THE 590 DAY LONG-TERM PERIODICITY OF THE MICROQUasar GRS 1915+105

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ABSTRACT

We report on the discovery of a 590 day long-term periodicity in the hard X-ray component of the microquasar GRS 1915+105 found from a comprehensive study of more than 4 years of Rossi X-Ray Timing Explorer observations. The periodicity is also observed in the hard X-ray flux observed by BATSE and in the radio flux as seen with the Green Bank Interferometer and the Ryle Telescope. We discuss various possible explanations, including the precession of a radiation-induced warped accretion disk.

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

1. INTRODUCTION

The galactic X-ray binary system GRS 1915+105 is the most prominent microquasar showing dramatic variability in its light curve (Greiner, Morgan, & Remillard 1996), quasi-periodic oscillations, phase lags, and coherence behavior (Morgan, Remillard, & Greiner 1997; Muno et al. 2001). Microquasars are thought to be downscaled analogs to quasars harboring a stellar mass black hole that accretes matter from a companion star. They show superluminal ejections (Mirabel & Rodriguez 1994), making the sources potential laboratories for studying accretion and relativistic jets near black holes (Mirabel et al. 1992). GRS 1915+105 is the most energetic object known in our galaxy, with a luminosity of \(-5 \times 10^{39} \text{ ergs s}^{-1}\) in the high state and \(-10^{38} \text{ ergs s}^{-1}\) in the low state. The binary system, located at a distance of \(12 \text{ kpc}\), contains a \(1 M_{\odot}\) late-type giant (Greiner et al. 2001b) in a 33.5 day orbit around a \(14 M_{\odot}\) black hole (Greiner, Cuby, & McCaughrean 2001a), making it the most massive stellar black hole known.

Originally discovered by Granat (Castro-Tirado, Brandt, & Lund 1992), GRS 1915+105 has been extensively monitored by the Rossi X-Ray Timing Explorer (RXTE) satellite since 1996, and a number of investigations of these data have been published (e.g., Greiner et al. 1996; Morgan et al. 1997; Belloni et al. 1997, 2000; Muno et al. 1999, 2001; Rau & Greiner 2003, hereafter RG03).

In a recent paper (RG03), we presented a comprehensive study of the X-ray spectral behavior of GRS 1915+105 in the \(\chi\)-state (Belloni et al. 2000) for over nearly 4 years of observation with RXTE. Within this study, a remarkable long-term periodicity was found that was mentioned briefly by Kuulkers et al. (1997). They found a 19 month long-term variability comparing the X-ray outbursts observed with BATSE and RXTE data from 1992 August, 1994 March, 1995 October, and 1997 May. This is consistent with our presented result.

A number of X-ray binaries, including low-mass X-ray binaries (LMXBs) as well as high-mass X-ray binaries, exhibit long-term variability in their X-ray flux with periods remarkably longer than their orbital period. Tananbaum et al. (1972) found a 35 day period in Her X-1, which they explained by the precession of a warped accretion disk in the system. The same process is used to describe the long-term variations in SMC X-1 (Wojdowski et al. 1998), LMC X-3 (Cowley et al. 1991), and LMC X-4 (Heemskerk & van Paradijs 1989). In this Letter, we discuss the detection of a new long-term periodicity in GRS 1915+105.

2. DATA REDUCTION AND ANALYSIS

The analysis presented here is based on the data reduction described in full detail in RG03. We investigated public RXTE data from GRS 1915+105 from 1996 November to 2000 September obtained from the High Energy Astrophysics Science Archive Research Center. We analyzed data of the PCU0 detector of the Proportional Counter Array from 3 to 25 keV and data of the High-Energy X-Ray Timing Experiment cluster 0 from 20 to 190 keV for 139 \(\chi\)-state observations from 89 different days. The \(\chi\)-states correspond to the low/hard state of GRS 1915+105, exhibiting relatively low flux from the accretion disk and showing a hard power-law tail. These states are characterized by the lack of obvious variations in light curve and spectrum and are connected by continuous radio emission of varying strength.

For the spectral fitting in XSPEC 11.0 (Arnaud 1996), we used a model consisting of (1) photoelectric absorption (WABS; Balucinska-Church & McCammon 1992), (2) a spectrum from an accretion disk consisting of multiple blackbody components (DISKBB), and (3) a power-law spectrum reflected from an ionized relativistic accretion disk (REFSCH; Fabian et al. 1989; Magdziarz & Zdziarski 1995).

The analysis of the X-ray model parameters for all \(\chi\)-state observations of GRS 1915+105 reveals a remarkably periodic behavior of the power-law slope, \(\Gamma\), which dominates the hard X-ray spectrum. It shows a nearly sinusoidal variation (Fig. 1; see also RG03) on a timescale much longer than the orbital period, \(P_{\text{orb}}\). The recently found correlation of the power-law slope and the radio flux, \(F_{\text{r}}\), in the \(\chi\)-states (RG03) suggests that one should also search for a long-term periodicity in the radio data of the Green Bank Interferometer (GBI; 2.25 and 8.3 GHz) and the Ryle Telescope (RT; 15 GHz).

