DISCOVERY OF TWO SIMULTANEOUS KILOHERTZ QUASI-PERIODIC OSCILLATIONS IN THE PERSISTENT FLUX OF GX 349+2

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ABSTRACT

We report the discovery of two simultaneous quasi-periodic oscillations in the persistent flux of GX 349+2 at frequencies 712 ± 9 and 978 ± 9 Hz, with rms amplitudes 1.25% ± 0.34% and 1.34% ± 0.32%, respectively. During our 152 ks observation with the Rossi X-ray Timing Explorer, GX 342+2 was in either the normal branch or the flaring branch with count rates in the nominal 2–60 keV RXTE-PCA band ranging from a low of 8000 counts s⁻¹ to a high of 15,000 counts s⁻¹. The kHz QPOs were observed only when the source was at the top of the normal branch, when the count rate was about 8200 counts s⁻¹, corresponding to a flux of $1.4 \times 10^{-8}$ ergs cm⁻² s⁻¹ in the 2–10 keV band. With this report, now kHz QPOs have been observed in all six Z sources.

Subject headings: accretion, accretion disks — stars: individual (GX 349+2) — stars: neutron — X-rays: stars

1. INTRODUCTION

GX 349+2, also known as Sco X-2, is one of six bright low-mass X-ray binaries whose X-ray color-color diagrams resemble the shape of the letter “Z,” which, therefore, have been referred to as the Z sources (Hasinger & van der Klis 1989). They are among the brightest X-ray sources in the sky. Their time variability in the frequency domain below 100 Hz as characterized by their FFT power spectra is closely correlated with their energy spectral state as characterized by their X-ray color-color diagram. Since the launch of the Rossi X-Ray Timing Explorer (RXTE), quasi-periodic intensity oscillations with frequencies in the range of several hundred hertz to over one thousand hertz have been discovered in five of the six Z sources: Sco X-1 (van der Klis et al. 1996b), Cyg X-2 (Wijnands et al. 1998), GX 17+2 (Wijnands et al. 1997), GX 5-1 (van der Klis et al. 1996a), and GX 340+0 (Wijnands et al. 1998). GX 349+2 is the only source from which no kHz QPOs have been reported to date.

In this Letter we report the discovery of kHz QPOs in GX 349+2 and compare their characteristics with those of the QPOs observed in the other Z and atoll sources.

2. OBSERVATIONS

RXTE was launched on 1995 December 30. It carries three X-ray instruments: an array of five xenon gas proportional counters that has a nominal bandwidth of 2–60 keV, eight Na I and Cs I scintillation detectors sensitive to X-rays in the 15–250 keV band, and an all-sky monitor (ASM) sensitive to X-rays in the 1.5–10 keV band. The salient features of the RXTE satellite are its large X-ray collection area (6250 cm² for the PCA alone) and its large telemetry bandwidth enabling time-tagging each X-ray to a microsecond accuracy. For the results reported in this Letter, we use only the proportional counter array (PCA).

The observation took place between 1998 January 9 and 29 with a total accumulated exposure time of 152 ks. It was broken up into 55 pieces by the satellite observation planning process, the South Atlantic Anomaly, and Earth occult of the source, with the shortest being only 400 s and the longest 3900 s, 2800 s being the typical duration.

In addition to the two standard data modes that are available to all RXTE-PCA observations, we used four additional data modes: three single-bit modes each with a time resolution of 128 µs (1 µs = 2⁻¹⁰ s) and covering the PCA pulse height channels 1–13, 14–17, and 18–23, which correspond to energy bands 2–5.0, 5.0–6.5, and 6.5–9.0 keV, respectively. Photons with energies above channel 23 (9.0 keV) are recorded with an event mode that has a time resolution of 128 µs and 64 energy channels.

3. DATA ANALYSIS AND RESULTS

We constructed the color-color diagram as shown in Figure 1 using the Standard-II data and the standard PCA background model. Then we combined the three single-bit data streams and the event mode data stream to form a single time series with a time resolution of 256 µs to construct an FFT power spectrum for every 32 s of the data. We then obtained the average power spectrum for each of the 55 segments and rebinned it from a frequency resolution of 1/32 Hz by a factor of 512–16 Hz per bin. Visually scanning all the 55 average powered spectra, we found that one of the 55 segments showed two significant peaks at 706 and 999 Hz, respectively. All the other segments did not have any significant peaks anywhere above 100 Hz.

We then tried the following procedures to enhance the detection significance of the peaks: (1) summing up all the 55 segments; (2) summing up only those segments with count rates below 9000 counts s⁻¹; (3) removing events in the first single-bit data stream, i.e., those events with pulse height channel below 14; and (4) summing up those segments at the top of the normal branch in the color-color diagram. Procedures 1 and 2 washed out the peaks completely. Procedure 3 did not measurably alter the final significance. Only procedure 4 significantly enhanced the significance. The resulting power spectrum is shown in Figure 2.

We fitted the power spectrum in Figure 2 to two Gaussian peaks plus a Poisson noise term:

$$P(f) = A_1 \exp\left(-\frac{(f-f_1)^2}{2\sigma_1^2}\right) + A_2 \exp\left(-\frac{(f-f_2)^2}{2\sigma_2^2}\right) + C.$$ (1)
The best-fit parameters are listed in Table 1. Their errors correspond to a change $\Delta \chi^2 = 1$.

