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DOI
10.1086/310595

Publication date
1997

Published in
Astrophysical Journal

THE ASTROPHYSICAL JOURNAL, 479:L145–L148, 1997 April 20

AN UNSTABLE CENTRAL DISK IN THE SUPERLUMINAL BLACK HOLE X-RAY BINARY GRS 1915+105

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Received 1996 November 15; accepted 1997 February 4

ABSTRACT

We have analyzed the X-ray spectra of the microquasar GRS 1915+105, as observed with the Proportional Counter Array (PCA) on the *Rossi X-Ray Timing Explorer*, during periods of stable weak emission, outbursts, and rapid flaring. We find that the complicated X-ray intensity curve of this source can be described by the rapid removal and replenishment of matter forming the inner part of an optically thick accretion disk, probably caused by a thermal-viscous instability analogous to that operating in dwarf novae, but here driven by the Lightman-Eardley instability. We find that the mass accretion rate in quiescence is about $10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$. Only a small fraction of the energy liberated by accretion is emitted as radiation. We suggest that most of this energy is advected into the black hole in the high-viscosity state of the outburst cycle.

Subject headings: accretion, accretion disks — binaries: close — black hole physics — instabilities — stars: individual (GRS 1915+105) — X-rays: stars

1. INTRODUCTION

The X-ray source GRS 1915+105 was the first Galactic object to show superluminal expansion in radio observations (Mirabel & Rodríguez 1994). The standard interpretation of this phenomenon in terms of relativistic jets (Rees 1966) unambiguously places the source at a distance $D = 12.5$ kpc, with the jet axis at an angle $i = 70°$ to the line of sight (Mirabel & Rodríguez 1994). GRS 1915+105 was discovered as an X-ray transient in 1992 (Castro-Tirado, Brandt, & Lund 1992). It was found to be in a bright state with the *Rossi X-Ray Timing Explorer* (*RXTE*) in 1996 April and has been bright in X rays since. During this period it has shown a remarkable richness in its variability behavior. It showed quasi-periodic oscillations, with frequencies ranging from 10^{-3} Hz to 67 Hz (Morgan, Remillard, & Greiner 1997). On several occasions its light curve showed a complicated pattern of dips and rapid transitions between high and low intensity, which repeated on a timescale between 30 and 400 minutes (Greiner, Morgan & Remillard 1996). The source is suspected to be a black hole binary because of its similarities to the other Galactic superluminal source GRO J1655−40 (Zhang et al. 1994), which has a dynamical mass estimate implying a black hole (Bailyn et al. 1995), and because it has often been well above the Eddington luminosity for a neutron star. Here we show that the complicated light curve of GRS 1915+105 can be described by the rapid ($\sim$1 s) appearance and disappearance of emission from an optically thick inner accretion disk, probably caused by a thermal-viscous instability analogous to that operating in dwarf novae.

2. X-RAY OBSERVATIONS

The observations discussed here were carried out with the Proportional Counter Array (PCA) on the *RXTE*, on 1996 June 19, September 27 and October 1 to 29. During these observations the source was both very luminous ($L_X \simeq 5 \times 10^{38}$ to 3×10^{39} ergs s^{-1} at $D = 12.5$ kpc in the 2–50 keV band) and very variable (see Fig. 1), similar to the observations reported by Greiner et al. (1996) and Morgan et al. (1997).

The variability is highly complex, but quite structured. We identify three types of variability ("states") from the light curves (see Fig. 1): a *quiescent* state at a relatively low count rate and with little variability, an *outburst* state at a high count rate with strong red-noise variability, and a *flare* state in which the flux shows rapid alternations between two flux levels, which can be extremely complex in shape. When more than one state is observed within the same observation (a typical observation spans a few hours), the sequence is always the same: quiescent, outburst, flare, quiescent, etc., sometimes with a highly repetitive pattern. In some observations, the source is observed in only the quiescent or flaring state, but never only in the outburst state. These states are similar to the lull, flare, and sputter states described in Greiner et al. (1996) on the basis of previous observations of the source.

