Spectral Signature of Wind Generation From The Post-Shock Region in GRS1915+105 Accretion Disk

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Abstract. Accretion and outflows are common in systems which include black holes. Especially important is the case of the well known micro-quasar GRS1915+105 in our own galaxy, where super-luminal outflows are detected. We present a few observation which are suggestive of an outflow which is generated very close to the black hole, within a few tens of Schwarzschild radii. In the presence of mass loss (e.g., an outflowing wind), the electron density of matter within the centrifugal pressure supported region (which generates hard X-rays) goes down and it is easier to cool these electrons by soft photons coming from the Keplerian disk. If, on the other hand, the post-shock region gains mass from outside, the spectra would be harder. These properties of spectral ‘softening’ of the low state and ‘hardening’ of the high state have been detected in several days of RXTE data of GRS1915+105 which we present here.

Key words: X-rays: stars – outflows – winds – Comptonization – black hole physics – GRS1915+105

1. Introduction

GRS1915+105 is a well known example of a micro-quasar which resembles a quasar in all aspects including having jets which are ejected at an apparent superluminal speed (Mirabel & Rodriguez, 1994). Several observations have been made (Pooley et al. 1997 Eickenbery et al. 1998; Feroci et al., 1999; Fender et al. 2000a; Dhawan et al. 2000) which suggest that there is a distinct correlation between the Comptonizing region and the outflowing jets. For instance, Pooley et al (1997) showed that when the source goes from the burst-off state to the burst-on state via the X-ray dip, the radio oscillation starts. Eikenbery et al. (1998) pointed out that X-ray and IR flares are triggered by the same
events very close to the black hole. Using data of the light curve (of the so-called \( \beta \) class, Belloni et al. 2000a), they noted that IR flares are associated with a spike formation and right after the spike matter may have come out as baby jets. Feroci et al. (1999) associated disappearance of the inner part of the disk with the creation of radio flares. Fender et al. (2000a) find that only in hard states there are continuous outflows while in very soft states the outflow could be missing. Dhawan et al. (2000) observed that the starting time soft X-ray flares and radio flares are correlated while hard X-ray is anti-correlated with radio intensity. Not only GRS 1915+105, similar conclusions were drawn using observational data from using other black hole candidates such as Cyg X-1 (Fender et al. 2000a), GX 339-4 (Fender et al. 1999a).

In this paper, while supporting the general observations made so far, we present spectral signatures which indicate activities associated with winds as well. The effect we discuss was predicted in 1998 (Chakrabarti, 1998a) and we find that in several days of spectra of GRS 1915+105 this effect is observed. While our search is not exhaustive, we believe that this observation should be true in general and in other objects as well. These would be reported elsewhere. Based on the theoretical paradigm and the observations we believe that winds emerge from the centrifugal pressure supported innermost region of the disk, where hard X-rays are also emitted. To establish this we need to describe briefly the black hole accretion/outflow paradigm as we know it today.

As matter enters into the horizon of a black hole, the accretion flow has to be necessarily supersonic and thus sub-Keplerian (Chakrabarti, 1990; hereafter C90, Chakrabarti & Titarchuk, 1995, hereafter CT95; Chakrabarti 1996a), i.e., it must deviate from a Keplerian disk. The centrifugal barrier dominated boundary layer (CENBOL for short) of a black hole (CT95) puffs up and intercepts soft photons from the pre-CENBOL Keplerian disk. Depending on whether the Keplerian disk rate or the sub-Keplerian halo accretion rate dominates, the emerging spectra may be harder or softer (CT95, Chakrabarti 1997). It is seen that if the Keplerian disk rate is low \( \dot{m} = \frac{\dot{M}}{\dot{M}_{\text{Edd}}} \sim 0.01 - 0.3 \) and the halo rate is high \( \dot{m} \sim 1 \) the spectra would be hard. In this case, the soft photons are fewer in number and they are unable to cool down the electrons in CENBOL by inverse Comptonization. With this disk composition, the black hole would be in the so-called ‘hard state’ (Tanaka & Lewin, 1995; CT95). On the other hand, if the Keplerian disk rate is high \( \dot{m} \sim 0.3 - 1 \) or more, the spectrum would be soft. In this case, soft photons are profuse in number and since optical depth inside CENBOL crosses unity \( \tau > 1 \), the resulting spectrum is softened. The black hole would be said to be in a soft-state in this case. In fact, Chakrabarti (1997) proved that even when the Keplerian rate is low, the spectrum could be soft depending on the size and composition (whether there are sub-Keplerian flow or not) of the Comptonizing region since they determine the degree of interception of soft photons and the optical depth.

