SPECTRAL SIGNATURES OF KILOHERTZ QUASIPERIODIC OSCILLATIONS FROM ACCRETING NEUTRON STARS

Philip Kaaret

*Harvard-Smithsonian Center for Astrophysics*

ABSTRACT

Correlations discovered between millisecond timing properties and spectral properties in neutron star x-ray binaries are described and then interpreted in relation to accretion flows in the systems. Use of joint timing and spectral observations to test for the existence of the marginally stable orbit, a key prediction of strong field general relativity, is described and observations of the neutron star x-ray binary 4U 1820-303 which suggest that the signature of the marginally stable orbit has been detected are presented.

KEYWORDS: accretion, accretion disks — gravitation — relativity — stars: individual (4U 1820-303) — stars: neutron — X-rays: stars

1. INTRODUCTION

The orbital periods associated with the innermost orbits around solar mass compact objects are in the millisecond range. The millisecond quasi-periodic oscillations (QPOs) discovered (Strohmayer et al. 1996; van der Klis et al. 1996) with the *Rossi X-Ray Timing Explorer* (RXTE; Bradt, Rothschild, & Swank 1993) in the x-ray emission from accreting neutron stars are most likely associated with orbital motion near the neutron star, and, thus, potentially offer a new probe of accretion flows and strong gravitational fields near neutron stars in x-ray binaries (for a brief review, see Kaaret & Ford 1997). The key to exploiting the kHz QPOs as probes of strong gravity is to understand the QPOs at a sufficient level so that those aspects of the QPOs which depend on the properties of the gravitational field can be separated from the aspects which depend on details of the accretion physics. It may not be necessary to construct a full theory of the QPO generation mechanism, just as a binary pulsars are excellent test beds for the study of relativity even in the absence of an adequate theory for the generation of the radio pulses.

Here, I present some initial steps of attempts to understand the key quantitative features of the QPOs, such as the centroid frequency, and their relation to the properties of the accretion flow. I consider several key questions:

1. Is the x-ray spectral state of a source correlated with QPO frequency?
2. Is the QPO frequency related to the geometry of an accretion disk?

3. Is the QPO frequency determined by the mass accretion rate?

In the following, I present and then interpret observational data to attempt to answer these three questions.

If an adequate understanding of the QPOs can be obtained, we can then extend our study to address the properties of the gravitational field surrounding the neutron star. One important question is whether there exists an innermost radius, the marginally stable orbit also referred to as the innermost stable circular orbit, inside of which there exist no stable circular orbits. The lack of stability of circular orbits sufficiently close to a compact object is a key prediction of strong field general relativity (e.g. Misner, Thorne, & Wheeler 1970). The relevance of the existence of the marginally stable orbit to the physics of accretion around black holes has long been understood (e.g. Shakura & Sunyaev 1973). More recently, it was pointed out by Kluzniak and Wagoner (1985) that, for most of the preferred equations of state of nuclear matter, the marginally stable orbit lies outside the neutron star radius and thus should be dynamically important for the accretion flow on to neutron stars. The kHz QPOs appear to provide an observational means to test these predictions.

2. CORRELATION OF QPO FREQUENCY WITH SPECTRAL STATE

We wish to use the kHz QPOs as kinematic probes and, thus, must understand the relation of the QPO parameters, particularly the centroid frequency, to the geometry of the accretion flow. We begin by searching for correlations in the time variations of QPO parameters and x-ray spectral properties.