In this Letter we take the observation of 1996 October 7 (6:36 to 7:36 UT; see Fig. 1) as a prototype containing all three states. The highly organized complex variability also shows up in a plot of hardness ratio versus time (Fig. 1, *bottom*). The count rate and hardness ratio histories can be combined in a hardness-intensity diagram (Fig. 2). The approximately hyperbolic shape of this plot suggests that to a first approximation, the source can be understood as the superposition of a constant and a varying source, each with nearly constant hardness ratio. An explicit example of this is seen in the data of Figure 1 (*bottom*), where the hardness ratio varies in a near–square wave pattern as the count rate alternates between a low and high value. The spectra in these two brightness levels are strikingly different (Fig. 2, *inset*), mainly because of a large excess of emission below 20 keV at high count rate. This would appear to be the varying component invoked above. We confirmed this idea by the following procedure.

We accumulated X-ray spectra for the quiescent and outburst intervals for the observation of 1996 October 7 (Fig. 2, *inset*). Fits with simple single-component models did not give acceptable results. We obtained good fits (reduced $\chi^2 = 1.2$

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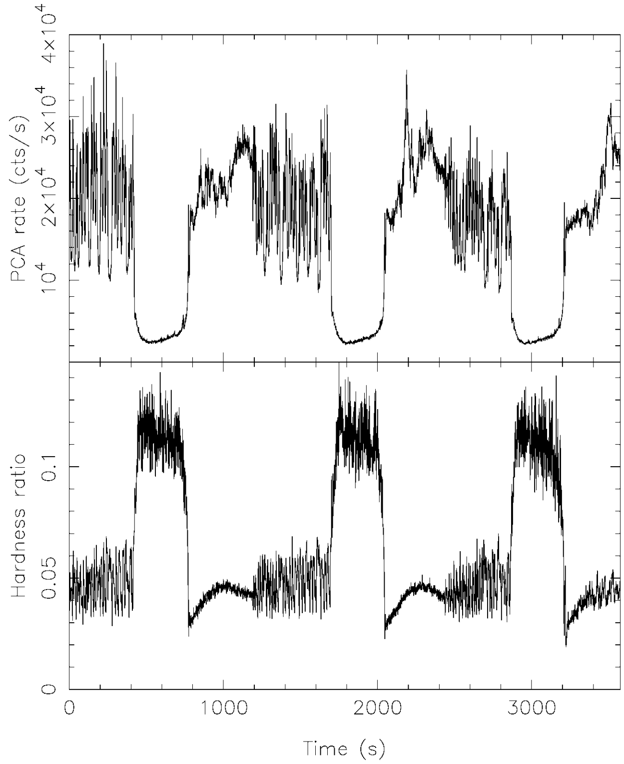

FIG. 1.—*Top*: The 2.0–13.3 keV PCA light curve. Time zero corresponds to 1996 October 7 6:36 UT. *Bottom*: Corresponding hardness ratio (13.3–60.0 keV/2.0–13.3 keV). Examples of the three states can be identified as follows: quiescent state, $T \sim 400$–800; outburst state, $T \sim 800$–1200; flaring state, $T \sim 1200$–1700.

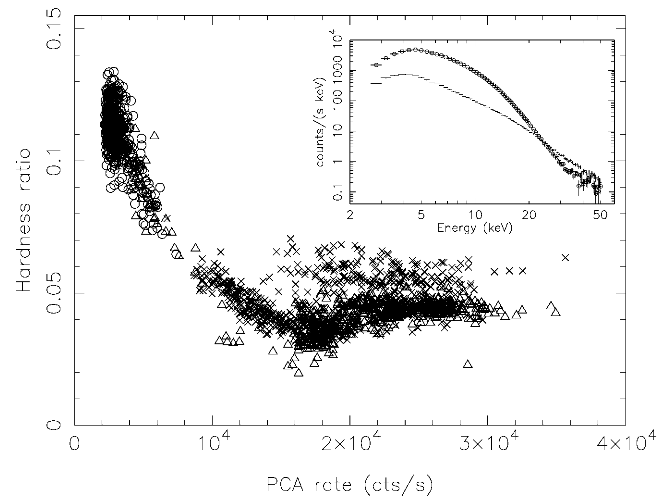

FIG. 2.—Hardness-intensity diagram for the data in Fig. 1. Rate and hardness ratio are defined as in Fig. 1. *Inset*: PCA energy spectra for the average quiescent (*points*) and outburst (*circles*) states.

