LOW-FREQUENCY COHERENCE BREAK IN THE SOFT X-RAY STATE OF GRS 1915+105

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ABSTRACT

We present results from the analysis of X-ray power density spectra and coherence when GRS 1915+105 is in soft states. We use three data sets that belong to $\mu$, $\phi$, and $\delta$ classes as found in the work of Belloni et al. We find that the power density spectra appear to be complex, with several features between 0.01 and 10 Hz. The coherence deviates from unity above a characteristic frequency. We discuss our results from different models. The corona size in the sphere-disk model implied by this break frequency is on the order of $10^6 GM/c^2$, which is unphysical. Our results are more consistent with the prediction of the model of a planar corona sustained by magnetic flares, in which the characteristic frequency is associated with the longest timescale of an individual flare, which is about 8 s.

Subject headings: accretion, accretion disks — stars: individual (GRS 1915+105) — X-rays: binaries

1.INTRODUCTION

The X-ray source GRS 1915+105 was discovered by the Granat Observatory in 1992 (Castro-Tirado et al. 1994). It is one of several Galactic objects observed to produce superluminal jets (Mirabel & Rodríguez 1994). As the first Galactic superluminal jet source, the so-called microquasar, GRS 1915+105 is a unique and very important astrophysical laboratory for relativistic astrophysics (Mirabel & Rodríguez 1998, 1999). Zhang, Cui, & Chen (1997) first suggested that the black hole in this system is highly spinning; subsequent studies on the high-frequency quasi-periodic oscillation (QPO) phenomena from this source tend to support the spinning black hole model for this source (see, e.g., Cui, Zhang, & Chen 1998; Remillard et al. 2002), although the case is not settled yet.

The spectral type of the companion has been recently identified as a K–M III star (Greiner et al. 2001); thus, the source is classified as a low-mass X-ray binary. The estimated mass of the black hole ($\sim 1.4 M_\odot$) in this system is significantly higher than the black hole masses in most other stellar mass black hole systems (Greiner et al. 2001). This system thus may have a unique evolutionary history, and this also poses a major challenge to the theories of massive star evolution.

GRS 1915+105 displays rich QPO phenomena. The 328 Hz QPO (Remillard et al. 2002), the highest QPO in this source, is believed to be associated with the innermost stable radius of the accretion disk. A stable $\sim 67$ Hz QPO (Morgan, Remillard, & Greiner 1997) accompanied with a 40 Hz QPO (Strohmayer 2001) has also been observed. The 0.5–10 Hz QPOs, observed only during the hard state, are probably linked to the properties of the accretion disk, since their centroid frequency and fractional rms have been reported to correlate with the thermal flux (Markwardt, Swank, & Taam 1999; Trudolyubov, Churazov, & Gilfanov 1999; Reig et al. 2000) and apparent temperature (Muno, Morgan, & Remillard 1999). At much lower frequencies ($0.001–1.0$ Hz), the source occasionally shows high-amplitude QPOs or brightness “sputters” (Morgan et al. 1997). These variations correspond probably to the disk instability.

The 67 Hz QPO shows a marked hard lag when the low-frequency (well below 1 Hz) QPO shows a complex hard/soft lag structure (Cui 1999). The 0.5–10 Hz QPO shows a complex lag behavior (Reig et al. 2000). The lag between hard and soft photons decreases as the frequency of the QPO increases, changing the sign of the lag for $\nu_{\text{QPO}} \geq 2$ Hz. Negative lags occur when the power-law spectrum is soft, and positive lags occur when the spectrum is hard. The 0.5–10 Hz QPO disappears when the Proportional Counter Array (PCA) intensity is high ($\geq 2000$ counts s$^{-1}$; Reig et al. 2000).

Based on the X-ray color-color diagram, Belloni et al. (2000) found that the complex X-ray variability of GRS 1915+105 can be reduced to transitions between three basic spectral states, which they called “A,” “B,” and “C.” The spectrally soft states A and B correspond to an observable inner accretion disk with different temperatures: in state B the inner disk temperature is higher compared to state A. For the spectrally hard state C, the inner part of the accretion disk is either missing or just unobservable.

