THE ORIGIN OF KILOHERTZ QPOs AND IMPLICATIONS FOR NEUTRON STARS

Frederick K. LAMB
University of Illinois at Urbana-Champaign, Departments of Physics and Astronomy, 1110 W. Green St., Urbana, IL 61801, USA, f-lamb@uiuc.edu
M. Coleman MILLER
University of Chicago, Department of Astronomy and Astrophysics, 5640 S. Ellis Ave., Chicago, IL 60637, miller@bayes.uchicago.edu
Dimitrios PSALTIS
Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA, dpsaltis@cfa.harvard.edu

Abstract

One of the most dramatic discoveries made with the *Rossi X-Ray Timing Explorer* is that many accreting neutron stars in low-mass binary systems produce strong, remarkably coherent, high-frequency X-ray brightness oscillations. The ∼325–1200 Hz quasi-periodic oscillations (QPOs) observed in the accretion-powered emission are thought to be produced by gas orbiting very close to the neutron star, whereas the ∼360–600 Hz brightness oscillations seen during thermonuclear X-ray bursts are produced by one or two hot spots rotating with the star and have frequencies equal to the stellar spin frequency or its first overtone. The oscillations constrain the masses and radii of these neutron stars, which are thought to be the progenitors of the millisecond pulsars. Modeling indicates that the stars have spin frequencies ∼250–350 Hz and magnetic fields $\sim 10^7 - 5\times 10^9$ G.

1. Introduction

The discovery of strong and remarkably coherent high-frequency X-ray brightness oscillations in at least sixteen neutron stars in low-mass binary systems has provided valuable new information about these stars, some of which are likely to become millisecond pulsars. Oscillations are observed both in the persistent X-ray emission and during thermonuclear X-ray bursts (see van der Klis 1997).

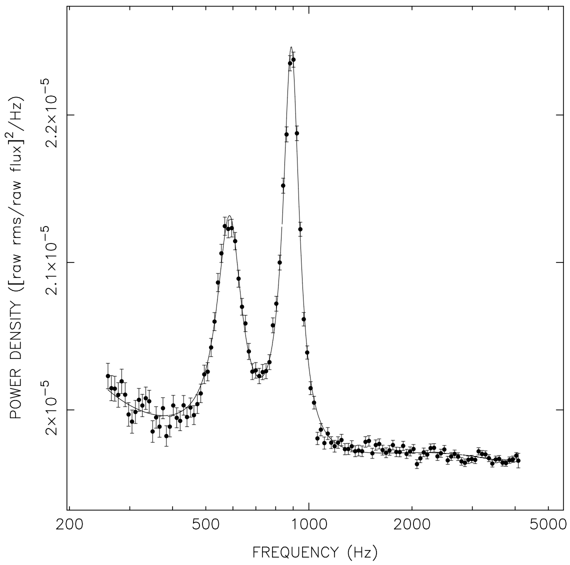

Fig. 1. Power density spectrum of Sco X-1 brightness variations, showing the two simultaneous kilohertz QPOs that are characteristic. These are two of the weakest kilohertz QPOs observed, with rms amplitudes $\sim$ 1%. The continuum power density is consistent with that expected from photon counting noise. From van der Klis et al. (1997).

The kilohertz quasi-periodic oscillations (QPOs) observed in the persistent emission have frequencies in the range 325–1200 Hz, amplitudes as high as $\sim$ 15%, and quality factors $\nu/\delta\nu$ as high as $\sim$ 200. Two kilohertz QPOs are commonly observed simultaneously in a given source (see Fig. 1). Although the frequencies of the two QPOs vary by hundreds of Hertz, the frequency separation $\Delta\nu$ between them appears to be nearly constant in almost all cases (see van der Klis et al. 1997 and Méndez et al. 1997).

