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Discovery of decaHz flaring in SAX J1808.4-3658

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Abstract. We report on the discovery of strong decaHz flaring in the early decay of two out of five outbursts of the accreting millisecond X-ray pulsar SAX J1808.4-3658. The decaHz flaring switches on and, after ~3 days, off again, on a time scale of 1-2 hours. When the flaring is present, the total 0.05-10 Hz variability has a fractional rms amplitude of 20 to 30 percent, well in excess of the 8 to 12 percent rms broad-band noise usually seen in power spectra of SAX J1808 in this frequency range. Coherent 401 Hz pulsations are seen throughout the observations in which the decaHz flaring is detected. We find that the absolute amplitude of the pulsations varies with the flux modulation of the deca-Hz flaring, indicating that the flaring is caused by an accretion rate modulation already present in the accretion flow prior to matter entering the accretion funnel. We suggest that the decaHz flaring is the result of the Spruit-Taam instability [1]. This instability arises when the inner accretion disk approaches co-rotation. The rotation of the stellar magnetosphere then acts as a propeller, suppressing accretion onto the neutron star. A matter reservoir forms in the inner accretion disk, which episodically empties onto the neutron star, causing flares at a decaHz timescale. A similar explanation was proposed earlier for 1 Hz flaring occurring late in three of five outbursts, mutually exclusive with the decaHz flaring. The 1 Hz flaring was observed at luminosities a factor 5 to 10 below where we see the decaHz flaring. That a different branch of the Spruit-Taam instability could also act at the much higher luminosity levels of the decaHz flaring had recently been predicted by D'Angelo & Spruit [2, 3]. We discuss these findings in the context of the parameters of the Spruit-Taam-d'Angelo model of the instability. If confirmed, after millisecond pulsations, 1 Hz and decaHz flaring would be another diagnostic of the presence of a magnetosphere in accreting low-magnetic field neutron stars.

1 Introduction

The accreting millisecond X-ray pulsar SAX J1808.4-3658 (SAX J1808) is well known for being the first discovered X-ray binary to be seen pulsating in the millisecond domain [4]. These millisecond pulsations provide direct evidence of the presence of a magnetosphere and as such offer a potential probe for the neutron star magnetic field, the accretion disk and their interaction. Being an ideal candidate to study the magnetosphere/accretion-disk interaction, SAX J1808 has been the target of many observation campaigns. In particular RXTE has provided a wealth of data by observing 6 outbursts over a time span of nearly 14 years. Using these RXTE observations a myriad of variability

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phenomenon have been observed in the X-ray emission of SAX J1808. In addition to the 401 Hz pulsations, SAX J1808 has shown twin kHz QPOs [5], radius expansion X-ray bursts [6] and a violent 1 Hz flaring QPO [7]. The more common stochastic variability of atoll class neutron star binaries is also seen in the power spectra of SAX J1808, and shows very consistent trends in each of the several outbursts [8].

In addition to similarities in their respective power spectra, the overall light curves of SAX J1808's outburst all show a remarkably common evolution. Each taking a few days to reach maximum luminosity, spending almost a day at peak intensity and subsequently decaying in a 2 week exponential *slow* decay phase, followed by a week long linear *fast* decay phase [9]. During several weeks to months after the main outburst, SAX J1808 enters the so-called *flaring-tail*, which constitutes to ~5 day periods of renewed activity at $L_x \sim 10^{35}$ erg s^{-1} separated by by short periods of near quiescence with $L_x \sim 10^{32}$ erg s^{-1} [10, 11].

It is at the low luminosities during the tail of renewed activity that the 1 Hz QPO is observed[10]. Considering that the 1 Hz QPO only occurs during the flaring tail, it has been suggested that the QPO is caused by the Spruit-Taam mechanism [12].

Here we present the discovery of yet another flaring phenomenon, observed at the peak of the 2008 and 2011 outbursts. We compare this newly discovered decaHz flaring with the 1 Hz QPO, which occurs at an order of magnitude lower luminosity, and discuss the dead-disk accretion instability as a potential common explanation for both phenomena.

2 Anomalous power spectra

The power spectra of SAX J1808 are very similar between the separate outbursts and in line with those of standard atoll sources in the (hard) island state [8]. Generally the power spectra are well described by a sum of 4 Lorentzian profiles, reflecting the break, hump, hectoHz and upper kHz QPO components.

