Detection of a 5-Hz QPO from X-ray Nova GRS 1739-278

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ABSTRACT

The X-ray nova GRS 1739-278 flared up near the Galactic center in the spring of 1996. Here we report on the discovery of a \(\sim 5\)-Hz quasi-periodic oscillations (QPO) in RXTE/PCA observations of GRS 1739-278. The QPO were only present when the source was in its very high state, and disappeared later, when it made a transition down into the high state. We present the energy spectra of this black hole candidate measured in both high and very high states, and discuss the similarities between this system and other X-ray transients.

Subject headings: black hole physics — binaries: close — stars: individual (GRS 1739-278) — X-rays: stars

1. INTRODUCTION

X-ray novae are outbursts of X-ray emission, often from black hole candidates, that exceed their quiescent flux levels by many orders of magnitude. About 50 X-ray novae have been detected in the last 35 years, each lasting typically several hundred days before their return back to quiescence (Chen, Shrader & Livio 1997). Perhaps all of them are recurrent, but the recurrence period is unknown for most. Probably, just small percentage of such systems in the Galaxy have been discovered so far.

During outburst, X-ray novae are typically found in one of several distinguishable spectral states (e.g. Sunyaev et al. 1994, Tanaka & Lewin 1995, Tanaka & Shibazaki 1996). In the high state, the spectrum is composed of a bright thermal component and an extended steep power-law with photon index around \(\sim 2.5\). In the low state, the spectrum is a hard power-law with a photon index of \(\sim 1.5\) and an exponential high energy cutoff. A third state, the so-called very high state has also been recognized. It has a two component spectrum

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similar to the high state, but with somewhat stronger power-law component and with much more prominent fast variability (Miyamoto et al. 1991, Takizawa et al. 1997). Many X-ray novae demonstrate state transitions during the outburst that are associated with X-ray flux changes. It is widely believed that both the state transitions and the flux variations are regulated by variations in the accretion rate. Similar states and state transitions were also observed in the persistent black hole systems, namely, Cyg X-1 and GX 339-4, but the dynamics of these systems is much slower, so they are more often observed in one of these states for extended period of time with occasional unpredictable transitions (Sunyaev & Truemper 1979, Makishima et al. 1986, Dove et al. 1998, Trudolyubov et al. 1998).

A new hard X-ray source GRS 1739-278 was discovered near the Galactic Center on March 18, 1996 by the SIGMA/Granat gamma-ray telescope (Paul et al. 1996). Initial SIGMA localization was refined by the TTM/Kvant instrument (Borozdin et al. 1996). VLA radio observations revealed a radio source within the TTM error region (Durouchoux et al. 1996). Mirabel et al. (1996) measured the optical/infrared flux from this object.

In 1996, the source was observed in the X-ray band by ROSAT (Greiner et al. 1997), Granat (Vargas et al. 1997), RXTE (Takeshima et al. 1996), and the Kvant module of the Mir Space Station. Borozdin et al. (1998) presented the spectral analysis of Mir-Kvant and RXTE data, and classified the GRS 1739-278 as a soft X-ray nova and a black-hole candidate. In this letter, we report on the discovery of a 5-Hz QPO in the power density spectrum, which supports the classification of this system as a binary of black hole with low-mass companion.

2. OBSERVATIONS AND DATA REDUCTION

The RXTE satellite observed X-ray nova GRS 1739-278 on March 31, 1996 and nine more times from May 10 through May 29 of that year, each with an exposure of several kiloseconds. The total exposure was about 24 ksec.

The RXTE satellite has two co-aligned spectrometers with ∼1 degree field of view each: a set of five xenon proportional counters, PCA, with maximum sensitivity in 4-20 keV energy range; and a scintillation spectrometer, HEXTE, which consists of eight NaI(Tl)/CsI detectors that are sensitive to 15-250 keV photons. HEXTE detectors are combined into two independent clusters of four detectors each, which alternate between measuring the source and the X-ray background.

We used PCA Binned and Single Binned mode data in our timing analysis. We generated power density spectra (PDS) in the 0.001–256 Hz frequency range (2–13 keV
energy band). For lower frequencies (below 0.3 Hz) a single Fourier transform on the data binned in 0.125 s time intervals was performed. For higher frequencies we summed together the results of Fourier transforms made over short stretches of data with 0.002 s time bins. The resulting spectra were logarithmically rebinned when necessary to reduce scatter at high frequencies and normalized to square root of $rms$ fractional variability. The standard technique of subtracting the white–noise level due to the Poissonian statistics, corrected for the dead–time effects, was employed (Vikhlinin, Churazov & Gilfanov 1994, Zhang et al. 1995). For spectral analysis we used FTOOLS v.4.2 and the PCA response matrix v.3.3 (see Jahoda et al. 1997 for computations of the matrix and Stark et al. 1997 for simulations of the background).