and 0.8, respectively) with a "standard" model for black hole candidates, consisting of a multitemperature disk-blackbody plus a power law (Mitsuda et al. 1984). The addition of an iron line plus absorption edge was necessary to fit the data around 6 keV. All fits were performed in the range 2–50 keV, and a 1% systematic uncertainty was added to the data to account for the uncertainties in the response matrix calibration (Cui et al. 1997). The best-fit parameters, using the known distance and inclination (we assume that the latter is the same as the inclination of the radio jets to the line of sight), are shown in Table 1. For the outburst state we find a column density $N_H = 8.0 \times 10^{22}$ cm^{-2}, somewhat higher than the *ROSAT* value (6×10^{22} cm^{-2}; see Greiner et al. 1996). For the quiescent state we have fixed N_H to the outburst value. The marked spectral changes between quiescence and outburst are due to a steepening of the power-law component and a large change in the temperature of the disk-blackbody. From additional fits to other parts of the light curve and to other observations, we find that while the power-law index can assume values anywhere in the range 2.3–3.9, the inner temperature of the disk-blackbody component switches between two values: about 0.5 keV, which corresponds to an inner radius of several hundred kilometers, and about 2.2 keV, with an inner radius of about 20 km. This hot disk component switches on at count rates larger than 20,000 counts s^{-1} (see Fig. 2), even during the brief peaks of the oscillating events in the flaring state. Below 20,000 counts s^{-1}, the hardness ratio changes in Figure 2 are due primarily to changes in the power-law index.

By looking at the light curve in Figure 1 at high time resolution, one sees that the fastest rise and fall times for the flare state remain constant. The shortest doubling rise times are about 2 s, while the corresponding shortest decay times are significantly less, i.e., 0.5–1.0 s. Two further characteristic timescales apparent in the X-ray light curve (see Fig. 1) are the duration of the quiescent state and of a complete quiescent-outburst-flare cycle. For the light curve plotted in Fig. 1, these are approximately 300 and 1000 s, respectively.

3. INTERPRETATION

If we take the simplest possible interpretation of the multitemperature blackbodies, i.e., as the emission from optically thick regions of an accretion disk around a compact object of mass M, we have $R_{\mathrm{in},v} \simeq 20$ km for the brightest state of the varying source, and $R_{\mathrm{in},c} \sim 300$ km for the constant source. From R_{in} and T_{in} we can infer the mass accretion rate according to

$$\dot{M} = 8\pi R_{\mathrm{in}}^3 \sigma T_{\mathrm{in}}^4 / 3GM. \quad (1)$$

$R_{\mathrm{in},v}$ cannot be smaller than the innermost stable orbit around a black hole. This gives $M \lesssim 2.4\, M_\odot$, $\dot{M} \gtrsim 1 \times 10^{-7}\, M_\odot$ yr^{-1}

TABLE 1

BEST-FIT PARAMETERS FOR OCTOBER 7 QUIESCENCE AND OUTBURST SPECTRA

State	N_H	kT_{in}	R_{in}	Γ	Disk-Blackbody Flux	Power-Law Flux
Quiescence..........	8.0	0.57 ± 0.03	319 ± 9	2.22 ± 0.05	(0.96 ± 0.01) × 10^{-8}	(0.80 ± 0.03) × 10^{-8}
Outburst............	8.0 d± 0.5	2.27 ± 0.03	20.3 ± 0.3	3.57 ± 0.03	(3.99 ± 0.07) × 10^{-8}	(4.65 ± 0.22) × 10^{-8}

NOTES.—Best-fit parameters for the quiescence and outburst spectra of October 7. N_H is the column absorption in 10^{22} cm^{-2}, kT_{in} is the inner temperature of the disk-blackbody (in keV), R_{in} is the inner radius in km, Γ is the power-law photon index. The (unabsorbed) fluxes are in units of ergs cm^{-2} s^{-1} in the 2–50 keV band.

in outburst and $\dot{M} \gtrsim 6.8 \times 10^{-7}\ M_{\odot}\ \mathrm{yr}^{-1}$ in quiescence for a Schwarzschild hole ($R_{\mathrm{in},\nu} \geq 6GM/c^2$). For an extreme Kerr hole we have $R_{\mathrm{in},\nu} \geq GM/c^2$, so $M < 14\ M_{\odot}$, and $\dot{M} \gtrsim 1.5 \times 10^{-8}\ M_{\odot}\ \mathrm{yr}^{-1}$ in outburst and $\dot{M} \gtrsim 1 \times 10^{-7}\ M_{\odot}\ \mathrm{yr}^{-1}$ in quiescence. The fact that the inferred accretion rates anticorrelate with the total luminosity implies that the accretion yield is lower when the accretion rate is high. This can be accomplished by the trapping of the radiation and quasi-spherical infall ("advection") of the accretion energy into a black hole (see Katz 1977; Begelman 1978; Narayan 1996). We shall see that the disk interpretation indeed suggests that just this occurs.