The most obvious spectral parameter with which to correlate the QPO frequency is the total X-ray flux. In a neutron star system, accreted matter must eventually come to rest on the neutron star surface, and, therefore, the total luminosity, \( L \), of a neutron star system must be directly proportional to the total mass accretion rate onto the stellar surface \( \dot{M} \) via

\[
L = GM\dot{M}/R,
\]

where \( G \) is the gravitational constant, and \( M \) and \( R \) are the mass and radius of the neutron star. If the emission is isotropic, or, more generally, if the beaming pattern of the emission does not change with time, then the bolometric flux from a source must also be proportional to \( \dot{M} \). In Fig. 1, we show the relation between QPO frequency and X-ray flux in the 2.5–25 keV band for the neutron star binary 4U 1728-34 (GX 354-0). The figure includes data from observations spanning three years. It is apparent from the figure that, while the QPO frequency and X-ray flux may be correlated for subsets of the data, the overall behavior shows no correlation. The lack of correlation between QPO frequency and X-ray flux may be due to one or more of several different factors: time variable beaming of the X-rays, the contribution of significant flux outside the measurement band, an outflow from the system, or a fundamental lack of physical correlation between QPO frequency and total mass accretion rate.

Spectral shape has long been employed as an indicator of mass accretion rate in neutron star systems. For sources with x-ray spectra which can be adequately
Flux ($10^{-9}$ erg cm$^{-2}$ s$^{-1}$)

FIGURE 1. QPO centroid frequency versus x-ray flux in the 2.5–25 keV band for 4U 1728-34 (GX 354-0). Included are data from observations spanning three years. The different symbols indicate data from different years.

described with a simple power law model (often used for black hole candidates and low luminosity neutron star binaries), a natural indicator of spectral state is the power law photon index. Kaaret et al. (1998) showed that the QPO frequency is well correlated with photon index, but not with x-ray flux, in the neutron star x-ray binaries 4U 0614+091 and 4U 1608-52. This suggests that the spectral state and QPO frequency are related to a common physical parameter. Kaaret et al. (1998) suggested that common parameter is the mass accretion rate through the accretion disk.

A more general indicator of spectral state is an x-ray color, defined as the ratio of count rates in two different energy bands. X-ray colors can be applied to any source and do not rely on an assumed spectral model. However, they are strongly instrument dependent, making it difficult to compare colors obtained from different instruments, and they have no direct interpretation in terms of physical parameters of the source. X-ray colors have been used as spectral state indicators both individually and in pairs forming a “color-color” diagram. When their time varying spectral state is plotted on a color-color diagram, each individual neutron star x-ray binary tends to follow a well-defined track, see Fig. 2 where we present a color-color diagram for 4U 1728-34. This collapse of a potentially two dimensional pattern to a one-dimensional track suggests that a single parameter determines the spectral state. This parameter has usually been interpreted as the total mass accretion rate in the system (Hasinger & van der Klis 1989). However, the lack of correlation between total flux and spectral state may indicate that the parameter is not the total mass accretion rate.
FIGURE 2. Color-color diagram for 4U 1728-34 (GX 354-0). The soft color is defined as the ratio of counts in the 3.5–6.4 keV band to counts in the 2.0–3.5 keV band and the hard color as 9.7–16.0 keV to 6.4–9.7 keV. The plot symbols are the same as in Fig. 1.

FIGURE 3. QPO centroid frequency versus position in color-color diagram for 4U 1728-34. Larger values of the position in the color-color diagram indicate higher inferred mass accretion rates. The upper and lower branches correspond to the upper and lower frequency kHz QPOs which often appear simultaneously. The plot symbols are the same as in Fig. 1.
FIGURE 4. QPO frequency versus magnitude of reflection for 4U 0614+091. The inclination angle for the reflection component was fixed to 0°.

Position in the color-color diagram can be parameterized by position along a fiducial track drawn through the diagram (Hasinger et al. 1990; Hertz et al. 1992). In Fig. 3, we show the QPO frequency versus position in the color-color diagram (Fig. 2) for the same observations presented in Fig. 1. The correlation between QPO frequency and position in the color-color diagram appears robust across several years of observations. A robust correlation is found between QPO frequency and x-ray colors, either position in a color-color diagram or simply a hard x-ray color, for most neutron star x-ray binaries (e.g. Mendez 1999).

