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QPO IN TRANSIENT PULSARS

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ABSTRACT

QPOs have now been observed from five transient X-ray pulsars. Four of these are in Be/X-ray systems, and one is the newly discovered LMXB transient GRO J1744-28. I review the observations, and discuss their interpretation in terms of the beat or Keplerian frequency models. These models are successful in explaining the observations for two of the Be/X-ray transients. For one of these, A0535+262, the observations constrain the ratio of the radius of the accretion disk inner edge to the Alfvén radius, providing new information on the accretion disk-magnetosphere boundary region. Neither model can explain the QPO in the remaining two Be/X-ray systems, nor that in GRO J1744-28. It is likely therefore that two or more QPO mechanisms are at work. I discuss the potential for gaining new insight into QPOs from analysis tools unique to pulsed systems, and discuss what we can learn from new observations.

INTRODUCTION

The discovery of Quasi Periodic Oscillations (QPOs) in the power spectra of the flux from x-ray binary pulsars (Angelini *et al.* 1989) offers a new probe of accretion physics in these systems. Observations of the transient pulsars EXO 2030+375 and A0535+262 have revealed QPOs at either the Keplerian orbital frequency at the magnetospheric radius, or its beat with the neutron star spin frequency. QPOs can therefore offer direct information on the poorly-understood accretion disk–magnetosphere boundary region. Unlike most unpulsed sources, for many x-ray pulsars the basis system variables of spin period, orbital parameters, and surface magnetic fields have been determined. In addition, pulse timing allows measurements of accretion-induced torques, which can provide a measure of mass-accretion rate unaffected by distance or spectral uncertainties. Study of QPOs in pulsars therefore has great promise for testing QPO models and providing new insights into accretion physics.

I review here QPOs in the transient X-ray pulsar systems, which should be the simplest to interpret. While QPO have been observed in several persistent X-ray binary pulsars, interpretation of these observations is complicated by several factors. Both the beat frequency and the Keplerian frequency QPO models predict a systematic change of QPO frequency with mass-accretion rate, which can be tested by comparing QPO frequency with either X-ray flux or spin-up rate, assuming these are simply related to the mass-accretion rate. However, this assumption may not be valid in all of the persistent

Table 1: QPO Observations in Transient X-ray Pulsars

Source	ν_{QPO}	ν_{QPO}/ν_{ns}	FWHM	r_{QPO}	r_{cont}	Reference
LMXB Systems:						
GRO J1744-28	40 Hz	18.7	48%	1.5-5.9%	> 30%	1
Be/X-ray Systems:						
V 0332+53	51 mHz	0.22	65%	4.8%	25%	2,3
4U 0115+375	62 mHz	0.22	65%	⋯	⋯	4
EXO 2030+375	187–213 mHz	8.0–9.1	24%	3.6%	25%	5
A 0535+262	25–72 mHz	2.6–7.4	50%	9–12%	25%	6

References:
[1] Zhang et al.(1996)
[2] Takeshima et al. (1994)
[3] Makishima et al. (1989), for r_{cont}
[4] Soong & Swank (1989)
[5] Angelini, Stella & Parmar (1989)
[6] Finger, Wilson & Harmon (1996a)

systems. For example, in Cen X-3 the X-ray flux, due to variable absorption by circumstellar material, is known to be an unreliable indicator of the mass-accretion rate (Van der Klis *et al.* 1980). The disk fed persistent systems may be near equilibrium, with direct accretion of angular momentum being roughly balanced by magnetic breaking torques. In this regime the relationship between torque and mass-accretion rate is poorly understood, making comparisons of spin-up rate and QPO frequency more difficult to interpret. In contrast, during transient pulsar outbursts, breaking torques are small compared to the direct accretion of angular momentum, resulting in a mass-accretion rate versus torque relation which is nearly a power law. Finally, the range of mass accretion rates explored with the persistent systems is relatively narrow, while the transients experience change by a factor of 10^3 or more.

