Comptonization, the X-ray-radio correlation and the long-term periodicity in the $\chi$-states of GRS 1915+105

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Abstract. We analyzed 139 $\chi$-state observations of GRS 1915+105 with RXTE from 1997 to 2000 and found i) that the observations fall into two groups with different Comptonization behavior, ii) that the slope of the hard X-ray component correlates with the radio flux, thus revealing the interaction of jet and corona, and iii) a 590 days long term periodicity in the hard X-ray and radio components.

1. Introduction

The prototypical microquasar GRS 1915+105 was discovered by Granat [1] as a transient X-ray source. RXTE observations revealed astonishing X-ray variability [2] which has been classified by Belloni et al. [3] into twelve different X-ray states. The analysis presented here is based on the data reduction described in full detail in Rau & Greiner [4]. We analyzed 139 observations from 89 days from the RXTE public archive of GRS 1915+105 from November 1996 to September 2000, when the source was in the $\chi$-state [3]. The absence of large amplitude variations and structured variability in these states suggests quasi-stable geometry and parameters during each observation and allows to fit the spectrum of an entire observation at once. $\chi$-states are connected with radio emission of varying strength and the most common states observed.

From each observation we used data from PCU0 and HEXTE cluster 0 and fitted these with a model consisting of cold absorption (WABS), a disk blackbody (DISKBB) and a power-law spectrum reflected from an ionized relativistic accretion disk (REFSCH [5],[6]) in XSPEC [7]. Energies between 4 and 8.5 keV were ignored during the fitting process because of the known response problems of the PCA at these energies. The hydrogen column density was fixed at $N_H=5\cdot10^{22}$ cm$^{-2}$.

Our model implies obvious simplifications, e.g. compared to the theoretical Comptonization models the power law overestimates the flux at low energies. Despite the simplicity of the three component model, we achieved surprisingly good fit results for our sample of $\chi$-state observations (reduced $\chi^2<2$ for all and $\chi^2<1.1$ for more than 60% of the observations).

2. Comptonization of the X-ray radiation

Two main models for the origin of the hard power-law tail in X-ray binaries exist. i) the bulk motion Comptonization [8],[9], where the soft disk photons are inverse Compton scattered on a cloud of free falling, hot electrons inside the last inner stable orbit around the black hole and ii) the disk corona geometry (e.g.
where the soft seed photons are scattered on a distribution of hot electrons located above the accretion disk.

The bulk motion model predicts a time lag between hard and soft X-ray photons of $\sim 0.2 \text{ ms}$, much smaller than the observed time lags of $0.1 \text{ s}$ [10], [4]. This rules out the bulk motion Comptonization as the origin of the hard X-ray photons in the $\chi$-states of GRS 1915+105. Therefore, the disk corona is the most probable geometry. It is still unresolved if the hard power law tail continuous up to the MeV-range or if the spectrum cuts off. The electron distribution can either be thermal, non-thermal or hybrid. The absence of a clear cut off in the RXTE spectra however, requires high coronal temperatures ($\sim 200 \text{ keV}$) and an optical depth, $\tau_T \ll 1$.

The analysis shows a bimodal distribution of an increasing normalization, $K_{po}$, with increasing slope, $\Gamma$, of the power law (Fig. 1), suggesting a pivoting of the hard X-ray tail. Pivoting was recently found also in Cyg X-1 [12] and can be explained by a variation in the flux of the soft seed photons or in the size of the corona. Assuming constant $\tau_T$, if the amount of intercepted soft seed photons is high, the electrons in the corona are cooled efficiently and the hard X-ray spectrum is steep. On the other hand, if the soft seed flux decreases, the temperature of the corona increases and the spectrum hardens.

The two branches in Fig. 1 represent observations during which long radio flares occurred (upper) and observations of times with short radio flares or without radio emission (lower) [4]. Therefore, the different Comptonization behavior results probably from a difference in the optical depth or in the electron composition (thermal, hybrid).