3. QPO FREQUENCY AND REFLECTION

The robust correlation between QPO centroid frequency and various indicators of spectral state, photon index or x-ray colors, suggest that a single physical parameter determines both spectral state and QPO frequency. To determine the physical nature of this parameter, we performed a detailed analysis of high quality x-ray spectra of 4U 0614+091 obtained with BeppoSAX (Piraino et al. 1999). When fit with a simple power-law model, the spectra showed strong and systematic residuals near 10–30 keV with a shape characteristic of that expected for a reflection component in the spectrum. Addition of reflection to the spectral model greatly improved the quality of the fits and gave residuals with no systematic variations. Thus, there is strong evidence for a reflection component in the spectra of 4U 0614+091. We found that the magnitude of reflection is well correlated with photon index, confirming a relation suggested by Zdziarski et al. (1999).

The reflection component found in the spectra requires the presence of cool matter located close to the primary x-ray source, presumably the neutron star,
and subtending a large solid angle as viewed by the primary source. The most natural interpretation is that the reflection occurs in an accretion disk surrounding the neutron star. In this case, the magnitude of reflection should be related to the properties of the disk. In particular, if the disk has a variable inner radius, then higher magnitudes of reflection will result for smaller disk inner radii.

Fig. 4 shows the QPO centroid frequency plotted versus magnitude of reflection for 4U 0614+091. The QPO parameters are from RXTE observations while the magnitude of reflection is from BeppoSAX observations. For the two points with lower frequency, we had simultaneous RXTE and BeppoSAX observations. For the upper two points, we inferred the QPO frequency based on the QPO frequency versus photon index relation from Kaaret et al. (1998) and the photon index measured with BeppoSAX and allowing for a systematic offset in photon indices between BeppoSAX and RXTE measured using simultaneous observations. The large error bars for these two points are due to the uncertainty in this extrapolation. The QPO frequency appears correlated with the magnitude of reflection. The correlation is consistent with that expected if the QPO frequency is determined by the orbital frequency at the inner edge of the disk and the variation in reflection is due to changes in the inner disk radius.

4. KHZ QPOS AND ACCRETION GEOMETRY

I suggest the following physical picture to explain the correlations of QPO frequency with spectral state and magnitude of reflection presented in the previous sections. Mass accretion can occur in neutron star x-ray binaries both through the accretion disk and radially (e.g. Ghosh & Lamb 1978). The total mass accretion rate, disk plus radial, determines the total luminosity of the system. The mass accretion rate through the disk determines the radius of the inner edge of the disk and, via the dependence of the overall spectrum on the soft photon flux emitted from the disk, the spectral state of the system. The QPO frequency is determined by the radius of the inner edge of the disk. The data presented above are fully consistent with this picture.

To answer the questions posed earlier:

1. The spectral state of a source is correlated with QPO frequency as demonstrated by the robust correlations found between QPO frequency and photon index or x-ray color.

2. The QPO frequency is related to the geometry of the disk as demonstrated by the correlation between QPO frequency and magnitude of reflection in the x-ray spectrum.

3. The QPO frequency is determined by the mass accretion rate, but the important parameter is the mass accretion rate through the disk and not the total mass accretion rate.
5. **KHZ QPOS AND THE MARGINALLY STABLE ORBIT**

The existence of the marginally stable orbit will have a strong effect on the configuration of the accretion disk near the neutron star as the lack of stable orbits inwards of the marginally stable orbit implies that a stable disk can not exist in that region. The inner radii of disks around neutron stars appear to be variable. The truncation of the disk may be caused by the neutron star magnetic field, by radiation forces acting on the disk, or by a disk instability. In general, the inner disk radius decreases with increasing mass accretion rate through the disk. The marginally stable orbit will modify this behavior by limiting the minimum possible inner disk radius, see figure 5. Thus, saturation at a minimum disk radius for large mass accretion rates is a signature of the marginally stable orbit (Miller, Lamb, & Psaltis 1998). As described in Kaaret, Ford, & Chen (1997), when the disk reaches the marginally stable orbit, the inner radius will not approach a single value, but instead wander over some range due to the properties of the transonic flow near the marginally stable orbit.