For the determination of a cycle duration, an analysis of variance for several model parameters and X-ray and radio fluxes was performed using the Fisher-Snedecor distribution function (Schwarzenberg-Czerny 1989). The results for \(\Gamma\), the 20–200 keV X-ray Compton Gamma Ray Observatory (CGRO)/BATSE flux, and the 8.3 GHz RT flux are given in the periodogram in Figure 2. It shows a maximum at a period, \(P_{\text{long,}G}\), of 590 ± 40 (FWHM) days. Here \(\Gamma\) and \(F_{\text{r}}\) show several
identical local maxima around 200, 300, and 400 days, which are caused by the three major radio outbursts (Fig. 3, right panel) during a 590 day period. These local maxima result from the time separation of the outbursts at phase ~0.6 and ~0.85 (200 days), ~0.2 and ~0.6 (300 days), and ~0.2 and ~0.85 (400 days). These local maxima in the analysis of the variance of Gamma arise from a combination of two factors. First, the $\chi$-states are usually connected with radio emission, and second, the $\chi$-states have nonstochastic distribution within the RXTE observations. The latter factor results in an uneven coverage of data points within the time period.

Figure 3 shows the power-law slope and the GBI radio flux at 2.25 GHz displayed in segments of 590 days each. These light curves demonstrate that 590 days is the preferred period rather than 200, 300, or 400 days. Even though the coverage with GBI data is shorter than with RXTE observations, the periodicity is clearly visible in the radio outbursts. Both the broad outburst with exponential cutoff at phase ~0.2 and the shorter and steeper outbursts repeat periodically.

The soft X-ray component did not show any periodicity in the $\chi$-states. This is true for the all-sky monitor (ASM) count rate and hardness ratio as well as for the fit parameters of the accretion disk, i.e., effective temperature and the inner disk radius.

The 590 day period in the hard X-rays is also seen in the 20–200 keV BATSE earth occultation fluxes (Table 1). However, the long-term periodicity seems to be variable on a larger timescale. Figure 4 shows the 20–200 keV light curve with a 52 day (orbital precession period of CGRO) binning. This binning ensures the removal of any periodicity arising from the precession of the satellite orbit. Although the 590 day period is also visible when analyzing the data from JD 2,448,300 to JD 2,450,300 (before RXTE observations were performed; Table 1), the structures in the light curve show remarkable differences, and a somewhat shorter period of 545 ± 25 days is found when analyzing all available BATSE data from JD 2,448,300 to JD 2,451,800 together. A first hint for this variation is seen when fitting the power-law slope behavior with a simple sinusoidal function with a 590 day period (Fig. 3, left panel). The minimum in the power-law slope of the long-duration $\chi$-state from JD 2,450,400 to JD 2,450,600 lies outside the minimum of the sinusoidal function (Fig. 3, top). Also, an additional maximum is seen around phase $= 0.6$, particularly in the bottom panel. The persistent behavior is not
surprising and probably reflects the known transient behavior of GRS 1915+105.

3. INTERPRETATION

The observation of the 590 day periodicity in GRS 1915+105 suggests a precessing warped accretion disk, analogous to what is seen in other X-ray binaries. However, in all previous sources it was the soft X-ray flux that showed the long-term modulation. In contrast, in the case of GRS 1915+105, it is the spectral slope of the power law and the radio flux. The radio flux is connected with the hard X-ray component and probably originates near the inner part of the disk. It is unlikely that the periodic behavior of $F_\alpha$ and $\Gamma$ can be explained by a geometric effect of obscuration of the inner disk by the outer accretion disk.

It has long been known (Katz 1973) that a precession of a warped disk can be caused by tidal forces of the donor star, assuming that the accretion disk consists of small concentric rings that are tilted away from the orbital plane. Because of their fast rotation, the rings behave gyroscopically. Without interaction of the various individual ring elements, a retrograde precession around an axis perpendicular to the orbital plane will be excited by the tidal torque. The precession rate depends on the radius of the ring element that will lead to a tilted disk. In a fluid disk, an internal torque between the ring elements acts against the tilting. The resulting torque can enforce a precession of the disk. But the internal torque arises only if the disk is inclined with respect to the orbital plain and is connected with a dissipation of energy and a backward aligned movement of the disk into the orbital plane.