The coherence function between the light curves in two different energy bands measures how the photons in the two energy bands are related (Vaughan & Nowak 1997). For black hole binaries, the coherence function often appears to be around unity over a wide frequency range (Vaughan & Nowak 1997; Cui et al. 1997; Nowak et al. 1999a; Nowak, Wilms, & Dove 1999b), indicating that high-energy photons are closely related to low-energy photons, or the low-energy photons are the seed photons of the high-energy photons. Reduced coherence was observed from Cyg X-1 when the source was in the transition state (Cui et al. 1997), indicating that the hard X-ray production region was not stable during the transition state. Therefore, the coherence function provides a useful probe into the physical properties of the hard X-ray production region.

The source’s X-ray temporal properties change with the radio flux. In the steady hard state, as the radio emission becomes brighter and more optically thick, the rms of the 0.5–10 Hz QPO decreases, the Fourier phase lags in the frequency range of 0.01–10 Hz change sign, the coherence at low frequencies decreases, and the relative amount of low-frequency power in hard photons compared to soft photons decreases (Muno et al. 2000).
TABLE 1

The List of RXTE/PCA Observations of GRS 1915+105 Used for the Analysis

| Observation ID | Date (UT) | Start (UT) | Exposure (s) |
|---------------|-----------|------------|--------------|
| 10408-01-09-00 | 1996 May 29 | 12:44 | 5744 |
| 10408-01-11-00 | 1996 May 31 | 11:26 | 10432 |
| 10408-01-12-00 | 1996 Jun 05 | 11:36 | 10600 |
| 10408-01-13-00 | 1996 Jun 07 | 09:39 | 10832 |
| 10408-01-17-01 | 1996 Jun 22 | 17:52 | 3392 |
| 10408-01-18-00 | 1996 Jun 25 | 06:44 | 3680 |
| 10408-01-19-00 | 1996 Jun 29 | 19:57 | 2160 |
| 10408-01-19-01 | 1996 Jun 29 | 13:12 | 3344 |
| 10408-01-19-02 | 1996 Jun 29 | 16:28 | 3184 |
| 10408-01-20-00 | 1996 Jul 03 | 08:27 | 3328 |
| 10408-01-20-01 | 1996 Jul 03 | 11:39 | 2936 |
| 10408-01-34-00 | 1996 Sep 16 | 10:04 | 7920 |
| 10408-01-35-00 | 1996 Sep 22 | 06:30 | 6624 |
| 10408-01-36-00 | 1996 Sep 28 | 00:09 | 5600 |
| 10408-01-14-00 | 1996 Jun 12 | 00:06 | 1312 |
| 10408-01-14-01 | 1996 Jun 12 | 01:42 | 1072 |
| 10408-01-14-02 | 1996 Jun 12 | 03:18 | 1072 |
| 10408-01-14-03 | 1996 Jun 12 | 04:54 | 1072 |
| 10408-01-14-04 | 1996 Jun 12 | 06:30 | 1408 |

TABLE 2

Data Modes, with Their Energy Ranges, Number of Energy Channels, and Time Resolution

| Data Mode | Energy Range (keV) | Number of Channels | Time Resolution (s) |
|-----------|--------------------|--------------------|--------------------|
| B_2ms_4B_0_35_H | 0–12.99 | 4 | 2.16 |
| E_16us_16B_36_1s | 12.99–100.0 | 16 | 2.16 |

2. DATA AND ANALYSIS

The data used in this work are retrieved from the public RXTE archive (see Table 1). They belong to the soft states without prominent 0.5–10 Hz QPOs, belonging to the spectral classes $\phi$, $\mu$, and $\delta$, respectively (Belloni et al. 2000). Because within each class the temporal properties of the source may vary at different times, we first examined the data for each individual observation. We found that the data for the first and third sets show consistent temporal properties within each set, and therefore in the following we combine the PDSs and coherence of all observations within the first and third sets. For the second set, we found that although the general shape of the PDSs for all observations is the same, the fine features vary between the three observations. We therefore present the results of each individual observation for the second set separately.

The PCA data modes that we used are listed in Table 2. “Good time intervals” were defined when the elevation angle was above 10°, the offset pointing was less than 0.02, and the number of Proportional Counter Units turning “on” equaled 5.