The $\sim$250–600 Hz brightness oscillations observed during type I X-ray bursts are different in character from the QPOs observed in the persistent emission (see Strohmayer, Zhang, & Swank 1997). Only a single oscillation has been observed during X-ray bursts, and the oscillations in the tails of bursts appear to be highly coherent (see, e.g., Smith, Morgan, & Bradt 1997), with frequencies that are always the same for a given source (comparison of burst oscillations from 4U 1728−34 over about a year shows that the timescale for any variation in the oscillation frequency is $\gtrsim$3000 yr; Strohmayer 1997). The burst oscillations in 4U 1728−34 and 4U 1702−42 (see Strohmayer, Swank, & Zhang 1998) have frequencies that are consistent with the separation frequencies of their kilohertz QPO pairs. The burst oscillations in 4U 1636−536 (Zhang et al. 1997) and KS 1731−260 (Smith et al. 1997) have frequencies that are consistent with twice the separation frequencies of their kilohertz QPO pairs (Zhang et al. 1997; Wijnands & van der Klis 1997). The evidence is compelling that the burst oscillations are produced by rotation with the star of one or two nearly identical emitting spots on the surface (see Strohmayer et al. 1997). The frequencies of the burst oscillations are therefore the stellar spin frequency or its first overtone.

The frequency separation $\Delta\nu$ between the two kilohertz QPOs observed in the persistent emission of a given star is closely equal to the spin frequency of the star inferred from its burst oscillations (see Miller, Lamb, & Psaltis 1998, hereafter MLP).

2. Origin of Kilohertz QPOs

Although other types of models have been suggested (Klein et al. 1996; Titarchuk & Muslimov 1997), the evidence favoring beat-frequency models of the two kilohertz QPOs is very strong (see van der Klis 1997), and we therefore focus on these.

The magnetospheric beat-frequency model was developed to explain the single, $\sim$15–60 Hz "horizontal branch oscillation" (HBO) observed in the Z sources (see Lamb 1991). In this model, the frequency of the HBO is the difference between the Keplerian orbital frequency $\nu_{\rm Km}$ at the main radius where the stellar magnetic field picks up and channels gas from the accretion disk onto the magnetic polar regions and the stellar spin frequency $\nu_{\rm spin}$. Strohmayer et al. (1996) applied the magnetospheric beat-frequency idea to the kilohertz QPO pairs, interpreting the frequency of the higher-frequency QPO in a pair as $\nu_{\rm Km}$ and the frequency of the lower-frequency QPO as $\nu_{\rm Km} - \nu_{\rm spin}$. Although it explains naturally why the frequency separation between the QPOs in a pair is nearly constant in most sources and equal to the burst oscillation frequency or half this frequency, there are many serious difficulties with the magnetospheric beat-frequency interpretation of the kilohertz QPOs (see MLP).

The most fully developed and successful model of the kilohertz QPOs is the so-called sonic-point beat-frequency model, in which the higher frequency in a QPO pair is the orbital frequency of gas at the inner edge of the Keplerian disk flow and the lower frequency is the difference between this frequency and the spin frequency of the neutron star. The sonic-point model was developed (MLP) specifically to explain the kilohertz QPO pairs and is based on previous work (Miller & Lamb 1996) which showed that the drag force produced by radiation from a central star can terminate a Keplerian disk flow near the star. In the sonic-point model, some accreting gas spirals inward in nearly circular Keplerian orbits until it is close to the neutron star, where radiation forces or general relativistic effects cause a sudden increase in the inward radial velocity, which becomes supersonic within a small radial distance (see Fig. 2a). The sharp increase in the radial velocity is usually caused by the drag exerted on the accreting gas by radiation from the star, but may instead be caused by general relativistic corrections to Newtonian gravity if the gas in the Keplerian disk flow reaches the innermost

