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ScienceDirect
Advances in Space Research 38 (2006) 2684–2688
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
www.elsevier.com/locate/asr

Kilohertz quasi-periodic oscillations in SAX J1808.4–3658

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Received 20 June 2005; received in revised form 28 February 2006; accepted 28 February 2006

Abstract

I present a short overview of the behavior and properties of the two simultaneous kilohertz quasi-periodic oscillations (kHz QPOs) seen in the accreting millisecond X-ray pulsar SAX J1808.4–3658. I will focus on the behavior of the upper frequency QPO as a function of time and count rate as seen during the 2002 outburst of this source. I will also discuss briefly the correlated behavior of this QPO with QPOs at lower frequencies (several tens of hertz).

Keywords: Accretion; Accretion disks; Pulsars; X-ray, binaries; Stars, neutron

1. A short history of SAX J1808.4–3658

In September 1996, a new transient was discovered with the WFCs aboard the *BeppoSAX* satellite and the source was designated SAX J1808.4–3658 (In 't Zand et al., 1998). Three type-I X-ray bursts were detected, demonstrating that the compact object in this system is a neutron star. From those bursts, a distance estimate of 2.5 kpc was determined (In 't Zand et al., 1998, 2001). The maximum luminosity during this outburst was $\sim 10^{36}$ erg s^{-1}. The outburst continued for about three weeks after which the source returned to quiescence. Only *BeppoSAX* observed the source during this outburst and this did not allow for detailed studies of the rapid variability properties of the source.

On April 9, 1998, *RXTE*/PCA slew observations indicated that SAX J1808.4–3658 was active again. Using public TOO observations of this source from April 11, it was discovered (Wijnands and van der Klis, 1998) that coherent 401 Hz pulsations were present in the persistent X-ray flux of the source, making it the first known accretion-driven millisecond X-ray pulsar. A detailed analysis of the coherent timing behavior (Chakrabarty and Morgan, 1998) showed that the neutron star is in a tight binary with a very low-mass companion star in a 2-h orbital period. Studies of the X-ray spectrum and the aperiodic rapid X-ray variability showed an object that, apart from its pulsations, is remarkably similar to other low-mass X-ray binaries with comparable luminosities (the atoll sources; see, e.g., Van Straaten et al., 2005). However, the kilohertz quasi-periodic oscillations (the kHz QPOs; often observed in the atoll sources) were not seen for SAX J1808.4–3658 during the 1998 outburst.

On January 21, 2000, SAX J1808.4–3658 was again detected (Wijnands et al., 2001) with the *RXTE*/PCA at a flux level of ~10–15 mCrab (2–10 keV), i.e., about a tenth of the peak fluxes observed during the two previous outbursts. Using follow-up *RXTE*/PCA observations, it was found that the source exhibited low-level activity for several months (Wijnands et al., 2001). Due to solar constraints the source could not be observed before January 21 but likely a true outburst occurred before that date and we only observed the end stages of this outburst. Again, no kHz QPOs were detected although violent flaring behavior with a repetition frequency of ~1 Hz was discovered.

In 2002 October, a 4th outburst of SAX J1808.4-3658 was detected, immediately launching an extensive *RXTE*/PCA observing campaign. During these observations kHz QPOs (Wijnands et al., 2003) and type-I

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0273-1177/$30
doi:10.1016/j.asr.2006.02.076

X-ray bursts and associated burst oscillations (Chakrabarty et al., 2003) were found. In the summer of 2005 a 5th outburst of the source occurred and again the kHz QPOs were seen. However, I will focus on the QPOs as seen in the 2002 outburst.

