The viscous disk of GRS 1915+105

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GRS 1915+105, one of the two known galactic microquasars, shows an extremely complex variability in the X-ray band, comparable to no other X-ray source in the sky. Making use of RXTE/PCA data, we have analyzed the X-ray spectral distribution throughout the variability. We find that all variations can be attributed to the rapid appearance and disappearance of the inner region of an optically-thick accretion disk. Since the time scale for each event is related to the maximum radius of the disappearing region, the difference in time structure is due to the time distribution of such radii. The observed relation between the extent of the missing inner region of the disk and the duration of an event is in remarkable agreement with the expected radius dependence of the viscous time scale of the radiation-dominated region of an accretion disk.

1. INTRODUCTION

GRS 1915+105 is the first galactic object for which radio jets moving at superluminal speed have been observed [1]. Radio observations have also led to the estimate of its distance (~12.5 kpc) and the inclinations of the jets (70° from the line of sight). The source is considered to host a black hole because of its high X-ray luminosity and its similarities to GRO 1655–40, whose dynamical mass estimate indicate the presence of a black hole [2]. GRS 1915+105 is a transient source, in the sense that it has made its appearance in the X-ray sky in 1992 [3], but most likely never returned into quiescence since then. The Rossi X-ray Timing Explorer (RXTE) monitors regularly GRS 1915+105 since the start of the mission. During this period, the source has shown a remarkable richness in variability, ranging from quasi-periodic burst-like events, deep regular dips and wild oscillations, alternated with quiescent periods [4–9]. We present here the results of the analysis of RXTE data of GRS 1915+105 and propose an interpretation for the variability in the spectral parameters. A more detailed discussion can be found in [8].

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2. X-RAY OBSERVATIONS

RXTE observed GRS 1915+105 in many occasions. Here we present the results of the analysis of one of these observations, the one obtained on 1997 June 18 starting at 14:36 UT and ending at 15:35 UT, as it reproduces within one day most of the variability observed from this source. The upper panel of Figure 1 shows 1200 s of the 2-40 keV light curve. It consists of a sequence of 'bursts' of different duration with quiescent intervals in between. All bursts start with a well-defined sharp peak and decay faster than they rise. The longer bursts show oscillation (or sub-bursts) towards the end.

The complexity of the light curve seems to be untractable: the only obvious comment that can be made is that it consists of high flux intervals somehow alternated with low flux intervals. In order to quantify the timing structure of the oscillations, we measured the length of the 'ups' and 'downs', an unambiguous procedure given the square-wave structure of the light curve. Excluding the fastest oscillations where this measurement is not easy, we obtain durations spanning from a few seconds to three minutes.

To study the evolution of the spectrum of GRS 1915+105 during these oscillations between 'up' and 'down', we first produced a color-color (C-C) diagram of the whole observation A characteristic pattern emerged, pattern which is also observable, with small differences, in all other observations we analyzed, besides a few (see below). This strengthens the hypothesis that all the oscillations have the same nature. An analysis of separate C-C diagrams for oscillations of different length (see Figure 2) shows systematic differences. As it can also be seen from the light curve, the 'ups' are very similar to each other, while the 'downs' are different, in particular the longer the oscillation the deeper (light curve) and harder (C-C) is the 'down'. Both from the light curve and the C-C diagram it appears that the short 'low' periods are similar to the last part of the long ones. Since spectral analysis at the required time resolution is not possible, in order to transform the information in the C-C diagram into spectral parameters we divided it into small regions. For all the populated regions in the diagram we accumulated 1 second time resolution energy spectra in 48 energy bands. We measured a background spectrum from a blank sky observation, which we normalized to the highest energy channels where the contribution of the source was negligible. We subtracted this background spectrum from each of the source energy spectra. We used the latest detector response matrix available, and added a systematic error of 2% to account for the calibration uncertainties. For each of the regions in the C-C diagram we fitted the data with a "standard" spectral model for BHCs, consisting of a disk-blackbody (DBB) model and a power law, both affected by interstellar absorption. To avoid problems due to the background subtraction, and as we were only interested in the properties of the DBB component, we limited our fits to energies below 30 keV. Since both the distance to this system and the inclination of the accretion disk are known (we assume that the jet is perpendicular to the disk), we can derive the inner radius of the accretion disk directly from the fits without significant additional uncertainties.

This rather complicated procedure allowed us to obtain time histories for the inner radius and the temperature of the disk (bottom two panels of Figure 1). During 'ups' the temperature is above 2 keV and the radius is stable around 20 km. During 'downs', the temperature drops to less than 1 keV and the radius increases.