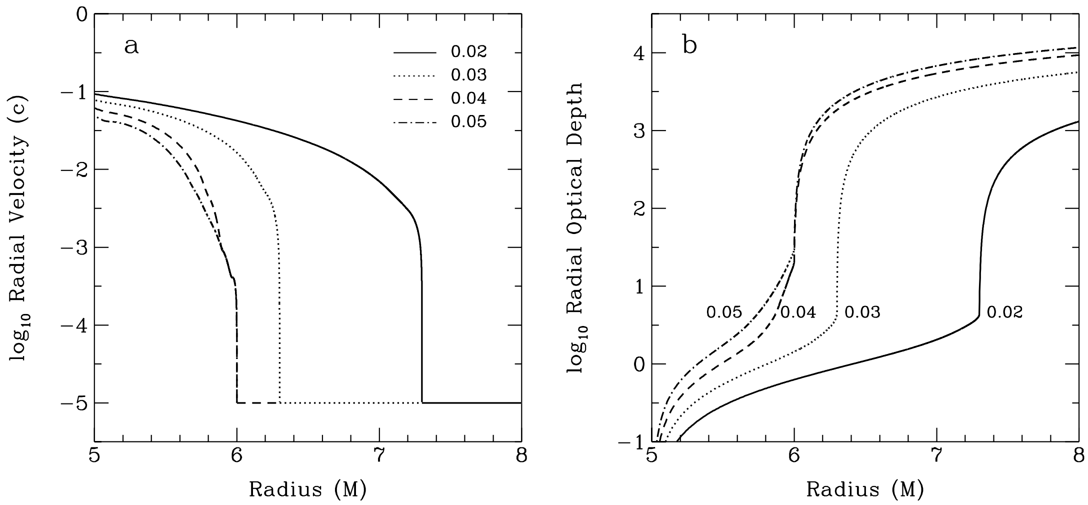

Fig. 2. Results of fully general relativistic numerical computations of the gas dynamics and radiation transport in the inner disk in the sonic-point model, for a neutron star of radius $5M$. (a) Inward radial velocity $v^{\hat{r}}$ of the gas in the disk measured by a local static observer, as a function of the Boyer-Lindquist radial coordinate expressed in units of the stellar mass M. (b) Radial optical depth from the stellar surface through the disk flow to the radius shown on the horizontal axis. Each curve is labeled with the assumed accretion rate $\dot{M}$ measured in units of the accretion rate $\dot{M}_E$ that would produce an accretion luminosity at infinity equal to the Eddington critical luminosity. From MLP.

stable circular orbit without being significantly affected by radiation.

As the disk flow approaches the sonic point, the optical depth of the flow in the radial direction (measured from the stellar surface) typically falls steeply with decreasing radius (see Fig. 2b). The change from optically thick to optically thin disk flow occurs within a few photon mean free paths and is somewhat analogous to the ionization front at the boundary of an H II region, except that here the photon mean free path increases because the radiation is removing angular momentum and the flow is accelerating inward, causing the density to fall sharply, whereas in an ionization front the mean free path is increases because radiation is removing bound electrons from atoms and molecules, causing the opacity to fall sharply. Once the accreting gas is exposed to the radiation from the star, it loses its angular momentum to radiation drag in a radial distance $\delta \lesssim 0.01\,r$. It then falls inward supersonically along spiral trajectories and collides with the neutron star around its equator, producing an X-ray emitting equatorial ring.

Gas streaming inward from clumps orbiting near the sonic radius along trajectories with the tight spiral shape shown in Figure 3a generates the more open spiral density pattern shown in Figure 3b. Collision of the denser gas from