We arrive at the following picture. The "constant" source is the emission from the outer parts of the accretion disk. This component varies only on the long viscous timescales characteristic of the outer disk. The varying source is the emission from the inner disk region and from a hot Comptonizing corona above the disk, whose spectrum varies in response to changes in the disk continuum. As we shall explain below, the inner disk region empties and refills on timescales of seconds, thus causing the rapid flux and spectral changes. Radiation pressure becomes important in the inner region: it exceeds gas pressure for disk radii

$$R \lesssim 10^8 \alpha^{0.1} \dot{M}_{18}^{0.8} M_{10}^{-0.14}\ \mathrm{cm} \qquad (2)$$

(see Frank, King, & Raine 1992). Here α is the Shakura-Sunyaev viscosity parameter, $\dot{M}_{18}$ is the accretion rate in units of $10^{18}\ \mathrm{g\ s}^{-1}$, and M_{10} is the black hole mass in units of $10\ M_{\odot}$. In such regions the disk scale height H is almost constant with radius, so that

$$\frac{H}{R} \simeq 0.15 \dot{M}_{18} R_7^{-1} \qquad (3)$$

(see Frank, King, & Raine 1992), and the thin disk approximation necessarily breaks down near the inner edge of the disk ($R_7 \sim 0.1$). Here R_7 is the radial coordinate in units of 10^7 cm.

Thermal balance at a given radius of a disk can be expressed in terms of a relation between the local accretion rate $\dot{M}$ and the surface density Σ. It is well known that for regions with $P_{\mathrm{rad}} \sim P_{\mathrm{gas}}$, the $\dot{M}(\Sigma)$ curve has a branch with a negative slope, which is thus thermally and viscously unstable (Lightman & Eardley 1974). As pointed out by Abramowicz et al. (1988), Lasota & Pelat (1991), and Chen et al. (1995), inward advection of the hot gas in the high $\dot{M}$ state is likely to stabilize the system. This leads to an S-shaped thermal balance curve in the $\dot{M} - \Sigma$ plane, at typical disk effective temperatures of about a few ($\times 10^6$) K on the lower branch. This is very similar to the familiar thermal balance curve found near the hydrogen ionization temperature of about 10^4 K in dwarf nova disks. In the same way as there, the disk is locally thermally stable on the branches with positive slope and locally unstable on the middle branch with negative slope. We obviously again have the possibility of limit-cycle behavior, this time only in central regions of the disk with temperatures exceeding a few million degrees. Cannizzo (1996) has modeled the variability of the bursting pulsar GRO J1744−28 (Kouveliotou et al. 1996) in these terms. For that source the large assumed value of the inner disk radius (because of the neutron star magnetic field) leads to much longer timescales than for GRS 1915+105. We note that the Lightman-Eardley instability is only expected to operate inside the radius given by equation (2), which indeed is close to the inner radius that we estimate for the "constant" source.

Since the upper branch of the S-curve involves physics that is currently unclear, we confine ourselves to estimating the timescales of the X-ray variation. After an outburst, the outer disk attempts to refill the central disk via steady inflow on its viscous timescale, initially causing the slow recovery during the quiescent phase. A brightness rise occurs as a heating wave propagates outward into the central disk from its inner edge before it has been refilled to a steady state density profile. The hot radiating matter is removed by infall into the central black hole on the effective viscous time in the outbursting state. The latter time is not well known, as the thin disk approximation fails in this state. Heating fronts and infall can alternate many times in the flaring state, before the central disk eventually returns to the quiescent state. The whole cycle repeats roughly on the viscous time of the outer disk.

We can estimate the expected timescales as follows. The rise time is the time for the heating wave to pass through the central disk. Assuming that the heating front travels with subsonic velocity, the sound speed c_S being calculated in the cool ($\lesssim 6 \times 10^6$ K) disk state, we get

$$t_{\mathrm{rise}} \gtrsim \frac{R_{\mathrm{out}}}{c_S} \simeq 1 R_{\mathrm{out},7}\ \mathrm{s}, \qquad (4)$$

where $R_{\mathrm{out},7} = R_{\mathrm{out}}/10^7$ cm. The decay time cannot be shorter than the free-fall timescale, giving

$$t_{\mathrm{decay}} \gtrsim 0.03 R_{\mathrm{out},7}^{3/2} M_{10}^{-1/2}\ \mathrm{s}\,. \qquad (5)$$