We produced similar C-C diagrams for a number of other RXTE observations of GRS 1915+105. All the observations that we analyzed can be fitted in the same manner, except that of 1996 June 16th [4] (and some later observations in October 1997). The quasi-periodic bursts observed in many of the observations [9] are consistent with repetitive short events like the ones described here.

This analysis brought us to consider more seriously the 'up' and 'down' paradigm: to be consistent with our previous work, we will call them 'outburst' and 'quiescent' states. A sequence of quiescence and outburst we call an 'event'.

3. DISCUSSION

The main conclusion that can be derived from Figure 1 is that the inner radius of the accretion disk is not constant in time. If we interpret the small and stable radius of ∼20 km observed during outburst as the minimum stable orbit around a black hole (see [7] for a more detailed discussion), this implies that during quiescence the central section of the disk disappears, i.e. a central hole appears in the disk. The radius of this central hole varies between events, ranging in this observation between 30 and 90 km (see Figure 1). This can be interpreted within the model presented by us in [7], providing a unified picture of the variability observed in GRS 1915. In [7], we modeled the large amplitude changes as emptying and replenishing of the inner accretion disk caused by a viscous-thermal instability. The small radius observed during the quiescent period was identified with the innermost stable orbit

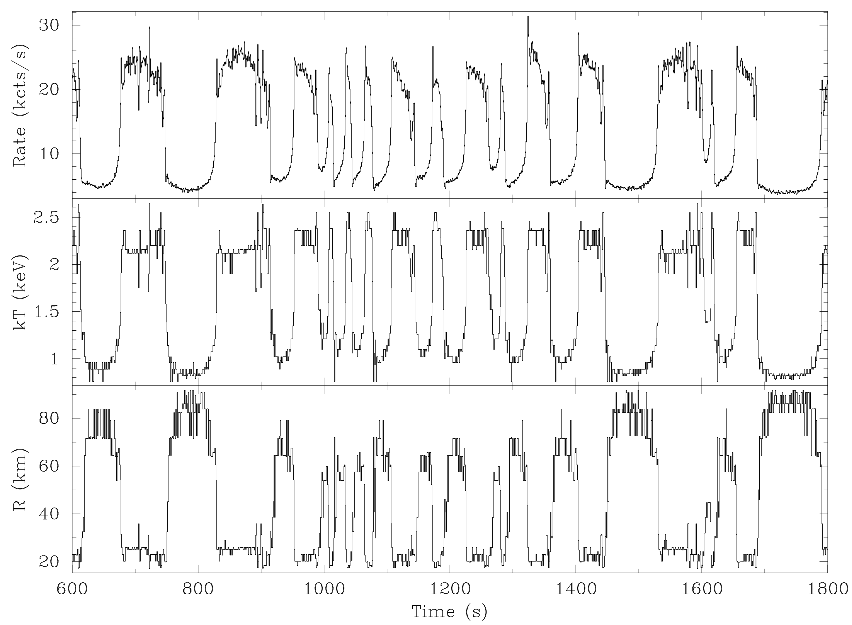

Figure 1. Upper panel: 2-40 keV PCA light curve. Time zero corresponds to 1997 June 18th, 14:36 UT. Middle and lower panels: corresponding inner radius and temperatures (see text)

around the black hole, while the large radius during the burst phase was the radius of the emptied section of the disk. The smaller oscillations were interpreted as failed attempts to empty the inner disk. As it can be seen from Figures 1 and 2, from this observation we find that all variations, from major events like the ones described in [7] to small oscillations observed at the end of a large event, can be modeled in exactly the same fashion. In this scenario, the "flare state" presented in [7] is simply a sequence of small events following a big one, similar to the small oscillations in Figure 1.

Both the spectral evolution and the duration of the event are determined by one parameter only, namely the radius of the missing inner section of the accretion disk. It is natural to imagine that the bigger the missing inner section of the disk, the longer it will take to re-fill it. Indeed, if we identify the re-filling time for each event with the time spent in 'quiescence', this is what is observed (Figure 3). Following [7], we can naturally associate the re-filling time of an event t_q to the viscous time scale of the radiation-pressure dominated part of the accretion disk. This can be expressed as $t_{\rm visc} = R^2/\nu$, where $\nu = \alpha c_S H$. using the expressions for the scale-height H and sound speed c_S found in [10], we obtain:

$$t_q \sim t_{\rm visc} = 30\alpha_2^{-1} M_1^{-1/2} R_7^{7/2} \dot{M}_{18}^{-2} \text{ s} \qquad (1)$$

where $\alpha_2 = \alpha/0.01$, R_7 is the radius in units of 10^7 cm, M_1 the central object mass in solar masses, and $\dot{M}_{18}$ is the accretion rate in units of 10^{18} g/s. Notice that even the largest radii derived here are well within the radiation-pressure dominated part of the disk (see Equation 2 in [7]). The line in Figure 3 represents the best fit to the data with a relation of the form $t_{\rm q} \propto R^{7/2}$. The fit is excellent, with the exception of the point corresponding to the longest event. The qualitative agreement with the theoretical expectation is striking, although by substituting the appropriate values for the mass and accretion rate we find that our best fit predicts rather small values of α_2 (0.004 and 0.05 for the Schwarzschild and extreme Kerr cases respectively). This indicates a small viscosity in the disk, although we stress that t_{visc} is only a time scale, so that additional corrections might be necessary in order to allow a precise quantitative comparison.