To date, QPOs have been seen in five transient X-ray pulsars: the transient LMXB pulsar GRO J1744-28, and four pulsars in Be/X-ray systems. Table 1 summarizes the observations, giving the observed QPO frequency ν_{QPO}, the ratio of the QPO frequency to neutron star spin frequency ν_{ns}, the full width half maximum width of the QPO relative to the QPO frequency, FWHM, and the fractional R.M.S. power of the QPO, r_{QPO}, and of the observed continuum, r_{cont}. All of these observations are of broad power spectral features, with several not meeting the strict (FWHM < 50%) definition applied to QPO in LMXB systems. Nevertheless they all represent a substantial concentration of power in a limited frequency range, with fractional RMS's ranging from 1.5 to 12%. In all of the sources the QPO is observed in the presence of a strong red-noise continuum, with RMS of 25% or more. The flux modulation represented by the continuum is often stronger than that of the coherent pulsations, and consistently dominates that due to the QPO.

These five sources are only a small fraction of the 30 known transient X-ray pulsars. However, sensitive wide-band power spectral studies have been performed for only a small fraction of the transient pulsar outbursts that have occurred over the last 20 years. With the combined timing capabilities and sensitivity of RXTE, and the pulsar monitoring capabilities of BATSE/CGRO, I expect in the next few years many new discoveries of QPO in X-ray pulsars. Outbursts from transient LMXB pulsars are clearly rare, but those from Be/X-ray pulsars are fairly common.

THE BEAT AND KEPLERIAN FREQUENCY MODELS

In the beat frequency model (Alpar & Shaham 1985) blobs of matter, in the process of being entrained in the neutron star's magnetic field, orbit the neutron star at approximately the Keplerian orbital frequency ν_k of the inner edge of the accretion disk, accreting at a rate that is modulated by the magnetic field, which rotates with the neutron star at a frequency ν_{ns}. This produces a QPO at the beat frequency $\nu_{QPO} = \nu_k - \nu_{ns}$. In the Keplerian frequency model (Van der Klis *et al.* 1987) the inner edge of the accretion disk contains structures that persist for a few cycles around the neutron star, and modulate the observed flux by obscuration producing a QPO at the Keplerian frequency ν_k.

The radius r_0 of the disk inner edge determines the Keplerian rotation frequency there via Kepler's third law, $2\pi\nu_k = (GM)^{1/2} r_0^{-3/2}$. At the inner disk edge the magnetosphere disrupts the Keplerian rotation of the disk, forcing matter to accrete along magnetic field lines. The dependence of r_0 on the mass-accretion rate may be approximately expressed as (Pringle & Rees 1972):

$$r_0 = K\mu^{4/7}(GM)^{-1/7}\dot{M}^{-2/7} \tag{1}$$

where K is a constant of order 1, μ the neutron star magnetic moment, G Newton's gravitational constant, and M the gravitational mass of the neutron star. Eq. 1 with $K = 0.91$ gives the Alfvén radius for spherical accretion. Ghosh and Lamb (1979) give a value of $K = 0.47$. The accretion torque is

$$N = I2\pi\dot{\nu}_{ns} = \dot{M}(GMr_0)^{1/2} \ . \tag{2}$$

Here I is the moment of inertia of the neutron star. $(GMr_0)^{1/2}$ is the specific angular momentum of matter in a Keplerian orbit at the inner disk radius r_0. Eq. 2, which considers only the transport of orbital angular momentum from the disk to the neutron star, should be valid at high mass-accretion rates. The hard x-ray flux is directly dependent on the mass-accretion rate $\dot{M}$,

$$F = \frac{\alpha\beta}{4\pi d^2}\frac{GM}{R}\dot{M} \tag{3}$$

where α is the fraction of the total luminosity within the observational energy band, β accounts for the effects of beaming, d is the source distance, and R is the neutron star radius.