The whole cycle should repeat roughly on the viscous timescale at the outer edge of the central disk, i.e.,

$$t_{\mathrm{rec}} = \frac{R^2}{\nu} = \frac{R}{H}\frac{R}{\alpha c_S} = 6\alpha^{-1}\dot{M}_{18}^{-1} R_7^2\ \mathrm{s}, \qquad (6)$$

where we have written the kinematic viscosity as $\nu = \alpha c_s H$ and used equations (3) and (4). We note that equations (4) and (5) are in rough agreement with the observed rise and decay times of about 2 and 0.5 s, while typical values $\alpha \sim 10^{-2}$ assumed for quiescent disks imply recurrence times of about $600 R_7^2$ s, quite close to the observed values. Note that the X-ray rise and fall episodes differ from the case considered by Cannizzo (1996). There the infall onto the central neutron star is the process that raises the X-ray production rate, whereas here infall causes hot matter to be lost down the black hole, leading eventually to a decay of the X-rays.

We note that the several features of the X-ray light curves strongly resemble the results of dwarf nova disk instability calculations. Even though the basic cause of the instability differs here, the general picture of heating and cooling fronts traveling back and forth leads us to expect generic similarities. In particular, alternating wide and narrow outbursts, and series of narrow outbursts followed by a wide one, are common features (see Van Paradijs 1983 for the outburst width distribution for dwarf novae). These typically result when the heating wave stalls before crossing the entire unstable region. Similarly, a generic prediction of this type of model comes from the fact that the rise and decay episodes are fundamentally asymmetric. When observed with high enough time resolution, the system should perform a hysteresis loop in an X-ray color-color diagram. Unfortunately, the large variations in the power-law component do not currently allow one to draw a conclusion from simple color-color plots. The accumulation of high time resolution energy spectra, not available in the current data, will allow one to test for the presence of such a hysteresis loop. A full quantitative discussion will be presented in a future paper.

The extremely high values of the mass accretion rate we infer from the spectral fits in the quiescent state do not lead to a correspondingly high X-ray luminosity generation in the inner disk (with a canonical efficiency of 0.2 c^2 g^{-1}, one would have expected an X-ray luminosity in excess of 10^{40} ergs s^{-1}). This indicates that a major fraction of the gravitational energy released in the inner disk is not emitted as radiation, suggestive of advection into a black hole. Assuming that the accretion rates derived from our spectral model are essentially correct and that ejection is relatively unimportant, a substantial fraction of the inflow disappears into the central object without broadcasting a signal to the outside world. This supports the idea that it does not have a solid surface and thus has the most characteristic property of a black hole. We note that the interpretation proposed in this Letter depends on the spectral model we have used. We emphasize that at this point it is difficult to exclude absolutely the possibility that the compact object in GRS 1915+105 is a neutron star, as the study of X-ray spectra of neutron stars accreting at a hyper-Eddington rate is fairly unexplored. However, a black hole surrounded by an optically thick accretion disk of variable inner radius provides a natural explanation for the otherwise apparently intractable phenomenology presented by GRS 1915+105.

It is improbable that the high inferred accretion rate represents the high state of some much longer term instability in the outer disk. It seems more likely that the mass transfer rate is always very high, and that the outbursts of GRS 1915+105 are not caused by an increase of the mass transfer rate, but quite possibly by a decrease from a value high enough to smother the X-ray emission. In the smothered state, the object would then appear only as a bright infrared source. Average mass transfer rates of the required order (10^{-7}–10^{-6} $M_\odot$ yr^{-1}) can easily be supplied, for example, by a donor star crossing the Hertzsprung gap and thus undergoing thermal timescale radius expansion (Kolb et al. 1997).

M. M. is a fellow of the Consejo Nacional de Investigaciones Científicas y Técnicas de la República Argentina. This work was supported in part by the Netherlands Organization for Scientific Research (NWO) under grant PGS 78-277 and the Netherlands Foundation for Research in Astronomy (ASTRON) under grant 781-76-017. A. R. K. gratefully acknowledges a PPARC Senior Fellowship and the hospitality of the Astronomical Institute "A. Pannekoek" at University of Amsterdam. J. V. P. acknowledges support from NASA under contract NAG 5-3003. We thank Keith Jahoda for helping with the calibration of the PCA data, and the *RXTE* team for making these data publicly available.

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