It is a general property of the advective disks that outflows must be present (C90) since they are generalizations of the spherical Bondi (1952) flow which also showed outgoing winds which we term as Parker-winds (Parker, 1982). It was therefore no surprise that when the anti-correlation of hard X-rays and radio intensity were first reported (Mirabel & Rodrigues, 1994) immediate explanation was that “. . . the collapse of fields in the funnel would cause destruction of the inner part of the disk and formation of blobby radio jets. Detailed observation of GRS 1915+105 shows these features. Since inner part of the accretion disk could literally disappear by this magnetic process, radio flares should accompany reduction of X-ray flux in this objects.” (1996b; see also Chakrabarti 1994). It was subsequently shown, that the CENBOL, which is only around few tens of the Schwarzschild radii large, could actually be responsible to
form outflows and jets. Chakrabarti (1998b, 1999a) estimated the ratio $R_{\dot{m}}$ of outflow rate to inflow rate and found that in the limit when the flow is isothermal till the sonic point of the outflow, $R_{\dot{m}}$ depends only on the compression ratio $R$ of the gas at the shock. Chakrabarti (1999b) showed that the presence or absence of outflows are directly related to the spectral states. In a truly soft state, the shock is absent ($R \sim 1$) and no significant wind would be produced. In a hard state, shock could be strong, ($R \sim 5 - 7$). The outflow rate would be reduced but QPO may exist due to shock oscillation. For an intermediate shock (say $R \sim 2.5 - 3$), the outflow rate is large and the sonic surface in the outflow is close enough to be filled in quickly to create the burst-on/burst-off phenomenon and to form blobby jets. Subsequently, Das and Chakrabarti (1999) computed $R_{\dot{m}}$ rate more accurately using globally complete inflow and outflow transonic solutions and found that in some region of the parameter space the entire sub-Keplerian region could be completely evacuated.

While there is much confusion in the literature about the nomenclature of states, we would like to define the states in a manner that is generally accepted in the literature. (Some works where these definitions are given are: Tanaka & Lewin, 1995; CT95; Pooley et al. 1997; Honam et al., 2000; Belloni et al. 2000a; Kong et al. 2000). In the Very High State (VHS), X-ray spectrum is a combination of the disk black-body ($kT \sim 1.2\text{keV}$) and photon spectral index is $\alpha \sim 2.5$. In the High State (HS), X-ray spectrum is dominated by the disk blackbody component ($kT \sim 1\text{keV}$) and the power law component ($\alpha \sim 2 - 3$) is weak or absent. In the Intermediate State (IS) X-ray spectrum shows both power-law ($\alpha \sim 2.5$) and disk blackbody component ($kT \leq 1\text{keV}$). In the Low State (LS) the $2 - 10\text{keV}$ photon spectral index is around $\alpha \sim 1.5$ and sometimes very weak disc black body component ($kT \leq 1\text{keV}$) may be observed. In the Off State (OS) the X-ray fast time variability is similar to that of an LS, but the $2 - 10\text{keV}$ flux is about 10 times lower or even fainter compared to LS. In the case of objects like GRS 1915+105, a few other states are in the literature: In the Burst-Off State (BOffS) the spectrum is hard, but not as hard as in a LS or OS. Here the count rate is low and low Hardness ratio HR1 (Belloni et al 2000a), and variable HR2 depending on the length of the event. In the Burst-On State (BOnS), count rate is high and high HR1 is seen. A transition from BOffS to BOnS always accompany a lowering of the count with low HR1 and HR2 (Belloni et al. 2000) and this is called a Dip State (DS).