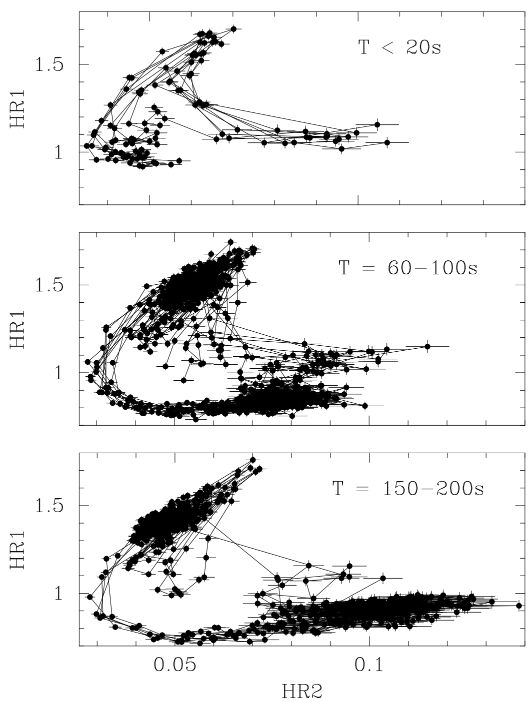

Figure 2. Color-color diagrams for events of different duration. The 'low' intervals are correspond to the populated clouds of points on the low part of the diagrams. The sequence 'low'-'high'-'low' moves clockwise

Let us follow an event and describe it in terms of the model. The accretion rate $\dot{M}_0$ provided by the secondary is constant (within one observation). At the start of a quiescent period, the disk has a central hole, whose radius is R_{max}. Outside the hole, $\dot{M}_0$ lies on a stable branch in the $\dot{M}-\Sigma$ curve (see [7]). At all radii inside the hole, $\dot{M}_0$ lies on the unstable branch: the disk lies on the lower (stable) branch. This means that the hole does not have to be empty, but rather filled with gas whose radiation is too soft to be detected. Slowly the hole in the disk is re-filled by a steady accretion rate $\dot{M}_0$ from outside. Each annulus of the disk will move along the lower branch of its S-curve in the $\dot{M}-\Sigma$ plane trying to reach $\dot{M}_0$. The local density at each radius increases as the annulus moves towards the unstable point at a speed determined by the local viscous time scale. During this period, no changes are observed in the radius of the hole, since all the matter inside does not radiate in the PCA band. In the XTE data the disk appears to have a roughly constant radius. The observed accretion rate during this phase is $\dot{M}_0$ since it is determined from the spectrum of the radiation coming from stable regions. At the end of this phase, one of the annuli will reach the unstable point and switch to the high-$\dot{M}$ state, where the accretion rate is larger than $\dot{M}_0$, causing a chain-reaction that will "switch on" the inner disk. The observed accretion rate is now higher than the external value $\dot{M}_0$ since it is determined from the spectrum of radiation originating from the unstable part of the disk, through which a higher $\dot{M}$ is flowing. A smaller, hot radius is now observed. At the end of the outburst, the inner disk runs out of fuel and switches off, either jumping back to the $\dot{M} < \dot{M}_0$ state or possibly emptying completely. A new hole in the disk is formed and a new cycle starts. Notice that in this scenario the more "normal" state for the source is the one at high count rates, where the disk extends all the way to the innermost stable orbit: in this state the energy spectrum is similar to that of conventional black-hole candidates (see [11]).

