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DISCOVERY OF 800 Hz QUASI-PERIODIC OSCILLATIONS IN 4U 1608–52

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ABSTRACT

We present results of *Rossi X-Ray Timing Explorer* observations of the low-mass X-ray binary and atoll source 4U 1608–52 made over 9 days during the decline of an X-ray intensity outburst in 1996 March. A fast-timing analysis shows a strong and narrow quasi-periodic oscillation (QPO) peak at frequencies between 850 and 890 Hz on March 3 and 6, as well as a broad peak around 690 Hz on March 9. Observations on March 12 show no significant signal. On March 3, the X-ray spectrum of the QPO is quite hard; its strength increases steadily from 5% at ~ 2 keV to $\sim 20\%$ at ~ 12 keV. The QPO frequency varies between 850 and 890 Hz on that day, and the peak widens and its rms decreases with centroid frequency in a way very similar to the well-known horizontal branch oscillations (HBO) in Z sources. We apply the HBO beat frequency model to atoll sources and suggest that, whereas the model could produce QPOs at the observed frequencies, the lack of correlation we observe between QPO properties and X-ray count rate is hard to reconcile with this model.

Subject headings: accretion, accretion disks — stars: individual (4U 1608–52) — stars: neutron

1. INTRODUCTION

The low-mass X-ray binary 4U 1608–52 was first observed in 1971 (Tananbaum et al. 1976). It is the same source as the Norma burster, from which the first X-ray bursts were discovered (Belian, Conner, & Evans 1976), independent from the X-ray burst discovered by Grindlay et al. (1976) from 4U 1820–30. 4U 1608–52 is a soft X-ray transient, which shows outbursts at intervals varying between ~ 100 days and several years (see, e.g., Lochner & Roussel-Dupré 1994).

Hasinger & van der Klis (1989) classified 4U 1608–52 as an atoll source, based on the correlated X-ray spectral variability and $\lesssim 10$ Hz noise in the X-ray intensity that is characteristic for this class of objects. In the standard description of atoll sources (e.g., van der Klis 1995), the correlated changes in X-ray spectral and timing properties are attributed to changes in mass accretion rate. At low accretion rates (island state of atoll sources), the X-ray spectrum of 4U 1608–52 contains a hard power-law component (up to about 100 keV) that is somewhat similar to the X-ray spectra of black hole candidates in their low state (Mitsuda et al. 1989). Yoshida et al. (1993)

found that the power-density spectrum of 4U 1608–52 in its island state has the shape characteristic of black hole candidates in the low state, and they reported 2–9 Hz quasi-periodic oscillations (QPO) from this source, which is unusual in atoll sources.

In this Letter, we report the discovery of 650–850 Hz QPO from 4U 1608–52. A preliminary announcement of this discovery has already been made by van Paradijs et al. (1996). 4U 1608–52 is the second atoll source showing 800 Hz QPO after 4U 1728–34 (Strohmayer, Zhang, & Swank 1996a). QPO at 800 and 1100 Hz have recently also been reported for the Z source Sco X-1 (van der Klis 1996a, 1996b).

2. OBSERVATIONS AND ANALYSIS

We observed 4U 1608–52 using the proportional counter array (PCA) on board NASA's *Rossi X-Ray Timing Explorer* (*RXTE*; Bradt, Rothschild, & Swank 1993) during the decay of an X-ray outburst on 1996 March 3, 6, 9, and 12. Each observation had a duration of several satellite orbits, in each of which the source was visible for about 3600 s and occulted by Earth for about 1800 s.

The source count rate during the March 3 observation varied between 2910 and 3400 counts s^{-1} (in the PCA energy range of 5–60 keV); on March 6 it had declined to 530–820 counts s^{-1} , and on March 9 and 12 the rates were 610–730 and 460–710 counts s^{-1} , respectively. No X-ray bursts were seen. The background count rate was about 90 counts s^{-1} . In all observations—except for the March 6 observation, which used 16 kHz sampling—data were collected with a sampling rate of 8 kHz. No spectral analysis of the data has been done as of yet, but the drop by a factor of 5 in X-ray intensity could be due to a change from banana to island state (see Fig. 1 of Mitsuda et al. 1989).