The techniques that we used to calculate the coherence for GRS 1915+105 are discussed in Vaughan & Nowak (1997) and Nowak et al. (1999a). We applied equation (8) of Vaughan & Nowak (1997) to our data. We use equation (1) of Morgan et al. (1997) throughout this work to estimate the dead-time–corrected Poisson noise level; all averaged PDSs we present have been subtracted by the Poisson noise level.

For the first and second data sets, we performed fast Fourier transform (FFT) with two segment lengths, 1024 and 256 s, respectively. Segments with data gaps of any duration were ignored. In these results, the frequency range of 0.00097–0.01 Hz is computed from the 1024 s data segments, and the frequency range of 0.0039125–64 Hz is computed from the 256 s data segments. For the third data set, we only performed FFT with segments of 256 s because of the shorter exposure time. Throughout this work, we have used a logarithmic frequency binning

Fig. 1.—PDSs with associated uncertainties. All PDSs are for the one-sided normalization of Belloni & Hasinger (1990). The PDSs for bands B, C, D, and E are multiplied by factors of 10, 100, 1000, and 10,000, respectively.
with a binning factor of 0.1. We also divided our data into five energy bands. The ranges of these energy bands are listed in Table 3.

### 3. RESULTS

#### 3.1. Power Density Spectra

In Figure 1, we present the PDSs of all three data sets in five energy bands. From the figure, we find:

1. The overall shape of the PDSs for all three sets is power-law–like, superposed with QPOs or broad features at different frequencies, characteristic of black hole binaries in the soft state.
2. For the first data set, there is a knee at about 2 Hz. There may be a broad feature at about 0.02 Hz.
3. For the second data set, the PDS for each observation is shown separately. For the second set 1 and second set 3, there are three QPOs at around 0.01, 0.03, and 0.07 Hz. For the second set 2, there are two QPOs at around 0.01 and 0.05 Hz. In all these observations, there are two features at about 5 and 10 Hz. The 5 Hz feature increases with energy but decreases remarkably in the highest energy band. However, the 10 Hz QPO is very weak in the low-energy band but suddenly enhanced in the highest energy band.
4. For the third set, there is a QPO at about 0.03 Hz.

#### 3.2. Coherence

In Figure 2, we present the coherence for all energy bands for every data set. All comparisons shown are relative to the band A. From the figure, we find:

1. For the first and second sets, the coherence between 0.03 and 10 Hz becomes weak for higher energies. For the third set, this trend is weaker.
2. For the first and second sets, the coherence is remarkably close to unity below about 0.02 Hz for all energy bands, whereas for the third set, the break frequency is about 1 Hz.
3. For the second set 1 and second set 3, there is a remarkable dip at about 0.3 Hz in the coherence curve; the dip is deeper for higher energies.
4. For all data sets, the coherence deviates quickly from unity above about 10 Hz.

### 4. DISCUSSION AND CONCLUSIONS

We have studied the temporal properties of the spectral classes $\phi$, $\mu$, and $\delta$ in the soft states of the microquasar GRS 1915+105. We found in their PDSs there are several low-frequency QPOs or broad features between 0.01 and 10 Hz.
For the observations we have analyzed, the temporal properties for classes $\phi$ and $\delta$ do not show significant variations across different observations. For class $\mu$, we found significant variations on its temporal properties in different observations.

The main results of this work are on the coherence function of different classes. For all three classes, the coherence function shows a significant drop above about 10 Hz; an energy-dependent coherence break between 0.01 and 1 Hz also exists. In particular, for class $\mu$, there also exists a coherence dip at around 0.03 Hz, which corresponds to a dip between two broad peaks on its PDS.

The quick loss of coherence above about 10 Hz seen for GRS 1915+105 in the soft state is similar to that seen in Cyg X-1 and GX 339–4 in the hard state; this may be due to some nonlinear processes at high frequencies (Nowak et al. 1999a). However, the coherence loss between 0.02 and 10 Hz in GRS 1915+105 is different from that seen in Cyg X-1 and GX 339–4. This difference may be caused by the different spectral states when the sources were observed.