![Figure 1. Power law slope, $\Gamma$, as a function of power law normalization, $K_{po}$. Each RXTE observation is represented by one data point. (dotted lines: correlation function)](image)

3. Correlation of X-ray and radio emission

We analyzed 39 Ryle Telescope, RT, (15 GHz) and 9 Green Bank Interferometer, GBI, (2.25 & 8.3 GHz) observations taken simultaneously with the RXTE observations and searched for correlations in all model parameters and fluxes. No correlation is seen between the soft X-ray and radio components. Instead, the slope of the hard power law tail correlates with the radio flux, $F_R$. (Fig. 2).

It is generally assumed that both the radio jets [13], [14] and the hard spectral component originate near the black hole. Similar to the interpretation of the
pivoting behavior of the X-ray spectra, an increasing outflow of matter implies an increasing size of the scattering medium and therefore an increasing amount of intercepted soft seed photons. This leads to a lower plasma temperature due to cooling and to a softer X-ray spectrum.

This suggests the following scenario: when the radio emission is weak or absent, the Comptonization takes place in the corona above the accretion disk. With increasing outflow (higher radio emission) the matter in the jet intermingles with the corona. At high outflow rate the corona is blown away and the soft seed photons are scattered on the base of the jet [14], [4].

4. Long term periodicity

The analysis of the X-ray model parameters for all $\chi$-state observations of GRS 1915+105 reveals a remarkably periodic behavior of the hard X-ray component, for example the power law slope (see Fig. 4 in [4]). An analysis of variance for several model parameters and X-ray and radio fluxes was performed using the Fisher-Snedecor distribution function [15]. It shows a maximum at a period of $590\pm40$ (FWHM) days in the hard X-ray components and in the radio fluxes of $RT$ and $GBI$ [16]. This confirms the 19 month periodicity which was already briefly mentioned by Kuulkers et al. [17].

Fig. 4 shows the power law slope (left) and the $GBI$ radio flux at 2.25 GHz in periods of 590 days. Where $\Gamma$ has a quasi-sinusoidal behavior the periodicity in the radion flux is visible in the radio outbursts. Both the broad outburst with exponential cutoff at phase $\sim0.2$ and the shorter and steeper outbursts repeat periodically.

Long-term periodicity in X-ray binaries is known since more than two decades [18] and radiation-driven warping of the accretion disk is the generally assumed mechanism for the periodicity in low-mass X-ray binaries [19], [20]. The outer, tilted part of the accretion disk is irradiated by the central source. If the radiation is absorbed and re-emitted parallel to the local disk gradient, a torque due to gas pressure affects the disk. A small warp grows exponentially if the luminosity is sufficient to depress the dissipative processes forcing the disk back into the orbital plane [19].

The periodicity accrues because the Roche lobe overflow of the donor star hits the not co-rotating accretion disk at different disk radii during an orbital cycle. This leads to regions in the disk with differing mass density. The radial flow in the inner part of the accretion disk is therefore not homogeneous leading to a periodic variation of the amount of soft seed photons being comptonized in the corona. Therefore, the electron temperature in the corona varies on the same time scale due to Compton cooling and the power law slope varies. The amount of matter to be ejected in a jet changes with similar periodicity which explains the overall periodicity in the radio flux.
Figure 3. Power law slope of 139 χ-state observations (left) and 2.25 GHz radio flux (right) from JD 2450350–2450940, JD 2450940–2451530 and JD 2451530–2452120 (top to bottom) in periods of 590 days. The solid lines visualize the best fitting sinusoidal function (left) and illustrate the repeating outbursts in the radio flux (right).

The soft X-ray component (ASM count rate & hardness ratios, soft model components) do not show any periodicity in the χ-state observations. The periodicity can simply be masked by the high short term variability in timing and spectral behavior of GRS 1915+105.

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