For tidally forced precession, a correlation of $P_{\text{long}}/P_{\text{orb}}$ and $q$ is theoretically expected but not found (Wijers & Pringle 1999). Neither the existence of a long-term period nor the ratio $P_{\text{long}}/P_{\text{orb}}$ is correlated with the mass ratios of the components of the binary systems, ruling out tidal forces as the generally dominant mechanism for the long-term periodicities in these systems. Thus, another mechanism is required that provides continuous warping of the accretion disk. Radiation-driven warping is one possible mechanism (Petterson 1977; Pringle 1996; Maloney, Begelman, & Pringle 1996; Ogilvie & Dubus 2001). The outer tilted part of the accretion disk is irradiated by the central source. If the radiation is absorbed and reemitted parallel to the local disk gradient, a torque due to gas pressure affects the disk. Therefore, a small warp grows exponentially if the luminosity is sufficient to depress the dissipative processes forcing the disk back into the orbital plane (Petterson 1977).

In principle, for every system a combination of viscosity and accretion efficiency can be found that makes the system stable, unstable, or highly unstable against radiation-driven warping. A deeper knowledge of the internal physics of the accretion disk is therefore required to determine the cause of the warping. Recently, Ogilvie & Dubus (2001) found that radiation-driven warping in LMXBs becomes relevant when the orbital period is above $\sim 1$ day, which makes it possibly important for GRS 1915+105.

Whether or not a warped accretion disk is the relevant cause of the long-term periodicity in GRS 1915+105 remains uncertain, because the 590 day period is visible in the nonthermal part of the X-ray spectrum and in the radio flux but not in the disk parameters. However, it is worth mentioning two issues: (1) a possibly existing long-term variability in the soft X-ray flux and the disk parameters can be easily masked by the high short-term variability in timing and spectral behavior of GRS 1915+105, and (2) the observed periodicity can originate because of variability of the mass accretion rate or the viscosity of the inner part of the disk. One can assume that the Roche lobe overflow of the donor star deposits its mass at different disk radii, depending on the mass transfer rate, thus differing mass density. The radial flow in the inner part of the accretion disk is therefore not constant, 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 timescale because of Compton cooling, as the power-law slope. The amount of matter to be ejected in a jet changes with similar periodicity, which explains the overall periodicity in the radio flux.

In the same way, periodic instabilities in the secondary affect the amount of accreted matter and may therefore cause or at least influence the observed periodicity. Wind-driven limit cycles (Shields, McKee, & Begelman 1983) as discussed for LMC X-3 (Wilms et al. 2001) can also exist in GRS 1915+105. In order to drive a wind from the outer parts of the accretion disk, the sound speed for the inverse Compton temperature, $kT_{\text{IC}}$, has to exceed the escape velocity in the outer disk. With an orbital separation of $a \sim 7.5 \times 10^{12}$ cm, the outer disk radii is likely of the order of $\sim 5 \times 10^{12}$ cm. Thus, GRS 1915+105 fulfills the criterium given in equation (3) of Wilms et al. (2001) for $kT_{\text{IC}} > 1$ keV and may therefore be driving a substantial Compton-heated wind.

A warped accretion disk would temporarily shadow the irradiated donor star. A search for the 590 day periodicity in the IR flux of the donor would also help in the understanding of the

TABLE 1

| Parameter                        | Data Range                  | Days |
|----------------------------------|-----------------------------|------|
| $T_{\text{e}}$                   |                             | 590 ± 40 |
| $P_{\text{orb}}$                 |                             | 590 ± 40 |
| $R_{\text{e}}$                   |                             | 590 ± 40 |
| 2.25 GHz GBI flux                |                             | 600 ± 40 |
| 8.3 GHz GBI flux                 |                             | 590 ± 40 |
| 15 GHz RT flux                   |                             | 600 ± 40 |
| GBI spectral index               |                             | 590 ± 40 |
| 1.5–12 keV ASM counts s$^{-1}$   |                             | 600 ± 40 |
| 20–200 keV BATSE flux            |                             | 590 ± 40 |
| 20–200 keV BATSE flux (JD 2,448,300–2,450,300) | | 40 |
| 20–200 keV BATSE flux (JD 2,448,300–2,451,800) | | 44 |

* For the analysis over the time span of JD 2,450,300–2,451,800, with exceptions explicitly stated otherwise. Note that periodicity is not detected.
origin and mechanism of the long-term behavior of GRS 1915+05.

4. CONCLUSION

We present the discovery of a 590 day long-term periodicity in the power-law slope of the hard X-ray spectrum, the hard X-ray flux, and the radio flux (at several frequencies) of the microquasar GRS 1915+05. No such periodicity is seen in the soft X-ray component. We discuss the observed behavior in the context of a warped accretion disk and of wind-driven limit cycles. We have found that a periodic mass density variation in the disk, produced by the warp and/or by periodic instabilities in the donor, can describe the observations, by producing a varying amount of soft seed photons for the Comptonization process and for the relativistic mass ejecta, very well. A wind-driven limit cycle is also a possible origin of the 590 day periodicity.

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