Near the peak of the outbursts of 2008 and 2011 we discovered a ~3 day interval during which the power spectrum deviates from its regular shape. The power density between 0.05 and 10 Hz increases from its typical 8 – 12% level up to 20 – 30%, such that the usual flat shape below the break frequency is replaced by increasing power with frequency (see Figure 1).

The broad shape of the decaHz component is highly unusual and is not well described by a set of Lorentzian or Gaussian profiles. In particular the rising power density at low frequency proves to be to steep to account for with the wings of standard fitting profiles. We find that using a Schechter function, i.e. a power-law with exponent cut off; $P_\nu \propto \nu^\alpha \exp(-\nu/\nu_c)$; instead of a Lorentzian for the break component provides a satisfactory fit to the power spectra. The characteristic frequency of the decaHz flaring component is then given by $\nu_{max} = \alpha\nu_c$.

2.1 2008

In the 2008 outburst of SAX J1808 the decaHz flaring is first seen at MJD 54739, just after the outburst has reached peak luminosity, and remains present in the power spectrum for the following 3.1 days. During this time the 2-16 keV flux of SAX J1808 steadily decays from 43 to 34 mCrab. The 0.05 to 10 Hz rms is 28% during this interval. Assuming the 8% rms that is seen before and after the decaHz flaring interval persists through the observations in which the flaring is active, an intrinsic rms amplitude of 27% percent is derived for the flaring component. The cut-off frequency of the flaring is $\nu_c \sim 3 - 4$ Hz such that $\nu_{max} \simeq 1.5$ Hz.

At MJD 54742.4 the decaHz flaring is observed switch-off as the 0.05-10 Hz rms decays back to 8% from an incidental high of 45%. As seen in Figure 3a the switch-off is strongly correlated with the

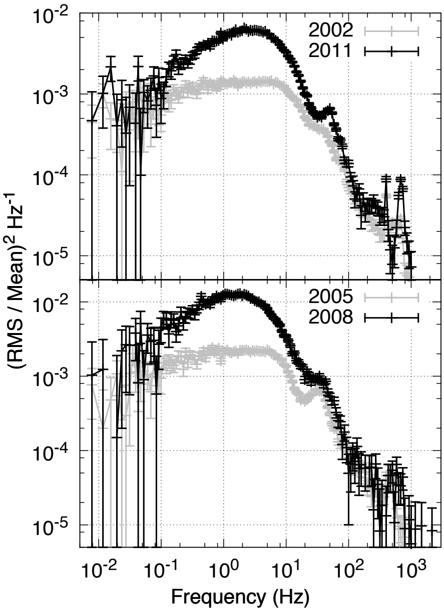


Figure 1. The power spectra of decaHz flaring in $P_\nu \times \nu$ representation. The top panel shows the power spectrum of the 2011 instance (black) of decaHz flaring versus a power spectrum of the 2002 outburst (grey) at a similar point in the hardness-intensity track. Similarly, the bottom panel shows the 2008 instance of decaHz flaring versus a power spectrum of the 2005 outburst.

X-ray flux. Assuming the decaHz flaring has completely disappeared at the 8% rms level, we deduce a lower limit on the switch-off timescale of 1 hr.

2.2 2011

The first pointed RXTE observation of SAX J1808 in the 2011 outburst occurred at MJD 55869.9. In this observation the decaHz flaring is already present and it remains active for the following 4 days. During this time the X-ray flux is observed to increase from 76 mCrab the outburst peak luminosity of ~80 mCrab, after which it decays to 69 mCrab.

The rms amplitude of the decaHz flaring is ~ 25%, while the cut-off frequency is $\nu_c \sim 3-6$ Hz with $\nu_{max} \simeq 3$ Hz. In the one observation during which the flux increases to 80 mCrab, the decaHz flaring amplitude shows a correlated drop in 0.05-10 Hz rms amplitude to 9%. In the following observation the flux started to decay and the decaHz flaring amplitude is back at ~25%.

At MJD 55873.9 the switch-off is observed as the rms amplitude steadily decreases from 25% to 8% (see Figure 3b). As seen in 2008 this decay is strongly correlated with the X-ray flux. The onset of the decay is not observed, we can therefore place an upper limit on the switch-off timescale of 2 hrs.

2.3 The flaring nature

During the 2008 instance of decaHz flaring, the rms amplitude briefly reached a peak strength of 45%, making it pronounced enough to show up directly in the light curve (Figure 2). The light curve shows clear flares of emission at a quasi-regular spacing of ~3 Hz.