It is to be noted that a very important and tight correlation between the average frequency of the quasi-periodic oscillations (QPO) and the duration of the so-called ‘burst-off states’ exists, all aspects of which could be explained satisfactorily when outflows are assumed to be present (Chakrabarti & Manickam 2000; hereafter CM00). They discuss that in the ‘burst-off’ states the winds loss out matter from the CENBOL, while in ‘burst-on states’, the subsonic region (the so-called sonic sphere) is cooled down. The driving force is thus lost, and matter falls back on the CENBOL, while at the same time the CENBOL size is reduced due to turbulent viscous effects (see, Chakrabarti and Nandi, 2000 for details). Figure 1(a-b) shows a cartoon diagram of the flows in the ‘burst-off’ (a) and ‘burst-on’ states (b). A similar correlation was found between the centroid frequency and the duration by Trudolyobov et al. (1999a) in some of the days of observation.

What could be the spectral signature of a CENBOL which is losing matter to winds? On the one hand, one might imagine that a CENBOL with lesser electron density and therefore optical depth would be hotter and harder. But, in presence of a large number of soft photons from the pre-CENBOL flow, fewer electrons of CENBOL would be easier to cool. Using this argument, Chakrabarti (1998a) computed the spectrum taking loss of matter due to the winds
Fig. 1. A cartoon of the accretion disk near a black hole which includes a boundary layer. Fig 1a shows the ‘burst-off’ state where the outflow material fills up the region up to the sonic point $R_s$. Fig 1b shows the cases with prominent ‘burst-on’ state where the material in the subsonic region cools and falls back on the CENBOL (see text) and takes time to drain.

from CENBOL into account and showed that emergent spectrum become softer. Similarly, when cooler matter of the subsonic region of the outflow falls back (Fig. 1b) by a return flow, enhanced optical depth of the CENBOL makes it harder to cool it down by the same number of soft-photons emerging from the Keplerian disk in the pre-CENBOL region. This means that in the burst-on state, the spectrum should be hardened in comparison to the spectrum in the high/soft state. Thus, softening of the hard state spectrum and hardening of the soft state spectrum could indicate that accretion rate is not preserved within CENBOL—i.e., matter is lost or gained. (We refer this as ‘SH-HS’ phenomenon for brevity.) Of course, the degree by which the spectrum changes depends on mass loss/gain. Since the drainage time of this matter which falls back is directly related to the duration of the ‘burst-on’ states (CM00), spectra of both burst-off and burst-on states are affected and as a result the energy of the pivotal point (where spectra of the hard and soft states intersect) increases. That the spectral pivoting takes place during normal low to high state excursions is well known, see, e.g., Ebisawa et al. (1994). What is new in our analysis is the observation of the significant shifting of the pivoting point in cases which exhibits prominent burst-on states. In the event burst-on state is not prominent and noisy, the spectra of the off states should still be softened. In other words, whenever wind is involved, spectra must exhibit SH-HS phenomena. Given that the outflow model enumerated above sharply differs from the earlier conception of jet formation (which stipulates that matter must emerge from regions all over the disk, see, Begelman, Blandford and Rees, 1984 and references therein) which would have no obvious effect on hardening/softening of the spectra and resultant shifting of the pivotal energy location, it would be interesting to see if GRS1915+105 data shows evidence of SH-HS phenomena. The question becomes very relevant since there are increasing evidence today (e.g., Junor, Biretta
and Livio 1999) that jets do emerge within tens to hundreds of Schwarzschild radii of a black hole for the active galaxy M87. Thus if one also observes similar behaviour for GRS1915+105, it would justify the term micro-quasar from all practical points of view.