The predicted dependence of the spin-up rate and flux on the Keplerian frequency are

$$\begin{aligned} \dot{\nu}_{ns} = \aleph_N \nu_k^2 \quad &\text{with} \quad \aleph_N = 1.6K^{7/2}B^2R^6(GM)^{-1}I^{-1} \\ \text{and} \quad F = \aleph_F \nu_k^{7/3} \quad &\text{with} \quad \aleph_F = 1.4\alpha\beta d^{-2}K^{7/2}B^2R^5(GM)^{-2/3} \ . \end{aligned} \tag{4}$$

where $B = 2\mu R^{-3}$ is the polar surface magnetic field.

Mass flow to the neutron star is expected to be stopped at the magnetospheric boundary by centrifugal inhibition of accretion if the Keplerian orbital frequency at the magnetospheric boundary is less than the neutron star spin frequency (Stella *et al.* 1986). This should occur with either wind fed or disk accretion, with the matter that is entrained in the magnetic field at the magnetospheric boundary being flung back by centrifugal force when it is constrained to corotate with the magnetosphere. Therefore QPOs below the neutron star spin frequency cannot be explained by the Keplerian frequency model. In the beat frequency model the mass flow to the neutron star is inhibited as the QPO frequency approaches zero. This occurs at a flux given by

$$F_{CI} = F_{QPO}\left(\frac{\nu_{ns}}{\nu_{ns}+\nu_{QPO}}\right)^{7/3} \tag{5}$$

where F_{QPO} is the flux at the time of the QPO observation. There should be a rapid transition from a low flux level (due to accretion onto the magnetosphere) to F_{CI} at the onset of an outburst, and outbursts should end with a rapid fall in flux once F_{CI} is reached (Corbet 1996).

OBSERVATIONS

GRO J1744-28

The only known transient LMXB pulsar, GRO J1744-28 was discovered in December 1995 due to its unusual bursting behavior (Kouveliotou *et al.* 1996). RXTE observations revealed a 40 Hz QPO, along with smaller, yet significant QPOs at 20 and 60 Hz (Zhang *et al.* 1996). The RMS of the QPO decreased with decreasing flux. An accretion disk was present during the observations as indicated by the high spin-up rate of the pulsar (Finger et al. 1996b). Over the course of the QPO observations the flux changed by a factor of 7.5, with little or no systematic change in the QPO frequency. This eliminates both the beat and Keplerian frequency models for these QPO since these predict a factor of 2.4 change in the QPO frequency for the observed change in flux. Zhang *et al.* (1996) conclude that "there is not a ready model in the literature that can adequately explain in quantitative terms the prominent characteristics of the QPO".

Be/X-ray Binary Outbursts

The remaining four QPO detections are in Be/X-ray transients. They occur fairly regularly, and often are observed in series of outburst repeating once per binary orbit. BATSE has detected a total of 55 outbursts from 11 different Be/X-ray pulsars in the last five years. These outbursts are of two types (Stella *et al.* 1986, Motch *et al.* 1991); "class I" or "normal" outbursts which are of lower flux, are confined to a limited range of orbital phase, and often repeat for several orbits, and "class II" or "giant" outbursts which have higher peak flux, show high rates of spin-up, and can last for several binary orbits. An example of both kinds of behavior is shown in Figure 1, which shows the flux and barycentric frequency history from a series outbursts of 2S 1417-624 observed by BATSE (Finger *et al.* 1996c). While it is clear that accretion disks are present during the giant outbursts, it is unknown whether they are present in the normal outbursts. Since the QPOs observed to date in x-ray pulsars are all associated with accretion disks, one method of investigating this issue would be to search for QPOs during the normal outbursts.