We analyze the light curve by applying a flux binning, dividing the light curve into four quartiles. For each quartile we fold the light curve on the orbital ephemeris and construct pulse profiles. We find that the absolute amplitude of the pulsations increases with flux such that the fractional amplitudes for each quartile is the same within their errors.

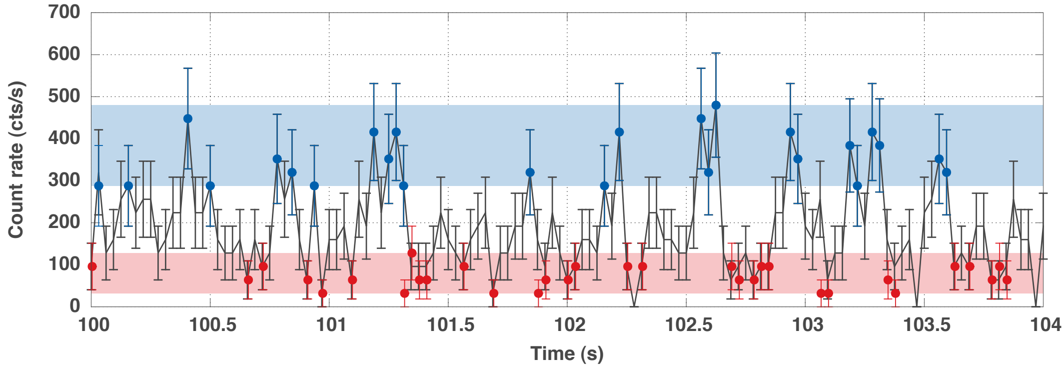


Figure 2: The light curve of SAX J1808 at 1/32 s resolution while the decaHz flaring has a peak rms amplitude of 45%.

The relation between the pulse amplitude and the flux modulation due to the flaring strongly suggests that the decaHz variability is present in the accretion stream prior to entering the accretion funnel. It is then very likely that the variability originates from the inner region of the accretion disk.

3 The 1 Hz QPO

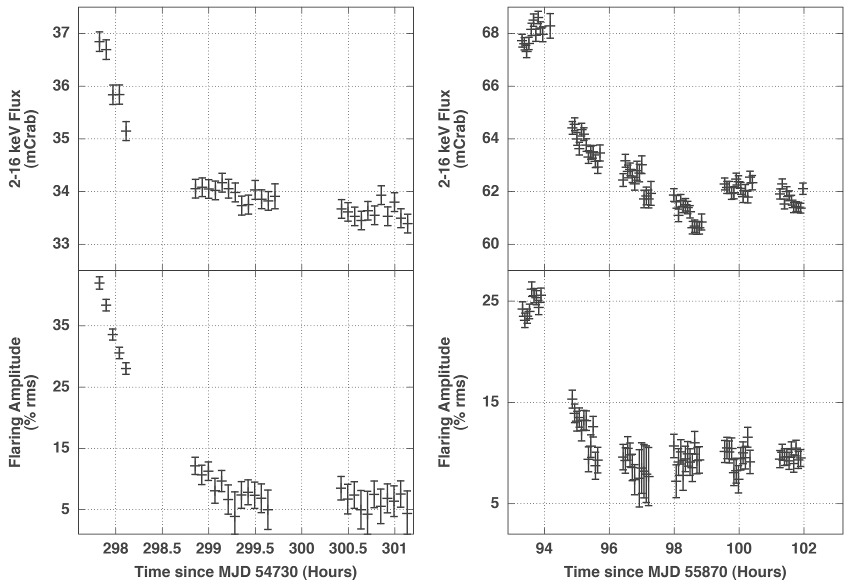
The decaHz flaring resembles the violent 1 Hz QPO, which sometimes appears in the tail of the outbursts of SAX J1808 [7]. Both phenomena present as a broad noise component in the power spectrum and exhibit a flaring phenomenology in the light curve. There are, however, also clear differences. The decaHz flaring has characteristic frequencies of 2-5 Hz, rms amplitudes of 20 to 30%, whereas the 1 Hz QPO has frequencies in the range of 0.5 – 2 Hz with amplitudes ranging from 40% up to 120% fractional rms.

