ON THE TWO TYPES OF STEADY HARD X-RAY STATES OF GRS 1915+105

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ABSTRACT

Using data from five years of Rossi X-Ray Timing Explorer observations, we investigate the X-ray spectral and timing properties of GRS 1915+105 during the hard steady states. The broadband energy spectrum of the source during these periods is dominated by an extended hard component with a characteristic cutoff or break at \( \sim 10-120 \) keV. The power density spectrum of the source's rapid aperiodic variability shows a dominant band-limited white-noise component breaking at a few hertz, accompanied by a group of strong quasi-periodic oscillation peaks and in some cases an additional high-frequency noise component with a characteristic cutoff at \( \sim 60-80 \) Hz. According to the results of our simultaneous X-ray spectral and timing analysis, the behavior of the source during the hard steady states can be reduced to two major, distinct types. (1) Type I states: The dominant hard component of the energy spectrum has characteristic quasi-exponential cutoff at 60–120 keV. The broadband power density spectrum of the source shows a significant high-frequency noise component with a cutoff at \( \sim 60-80 \) Hz. (2) Type II states: The hard spectral component has a break in its slope at \( \sim 12-20 \) keV. The high-frequency part of the power density spectrum fades quickly, lacking significant variability at frequencies higher than \( \sim 30 \) Hz. These two types of X-ray hard states are also clearly distinguished by their properties in the radio band: while during the type I observations the source tends to be "radio quiet," the type II observations are characterized by a high level of radio flux ("plateau" radio states). In this work we demonstrate the aforementioned differences using data from 12 representative hard steady state observations. We conclude that the difference between these two types can probably be explained in terms of a difference in accretion flow structure in the immediate vicinity of the compact object due to the presence of relativistic outflow of matter.

Subject headings: black hole physics — stars: individual (GRS 1915+105) — X-rays: stars

1. INTRODUCTION

The X-ray source GRS 1915+105, the first Galactic object found to generate superluminal jets (Mirabel & Rodriguez 1994), was discovered by the GRANAT observatory as a transient in 1992 (Castro-Tirado, Brandt, & Lund 1992). Long-term monitoring of GRS 1915+105 with the Rossi X-Ray Timing Explorer (RXTE) satellite (Bradt, Swank, & Rothschild 1993) has revealed a rich character of the source transient activity associated with different levels of its luminosity, which can be reduced to the sequence of varying soft steady, flaring, and hard steady states qualitatively distinguished by their spectral and temporal properties (Greiner, Morgan, & Remillard 1996; Trudolyubov, Churazov, & Gilfanov 1999a; Muno, Morgan, & Remillard 1999). It has been demonstrated that the major spectral and temporal properties of the source during these periods are similar to that of the Galactic black hole candidates in the "canonical" spectral states (Chen, Swank, & Taam 1997; Taam, Chen, & Swank 1997; Trudolyubov et al. 1999a).

For almost half the observation time, the source demonstrates steady periods characterized by a relatively hard broadband X-ray spectrum and X-ray luminosity of \( \sim (1-6) \times 10^{38} \) erg s\(^{-1}\) (assuming a source distance of 12.5 kpc)—i.e., hard steady states (Muno et al. 1999; Belloni et al. 2000). In general, the energy spectrum of GRS 1915+105 during these periods can be approximated by a sum of the weak soft thermal component with characteristic color temperature \( \sim 1 \) keV and the dominant extended hard component with turnover at high energies (Fig. 1; Trudolyubov et al. 1999a; Muno et al. 1999). The variation of the X-ray flux on the timescale of an individual observation does not exceed \( \sim 20\% \). The power density spectrum (PDS) of the source is dominated by a strong band-limited white-noise (BLN) component accompanied by a system of quasi-periodic oscillation (QPO) peaks with centroid frequencies of several hertz (Fig. 2; Morgan, Remillard, & Greiner 1997; Chen et al. 1997; Trudolyubov et al. 1999a). The pattern of correlation between X-ray and radio emission of the source is complicated: alternating periods of high- (so-called plateau states) and low-level radio emission associated with hard steady states have been reported (Foster et al. 1996; Fender et al. 1999; Muno et al. 1999).

In this work we demonstrate that the source shows two distinct branches of the hard steady state (hereafter type I and type II) distinguished by the properties of their energy spectra, high-frequency X-ray variabilities, and levels of radio flux. We discuss the difference between these two types of hard steady states in the framework of the two-phase model of the inner part of the accretion flow involving the outflow from the immediate vicinity of the compact object.

