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Super-Eddington Accretion in GRS 1915+105

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Abstract. Classical modeling suggests that, during the RXTE observations studied, GRS 1915+105 was near or above the critical accretion rate and the optically thick inner disk penetrated inside the advection-dominated flow. The system was very unstable leading to a rich pattern of variability, e.g. the *rings* which might be characteristic to disk instabilities very close to the innermost stable orbit. Small values of R_{in} obtained require a rapidly rotating Kerr hole, unless the central mass is smaller than 2-3 $M_{\odot}$. A thermal sombrero provides a reasonable modeling of the rings, although the broad-band RXTE/OSSE spectrum analyzed seems to require a significant injection of relativistic electrons, the hot phase being not a pure thermal one. Observations below 2 keV and simultaneous broad-band spectra between 2–400 keV are needed to better fix the size of the black body disk and the role of relativistic injection. Further, theoretical work on emerging spectra of Kerr-holes is required to replace the classical model used.

1. Introduction

The Galactic X-ray transient GRS 1915+105 was discovered by Castro-Tirado, Brandt & Lund (1992). After Mirabel and Rodriguez (1994) found superluminal jets in this black hole candidate, it received the nickname ‘microquasar’. A rich pattern of X-ray variability has emerged from the Rossi X-ray Timing Explorer (RXTE) showing a great potential to study accretion phenomena close to a black hole (e.g. Greiner et al. 1996; Morgan et al. 1997; Chen et al. 1997; Taam et al. 1997; Belloni et al. 1997a,b; Markwardt 1997; Vilhu and Nevalainen 1998).

In the present paper I discuss important parameters of the accretion theory, the accretion rate and the inner disk radius, as derived from classical disk models and RXTE observations. Two-phase thermal modeling of the *rings* discovered by Vilhu and Nevalainen (1998) is also presented.

2. Accretion Rate and Inner Disk Radius

Several RXTE/PCA observations (see the vertical lines in Figure 1) were analyzed using the DISKBB + POWER LAW model of the XSPEC software (Vilhu and Nikula, in prep.) . The disk model assumes that the viscously released energy is radiated away locally, without any advection (see Frank et al. 1992). Temperature scales with radius as $T = T_{in}(r/r_{in})^{-3/4}$ and the mass accretion rate

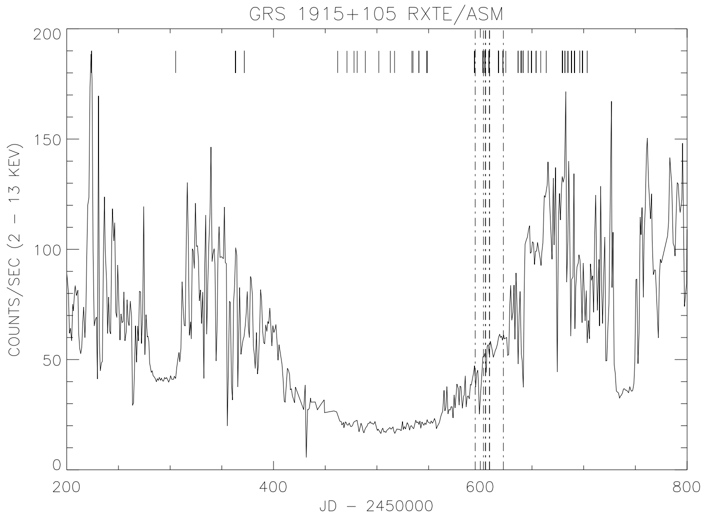

Figure 1. The RXTE/ASM light curve (2–13 keV) of GRS 1915+105. The ring-observations are marked with vertical dashed lines. The short lines show those PCA observations used to construct Fig. 2.

is given by $\dot{M} = 8\pi R_*^3 \sigma T_*^4/3GM$ where $T_{in} = 0.5T_*$ and $r_{in} = 49r_*/36$. This modeling is consistent with the disk luminosity $L_{disk} = \eta \dot{M} c^2$ **if** the radiation efficiency is computed from $\eta = 0.12(r_{in}/r_g)^{-1}$ where $r_g = 2GM/c^2$ is the gravitational radius. (At $3r_g$ this gives an efficiency 0.04 which is not far from 0.057 estimated by Zycki et al. 1997.) Further, we define the Eddington luminosity and accretion rate as $L_E = 4\pi GMm_pc/\sigma_T$ and $\dot{M}_E = L_E/c^2$, respectively.