In this Paper, we present the RXTE spectra of GRS1915+105 and show that there is a distinct signature of mass loss in the burst-off state and mass gain (fall-back of matter) in the burst-on state of the spectra. As a result, when both of these states are prominent, the pivotal energy during burst-off and burst-on transitions is shifted towards much higher energy than where it would have been had there been direct low-high transition. Even when these burst-on/burst-off states are not prominent SH-HS phenomena are still observed. These point to the fact that the hard X-ray emitting region, namely, the inner part of the advective disks, are directly responsible for producing the winds as well. This conclusion is in line that of other observers that the Comptonizing photons originate from the base of the jet (e.g., Eikenbery et al. 1998; Belloni et al. 2000b; Fender and Pooley, 2000). At this point we must point out that it is not the aim of this paper to prove that the theoretical prediction on the spectral slope is valid for all the observations made on all days because of obvious constraints. However, we shall choose sufficiently general observational data set and we would hope that the conclusions drawn would be valid for observations not covered in this paper. In fact, since the physical reasons are generic, we believe that the conclusions would be valid even objects other than GRS1915+105. These would be discussed separately.

2. RXTE PCA Spectral Data

The RXTE public archive contains several observations on GRS 1915+105 obtained using the RXTE Proportional Counter Array (PCA - see Jahoda et al. 1996 for a description of PCA). These observations typically last for a few thousand seconds and the observations are carried out roughly once a week. The source was in a low state from December, 1996 up to April, 1997. The spectral and temporal behavior during the low state was stable characterized by a hard spectrum (with the power-law photon index of \( \sim 2 \), and the total flux in the power-law component being \( \sim 80\% \)) and 1 – 10 Hz QPOs (Trudolyubov et al. 1999b; Muno et al. 1999). The fact that the canonical low states of black hole candidate sources have a negligible thermal component (Chitnis et al. 1998) prompted Trudolyubov et al. (1999b) to characterize this state as an “intermediate state” and they conclude that with the lowering of the accretion rate the source should go to the canonical hard state. Since the source was in similar state on several occasions (1996 July-August; 1997 October; 1998 September-October), we treat this state as the low state of GRS 1915+105. The source reached a high state in 1997 August. We have selected one observation each from the low state and high state to quantify the spectral parameters. The low state observation was carried out on 1997 March 26 with PID number of 20402-01-21-00 (spectral and temporal parameters for this observation has been reported in Muno et al. 1999 and Trudolyubov et al. 1999b). The high state observation was carried out on 1997 August 19 with a PID number of 20402-01-41-00 (Muno et al. 1999). Spectra of these two states are shown in Fig. 2(a-c) and are marked.

During the transition between these two states, the source exhibited several types of bursting behaviour. A detailed discussion of the classification of light curves are in Yadav et al. (1999), Belloni et al. (2000a) and Nandi, Manickam & Chakrabarti (2000). It was seen that for about a month the source was in a burst mode with a slow transition from regular bursts to irregular bursts and then again to a regular burst of shorter duration (Yadav et al. 1999). In
Yadav et al. (1999) it was postulated that the irregular bursts are manifestations of rapid state changes. As discussed earlier, Chakrabarti and Manickam (2000) explained the burst-off/burst-on transitions in terms of the repeated filling of the outflow region and its abrupt cooling due to inverse Comptonization. We present the spectral properties of the source during the irregular bursts observed on 1997 June 18 (PID 20402-01-33-00) in Fig. 2a, on 1997 July 10 (PID 20402-01-36-00) in Fig. 2b and on 1997 July 12 (PID 20402-01-37-01) in Fig. 2c.

We have generated the 129 channel energy spectra from the Standard 2 mode of the PCA for each of the above observations. Standard procedures for data selection, background estimation and response matrix generation have been applied. PCA consists of five units and data from all the units are added together. We have fitted the energy spectrum of the source using a model consisting of disk-blackbody and power-law with absorption by intervening cold material parameterized as equivalent Hydrogen column density, $N_H$. The value of $N_H$ has been kept fixed at $6 \times 10^{22}$ cm$^{-2}$. We have included a Gaussian line near the expected K$_\alpha$ emission from iron and absorption edge due to iron. These features help to mimic the reflection spectrum usually found in other Galactic black hole candidate sources like Cygnus X-1 (Gierlinski et al. 1997). Systematic errors of $1 - 2\%$ have been added to the data. XSPEC version 10.0 has been used to fit the spectra.