In GX 339–4 (Nowak et al. 1999b), there is also a dip in the coherence function. They suggested that there are multiple broadband processes occurring in the source that are individually coherent but are incoherent relative to each other. These dip frequencies are approximately the frequencies at which the different components overlap. For the second set, we compare the coherence with the PDS: there are two features at frequencies below 1 Hz; between these components, there is a dip in coherence (See Fig. 3); this is consistent with the above suggestion.

Nowak et al. (1999a) proposed an accretion disk model for black hole binaries in which the corona is inside the inner radius of the accretion disk and the soft photons from the accretion disk are upscattered to hard photons in the corona. Therefore, coherence loss will occur at timescales shorter than the dynamical timescale of the corona. The break frequency in the coherence may then be used to estimate the size of the corona and thus the inner accretion disk radius. For GRS 1915+105, the characteristic frequency of about 0.02 Hz implies that the corona’s size and the inner disk radius is on the order of $10^{5}GM/c^{2}$ if the black hole is about $10 M_{\odot}$. This is clearly unphysical.

As discussed in Poutanen & Fabian (1999), the X-/γ-rays may be produced in compact magnetic flares at radii $\leq 100GM/c^{2}$ from the central black hole. They predicted that the coherence will deviate from unity above a characteristic frequency. This characteristic frequency is then associated with the longest timescale of an individual flare $\tau_{\text{max}} = \frac{1}{2} \pi f_{\text{max}}$. If we take $f_{\text{max}} = 0.02$ Hz, then $\tau_{\text{max}} = 8$ s. In fact, the shape of the coherence curve is also remarkably similar to the prediction of their model.

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REFERENCES

Belloni, T., & Hasinger, G. 1990, A&A, 230, 103
Belloni, T., Klein-Wolt, M., Méndez, M., van der Klis, M., & van Paradijs, J. 2000, A&A, 355, 271
Castro-Tirado, A., et al. 1994, ApJS, 92, 469
Cui, W., 1999, ApJ, 524, L59
Cui, W., Zhang, S. N., & Chen, W. 1998, ApJ, 492, L53
Cui, W., Zhang, S. N., Focke, W., & Swank, J. 1997, ApJ, 484, 383
Greiner, J., Cuby, J. G., McCaughrean, M. J., Castro-Tirado, A. J., & Menickent, R. E. 2001, A&A, 373, L37
Klein-Wolt, M., Fender, R. P., Pooley, G. G., Belloni, T., Migliari, S., Morgan, E. H., & van der Klis, M. 2002, MNRAS, 331, 745
Markwardt, C. B., Swank, J. H., & Taam, R. E. 1999, ApJ, 513, L37
Mirabel, I. F., & Rodríguez, L. F. 1994, Nature, 371, 46
———, 1998, Nature, 392, 673
———, 1999, ARA&A, 37, 409
Morgan, E. H., Remillard, R. A., & Greiner, J. 1997, ApJ, 482, 993
Muno, M. P., Morgan, E. H., & Remillard, R. A. 1999, ApJ, 527, 321
Muno, M. P., Remillard, R. A., Morgan, E. H., Waltman, E. B., Dhawan, V., Hjellming, R. M., & Pooley, G. 2001, ApJ, 556, 515
Nowak, M. A., Vaughan, B. A., Wilms, J., Dove, J. B., & Begelman, M. C. 1999a, ApJ, 510, 874
Nowak, M. A., Wilms, J., & Dove, J. B. 1999b, ApJ, 517, 355
Poutanen, J., & Fabian, A. C. 1999, MNRAS, 306, L31
Reig, P., Belloni, T., van der Klis, M., Méndez, M., Kylafis, N. D., & Ford, E. C. 2000, ApJ, 541, 883
Remillard, R., Muno, M., McClintock, J. E., & Orosz, J. 2002, in New Views on Microquasars, ed. Ph. Durouchoux, Y. Fuchs, & J. Rodriguez (Kolkata: Center for Space Physics), 49
Strohmayer, T. E. 2001, ApJ, 554, L169
Trudolyubov, S., Churazov, E., & Gilfanov, M. 1999, Astron. Lett., 25, 718
Vaughan, B. A., & Nowak, M. A. 1997, ApJ, 474, L43
Zhang, S. N., Cui, W., & Chen, W. 1997, ApJ, 482, L155