3. LIGHT CURVE OF THE SOURCE

Fig. 1 shows GRS 1739–278 light curve as measured with RXTE all-sky monitor (ASM) during the 1996 outburst. Overall shape of the outburst may be characterized as fast-rise-exponential-decay (FRED - [Chen, Shrader & Livio 1997]). However, the rise of this outburst was not particularly fast, and decay was interrupted by multiple secondary maxima. Secondary maxima were observed in FRED-type light curves of many X-ray novae (Sunyaev et al. 1994, Tanaka & Shibazaki 1996).

The RXTE pointed instruments observed GRS 1739–278 during the decay of the outburst. The first observation (March 31) was made during the initial decay after the main maximum. X-ray flux from the source was about 600 mCrab in PCA band (2-30 keV). A series of observations were also performed in May after the secondary maximum. By that time the source had faded to 250-300 mCrab. During all of the May observations GRS 1739–278 displayed very similar energy spectra and featureless PDS shapes.

4. 5-HZ QPO IN POWER DENSITY SPECTRUM

Construction of the PDS for the first PCA/RXTE observation (March 31, 1996 - Fig. 2) revealed the presence of a QPO feature with central frequency near 5 Hz (see Table 1 for the QPO parameters). The QPO was seen clearly in 2-13 keV band, but was not significant at higher energies, where the number of photons was small and hence the errors were larger. Also present in the PDS was a band-limited noise component, and significant variability at low frequencies. The variability of the source during the March 31 observation is shown in Fig. 3. In contrast, much weaker fast variability was detected in the RXTE observations of
the same source in May 1996 (Fig. 2).

The pointing direction for the observations of GRS 1739–278 was offset by about 11 arcmin in order to reduce count rate from the pulsar-burster GRO J1744–28 (Takeshima, Canizzo & Corbet 1996). However, we were still concerned about the possible contamination of our power density spectra by this bright nearby source. So we analyzed the data from its observation of March 30, 1996, just one day before the first observation of GRS 1739–278 with RXTE took place. The flux from GRO J1744–28 in the PCA band (2-30 keV) was 925 mCrab, while for GRS 1739–278 (next day) it was only 604 mCrab. We built a PDS for GRO J1744–28 to compare it with PDS of GRS 1739–278. The result is presented in Fig. 4. A prominent peak at $\sim 2$ Hz corresponding to the pulsar period dominates the PDS of GRO J1744–28. But there is no indication of a $\sim 2$ Hz peak in the PDS we derived for GRS 1739–278. So we conclude that contamination of the GRS 1739–278 observations by GRO J1744–28, if any, was not a significant factor, and that the detected $\sim 5$ Hz QPO do belong to GRS 1739–278.

The energy spectra for all RXTE observations of GRS 1739–278 (see examples in Fig. 2) have the shape which is typical for X-ray novae (Tanaka & Shibazaki 1996). In general, such spectra are well fitted by a two-component model composed of “multicolor” accretion disk component (Makishima et al. 1986) in the soft part of the spectrum with a power-law component at higher energies. Detailed spectral analysis of GRS 1739–278 observations was presented by Borozdin et al. (1998, 1999). During the observation on March 31, 1996, when the QPO was detected, the power-law component in the energy spectrum was more prominent. During the subsequent observations in May 1996 the QPO was not detected, the power-law component waned, and no hard flux was detected by HEXTE.

Strong rapid variability in X-ray band and extended power-law component in energy spectrum are both features of black hole binaries, when in very high state (Miyamoto et al.

| Table 1: Fit parameters for PDS components of GRS 1739-278 |
|--------------------------|--------------------------|--------------------------|
|                         | Band-Limited Noise       |                          |
|                         | power-law index          | break frequency, Hz      | total rms (0.03 – 100 Hz)$^a$ |
| 3/31/96                 | $-1.22 \pm 0.22$         | $7.3 \pm 3.0$            | $1.9 \pm 0.1\%$               |
| 5/29/96                 |                          |                          | $0.4 \pm 0.2\%$               |
|                         | QPO and its harmonic      |                          |
|                         | centroid frequency, Hz    | width, Hz                | rms amplitude                 |
| 3/31/96                 | $5.01 \pm 0.04$          | $1.17 \pm 0.18$          | $1.62 \pm 0.13\%$             |
|                         | $9.80 \pm 0.35$          | $3.18 \pm 1.07$          | $1.17 \pm 0.22\%$             |

$^a$ – integrated total rms of fractional variability in the 0.03 – 100 Hz frequency range
We see that GRS 1739–278 was in this state on March 31 1996, and made a transition down to a high state sometime before May 10.