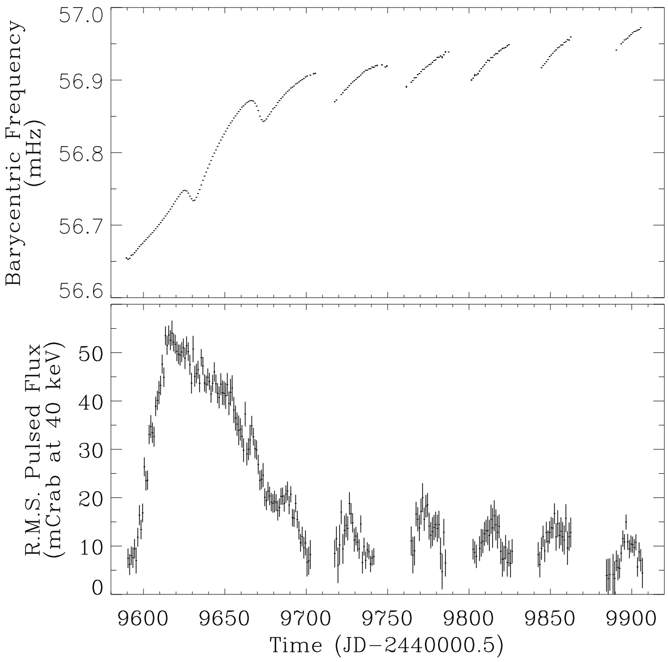

Fig. 1. The barycentric frequency and pulsed flux of 2S 1417-624 observed by BATSE during the August 1994 – July 1995 outbursts.

V0332+53 and 4U 0115+63

For both V0332+53 and 4U 0115+63 there have been single reported observations of QPOs, with these QPOs at a frequencies below the neutron star spin frequencies. A 51 mHz QPO in the flux of V0332+53 was observed with *Ginga* during an outburst of this Be/X-ray pulsar in September and October 1989 (Takeshima *et al.* 1994). This broad feature, which lay below the pulse frequency, was observed on October 1, when the 2.3-37.2 keV flux was 2.9×10^{-8} erg cm^{-2}s^{-1}. An earlier observation on September 19, when the flux was 1.9×10^{-8} erg cm^{-2}s^{-1}, showed no QPO. HEAO observations of 4U 0115+63 during an outburst in January of 1978 revealed a prominent power spectral feature, also below the pulse frequency, centered on 61 mHz (Soong & Swank 1989). During the observation the 2-60 keV flux was 8.7×10^{-9} erg cm^{-2}s^{-1} (Rose *et al.* 1979). Since these QPOs are below the neutron star spin-frequency, they cannot be explained by the Keplerian frequency model.

The peak flux of the September-October 1989 outburst of V0332+53 was simular to that in the giant outburst observed by Vela 5B in 1973, which lasted 100 days (Terrel & Priedhorsky 1984). The centrifugal inhibition threshold calculated from the QPO observation assuming the beat frequency model is $F_{CI} = 1.8 \times 10^{-8}$ erg cm^{-2}s^{-1} (2.3-37.2 keV). A series of three smaller normal outbursts occurring once per orbit were observed from November 1983 – January 1984 (Stella *et al.* 1986). For the first of these, Tenma observed (Makishima *et al.* 1990) a peak flux of 3.2×10^{-9} erg cm^{-2}s^{-1} (2-30 keV). The QPO therefore cannot be explained by the beat frequency model. Rapid X-ray fluctuations with an 0.01-1.0Hz fractional RMS of $\sim$25% were observed during the Tenma observations.

The January 1978 outburst of 4U 0115+634 also appears to be a giant outburst, lasting more than 30 days which is longer than the 24 day orbital period, and having one of the higher peak fluxes of the outbursts that have been observed from this source. The centrifugal inhibition threshold calculated from the QPO observation assuming the beat frequency model is $F_{CI} = 5.5 \times 10^{-9}$ erg cm^{-2}s^{-1} (2-60 keV). Observations made by the Einstein Observatory on January 15 1981 at the end of a small outburst (Kriss *et al.* 1983) detected pulsations and found a 2-10 keV flux of 3.3×10^{-9} erg cm^{-2}s^{-1}. The QPO observed in 4U 0115+634 therefore cannot be explained by the beat frequency model.

EXO 2030+375

QPO was observed with EXOSAT in the flux of the Be/X-ray binary pulsar EXO 2030+375 during the May – August 1985 discovery outburst (Angelini *et al.* 1989). This was clearly a giant outburst, showing high flux and rapid spin-up rates, and lasting several orbits. The QPO ranged in frequency from 187 mHz to 213 mHz, well above the 24 mHz pulse frequency.

