hard state and if yes, the system is in the soft state. The hard state is thus dominated by a power-law hard photon component produced by inverse Comptonization of the soft photons. In the soft state, the electrons in CENBOL cooled down and collapses, but due to the inner boundary condition of supersonicity, the matter accelerates rapidly and up-scatters photons to its energy ($\sim m_e c^2$). Thus, power-law photons can also be seen due to this, so-called, bulk motion Comptonization (BMC) (CT95). Occasionally, as we shall show below, photons of much higher energies are seen. But that does not imply that the BMC is not taking place. BMC only asserts what should be the minimum intensity of power-law photons in soft-states as dictated purely by gravitational pull of the black hole. Of course, in presence of other physical processes (such as synchrotron radiation, see, below), very high energy photons should be expected. It is to be noted that CT95 solution already incorporates all the iterations of re-processing between the Keplerian and sub-Keplerian components. Therefore, it is no longer necessary to include a ‘Compton reflection’ component that is usually assumed by some model builders.

Being almost freely falling, the sub-Keplerian flow would bring forth faster changes to spectral indices than the Keplerian flow which moves in viscous time-scale. Figure 2 shows the variation of photon flux and power-law index of Cyg X-1 (upper panel) and for GRS 1758-258 (lower panel) for more than four years as seen by RXTE. This distinctly different behaviour of a preferentially wind accretor (Cyg X-1) and the Roche-lobe accretor (GRS 1758-258) could be interpreted very clearly when two independent components as predicted by TCAF solution are used (Smith, Heindl and Swank, 2002). For instance, if there is a reduction in the accretion rate at the outer edge, the sub-Keplerian component at the inner edge will be reduced in free fall time $t_{ff} \sim r^{3/2}$. Until this information propagates through the Keplerian disk with viscous time scale, the source would behave like a soft state, but then, after the viscous time, the spectrum will harden as the soft photons go down. In Cyg X-1, Cyg X-3 etc. which are known to be wind accretors, the Keplerian disk is very small and the power-law index basically correlates with the photon flux. In 1E 1740.7-2942, GRS 1758-258, and GX 339-4, which are in low-Mass X-ray binary systems, the Keplerian disk is big and the delay of tens of days are common (Smith, Heindl and Swank, 2002). Another very important point made in C97 was that a single component ADAF (Esin et al. 1998) model is incapable of producing state transition unless the inner edge is moved back and forth unphysically. This problems are avoided when TCAF solution is chosen. The complete spectral variation of the type seen in Cyg X-1 and other binaries are presented in C97.
Figure 2. ASM light curves for a wind accretor (Cyg X-1) and a low-mass binary system (GRS1758-258) from RXTE data (Smith, Heindl and Swank, 2002) showing distinctly different behaviour due to the absence and presence of a dominant Keplerian disk in these objects.

Having thus established that the behaviour of a large population of galactic black hole candidates can be understood only with TCAF solution, attempts were made to explain fast variabilities. In case the shock oscillates back and forth (Molteni, Sponholz & Chakrabarti, 1996; Molteni, Ryu, & Chakrabarti, 1996; Ryu, Chakrabarti & Molteni, 1997; Chakrabarti, Acharyya, Molteni, 2004), the hard X-ray emission is likely to be modulated at the shock oscillation frequency. With the increasing of the Keplerian rate, i.e., cooling of the CENBOL, the shock moves in due to fall of pressure and the frequency of QPO rises. This behaviour is also well known. According to the TCAF solution, different length scales of the flow are responsible for different QPO frequency range or the break frequency. For instance, the oscillation at the transition radius is responsible for 0.1 – 0.3Hz QPO, the oscillation of the shock is responsible for 1 – 15Hz QPO, the oscillation of the inner transient shock is responsible for the 60 – 450Hz QPO and the cooling time
scale of the sonic sphere of the jet is responsible for the 0.01 – 0.03Hz QPO. The jets and outflows are also found to be coming out from the CENBOL region (Chakrabarti, 1999) and the outflow rates were computed exactly (Chakrabarti, 1999; Das and Chakrabarti, 1999) as a function of the inflow rate. These outflows are found to change the spectral slope of the outgoing radiation indirectly since they modify the particle density at CENBOL. Since the presence of CENBOL is a function of the spectral state, this paradigm naturally explains the relation between the outflow rate and the size of the Comptonizing region. These behaviours have now been verified by observers and model builders (e.g., Fender et al. 2000 and references therein).

When the magnetic field is included, the synchrotron photons must be included into the solution as they play a major role in cooling the sub-Keplerian flow. As the sub-Keplerian rate is increased, the density of soft photons goes up, but it needs not be sufficient to cool the electrons as the number of electrons themselves also goes up. Furthermore, the shocks in the flow can accelerate electrons to a high energy which in turn may be able to produce photons at very high energy $\gamma$-ray. In the next section, we shall discuss the spectral properties of black hole candidates in high energies.