The results of this classical modeling are shown in Figure 2 (r_{in} in units of r_g and $\dot{M}$ in units of M_E of $10M_\odot$). Due to advection, the accretion rates are probably lower limits. Further studies of realistic disk models and their 'skin' spectra should confirm (or disprove) the small inner disk radii derived from this classical treatment (being as small as 15 km). First attempts in this direction have already been taken by e.g. Beloborodov (1998). However, the present results indicate that the inner disk reaches $0.5r_g$ if the mass is $10M_\odot$ and $3r_g$ in the case of $1.5M_\odot$. In the more massive case we clearly need a rotating Kerr-hole which would not be a surprise due to the existence of jets. (Note that the innermost stable orbits are at $3r_g$ and $0.5r_g$ for non-rotating Schwarzschild and extreme Kerr holes, respectively.)

In the $10M_\odot$ case the inner disk lies inside the trapping radius where a significant part of the energy is advected to the black hole instead of being radiated away (see Beloborodov 1998). The only solution allowed is the advection-dominated flow (see Chen et al. 1995). How it can also contain an optically thick component (as indicated by the results presented here) remains to be studied. However, the solution must be very unstable due to the high variability seen

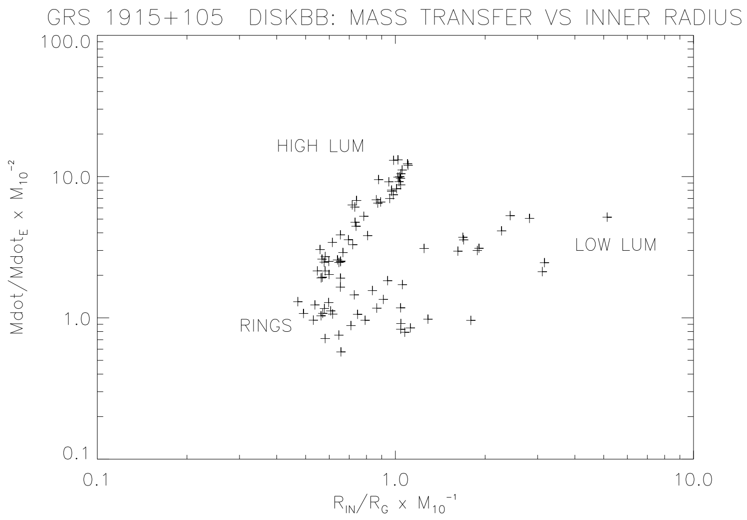

Figure 2. Results from classical disk modeling of observations marked in Fig. 1. Along the boomerang-shaped pattern (from LOW LUM to HIGH LUM) the disk luminosity, the PL-luminosity, the inner disk temperature and the photon index vary between 0.1 - 2.5 L_E, 0.2 - 0.6 L_E, 0.5 - 2.5 keV and 2.2 - 3.5, respectively ($10 M_\odot$) .