2. OBSERVATIONS AND RESULTS

The RXTE satellite performed regular pointed observations of GRS 1915+105 during 1996–2000, providing good coverage for the detailed study of the spectral and timing properties of the source in the hard steady states. In Table 1 we list the groups of observations covering hard
steady states and individual representative observations used for the detailed analysis.

2.1. Spectral and Timing Analysis

For processing the Proportional Counter Array (PCA) and High-Energy X-Ray Timing Experiment (HEXTE) data, we used the standard RXTE FTOOLS (version 5.01) tasks and methods recommended by the RXTE Guest Observer Facility.

For spectral analysis, we used PCA Standard 2 mode data collected in the 3–20 keV energy range. The PCA response matrices for individual observations were constructed using PCARMF (version 7.01), and background estimation was performed applying a very large events-based model. A standard dead-time correction procedure has been applied to the PCA data. Owing to the uncertainties of the response matrix, a 1% systematic error was added to the statistical error for each PCA energy channel. We used the HEXTE response matrices, released on 1998 October 20, and subtracted background collected in off-source observations for each cluster of detectors. In order to account for the uncertainties in the response and background determination, only data in the 20–150 keV energy range were used for the spectral analysis. Typical examples of the broadband power spectra of GRS 1915+105 during the hard steady states in 1996–2000 are shown in Figure 1.

Since we are interested in the general properties of the source energy spectrum during the hard steady state, we used only simple models to approximate its spectra. For the first group of observations showing a hard spectra with clear cutoff at energies ~60–120 keV (Fig. 1, left panels), we used only HEXTE data in the 20–150 keV energy range and approximated them by a power law with an exponential cutoff (Table 2, top). For the remaining observations (Fig. 1, left panels), the data of PCA and HEXTE instruments covering the 3–150 keV energy range were approximated by an absorbed broken power law (Table 2, bottom). For all the cases, there was a distinct residual corresponding to the iron emission/absorption; thus, a Gaussian line profile and an absorption edge were included to refine the overall fit. An equivalent hydrogen absorbing column density was fixed at the level of \( N_H L = 5 \times 10^{22} \) cm\(^{-2}\).

For the timing analysis in the 2–30 keV energy range, the RXTE PCA data in the binned and event modes containing X-ray events below and above 13 keV, respectively, were used. We generated power density spectra in the 0.001–512 Hz frequency range, combining the results of the summed Fourier transforms of short stretches of data (8 s) with 0.001 s time bins for the 0.3–512 Hz frequency range and a single Fourier transform on the data in 0.125 s time bins for lower frequencies. The resulting spectra were logarithmically rebinned, when necessary, to reduce scatter at high frequencies and normalized to the square root of fractional variability rms. The white noise due to the Poissonian statistics, corrected for the dead-time effects, was subtracted (Zhang et al. 1995; Revnivtsev, Gilfanov, & Churazov 2000). Typical examples of the broadband power density spectra of GRS 1915+105 during the hard steady state (in units of \( f \times \text{rms/mean}^2 \); Belloni et al. 1997) are shown in Figure 2.

The broadband PDS of the source is dominated by a strong BLN component with at least two characteristic breaks (at ~0.1 and approximately a few Hz) and a complex of relatively narrow peaks of QPOs lying near the second break in the slope of the BLN continuum (Fig. 2). For some observations (Fig 2, left panels), the additional broad high-frequency component with a characteristic cutoff at ~60–80 Hz was also notable.

To quantify the properties of the source rapid aperiodic variability, PDSs in the 0.05–128 Hz frequency range were fitted to analytic models using a \( \chi^2 \) minimization technique. We used a combination of two BLN components (approximated by zero-centered Lorentzian functions) and several QPO features (presented by the Lorentzian functions). For some observations (Fig 2, left panels), an additional high-frequency noise component was approximated by a zero-centered Gaussian function with characteristic width of ~60–80 Hz. Parameters of the PDS approximation are presented in Table 3.

2.2. Two Types of X-Ray Hard Steady States

As seen from Figures 1 and 2, representative hard steady state observations can be subdivided into two distinct
classes with qualitatively different spectra and PDSs (see also Tables 2 and 3). In the following we summarize characteristic spectral and timing properties of both groups.

Type I states.—The energy spectrum is dominated by an extended power-law hard component with photon index $\alpha \sim 1.8-2.3$ and a quasi-exponential cutoff at $\sim 60-120$ keV (Fig. 1, left panels; see also Table 2). A broadband PDS shows a prominent noise component with an average integrated rms amplitude of $\sim 4\%-5\%$ and characteristic cutoff frequency of $\sim 60-80$ Hz, detectable up to $\sim 150$ Hz (Fig. 2, left panels; see also Table 3). An average total fractional rms amplitude of the rapid aperiodic variability in the 2–30 keV energy range is $\sim 22\%$ (Table 3).