2. The kilohertz quasi-periodic oscillations in SAX J1808.4–3658

During the 2002 outburst, two simultaneous kHz QPOs were discovered during the peak of the outburst with

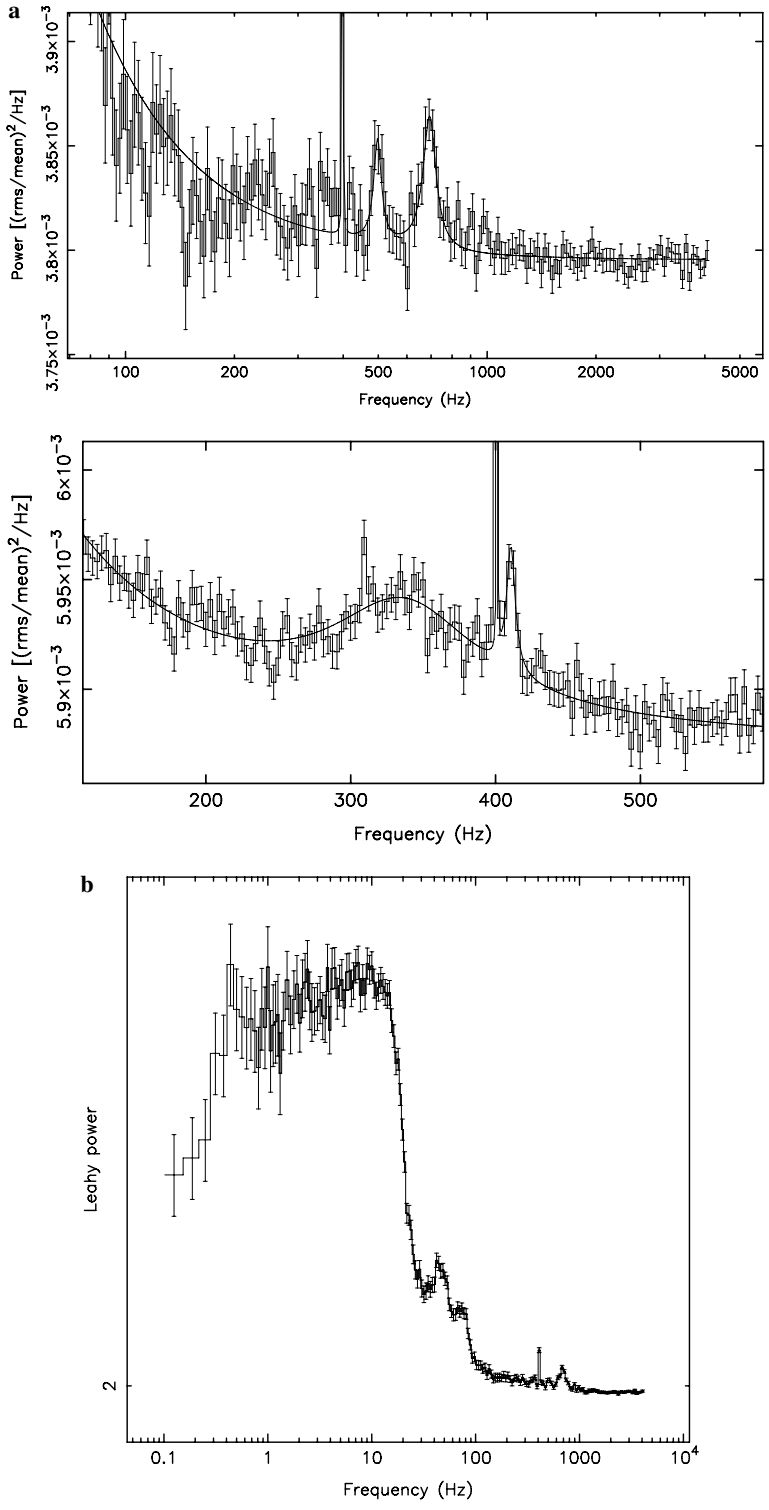

Fig. 1. The power spectra of SAX J1808.4–3658 obtained with *RXTE* during the 2002 outburst of the source. (a) The top panel shows the two simultaneous kHz QPOs; the bottom panel shows the enigmatic 410 Hz QPO (the figures are adapted from (Wijnands et al., 2003)). (b) The broad-band noise and the 40–80 Hz QPOs (called the hectoHertz or hHz QPOs) as seen on October 16, 2002 (the upper kHz QPO and the pulsation spike can also been seen).