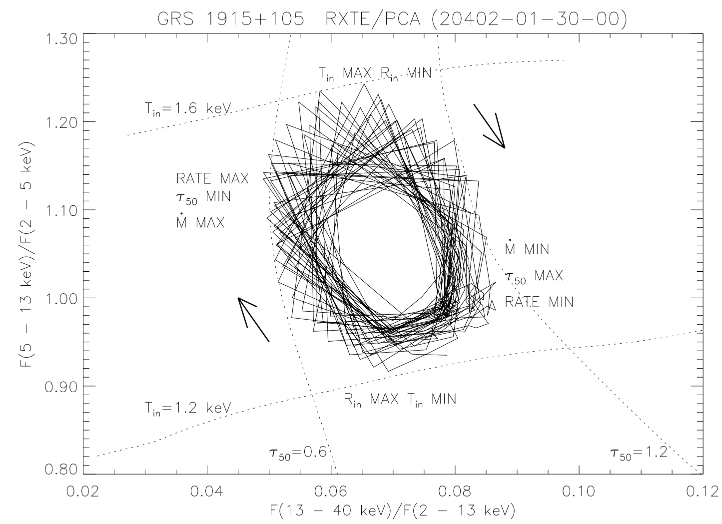

Figure 3. A ring-observation plotted in the 2-color diagram with 16 sec time-binning (from Vilhu and Nevalainen 1998). The big arrows show the clock-wise evolution with a 97 s mean cycle period. 2-phase model curves (thermal sombrero) are overplotted with dotted lines.

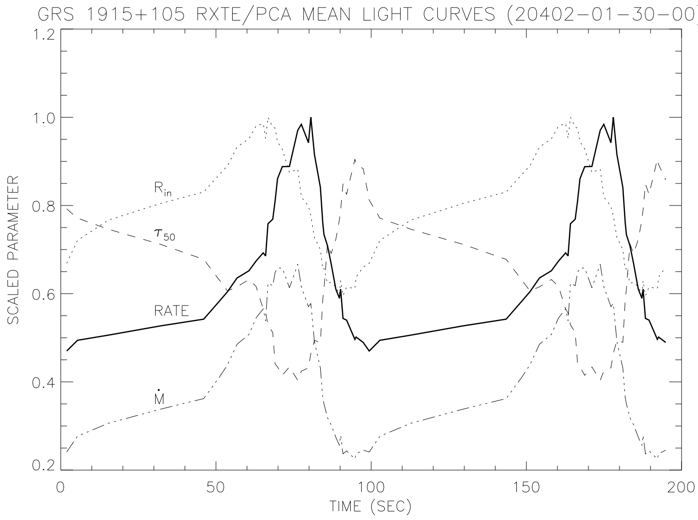

Figure 4. Mean light curves over one cycle for the observation of Figure 3. The parameters are scaled by the following values (in parentheses): RATE (15000 cts/s (5 PCU units), solid line), R_{in} (30 km, dotted line), $\tau_{50} = \tau(T_e/50)$ (1.4, dashed line) and $\dot{M}(3L_E/c^2$ of $10M_\odot$, dash-dotted line).

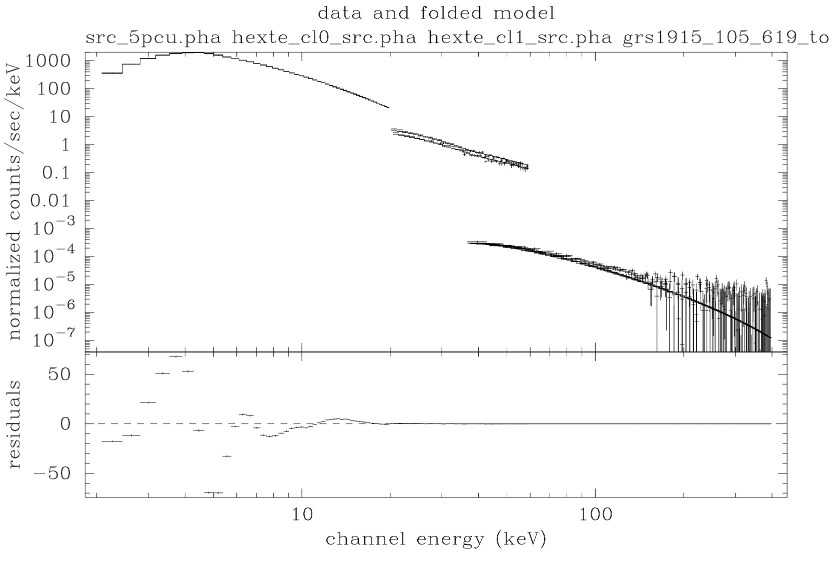

Figure 5. An average ring spectrum (RXTE/PCA/HEXTE and CGRO/OSSE) with a thermal sombrero fit. The high residuals between 4-5 keV are due to the istrumental artefact caused by the Xe L-edge of the PCA. The high energy tail clearly requires an additional injection of non-thermal relativistic electrons.

in all time scales from months to seconds. In the next Section we discuss one special type of variability.