As is shown in Figure 2, the QPO frequency is clearly correlated with the observed flux, which is a key prediction of the beat frequency and Keplerian frequency models. The figure shows the trends predicted by the beat and Keplerian frequency model, with the normalizations chosen to fit the data. While the data spans only a small range, the fit for either model is reasonable. Assuming a source distance of 5 kpc, the required normalization of the QPO-flux relations imply a surface (dipole) magnetic field of approximately 5×10^{12} G. The predicted onset of centrifugal inhibition of accretion is at a flux of 2×10^{-10} erg cm^{-2} s^{-1} (1-20 keV), which is nicely bracketed by the last flux measured in the discovery outburst of 4×10^{-10} erg cm^{-2} s^{-1} on August 13 1985, and following the upper limit of 1.3×10^{-11} erg cm^{-2} s^{-1} for the observation of August 25 1985 (Parmar *et al.* 1989).

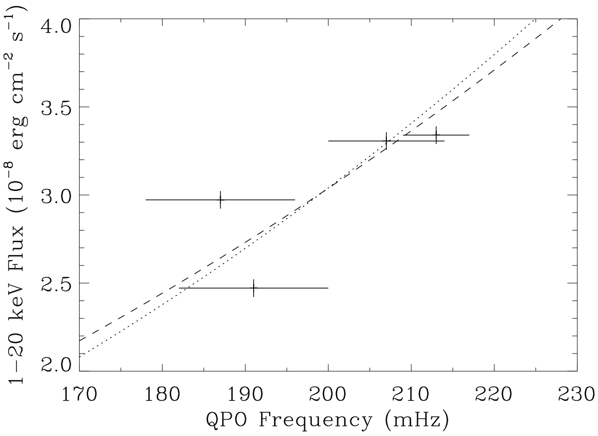

Fig. 2. QPO frequency versus 1-20 keV flux during the May – August 1995 outburst of EXO 2030+375. The data is from Angelini *et al.* (1989). The lines are the trends predicted by the beat frequency (dashed) and the Keplerian frequency (dotted) model.

A0535+262

QPO was observed with BATSE on the Compton Observatory during a giant outburst of A0535+262 in February-March 1994 (Finger *et al.* 1996a). The giant outburst, which reached a peak flux of 6 Crab at 40 keV, occurred within a series of six outbursts spaced roughly once per 110 day orbit. Figure 3 shows the pulse amplitude spin-frequency during these observations. An estimate of the binary orbital parameters based on pulsed timing during the first three normal outbursts (Finger *et al.* 1994) allowed the spin-up rate $\dot{\nu}_{ns}$ to be determined from pulse timing measurements during the giant outburst, in addition to the flux history obtained by occultation measurements.

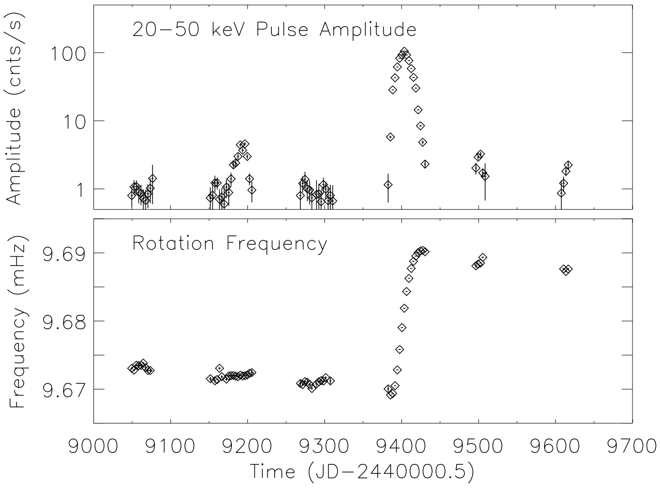

Fig. 3. BATSE observations of A0535+262.