The resultant unfolded spectra for the two spectral states presented in Figures 2(a-c) show that in the low state, the disk blackbody component has lower temperature ($kT_{in} = 0.60 \pm 0.05$ keV) and a larger inner disk radius ($R_{in} = 115 \pm 2$ km) compared to the high state, which has the inner disk temperature of $1.95 \pm 0.01$ keV and the inner disk radius of $26 \pm 1$ km. The inner disk parameters are calculated using a distance to the source of 10 kpc and inclination to the disk of 70°. The power-law index in the low state (2.40$\pm$0.01) is much flatter than that seen in the high state (3.61$\pm$0.02). The quoted errors are for nominal 90% confidence levels obtained by the condition of $\chi^2_{min} + 2.7$. The disk blackbody...
component has a $3 - 26$ keV flux of $<10\%$ of the total flux in the low state, which increase to $>65\%$. The two spectra intersect at around 17 keV. It should be noted here that the disk-blackbody inner radius gives systematically lower value when scattering effects are not considered and PCA generally shows steeper spectrum due to uncertainties in the response matrix. The results presented here, however, highlights the broad changes in the spectral states.

The corresponding unfolded spectra during the irregular burst of June 18, 1997 presented in Figure 2a shows that the burst-off state has spectral parameters similar to that of the low state ($kT_{in} = 0.76$ keV, index = 2.76) and the burst-on state spectrum resembles that of the high state ($kT_{in} = 2.2$ keV, index = 3.1). At the same time it is clear that the spectrum of the burst-off state is softer than that of the low state and the spectrum of the burst-on state is harder than that of the high/soft state. As a result, the energy at which the two spectra pivot is much high ($\sim 26$ keV). The same behaviour is seen also in Fig. 2b and 2c where the IDs used were 20402-01-36-00 and 20402-01-37-01.

The low and high states have been kept as above. The intersection in all these cases during the burst-on/burst-off transition is around 25 keV — far above the low/high intersection.

In a recent paper, Dhawan et al. (2000) pointed out a direct correlation between the ASM X-ray data from RXTE and IR/Radio observations. The radio activity at around 500AU made on 31st October, 1997 would be perturbed by CENBOL activity of around 28.5 October, 1997, if perturbation propagates with 0.98c. Unfortunately, no PCA data is available for 28th or 29th of October. Figure 3 shows the spectral properties on 30th October, 1997. This is drawn with observation ID 20402-01-52-02. To compare with the high/low spectrum, the low state observation closest to this day, namely, of 25th of October, 1997, we chose the same high state as mentioned above. This latter observation ID is 20402-01-52-00. The spectral slopes of the high, low, on and off states are $3.61 \pm 0.02$, $2.76 \pm 0.018$, $3.34 \pm 0.021$ and $2.85 \pm 0.013$, respectively. This again shows the softening of the hard and hardening of the soft states. The intersection of the spectra of low and high states is at around 14keV whereas that of the on and off states is at around 17keV. Thus the effect of winds is still prominent even after one and a half day of ejection of matter, though the effect is lesser.