3. Rings

Vilhu and Nevalainen (1998) found a peculiar X-ray variability in a narrow range of luminosity and called them *rings* (see the dashed lines in Figure 1). In Figure 2 the rings are situated at the knee of the V-type pattern (at smallest accretion rates and smallest inner disk radii). This variability was found as a ring-shaped pattern in the two-color diagram of count rates, where the hard hardness F(13-40keV)/F(2-13keV) is plotted against the soft hardness F(5-13keV)/F(2-5keV). The system runs one cycle with periods ranging between 50–100 s for different observations, one rotation in the 2-color diagram corresponding to the time between two contiguous maxima in the light curve.

An example of such a behavior is shown in Figures 3 and 4 and modeled with a thermal sombrero-model (see Poutanen 1998), where the optically thick classical disk penetrates into the spherical hot corona (the ISMBB model in our XSPEC). This geometry is similar to that of the popular advection-dominated accretion flow (see e.g. Esin et al. 1997). The model is basically the same as in the previous Section, except that the power-law is physically explained by Comptonization of soft disk photons in the central spherical hot phase. During these particular observations the inner disk radius varied with a 97 s period between 20–35 km with an anticorrelation between the coronal τT_e and the mass accretion rate $\dot{M}$, possibly indicating a coupling between the disk and coronal accretion.

To check the thermal/non-thermal nature of the radiation, one has to look at the hard part of the spectrum. Figure 5 shows such an average ring-spectrum which occasionally had nearly simultaneous OSSE/CGRO observations available (from Vilhu et al. 1998). A moderate fit with a thermal sombrero gave: $N_H = 2.27 \cdot 10^{22}$ cm^{-2}, T_{in}=1.57 keV, T_{cor}=68 keV and τ_{cor}=0.67, compatible with those found from the model curves of Figure 3. It can be seen that the thermal model alone does not reproduce well the hard part of the spectrum. Due to this hard tail, the electron distribution probably deviates from the Maxwellian one. A fraction of the energy input could be injected in the form of relativistic electrons (pairs). In the EQPAIR-model (again in the XSPEC software) this is allowed in addition to the direct heating of thermal electrons (Coppi et al. 1998). Using this model for the observations of Figure 5, the non-thermal efficiency becomes 28 % ($l_{nth}/l_h = 0.28$) while the ratio of the soft and hard compactnesses l_h/l_s equals 0.36. Most importantly, the fit is much better than in the case of the thermal sombrero.

4. Discussion

Using classical modeling for the RXTE data suggests that, during the observations studied, GRS 1915+105 was above or near the critical accretion rate where the accretion luminosity exceeds the Eddington one. The optically thick inner disk penetrated inside the advection-dominated inner trapping flow. The system is very unstable leading to a rich pattern of variability, e.g. the *rings*.

The ring-behavior might be characteristic to disk instabilities very close to the innermost stable orbit, where the relativistic potential barrier is small and just a small change in angular momentum leads to accretion through the horizon. However, the minimum values of r_{in} obtained (20 km) are too small for a non-rotating black hole and require a rapidly rotating one, unless the central mass is smaller than 2-3 $M_{\odot}$. Rapid rotation of the hole might be the energy reservoir for the blobs (jets) ejected frequently at almost the velocity of light.

Broad band X/γ ray spectra of black hole candidates have revealed that the radiation processes can be explained in terms of a disk black body and successive Compton scatterings of soft photons (Comptonization) in a hot electron cloud surrounding the object. However, the broad-band spectrum analyzed seems to require a significant injection of relativistic electrons, so the hot phase is not a pure thermal one.

One can safely conclude that observations below 2 keV and more simultaneous broad-band spectra between 2–400 keV are needed to better fix the size of the inner disk and the role of relativistic injection. Future satellites, such as XMM, SRG and INTEGRAL, are well tailored for these kinds of observations. In addition, theoretical work on 'skin'-spectra of Kerr-holes are necessarily required to replace the classical models used in the present paper.

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