The QPO was observed for 33 days, initially being detected at 27 mHz, rising to 72 mHz at the peak of the outburst, and falling to 25 mHz in a manner highly correlated with both the flux and the spin-up rate. The observed relationships between QPO frequency and spin-up rate, and between QPO frequency and flux are shown in Figures 4 and 5 respectively. In both cases squares are used for the rise of the outburst, and diamonds for the fall. The rise and fall behavior tracks fairly well. The plots give the predicted trends for the beat frequency model (dashed) and Keplerian frequency model (dotted), either of which fit the data reasonably.

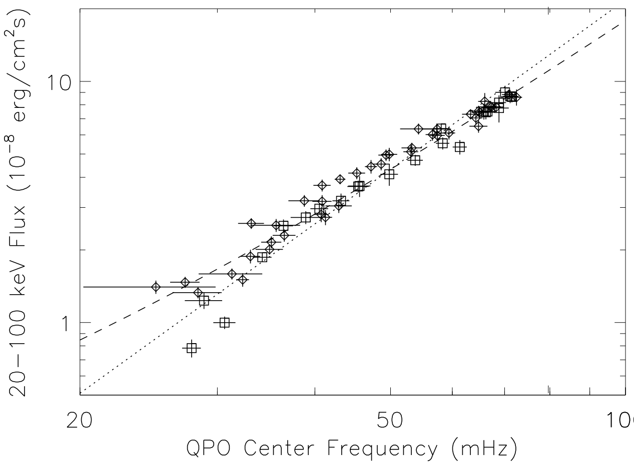

Fig. 4. Comparison of QPO frequency and Flux for A0535+262.

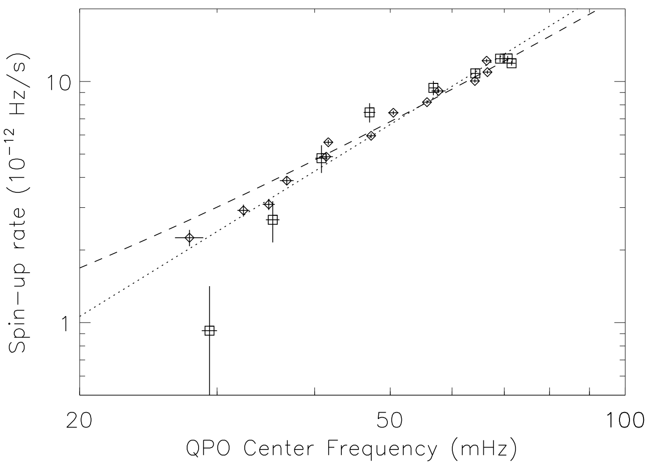

Fig. 5. Comparison of QPO frequency and spin-up rate for A0535+262.

Finger *et al.* (1996a) show that the measured normalization constants in the spin-up rate versus QPO frequency relationship and flux versus QPO frequency relationship (Eq. 4), are consistent with the 110 keV cyclotron line measured by OSSE during the 1994 giant outburst (Grove *et al.* 1996), estimates of the source distance, and reasonable neutron star parameters, if the constant K in the magnetospheric radius versus mass accretion rate relationship (Eq. 1) is approximately one. However, use of the value $K = 0.47$ estimated by Ghosh and Lamb (1979) requires a neutron star with a very stiff equation of state, or with a mass less than 0.5 $M_{\odot}$.

BEYOND POWER SPECTRA

The power spectrum is the standard means of characterizing a source's flux noise. If the statistical properties of this noise are unchanged with a translation in time (a stationary noise process) then the mean flux μ_F and the autocovariance function $R_F(\tau)$, or equivalently, the power spectrum $S_F(\nu)$ provide a complete description of the first and second order moments of the flux:

$$\begin{aligned} < F(t) > &= \mu_F \\ < [F(t_1) - \mu_F][F(t_2) - \mu_F] > &= R_F(t_2 - t_1) = \int S_F(\nu) e^{i2\pi\nu(t_2 - t_1)} d\nu \quad . \end{aligned} \tag{6}$$