Not only the start and end of a major burst, but also all the small amplitude oscillations within a burst show the same timing signature of decaying faster than they rise. This is in agreement with what was already noticed in [7]: the rise time is

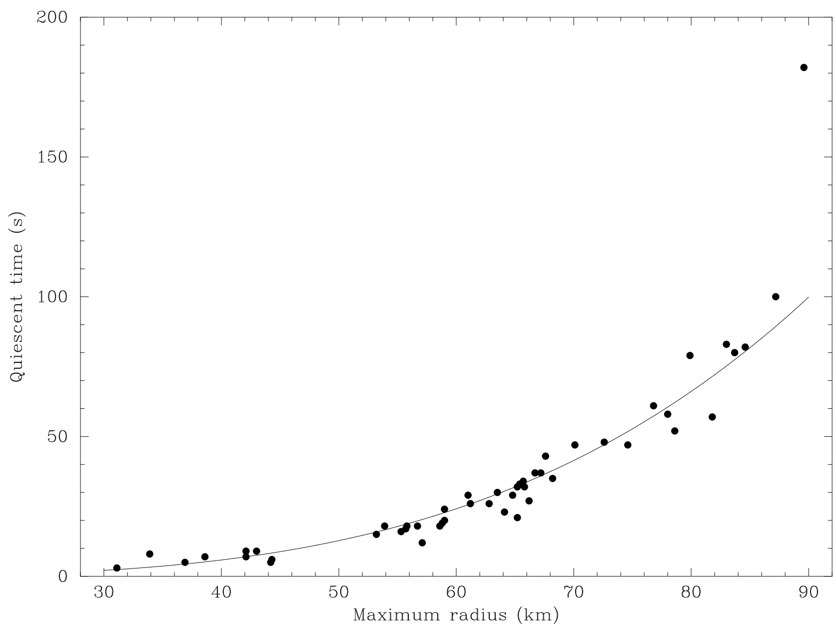

Figure 3. Correlation between the total length of an event and maximum inner radius of the disk. The line is best fit with a power law with fixed index Γ=3.5.

determined by the speed at which a heating wave moves through the central disk, while the faster decay time is due to the rapid fall of matter into the black hole (or ejection into a relativistic jet).

It has been found that when the hardness ratio HR2 exceeds 0.1, the power density spectrum is similar to the one observed in black-hole transient systems during the Very High State (see [12]). In these occasions, a strong 1-6 Hz QPO peak was found, positively correlated with the count rate [6]. The limit HR2>0.1 is an indication that the source was in a quiescent state. Our spectral results show that the fast timing features (both QPO and band-limited noise, see [5]) cannot originate from the innermost regions of the optically thick accretion disk, since those are missing during the quiescent phases. The fact that the QPO frequency increases with count rate is in qualitative agreement with the model, since a higher count rate indicates a smaller inner disk radius, and therefore shorter time scales. However, the QPO seems to be associated to the power law spectral component and not from the disk component, making this phenomenology very difficult to understand.

The radii for the disappearing region of the disk found here are considerably smaller than that reported in [7] from an observation where the length of the events was substantially longer. This is entirely due to the improved knowledge of the spectral response of the PCA. Interestingly,the length of the quiescent period and the maximum inner radius observed in [7] are in agreement with the curve in Figure 3 when the time is properly renormalized to take into account the difference in accretion rate (see Equation 1).

Our model reduces the complication of the spectral evolution of GRS 1915+105 to one parameter: the radius of the missing section of the accretion disk. The structure of the variability is however yet to be explained. The question to be answered is: what determines the length of the next outburst? The model outlined above does not provide an answer, but allows us to reformulate the question in more physical terms. What determines how large the next missing section of the disk will be? In some observations the events are very regular, in some others they seem to be random, and in some others no events are observed at all. The latter might be part of extremely long quiescent intervals. In the framework of this model, it is clear that a regular quasi-periodic structure of events arises naturally if the radii of the holes are all similar. In the observation reported here a striking one-to-one relation between quiescent and burst time is observed [8], a relation which applies to the burst and i quiescent states of the observation presented in [7] but is obviously not satisfied in other observations (see e.g. [9]) nor during the "flare" state of [7]. Moreover, as already mentioned, a few observations among the ones we analyzed does not fit this pattern and requires a different interpretation (1996 June 16th is a template). Both the timing structure and the spectral evolution in these observation is radically different from what presented here. Nevertheless, our model provides a satisfactory interpretation of the cause of the changes in the X-ray emission.

GRS 1915+105 is a remarkable X-ray source. Despite it uniqueness (and because of it), we have the chance to learn something fundamental about accretion disks around black holes. Some of its characteristics (the X-ray variability being the major one) are indeed peculiar, but others (the band-limited noise and QPO in power spectra, the thermal disk and the hard power law components in the energy spectra) are remarkably similar to many 'normal' black hole candidates. Whatever the different states in these sources are, so far we have been observing them on long time scales (years for persistent sources like Cyg X–1 and GX 339–4, months for black hole transients). Here we can observe more spectral and timing variations within one hour of observation. In addition, coordinated observations in different bands are beginning to provide us with the first links between what happens in the accretion disk (observed in X-rays) and the ejection of relativistic jets (observed in IR and radio) [13–15].

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