We calculated power spectra of these data. We find that during most of our observations these contain a clear QPO peak at high frequencies, which we fitted with a constant level plus a Lorentzian. We corrected the results of these fits for background and differential dead time (van der Klis 1989). The reduced χ^2 values of the fits were all ~ 1 .

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FIG. 1.—Leahy-normalized power spectrum of 4U 1608–52, from data of March 6. No corrections for counting statistics and dead time have been made for this figure.

3. RESULTS

In the March 3 and 6 observations, a clear QPO peak can be seen in the power spectrum (see, e. g., Fig. 1). In Figure 2 (Plate L2), the dynamical power spectra of these two observations are shown. The centroid frequency of the QPO varies between 850 and 890 Hz, and the peak is always narrow with Q -values (centroid frequency divided by full width at half-maximum) of up to ~ 200 . During the first orbit of the March 3 observation, the QPO frequency variations covered the 850–890 Hz range in less than 1000 s.

We made fits to the QPO in contiguous segments of 100 s of the March 3, orbit 1 data, in which the QPO frequency changes rapidly. The rms amplitude of the QPO is between $\sim 6\%$ and $\sim 8\%$, and its FWHM is between 4 and 15 Hz. In Figure 3, the rms amplitude and FWHM are plotted as a function of QPO frequency. As the QPO frequency increases, the peak becomes weaker and broader.

In the second orbit of March 3 and in the March 6 data, the

QPO frequency changes much less but still significantly (Fig. 2). The QPO strength, centroid, and width values of orbit 2 of March 3 are consistent with those of orbit 1. The March 6 peak widths are also consistent with those of March 3 for the frequency range that they have in common (850–870 Hz), but the fractional rms amplitude is twice as high ($\sim 14\%$). In both observations, changes in QPO frequency occur down to time-scales of tens of seconds, as can be seen in Figure 2.

In the March 9 observation, no QPO are evident in the dynamical power spectrum. Analyzing a power spectrum averaged over the entire observation, we find a broad peak with an amplitude of $13.9\% \pm 0.9\%$ rms, a FWHM of 131 ± 19 Hz, and a centroid frequency of 691 ± 6 Hz. The FWHM of the QPO must be intrinsically higher during this observation than during the earlier ones, or with this amplitude it would have been visible in the dynamical power spectrum.

On March 12, no ≈ 100 Hz QPO signal is detected in the integrated power spectrum, but a very weak and broadband-limited noise component can be seen at ~ 90 Hz. It is uncertain whether or not this feature is related to the ~ 800 Hz QPO.

On March 6, there is a correlation between X-ray count rate and QPO frequency. However, in the March 3 observation the changes in QPO frequency are not well correlated to the count rate changes; the drop in count rate by more than a factor 4 from March 3 to March 6 does not affect QPO frequency (or peak width), and in the March 9 observation—at nearly the same count rate as during March 6—the QPO frequency is 150 Hz lower than before. It is therefore possible that the correlation on March 6 is coincidence.

We looked for the presence of a harmonic to the QPO peak at twice the centroid frequency in the March 3, orbit 2 data; the 3σ upper limit to such a component is 1.7% rms, corresponding to an amplitude ratio of less than 4.1.

We measured the photon energy dependence of the QPO in the second orbit of the March 3 data by dividing the data into eight contiguous energy bands centered at 5.0, 7.1, 9.4, 11.8, 14.8, 18.2, 22.2, and 27.2 keV. We used these data because of the strength and stable frequency of the QPO, making it easy to construct an average power spectrum from each band. We analyzed the power spectra, as described above. The rms

FIG. 3a

FIG. 3b

FIG. 3.—Properties of the QPO of 4U 1608–52. In the left panel, the relation between QPO centroid frequency and FWHM is given. Right panel shows the relation between QPO frequency and fractional rms amplitude. Errors correspond to $\Delta\chi^2 = 1$ in the fit.

FIG. 4.—Root mean square vs. photon energy spectrum of the QPO. Plotted is the fractional rms amplitude of the fitted Lorentzian to the QPO.

amplitude of the QPO is plotted as a function of energy in Figure 4. The QPO relative amplitude increases up to about 12 keV.