The rms amplitude is calculated according to the following formula:

$$\text{rms} = \sqrt{2\pi A \sigma N_{ph} / 2048},$$

(2)

where $A$ and $\sigma$ are as defined in equation (1); $N_{ph} = 263,840$ is the number of photons in 32 s averaged over the entire time interval from which Figure 2 is constructed, and the factor 65,536/2048 converts the power amplitudes from per frequency interval to the original FFT amplitudes (van der Klis 1989). Plugging in all the numbers, we obtain the rms amplitudes for the two QPOs, $1.21\% \pm 0.33\%$ and $1.30\% \pm 0.31\%$, where we have folded both the errors in $A$ and the errors in $\sigma$ into the final rms amplitude errors.

There are two factors that have systematically suppressed the measured rms with respect to the true values: detector background events and detector dead time. Background event rate only constituted no more than 2% of the overall count rate, which translates into 1% error on the rms amplitude. Given that the PCA detectors have a dead time of 10 $\mu$s (Zhang 1995) and each detector had a count rate of 8000/5 counts s$^{-1}$, the overall correction to the rms amplitudes amounts approximately to 2% (van der Klis 1989). In other words, combining the effects of detector background events and the detector dead time, we should revise up the above quoted rms amplitudes by 3%, i.e., multiply them by a factor 1.03. The final rms amplitudes for the two QPOs are $1.25\% \pm 0.34\%$ and $1.34\% \pm 0.32\%$.

We note that there is an intriguing, but statistically insignificant peak at 1020 Hz in the GX 349+2 power spectrum reported by Kuulkers & van der Klis (1998). With the hindsight gained with our results, we think that their 2.6 $\sigma$ peak most likely is caused by the kilohertz QPOs in the flux, not a result of a statistical fluctuation.

4. DISCUSSION

We have reported the discovery of two simultaneous QPO peaks in the FFT power spectrum of GX 349+2. In this section we place our results in the context of the kHz QPO phenomenologies of the other Z sources.

GX 349+2 is the last Z source from which such characteristic twin QPO peaks have been found. The color-color diagram we observed is also quite characteristic of those observed in the past. Compared to other Z sources, GX 349+2 has never been observed to be on its horizontal branch. Four of the 6 Z sources, i.e., Cyg X-2, GX 5-1, GX 17+2, and GX 340+0, have clearly observable horizontal branches. The kHz QPO characteristics of those sources are nearly identical in that they all show up on the horizontal branch of the Z diagram. As the source moves along the Z track toward the vertex of the horizontal branch and the normal branch and further down the normal branch, the QPO centroid frequencies increase and their rms amplitudes decreases until they cease to be observable in the middle part of the normal branch. The frequency difference

| TABLE 1 | PARAMETERS OF THE BEST FIT IN FIGURE 2 |
|---------|-------------------------------------|
| Parameters | Best Estimates and Errors |
| $\chi^2$/d.o.f. | 114/112 |
| $A_1$ (Hz) | $712.2 \pm 8.8$ |
| $\sigma_1$ (Hz) | $31.3 \pm 9.9$ |
| $A_2$ (Hz) | $0.0142 \pm 0.0030$ |
| $\sigma_2$ (Hz) | $978.0 \pm 9.5$ |
| $C$ | $39.1 \pm 9.9$ |
| | $1.950 \pm 0.001$ |

The errors quoted all correspond to a change of $\chi^2$ by 1.
of the twin QPO peaks are consistent with being constant for all of these sources. The differences are, respectively, 343 ± 21, 327 ± 11, 294 ± 8, and 374 ± 24 Hz. In the case of Sco X-1, the kHz QPO peaks are observed on the normal branch. The separation of the two QPO peaks changes from a high of 292 ± 2 to a low of 247 ± 3 Hz as Sco X-1 moves down the normal branch toward the flaring branch (van der Klis et al. 1997).

The horizontal branch, if any, of the Z track of the GX 349+2 has not been observed. The kilohertz QPO characteristic we have observed in GX 349+2 is very similar to those of Sco X-1 and the other Z sources in that the kHz QPOs exist on the upper or middle normal branch. As the source approaches the flaring branch, the kilohertz QPOs become weak and cease to be observable. Unfortunately, our existing data from GX 349+2 are not sufficient in quantity to further investigate the characteristics of the observed QPOs. Further and more extensive observations, especially when GX 349+2 is at the upper normal branch, are highly desirable and encouraged.

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REFERENCES

Hasinger, G., & van der Klis, M. 1989, A&A, 225, 79
Kuulkers, E., & van der Klis, M. 1998, A&A, 332, 845
van der Klis, M. 1989, in NATO ASI Series C 262, Timing Neutron Stars, ed. H. Ogelman & E. P. J. van den Heuvel (Dordrecht: Kluwer), 27
van der Klis, M., Wijnands, R. A. D., Horne, K., & Chen, W. 1997, ApJ, 481, L97
van der Klis, M., et al. 1996a, IAU Circ. 6511
van der Klis, M., Swank, J. H., Zhang, W., Jahoda, K., Morgan, E. H., Lewin, W. H. G., Vaughan, B., & van Paradijs, J. 1996b, ApJ, 469, L1
Wijnands, R., et al. 1998, ApJ 493, L87
Wijnands, R., et al. 1997, ApJ, 490, L157
Zhang, W. 1995, RXTE-PCA Internal Memo., 1995 May 23