In a pulsar the mean flux, of course, depends on the pulse phase $\phi(t)$. In general we expect the statistical properties of the noise to be unchanged with a translation in time by an integer number pulse periods (a cyclostationary noise process). In general the second moments will be phase dependent. A complete description of the first and second order moments of the pulsars flux therefore require a phase dependent mean $\mu_F(\phi)$, and a phase dependent autocovariance $R_F(\tau, \phi)$, both being periodic in phase ϕ:

$$\begin{aligned} < F(t) > &= \mu_F(\phi(t)) \\ < [F(t_1) - \mu_F(\phi(t_1))][F(t_2) - \mu_F(\phi(t_2))] > &= R_F(t_2 - t_1, \phi([t_1 + t_2]/2)) \quad . \end{aligned} \tag{7}$$

Here I have chosen to specify the phase dependence of the autocovariance using the phase midway between the two times involved. This results in the autocovariance being symmetric in lag for fixed phase. For a pulsar, the power spectrum contains less information than the (phase dependent) autocovariance function.

Using the BATSE 20-50 keV rates during the peak of the A0535+262 giant outburst in 1994, I have estimated the phase dependent autocovariance function. Its phase averaged value versus lag is shown in Figure 6. The bump at 13 s is due to the QPO which was at a frequency of 72 mHz. At a lag of 7 s, QPO peaks align with QPO valleys, causing a dip in the autocovariance. The phase dependence of the autocovariance function is examined in Figure 7 for lags of 7.2 and 13.3 s. The phase dependence is significant in both cases, which show very different signatures.

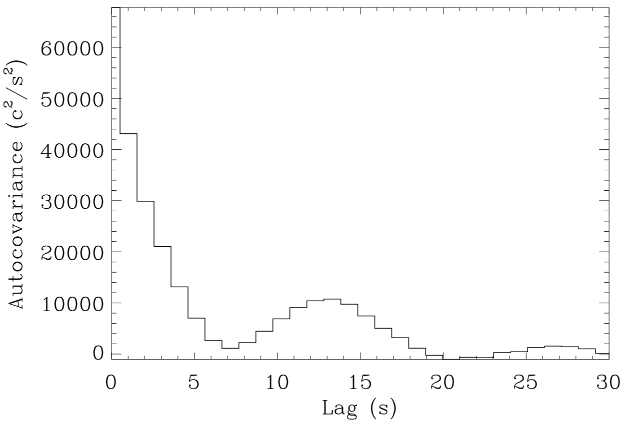

Fig. 6. Phase averaged autocovariance function for A0535+262 on February 16, 1994 using the BATSE 20-50 keV rates. The bump at a lag of 13 s is due to the QPO, which was at a frequency of 72 mHz.

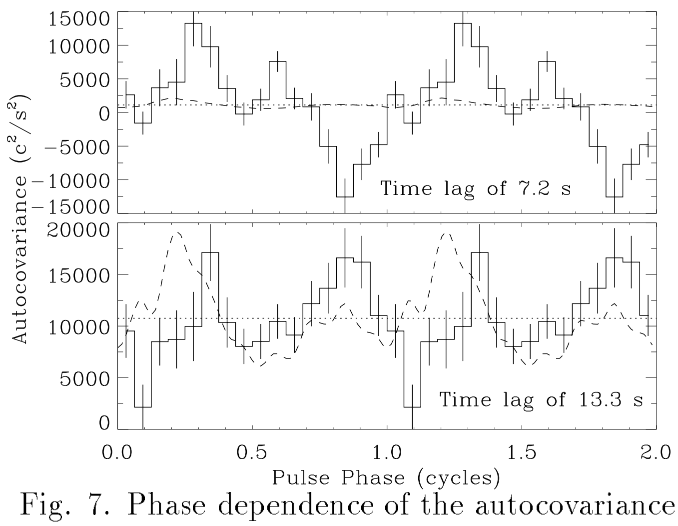

Fig. 7. Phase dependence of the autocovariance function for A0535+262 on February 16, 1994 using the BATSE 20-50 keV rates, at lags of 7.2 and 13.3 s.