4. DISCUSSION

In several respects, the ~ 800 Hz QPO we found in 4U 1608–52 are very similar to those in 4U 1728–34 (Strohmayer et al. 1996a). The frequency ranges, coherencies, peak shapes, and strengths are all approximately the same. An important difference of the ~ 800 Hz QPO in these two atoll sources and those at 800 and 1100 Hz in the Z source, Sco X-1 (van der Klis et al. 1996a, 1996b), is the much lower (about a factor 10) rms amplitude of the QPO in the latter. This could be due to scattering in circumstellar material or additional, unmodulated flux in the case of the near-Eddington accretion thought to characterize Z sources.

There are two lines of reasoning that suggest that the 800 Hz QPO in 4U 1608–52 may be caused by a beat between Keplerian disk rotation and neutron star spin. However, our data also provide a strong argument against this interpretation.

First, the correlation between the various QPO properties during March 3, orbit 1 is very reminiscent of the horizontal branch oscillations (HBO) seen in the Z source GX 5–1 (van der Klis et al. 1985; cf. their Fig. 3). When the QPO frequency increases, the peak width increases and the rms amplitude goes down. The rms versus photon energy spectrum of the QPO is very similar to that of GX 5–1 (Lewin et al. 1992), which increases from 4% to 15% rms between 2 and 15 keV. The width of the ~ 40 Hz QPO of GX 5–1 is between 5 and 12 Hz (Kuulkers et al. 1994), very similar to the 5–15 Hz width of the ~ 800 Hz QPO of 4U 1608–52. A small difference is that in GX 5–1 the rms amplitude of the QPO is between

2% and 6%, which is slightly lower than the 5%–15% seen in 4U 1608–52.

We note that many of these similarities could also be as result of the 800 Hz QPO in 4U 1608–52 being directly caused by the inner disk frequency (not the beat frequency).

The beat frequency model (Alpar & Shaham 1985; Lamb et al. 1985) for HBO in Z sources could, with an assumed neutron star spin rate of a few 100 Hz and with the lower magnetic field strengths expected for atoll sources as compared to Z sources (Hasinger and van der Klis 1989), very easily produce an 800 Hz beat frequency.

Second, Strohmayer et al. (1996b) have proposed that the 800 Hz QPO in 4U 1728–34 can be interpreted in terms of a beat frequency between the Keplerian disk frequency and a neutron star spin rate of 363 Hz. The report that five X-ray bursts of that source show a relatively coherent signal at 363 Hz, and the difference in frequency between the 800 Hz QPO peak with another peak present in their data, remains consistent with being equal to 363 Hz across the observations.

However, in spite of these arguments, the absence of a correlation between X-ray intensity, on the one hand, and QPO frequency and rms amplitude, on the other hand, poses a major problem for a beat frequency model interpretation. The QPO frequency remains constant—near 850 Hz between March 3 and 6—while the count rate drops by more than a factor 4, from ~ 3200 to ~ 600 counts s^{-1} (§ 2).

The beat frequency model predicts that if the QPO frequency remains constant, the mass flow through the inner edge of the disk should remain constant as well. Our data, therefore, are inconsistent with a beat frequency model interpretation if all accretion takes place via the inner edge of the disk. We note that the presence of a hypothetical additional (non-disk) mass flow component contributing more than 75% of the total flux on March 3 and being much weaker on March 6 cannot easily resolve this discrepancy. The rms amplitude of the QPO only increases by a factor 2 from March 3 to 6, while the X-ray intensity drops by a factor of more than 4, whereas a similar fractional change would be predicted in this explanation. Only by invoking rather large and entirely ad hoc changes in the beaming or bolometric correction could the model be maintained. The 150 Hz drop in QPO from March 6 to March 9 without a change in count rate presents similar difficulties.

Further observations of 4U 1608–52 during other outbursts and study of its X-ray bursts are required to shed further light on the relation of the 800 Hz QPO in 4U 1608–52 with those in 4U 1728–34, and with the QPO in Sco X-1.

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Fig. 2a

Fig. 2b

Fig. 2c