4. Spectral properties of galactic black holes in $\gamma$-rays

The TCAF solution usually has a single static, oscillating or a propagating shock. However, numerical simulations suggest the presence of a transient shock just before the flow passes through the inner sonic point (Samanta, Ryu, Chakrabarti 2004). Thus, there are possibilities to produce power-law high energy emissions by the power-law electrons generated by repeated passages through these shocks. Details are presented in Mandal & Chakrabarti (2004) and some of the highlights are presented in Mandal & Chakrabarti (this volume). It is entirely possible that the bulk of the high energy gamma-rays could be contributed by emissions from shocked regions of the outflow and jet. The physics of the shock formation in jets is not yet understood properly. Numerical simulations indicate periodic flaring of matter emerging as outflows as the shock oscillated back and forth (Chakrabarti, Acharyya and Molteni, 2004). Figure 3 shows the oscillation of the inner region of the advective flow. Arrows indicate puffs of matter getting out in the alternating sides during oscillation. Such oscillations of the accretion shocks are not only responsible for the QPOs, they may also be responsible for injecting non-linear perturbations in the outflows. These shocks may steepen up as they propagate away from the central body (see,
Fig. 3. Oscillating accretion shocks which are responsible for QPOs are also responsible for variable outflows which steepen into shocks in the jets (Chakrabarti, Acharyya & Molteni, 2004).

Figs. 4(a-b) shows generic nature of the spectra of galactic black hole candidates in both high and low states for two sets of black holes: Set A includes GROJ1719-24, GROJ0422+32 and CYGNUS X-1 while Set B includes GRO1655-40 and GRS 1915+105. The high energy regions are adapted from the results from McConnell et al. (2002), Ling & Wheaton (2003, 2004), Case et al. (2004), etc. Here ‘high’ and ‘low’ states mean the soft and hard states using the nomenclature as in Chakrabarti & Titarchuk (1995) (see also, Tanaka & Lewin, 1995) where the high power is observed in soft (∼1keV) and hard (∼40−100)keV energies, respectively. These states can also be defined using the energy spectral index $F_E \sim E^{-\alpha}$ in the 2−20keV range: $\alpha > 1$ for soft state and $\alpha < 1$ for hard state. CT95 model has been discussed in the previous section.

In the gamma-ray regime, the nomenclature is not unique yet. Ling & Wheaton (2004) like to call the above mentioned ‘canonical’ high and low states as the ‘low γ intensity state’ and ‘high γ intensity state’ respectively. When seen in high energy gamma rays $\gtrsim 400$keV, the high state also corresponds to the high (hard) γ-ray state and similarly for
Figure 4. Soft and hard state transitions of two classes of black holes which supposedly differ in the very high gamma-ray region for the high (soft) gamma intensity state. In A, it consists of thermal Comptonization till 200 – 300keV and power-law after that. In B, it consists of non-thermal power-law.

The difference in these two Sets (marked A and B) in Fig. 4(a-b) lies in the very high energy gamma-ray region: while in Set A, the so-called ‘high γ-ray intensity state’ has a thermal spectrum below 200 – 300keV and a weaker and softer power-law tail for higher energies, in Set B, the same state is manifested as simply a continuous non-thermal power-law with or without a break (Case et al. 2004).

Examples of the observations in the two sets are presented in Fig. 5 (from Ling and Wheaton, 2004) and in Fig. 6 (from Case et al. 2004). The latter Figures show the nature of changes which are taking place in the power law in the high (soft) gamma-intensity state during a hard X-ray flare. The spectrum steepens at the peak of the flare. Case et al. (2004) find that while Cyg X-1, GRO J0422+32, GRO J1719-24 belong to Set A (Fig. 4a), GRO 1655-40 and GRS 1915+105 belong to the Set B (Fig. 4b). It is interesting to note that while both candidates in Set B are considered to be LMXRBs, the candidates in Set A are mixed: only Cyg X-1 is HMXRB while others are LMXRBs. Thus, this difference in
Figure 5. Photon fluxes (in photons/cm$^2$/s/keV) of three black hole candidates which show thermal Comptonization and a non-thermal power component in canonical hard states (from Ling et al. 2004).