3. Theoretical Interpretations

As already discussed in the Introduction, the SH-HS phenomena, i.e., hardening of the soft-state spectrum and softening of the hard-state spectrum and the resulting shift towards higher energy in the pivotal point could be understood in terms of the presence of winds (Chakrabarti 1998a) or return flow of additional cooler matter to CENBOL (Chakrabarti and Nandi, 2000) (Fig. 1ab). In Fig. 4, we present two sets of calculated spectra to illustrate this. Calculations are done using models presented in CT95 and it subsequent modification by Chakrabarti (1997). Disk accretion rates for the soft and the hard states are $0.3\dot{M}_{Edd}$ and $0.1\dot{M}_{Edd}$ respectively. Halo accretion rate is kept fixed at $1.0\dot{M}_{Edd}$ and the shock is located at $X_s = 14$ and $X_s = 10$ respectively in low and high states. This is in line with the general conclusions that the inner edge moves in during soft states. Other parameters are kept identical. The solid curves are drawn to mimic the burst-off and burst-on state spectra. In these cases the disk accretion rates are kept as before, but the twenty percent of CENBOL matter is assumed to be lost in wind in the burst-off state and ten percent of matter is assumed to be falling back on the halo from the wind region in the burst-on state. Because of selective softening and hardening, the intersection point is located at a much higher energy exactly as observed. After inclusion of these models in XSPEC, in future, it would be possible to fit the spectra to obtain the flow and the wind parameters.
4. Discussion and conclusions

A comparison of the two spectral states in Fig. 2(a-c) and Fig. 3 shows that during the bursting phase the low energy component ($\lesssim 5$ keV) remains essentially same as that found during the extended low and high states of the source. The major change is above $\sim 10$ keV where the hard component of the low state softens to form a burst-off state and that of the high state hardens to form a burst-on state. Particularly interesting is the result in Fig. 3, where actual observations of outflow is present (Dhawan et al. 2000). We presented a possible scenario where we incorporated recent findings that loss of matter in winds might cause the spectral softening. We showed earlier that winds are lost from the centrifugal barrier in the burst-off state of the flaring phase and a part of the matter falls back to increase the sub-Keplerian flow thereby hardening the spectra during the burst-on state. It has already been argued (Chakrabarti, 1999a) that the wind formation rate may be dependent on the compression ratio of the flow at the shock and that the outflow rates are related to the spectral states (Chakrabarti, 1999b). These results are fully in line with multi-wavelength observations of correlated variabilities (Mirabel & Rodriguez 1999; Dhawan et al, 2000; Fender and Pooley, 2000; Belloni, Migliari and Fender, 2000). Our present result where matter loss/gain is seen to affect the Comptonized photons, thus indicates that winds are produced from the ‘boundary layer’ of a black hole.

The connection between winds from the accretion disk, the AU scale jets in the core of GRS 1915+105 (Dhawan et al. 2000) and the super-luminally moving synchrotron ejecta (Mirabel & Rodriguez 1994; Mirabel & Rodriguez 1999; Fender et al. 1999b) are not very clear at present and a detailed evaluation is beyond the scope of the present paper. The accretion-wind scenario presented in Chakrabarti (1999a) and Das & Chakrabarti (1999) gives a self-consistent way to generate winds from accretion disks, but the acceleration of such winds into superluminally moving ejecta is a separate matter. We can conjecture that GRS 1915+105 has a CENBOL location such that most of the times there is a strong wind emission. This wind can be confined in the sonic sphere (to give rise to the repeated outbursts),
Fig. 4. Typical nature of calculated spectra (uncorrected for absorption) for burst-off and burst-on states and low and high states of GRS1915+105. In burst-off state, spectrum appears to be softened with respect to low state, and in burst-on state, spectrum appear to be hardened with respect to the high state. See text for details.

can be accelerated steadily (to give flat spectrum radio emission) or ejected at superluminal velocities (to give rise to the steep spectrum synchrotron ejecta) depending on initial parameters (which in turn govern the shock compression ratio). The basic mechanism of the wind emission from the CENBOL and the consequential change in spectral slopes are not inconsistent with any known observations. A crucial aspect of this model is the scattering of the soft photons by modified opacity of the CENBOL: a subtle difference that has been confirmed in the present work. Due to obvious constarint we could not check our conjecture for all the days of observations or for other objects, but we believe that it would remain valid. The exact mechanism of the acceleration (steady as well as superluminal motion) probably requires some magneto-hydrodynamic mechanism.

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