We can show that two general classes of models are unable to explain this phase dependent autocovariance function. The first class of model is additive,

$$F(t) = L(\phi(t)) + N(t) \tag{8}$$

where $L(\phi)$ is periodic, and $N(t)$ is a stationary noise process which contains the QPO and red noise. This could result, for example, from a combination of a pulsed flux component $L(\phi)$, due to magnetically channeled accretion, with an unpulsed flux component $N(t)$, due to matter penetrating the magnetosphere without being channeled. This class of models results in a phase independent autocovariance $R_F(\tau, \phi) = R_N(\tau)$, which is shown by the dotted lines in Figure 7.

The second class of model is multiplicative,

$$F(t) = L(\phi(t)) \times N(t) \tag{9}$$

where $L(\phi)$ is periodic, and $N(t)$ is a stationary noise process. For example, $N(t)$ could represent the mass-accretion rate, and $L(\phi)$ the phase dependent emission profile, or $L(\phi)$ could represent an unabsorbed periodic flux and $N(t)$ absorption as a function of time. In this case the phase dependent autorcovariance function is of the form $R_F(\tau, \phi) = R_N(\tau) L(\phi - \tau\nu_{ns}/2) L(\phi + \tau\nu_{ns}/2)$. This is shown in Figure 7 by the dashed lines.

It is clear from Figure 7 that simple additive or multiplicative models are not capable of explaining the noise behavior in A0535+262. This general conclusion could not have been drawn from the power spectrum alone. The phenomena must be more complex, with accretion, emission, and absorption geometrically interlinked. The phase dependence of the noise can therefore provide us with a new probe of the source geometry.

FUTURE PROSPECTS

In the next few years we should expect to observe a number of transient x-ray pulsars that have QPO in their power spectrum. BATSE will be monitoring the galaxy for the onset of these transients, but can only examine the very brightest for QPO. RXTE, with its excellent timing capabilities and sensitivity, should provide a new wealth of information on their power spectra and associated QPO. At the same time, the spectral capabilities of RXTE should allow the observations of cyclotron lines, establishing the magnetic field of the neutron star.

To date, QPO in Be/X-ray binaries have only been seen during giant outbursts. This may be entirely due to sensitivity considerations, or may be due to an accretion disk only being present in the giant outbursts. By examining normal outbursts for QPO, we could address whether an accretion disk is present during these smaller outbursts, and if so, investigate the QPO in this lower flux regime.

The QPO features observed in 4U 0115+634 and V0332+53 could not be explained by the Keplerian or beat frequency model. Since these were isolated observations, it is difficult to draw any conclusions beyond the fact that more than one QPO mechanism is at work in transient pulsars. To understand these features further we will need to place them in the context of other observations where the dependence of the QPO on flux is determined.

From the example of A0535+262 it is clear that regular monitoring over the course of an outburst is extremely useful. This allows the simultaneous determination of flux, spin-up rate and QPO frequency. With enough range in flux we can demonstrate (or disprove) that a QPO is associated with either the beat for Keplerian frequency. By observing QPO at lower flux we should be able to differentiate between the beat and Keplerian frequency models. Of particular importance is regular monitoring at the tail of an outburst. It is here that counter torques produced by interactions between the accretion disk and the magnetic field should become evident, resulting a spin-down at the lowest fluxes. With an established beat or Keplerian frequency QPO monitored through this transition, a detailed mapping of the torque versus mass-accretion rate relationship would for the first time be established. At the end of an outburst the turn-off due to centrifugal inhibition of accretion might be observable.

Beyond using the QPO behavior to locate the disk-magnetosphere boundary, it should also be studied in its own right. The QPO models that have been developed in any detail are for unpulsed systems. Instabilities at the disk-magnetosphere boundary, magnetic channeling of accretion, and site dependent beaming of radiation all need to be considered in models of the continuum red noise and QPO's in pulsars. These models need to be able to explain the phase dependent autocovariance function as well as the power spectrum of the flux noise. This phase dependence of noise properties in pulsars should provide a level of geometrical information unavailable in unpulsed sources.

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