Type II states.—The energy spectrum exhibits a clear break in power-law slope near $\sim 12-20$ keV. The high-energy part of the spectrum has a roughly power-law shape with an almost constant photon index of $\alpha \sim 3.2-3.3$, in spite of significant changes in the slope of the lower energy part (Fig. 1, right panels; see also Table 2). As in the case of type I states, the PDS of the source is dominated by BLN and QPO components with characteristic peaks at a few hertz. Contrary to the type I states, the high-frequency part of the PDS in the type II state fades quickly, lacking any significant variability above $\sim 30$ Hz (Fig. 2, right panels). For some observations, an additional noise component with characteristic cutoff at $\sim 15$ Hz was marginally detected (Table 3). The average total fractional rms amplitude of the rapid aperiodic variability in the 2–30 keV energy range is $\sim 5\%$ lower than during the type I state observations (Table 3).

2.3. Correlated Properties of X-Ray and Radio Emission

To trace the simultaneous evolution of GRS 1915+105 in radio band, we used publicly available data from Green...
interrupting hard steady states (Mirabel & Rodriguez 1994; Ñares associated with X-ray Ñaring states, occasionally the radio light curve correspond to the radio optically thin and radio light curves of the GRS 1915 (Foster et al. 1996). Figure 3 shows examples of the X-ray

| Date (UT) | Power-Law Index | Cutoff Energy (keV) | $\chi^2$ (dof) | Flux $^b$ |
|-----------|-----------------|--------------------|----------------|---------|
| 1996 Dec 19 | 2.22 ± 0.06 | 85 ± 15 | 130.0 (115) | 2.141 |
| 1997 Feb 9 | 1.83 ± 0.05 | 63 ± 5 | 185.5 (154) | 1.521 |
| 1998 Sep 11 | 2.20 ± 0.17 | 66 ± 11 | 35.6 (37) | 2.274 |
| 1998 Sep 25 | 2.04 ± 0.07 | 66 ± 7 | 75.8 (76) | 2.018 |
| 1999 Jan 1 | 2.17 ± 0.06 | 66 ± 8 | 176.2 (154) | 2.215 |
| 2000 Apr 23 | 2.23 ± 0.08 | 83 ± 14 | 78.7 (76) | 1.985 |

B. Type II$^c$

| Date (UT) | Power-Law Index | Break Energy (keV) | Power-Law Index | $\chi^2$ (dof) | Flux $^b$ |
|-----------|-----------------|--------------------|-----------------|----------------|---------|
| 1996 Jul 23 | 2.37 ± 0.01 | 14.0 ± 0.3 | 3.29 ± 0.01 | 237.3 (193) | 2.640 |
| 1996 Aug 14 | 2.75 ± 0.01 | 13.5 ± 0.5 | 3.33 ± 0.02 | 274.4 (233) | 2.487 |
| 1997 Oct 8 | 2.76 ± 0.01 | 15.9 ± 0.5 | 3.31 ± 0.02 | 161.8 (116) | 2.273 |
| 1997 Oct 22 | 2.48 ± 0.01 | 16.1 ± 0.1 | 3.21 ± 0.01 | 382.7 (233) | 2.053 |
| 1998 Apr 6 | 2.54 ± 0.01 | 13.1 ± 0.3 | 3.33 ± 0.02 | 274.8 (153) | 2.434 |
| 1998 May 24 | 2.38 ± 0.01 | 15.9 ± 0.1 | 3.23 ± 0.02 | 130.7 (116) | 2.190 |

Note.—Parameter errors correspond to the 1σ confidence level.

$^a$ HEXTE data in the 20–150 keV energy range with a power-law model with an exponential cutoff.

$^b$ Total energy flux in the 3–150 keV energy range in units of $10^{-8}$ ergs s$^{-1}$ cm$^{-2}$.

$^c$ PCA and HEXTE data in the 3–150 keV energy range with an absorbed broken power-law model.