Figure 6. Example of non-thermal power-law in the very high energy gamma-ray region in the canonical hard state of GRO J1655-40 (from Case et al. 2004). Here, a flare is analyzed. The 2nd, 3rd and the 4th panels refer to the spectra of the marked regions of the photon flux shown in Panel 1. At the peak of the flare, the spectrum is steeper.

the spectra is puzzling. It is also important that for all the candidates in Set A, the time lag in hard X-ray with respect to the softer X-ray is around 0.1 – 1s (van der Hooft et al. 1999), which point to an extended region of hard X-ray emission region. It is possible that these two properties of Set A candidates are related. The explanation, may not thus lie in the difference in the primary composition of the accretion flow which is known to be predominantly of low angular momentum for HMXRBs and Keplerian for LMXRBs but to a common cause, namely, the shock formation.
Physically, it is clear that the accretion shocks and the shocks in jets and outflows could be responsible for the production of very high energy gamma rays. One of the advantages of the TCAF solution is that the accretion shocks, jets and shocks in jets are built into the solution. Thus, one could imagine having shock acceleration of electrons in the accretion and the power-law electrons producing power-law photons most naturally without having to guess about the origin of the shocks. As we mentioned, shocks in jets could be produced due to perturbations of the CENBOL (e.g., oscillation of shocks) or sudden deposition of energy at the base of the jet through reconnection of magnetic fields. Usual photopion production in the jets and gamma-ray production in pion decay cannot be ruled out also.

As a general comment, we might add that in the canonical soft states, the highest energy gamma ray is also the most intense (see Figs. 4(a-b)). One could ask the following questions:
Figure 8. Possible cause of soft state in Cyg X-1 and similar black hole candidates based on Chakrabarti & Molteni (1995) solution. In this case the inner part becomes Keplerian while outer region remains sub-Keplerian.

i) If the highest energy $\gamma$-rays are coming from the jets, and at the same time, if the Keplerian rate is so high that the object is in the canonical soft state, then, can the jets or outflows be very strong as well?

ii) If the jet and outflows are produced in harder states as the analytical work (Chakrabarti 1999) and some observations tend to show, then why the highest energy gamma rays are not seen in canonical hard states as well?

To understand this, one has to perhaps go back to the basics: Analytically it is easy to show that the ratio $R$ of the outflow rate ($\dot{M}_{out}$) to the inflow rate ($\dot{M}_{in}$) is very low in the soft state, and low in the hard state (see, Chakrabarti, 1999), but it is the highest when the strength of the shock is intermediate. In other words, if the inflow rate is high, as in a canonical soft state, the outflow rate could also be high, though it needs not be relativistic.

In the case of HMXRBs, such as Cyg X-1, the accretion is dominated by low-angular momentum winds and it needs not produce any strong accretion shocks or jets as the centrifugal barrier needs not be strong enough even in the hard state. Indeed, broad QPOs at very low frequency ($\sim 0.04$Hz) have been observed so far (Paul, Agrawal & Rao, 1998) which indicates a shock at around $10^3 - 10^4 r_g$. The jets are also found to be very slow, continuous (Fender et al. 2000). So, it may be easy to understand why in canonical hard states, the very high energy gamma-ray is weaker. In order to understand its behaviour in soft states, it may be pertinent to invoke the most relevant solution of this problem presented by Chakrabarti & Molteni (1995). Here, it was shown that the shock in an inviscid flow tends to recede outward in presence of viscosity parameter higher than a critical value (Fig. 7a).
The post-shock subsonic region acquires a Keplerian distribution and the inner part essentially becomes a Keplerian disk (Fig. 7b). (In fact, this is how a Keplerian disk forms in the first place.) It is possible that the temporary presence of a large viscosity is the reason for Cyg X-1 to go to a soft-state. The sub-Keplerian region at $r \sim 10^3 - 10^4 r_g$ could become the Comptonizing region (Fig. 8). It is not unlikely that some jets could come out from the interface of the Keplerian and sub-Keplerian flow taking away excess angular momentum. Could the shocks in this outer jet or at the propagating interface be responsible for the gamma-rays, as well as the time lag of $0.1 - 1s$ as observed? In GRO 1655-40 and GRS 1915+105, jets are present and they also show various class transitions because of slow variation of accretion rates and because of interaction of jets with Comptonized photons. These cause bloppy nature of the jets and perhaps stronger ultra-relativistic shocks in jets which, in turn, produce shock acceleration of particles eventually producing power-law $\gamma$-rays as reported by Case et al. (2004).

So far, we mostly discussed the solutions and interpretations in the case of galactic black holes. Fortunately, the nature of solutions does not change with the black hole mass and most of the considerations discussed above remain valid for supermassive black holes. The major difference would be in timing properties as all the time intervals will scale with the central mass. Since in this case, we do not expect any ‘binary companion’ to supply matter, the matter is likely to be from the winds of nearby stars or from disruption of the stars. Thus, the formation of steady, oscillating or propagating shocks will be even more relevant.

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