5. DISCUSSION

QPO features in power density spectra have been identified for a variety of black hole candidates including GX 339–4 (Miyamoto et al. 1991), Nova Muscae (Miyamoto et al. 1993, Ebisawa et al. 1994), XTE J1748-288 (Revnivtsev, Trudolyubov & Borozdin 1999), and 4U 1630–47 (Trudolyubov, Borozdin & Friedhorsky 2000). Significant low-frequency variability has been observed in Galactic microquasars GRS 1915+105 (Morgan et al. 1997) and GRO J1655–40 (Remillard et al. 1999), and also during the 1998 outburst of recurrent X-ray Nova 4U 1630–47 (Trudolyubov, Borozdin & Friedhorsky 2000). All of these objects were in their very high states during those observations. In many cases a correlation between the intensity of PDS noise components and relative strength of the power-law spectral component was reported (e.g. Miyamoto et al. 1993, Cui et al. 1999, Revnivtsev, Trudolyubov & Borozdin 1999, Trudolyubov, Churazov & Gilfanov 1999). GRS 1739–278 fits well into this picture as another example of transient LMXB (low-mass X-ray binary) and a black hole candidate.

An interesting energy spectrum was observed with TTM telescope on Mir-Kvant module in March 1996 during the rise of the flux from the GRS 1739–278 (Borozdin et al. 1998). It is well described by a power law with absorption and does not require the introduction of an additional soft blackbody component. At the same time, the slope of the power-law component (2.3-2.7) is much steeper than the typical value for the low state of black-hole candidates (1.5-2.0). A similar spectrum was observed earlier by Ginga and Granat satellite from the X-ray Nova Muscae 1991 (Grebenev et al. 1991, Gilfanov et al. 1991, Ebisawa et al. 1994) and by TTM/Kvant and SIGMA/Granat from KS 1730-312 (Borozdin et al. 1995, Trudolyubov et al. 1996). Later this type of spectrum was observed with RXTE from XTE J1748-288 (Revnivtsev, Trudolyubov & Borozdin 1999), 4U 1630-47 (Trudolyubov, Borozdin & Friedhorsky 2000), and XTE J1550-564 (Sobczak et al. 1999). These examples show that the power-law shape of the spectrum with a variable slope is typical of soft X-ray Novae during their flux rise and near the primary maximum. There is a clear tendency for the spectrum to steepen as the outburst progresses. However, the total X-ray luminosity is sometimes even higher than in the very high state observed later during the same outburst (Revnivtsev, Trudolyubov & Borozdin 1999, Trudolyubov, Borozdin & Friedhorsky 2000). The observation of power law spectrum with variable slope at the early phase of X-ray novae outbursts is important because this is when an accretion disk around
black hole is formed. The generation of such spectrum should be a key element of any sound dynamical model for an accreting black hole.

6. CONCLUSION

Using PCA/RXTE archival data we detected, for the first time, a QPO feature in the PDS of X-ray nova GRS 1739-278. QPO harmonics near 10 Hz and strong band-limited noise at low frequencies were also observed. Both the PDS and the two-component energy spectrum for this observation displayed the properties typical for the very high state in black hole candidates.

In the later stages of the 1996 outburst, GRS 1739-278 transitioned into a high state with much weaker rapid variability and soft energy spectra that were dominated by thermal component with an effective temperature $\sim 1$ keV. Observation of the two canonical states strongly supports the identification of GRS 1739-278 as a black hole candidate based on the similarity of its X-ray properties with other black hole X-ray binaries.

We note, that at the beginning of the outburst GRS 1739-278 exhibited a power-law energy spectrum with a variable slope and tendency to steepen with time (Borozdin et al. 1998). Similar spectra have been measured from several other X-ray novae during the early stages of their outbursts. These black hole candidates therefore seem to display a clear pattern in their spectral evolution.

7. ACKNOWLEDGMENTS

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Fig. 1.— The light curve of GRS 1739-278, according to ASM/RXTE data (1.3-12 keV). Tick marks indicate the times of pointed RXTE observations. The arrow denotes the time of 5-Hz QPO detection.
Fig. 2.— The results of PCA/RXTE observations of GRS 1739-278. Upper row: The power density spectra (PDS) constructed for the 2-13 keV band. Lower row: energy spectra. Left column is for the observation of March 31, 1996 (6.3 ksec), when 5-Hz QPO was observed. Right column presents PDS and energy spectrum typical for the series of observations in May 1996 (2.5 ksec exposure).
Fig. 3.— The PCA light curve of GRS 1739-278 for March 31, 1996 observation (2-30 keV). X-ray flux variations at time scales of tens of seconds are clearly seen.
Fig. 4.— Power density spectrum of GRO J1744–28 for the PCA observation of March 30, 1996. Dominating peak at $\sim 2$ Hz corresponds to the pulsar period. The absence of a noticeable peak at this frequency in the PDS of GRS 1739–278 (Fig. 2) demonstrates that a contamination from GRO J1744–28, if any, was not significant factor.