If one is willing to accept the assertions made in the previous section that the QPO frequency is determined by the radius of the inner edge of the accretion disk and that the x-ray spectral state is an indicator of mass accretion rate through the disk, then the relation of QPO frequency versus spectral state can be used to probe the relation of inner disk radius versus mass accretion rate through the disk. Thus, the shape of the QPO versus spectral state diagram, i.e. whether or not the QPO frequency saturates at high mass accretion rates, provides a test for the presence of...
FIGURE 6. QPO centroid frequency versus position in color-color diagram for 4U 1820-30 from Bloser et al. (1999). Larger values of the position in the color-color diagram indicate higher inferred mass accretion rates. Filled squares indicate the upper kHz QPO while open squares indicate the lower kHz QPO.

The QPO frequency versus spectral state diagram for 4U 1728–34, Fig. 3, shows no evidence for a saturation of QPO frequency at high mass accretion rates. This is also true for almost all neutron star binary for which kHz QPOs have been detected. There is only one source which does show a clear saturation of QPO frequency at high inferred mass accretion rates: 4U 1820-30. Zhang et al. (1998) demonstrated a saturation of QPO frequency versus x-ray count rate for 4U 1820-30. However, as QPO frequency is poorly correlated with count rate in most sources (the relation tends to look similar to the QPO frequency versus flux relation in Fig. 1), this approach came under significant criticism. Kaaret et al. (1999) showed that the QPO frequency saturates when plotted versus a spectral state indicator derived from a hard x-ray color. As QPO frequency is generally well correlated with hard x-ray color (e.g. Mendez 1999), this result is compelling evidence that the QPO frequency saturates at high disk mass accretion rates. Recently, Bloser et al. (1999) performed a similar analysis using position in a color-color diagram as a spectral state indicator, see Fig. 6, and again find a saturation of QPO frequency.

The fact that only 4U 1820-30 exhibits a saturation of the QPO frequency versus inferred disk mass accretion rate, and thus appears to be the only source for which the disk reaches the marginally stable orbit, merits some consideration. Interestingly, 4U 1820-30 also holds a unique position as the stellar binary system with the shortest known orbital period, see Fig. 7, and is thought to be a double degenerate binary which evolved through a common envelope phase (Rappaport et al. 1987). These unique features of 4U 1820-30 suggest that the neutron star may
have accreted more matter and thus is more massive than other neutron stars in x-ray binaries.

For the marginally stable orbit to be dynamically important, it must lie outside the neutron star surface. If there is a boundary layer on the neutron star surface formed by the accretion flow, then to be observed via kHz QPOs, the marginally stable orbit must lie outside the top surface of the boundary layer. Inogamov & Sunyaev (1999) have recently calculated the properties of such boundary layers and found typical equatorial thicknesses near 1 km. This is comparable to the separation between the marginally stable orbit and neutron star surface for a $1.4 \, M_\odot$ neutron star, rotating at 250–400 Hz, for many of the currently favored equations of state for nuclear matter. The separation increases as the neutron star mass increases since the surface generally moves inward and the marginally stable orbit moves outward. Thus, the signature of the marginally stable orbit is most likely to be observed from the most massive neutron stars.

6. CONCLUSIONS

Milliseconds x-ray timing is a promising probe of accretion flows in x-ray binaries. Robust correlations exist between millisecond timing properties and spectral properties. Study of these correlation may help improve our understanding of the physics and geometry of accretion flows in neutron star x-ray binaries and, perhaps, also of strong field gravity.
ACKNOWLEDGEMENTS
I thank Peter Bloser for use of Fig. 6 before publication.

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