More notably, however, is the luminosity at which the two types of variability are observed. The 1 Hz QPO was seen in 3 outbursts of SAX J1808 (i.e. 2000,2002 and 2005). It is seen exclusively the tail of the outburst as the source shows intermittent activity near quiescence [12]. As this phase of the outburst was not observed in the 1998 outburst, it cannot confirmed whether the 1 Hz was active[10]. In 2008 and 2011 the 1 Hz QPO was definitely not present [12, 13]. The decaHz flaring, on the other hand, was seen *exclusively* in 2008 and 2011, at their respective peak luminosities. The luminosity at which the decaHz flaring is active is then roughly an order of magnitude higher than where the 1 Hz QPO is seen. Remarkably, though, both variability appear to be active in a very narrow flux window of ~ 10 mCrab.

The 1 Hz QPO is proposed to be caused by the Spruit-Taam instability [12]. Given the phenomenological similarities between the 1 Hz QPO and the decaHz flaring we consider whether this instability can be extended to the explain the decaHz flaring as well.

4 Dead-disk accretion instability

When the inner edge of the accretion disk is near corotation the magnetosphere can form a centrifugal barrier, preventing accretion onto the neutron star [14]. If the inner disk radius is $< 1.3r_c$ the barrier is not strong enough to drive an outflow [1], and matter will be trapped in the inner disk. As mass transfer



(a) (b)

Figure 3: The decaHz flaring switch-off in the 2008 (a) and 2011 (b) outbursts of SAX J1808.

in the disk continues, matter accumulates in a reservoir. This reservoir pushes the disk edge back in as the increasing mass exerts more pressure magnetosphere. Eventually the reservoir overtakes the centrifugal barrier, triggering an episode of accretion, allowing the reservoir to empty and the cycle to start over.

Although the Spruit-Taam instability works for the 1 Hz QPO, it is incompatible with the observed pulsed emission of the decaHz flaring as the instability requires a full stop of the accretion as the reservoir accumulates mass. More recent investigations of this type of instability [2, 3] show that the instability is far more intricate than the simple picture described above. In particular D'Angelo & Spruit [2] find that the instability occurs in two regions, at different mass accretion rates. The low mass accretion rate region reflects the traditional Spruit-Taam instability, whereas the second region occurs at higher mass accretion rates in combination with continued accretion onto the neutron star.

The dead-disk accretion instability occurs at mass accretion rates of $\dot{m} \simeq 1 - 10\dot{m}_c$, where $\dot{m}_c$ is the mass accretion rate at which plasma is forced to corotate with the magnetosphere. For SAX J1808, at the luminosity where the decaHz flaring is observed, this mass accretion rate evaluates to $\sim 5 \times 10^{-(10\sim 11)} M_{\odot}/\mathrm{yr}$. The decaHz flaring therefore occurs at mass accretion rates at which the instability can be active. The predicted timescale of the instability is tied to the to the viscous timescale of the inner accretion disk, being $0.1 - 0.01\tau_{\nu}$. At the time of decaHz flaring the viscous timescale will be roughly $\tau_{\nu} = 40$ s, matching with the observed flaring frequency.

With a low and high mass accretion rate instability region, the dead-disk accretion instability can explain both the 1 Hz QPO decaHz flaring, respectively. Additionally, the model predicts that the frequency should increase with mass accretion rate[3], which is indeed observed if we compare the trend in rms and frequency between the 2008 and 2011 instance of decaHz flaring.

5 Conclusions

We presented the discovery of decaHz flaring in SAX J1808, a flaring phenomenon which appears in the power spectrum with 20-30% fractional rms and a characteristic frequency of 2-5 Hz. The flaring is seen only in the outburst of 2008 and 2011 at the outburst peak luminosity. After being present for ~3 days the flaring switches off on a timescale of 1 to 2 hours, showing a strong correlation with flux. For the 2011 instance we further observed a small increase in flux to be correlated with a decrease in the flaring rms amplitude. These observations suggest the flaring appears only in a very sharply bounded flux window, indicating that the instability region of the underlying mechanism is highly sensitive to mass accretion rate.

The decaHz flaring resembles the 1 Hz QPO, which can be observed in some outbursts of SAX J1808, but at an order of magnitude lower luminosity. The appearance of this flaring behavior at such different luminosities can be readily explained by the two instability regions of the dead-disk accretion instability. We compared the characteristics of the decaHz flaring with the high mass accretion rate instability region of the model and found that it offers a plausible explanation for the observations.

If confirmed, this type of flaring offers a new diagnostic of the magnetosphere in low-mass X-ray binaries, independent of the presence of pulsations. It would therefore be very interesting to see wether this behavior can also be found in other not-pulsating low-mass X-ray binaries.

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