Bank Interferometer monitoring observations at 8.3 GHz (Foster et al. 1996). Figure 3 shows examples of the X-ray and radio light curves of the GRS 1915 + 105 during the hard steady state in 1997–1998. The short “spikes” seen on the radio light curve correspond to the radio optically thin flares associated with X-ray flaring states, occasionally interrupting hard steady states (Mirabel & Rodriguez 1994; Fender et al. 1999).$^3$ We note that all periods of the type I X-ray hard steady state correspond to a low level of radio emission (the flux at 8.3 GHz is typically lower than 10–20

| Date (UT) | rms$_{tot}$ (%)| $f_{QPO}$ (Hz) | rms$_{QPO}$ (%) | $f_{\nu_{high}}$ (Hz) | rms$_{high}$ (%) |
|-----------|----------------|----------------|----------------|-------------------|----------------|
| Type I    |                |                |                |                   |                 |
| 1996 Dec 19 | 16.30 ± 0.10 | 0.49 ± 0.01 | 11.12 ± 0.21 | ...               | ...             |
| 1997 Feb 9  | 15.73 ± 0.04 | 2.68 ± 0.01 | 8.79 ± 0.19 | 16 ± 2 | 2.14 ± 0.63 |
| 1998 Sep 11 | 13.81 ± 0.05 | 2.62–2.96 | 10.71 ± 0.20 | ...               | ...             |
| 1998 Sep 25 | 18.16 ± 0.05 | 1.39 ± 0.01 | 11.45 ± 0.18 | 15 ± 2 | 2.85 ± 0.72 |
| 1999 Jan 1  | 16.11 ± 0.08 | 1.53–1.69 | 12.15 ± 0.31 | ...               | ...             |
| 1998 Apr 6  | 16.07 ± 0.09 | 0.70 ± 0.01 | 10.02 ± 0.25 | ...               | ...             |

| Date (UT) | rms$_{tot}$ (%)| $f_{QPO}$ (Hz) | rms$_{QPO}$ (%) | $f_{\nu_{high}}$ (Hz) | rms$_{high}$ (%) |
|-----------|----------------|----------------|----------------|-------------------|----------------|
| Type II   |                |                |                |                   |                 |
| 1996 Jul 23 | 16.30 ± 0.10 | 0.49 ± 0.01 | 11.12 ± 0.21 | ...               | ...             |
| 1996 Aug 14 | 15.73 ± 0.04 | 2.68 ± 0.01 | 8.79 ± 0.19 | 16 ± 2 | 2.14 ± 0.63 |
| 1997 Oct 8  | 13.81 ± 0.05 | 2.62–2.96 | 10.71 ± 0.20 | ...               | ...             |
| 1997 Oct 22 | 18.16 ± 0.05 | 1.39 ± 0.01 | 11.45 ± 0.18 | 15 ± 2 | 2.85 ± 0.72 |
| 1998 Apr 6  | 16.11 ± 0.08 | 1.53–1.69 | 12.15 ± 0.31 | ...               | ...             |
| 1998 May 24 | 16.07 ± 0.09 | 0.70 ± 0.01 | 10.02 ± 0.25 | ...               | ...             |

Note.—The parameters rms$_{tot}$, rms$_{QPO}$, and rms$_{high}$ represent total rms amplitude, rms amplitude of the fundamental QPO harmonic, and rms amplitude of the additional high-frequency noise component integrated over the 0.05–512 Hz frequency range, respectively. The parameters $f_{QPO}$ and $f_{\nu_{high}}$ denote the centroid frequency of the fundamental QPO peak and characteristic break frequency of the high-frequency component. Parameter errors correspond to a 1σ confidence level.

$^3$ In order to avoid possible interference from these radio outbursts, the hard steady observations that occurred shortly after large radio flares were excluded from the analysis.
mJy). On the other hand, periods of type II state are characterized by a much higher level of radio flux (∼ 50–100 mJy). The type II state is also referred to as a quasi-stable plateau radio state with a flat radio spectrum (Foster et al. 1996; Fender et al. 1999) and accompanying bright infrared emission (Bandyopadhyay et al. 1998). To explain the properties of the source during plateau states, the formation of the optically thick radio source powered by outflow of matter from the system has been proposed (Fender et al. 1999).

3. DISCUSSION

To explain the observational properties of black hole binaries in the hard and very high states (Tanaka & Lewin 1995), a number of models involving the hot Comptonization region near the compact object surrounded by the optically thick accretion disk (Shakura & Sunyaev 1973) have been proposed (Chakrabarti & Titarchuk 1995). According to these models, the soft thermal component of the energy spectrum is emitted by the optically thick accretion disk, while the hot inner region is responsible for generation of the hard spectral component. It was proposed that low- and high-frequency noise components in the power density spectrum are associated with outer, optically thick, and inner, optically thin parts of the accretion flow, respectively (Miyamoto et al. 1994). It is often assumed that the QPO phenomenon is caused by the interaction between these two distinct parts of the accretion flow occurring on the local dynamical timescale at the boundary between these regions related to the local Keplerian time (Molteni, Sponholz, & Chakrabarti 1996; Titarchuk, Lapidus, & Muslimov 1998). Supporting this model, the evidence of the correlation between an observed QPO frequency and the position of the boundary between optically thick and optically thin parts of the accretion flow was reported for the flaring states of GRS 1915 + 105 (Trudolyubov, Churazov, & Gilfanov 1999b; Chakrabarti & Manickam 2000).

