Thermal-viscous instabilities in the accretion disk of GRS 1915+105

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Abstract.
We use data obtained with the PCA onboard RXTE to analyze the spectral variations of the black hole candidate and superluminal source GRS 1915+105. Our results suggest that despite the complicated structure of the X-ray light curve, all spectral changes observed in this source can be explained as a sudden disappearing of the inner part of the accretion disk around the compact object, followed by a slower re-filling of the emptied region. The duration of an event and the size of the disappearing region fit remarkably well the expected radius dependence of the viscous time scale for the radiation-pressure dominated region of an accretion disk.

INTRODUCTION

The X-ray source and black hole candidate (BHC) GRS 1915+105 was the first galactic object to show relativistic jets with apparent superluminal motions \cite{1}. It is at a distance of 12.5 kpc \cite{2}, and the jet is oriented at an angle of 70° with respect to the line of sight. The Rossi X-ray Timing Explorer (RXTE) has observed this source systematically since April 1996, and since then GRS 1915+105 has shown a remarkable richness in variability: quasi-periodic burst-like events, deep regular dips and strong quasi-periodic oscillations, and long quiescent periods \cite{3–7}. Here we show that its complicated light curve can be described by the rapid appearance and disappearance of emission from the inner accretion disk.

OBSERVATIONS AND DATA ANALYSIS

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.

**FIGURE 1.** Upper panel: 2.0–40.0 keV PCA light curve. Time zero corresponds to 1997 June 18th 14:36 UT. Middle and lower panels: corresponding inner radius and temperature (see text).

To study the evolution of the spectrum of GRS 1915+105, we first produced a color-color (C-C) diagram of the whole observation (see [8], Figure 3) which we divided in small regions. For all the populated regions in this 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 we 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 plus 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.
We used the time resolved energy spectra to study the variations of the inner radius and the temperature of the disk as a function of time (bottom two panels of Figure 1). During bursts the temperature is above 2 keV and the radius is stable around 20 km. During quiescent phases, the temperature drops to less than 1 keV and the radius increases. There is a strong correlation between the length of an event and the largest radius reached (Figure 2).

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 [3]. All the quasi-periodic bursts observed in many of the observations [7] are consistent with repetitive short events like the ones described here.

![FIGURE 2. Correlation between the total length of an event and maximum inner radius of the disk. The line is the best fit with a power law with fixed index $\gamma = 3.5$. The last point has been excluded from the fit.](image)

DISCUSSION

The previous results can be interpreted as follows: The large amplitude changes reflect the emptying and replenishing of the inner accretion disk, caused by a viscous-thermal instability [6]. The small radius observed during the quiescent period can be identified with the innermost stable orbit around the black hole, while the large radius during the burst phase represents the radius of the emptied section of the disk. The smaller oscillations are simply failed attempts to empty the inner disk. Figure 1 shows that all variations, from major events [6] to small oscillations at the end of a large event, can be modeled in exactly the same manner.

Both the spectral evolution and the duration of the event are determined only by the radius of the missing inner section of the accretion disk. For a large radius, the
drop in flux is larger, and the time needed to re-fill the empty part of the disk is longer. It is natural to associate the length of the quiescent part of an event to the viscous time scale of the radiation-pressure dominated part of the accretion disk [6]. This can be expressed as $t_{\text{visc}} = 0.30\alpha^{-1}M_1^{-1/2}R_7^{7/2}\dot{M}_{18}^{-2}$ seconds, where $\alpha$ is the viscosity parameter, $R_7$ 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 [6]. The line in Figure 2 represents the best fit to the data with a relation of the form $t_q \propto R_7^{7/2}$. The fit is excellent, with the exception of the point corresponding to the longest event.

An event can therefore be pictured in the following way. At the start of a quiescent period, the disk has a central hole, whose radius is $R_{\text{max}}$. The hole is either empty or filled with gas whose radiation is too soft to be detected. Slowly 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 stabilize at $\dot{M}_0$ [6]. The surface gravity 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 the matter inside does not radiate in the PCA band. The observed accretion rate is $\dot{M}_0$. At some point, 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 $\dot{M}_0$. 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 emptying completely. A new hole 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 BHCs.

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