It seems natural to suggest that the BLN dominating the PDS of GRS 1915 + 105 may also be a product of the dynamic processes in the inner part of the accretion flow. Then the dynamic timescales on both inner and outer
broadening of the coherent oscillation feature. Most of this steady QPO and be interpreted as the effective possibility that the broad noise component can be related to the position of the recurrent stable QPO at 67 Hz (Table 3), is remarkably close to the position of the recurrent stable QPO at 67 Hz observed mainly during the soft steady state (Morgan et al. 1997; Remillard & Morgan 1998). This fact provides a possibility that the broad noise component can be related to this steady QPO and be interpreted as the effective broadening of the coherent oscillation feature. Most of the models explaining the stable 67 Hz QPO invoke some kind of oscillation near the inner edge of the accretion disk in the immediate vicinity of the compact object (Morgan et al. 1997 and references therein). These oscillations may explain the high-frequency noise component detected during the type I state observations.

Type II state: The properties of the X-ray and radio emission of GRS 1915+105 in the type II state imply significantly different geometry and characteristics for the accretion flow compared with that of the type I state. We suggest two possible interpretations of the observed shape of the hard spectral component in the type II state. A thermal Comptonization mechanism implies relatively low electron temperature in the inner region, $kT_e \sim 5$ keV. On the other hand, the observed break in the hard component can be explained as a result of the transmission of the hard X-rays through dense surrounding matter with average Thomson optical depth on the order of several units (assuming a power-law shape of the spectrum of illuminating radiation; Sunyaev & Titarchuk 1980, p. 132–133). The typical value of the QPO centroid frequency during the type II states is close to that of the type I states, indicating possible similarity in the position of the outer boundary of the optically thin part of the accretion flow. As seen from Figure 2, the PDS of the type II state demonstrates the lack of significant variability of the source at frequencies above ~30 Hz. This fact may hint at the larger inner radius of the hot Comptonization region with respect to the type I state. Assuming the noise generation mechanism described above and given the characteristic cutoff frequencies of the PDS in the type I ($f_{\text{I}}^{\text{high}} \sim 70$ Hz) and type II ($f_{\text{II}}^{\text{high}} \sim 15$ Hz) states (Table 3), the ratios of the inner radii of the accretion flow, $r_{\text{I}}^\text{in}$ and $r_{\text{II}}^\text{in}$, can be estimated as $(r_{\text{II}}^\text{in}/r_{\text{I}}^\text{in}) \sim (f_{\text{I}}^{\text{high}}/f_{\text{II}}^{\text{high}})^{1/3} \sim 3$. To explain the higher value of the inner radius in the type II state, the effective mechanism of the truncation of the accretion flow near the compact object in this state is needed. The observations at the radio and infrared wavelengths indicate the presence of a strong outflow of matter near the compact object coupled with a hot inner region (Fender et al. 1999; Eikenberry et al. 1998). It is usually assumed that such outflows originate very close to the compact object, modifying the structure of the innermost part of the accretion flow. Finally, we may suppose that, contrary to the type I state, in the type II state the accretion flow extends down to some transition radius, followed by an outflow region in the immediate vicinity of the compact object.

As a result, the difference between the properties of X-ray and radio emission of GRS 1915+105 during the type I and type II hard steady states may be explained in terms of the different structure of the inner part of the accretion flow. Contrary to the type I X-ray state, in the type II state an inner region of the accretion flow coupled with a strong outflow of matter near the compact object causes the aforementioned differences in the observational properties.

Finally, our two types of hard steady state may be compared with the previous systems of “states” used to characterize the X-ray variability of GRS 1915+105. According to the definition, the “C” state of Belloni et al. (2000, with four classes of variability, $x_1, x_2, x_3,$ and $x_4$) corresponds to our hard steady state. It should be also noted that a similar distinction for a limited sample of 1996–1997 “hard steady” observations based on the level of radio flux was proposed by Muno et al. (1999). The “radio-loud hard steady state”...
and “radio-quiet hard steady state” of Muno et al. (1999) are directly associated with our type I and type II hard steady states.

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