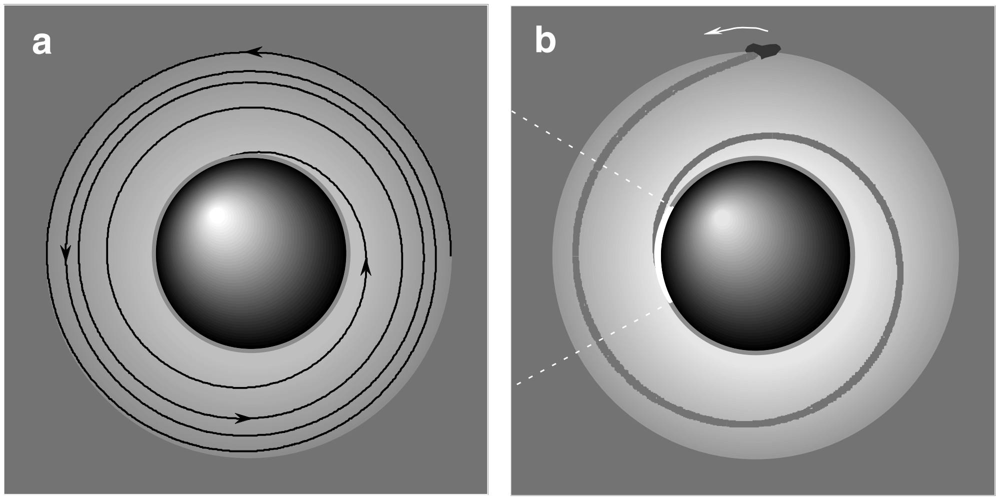

Fig. 3. View of the neutron star and disk along the rotation axis of the disk, which is rotating counterclockwise in this view. (a) Spiral trajectory followed by a single element of gas as it falls supersonically from the sonic radius to the stellar surface. (b) Spiral pattern of higher gas density formed by gas streaming inward along spiral trajectories with the shape shown in (a), from a clump orbiting near the sonic radius. The spiral trajectory and density pattern are from fully general relativistic calculations (see MLP).

the clumps with the stellar surface creates beams of brighter X-ray emission, like the beam indicated by the white dashed lines in Figure 3b. These beams move around the star's equator, generating a quasi-periodic brightness oscillation with frequency $\nu_{\rm Ks}$. The lower-frequency QPO is generated by weak X-ray beams produced by funneling of part of the accretion flow near the star by the star's weak magnetic field. These beams rotate *with the star* and modulate the radiation drag acting on the gas at the sonic radius, modulating the inward mass flux and the luminosity at the sonic-point beat frequency $\nu_{\rm Bs}$ ($\nu_{\rm Ks} - \nu_{\rm spin}$ or $\nu_{\rm Ks} - 2\nu_{\rm spin}$).

The sonic-point model is consistent with the accretion rates, stellar magnetic fields, and scattering optical depths inferred previously from *EXOSAT* and *Ginga* observations of the atoll and Z sources and accounts for the main features of the kilohertz QPOs, including their high and variable frequencies, their high amplitudes and coherences, and the common occurrence of kilohertz QPOs in pairs (see MLP). It also explains naturally why the frequency separation between the frequencies of a kilohertz QPO pair is nearly constant and equal to the burst oscillation frequency or half this frequency. Finally, the sonic-point model can account for the similar frequency ranges of the kilohertz QPOs in sources with very different accretion rates and magnetic fields.

3. Implications for Neutron Stars

The frequency of the higher-frequency QPO in a kilohertz QPO pair is almost certainly the orbital frequency of gas in Keplerian orbit around the star. If so, the high frequency and coherence these QPOs allow one to derive tight upper bounds on the masses and radii of the neutron stars that produce such QPOs and significant constraints on the equation of state of neutron star matter.

To see how such bounds can be constructed, suppose first that the star is not rotating and assume that, for the star in question, $\nu^*_{\rm QPO2}$—the highest observed value of the frequency of the higher-frequency (Keplerian-frequency) QPO in the kilohertz QPO pair—is 1220 Hz (this is the highest QPO frequency detected so far in any source; see MLP). Obviously, the radius $R_{\rm orb}$ of the orbit of the gas producing the QPO must be greater than the radius R of the star. This means that the star's representative point in the R,M plane must lie to the left of the cubic curve $M^0(R_{\rm orb})$ (the dashed curve shown in Figure 4a) which relates the star's mass to the radius of orbits with frequency 1220 Hz. In order to produce a wave train with tens of oscillations, $R_{\rm orb}$ must also be greater than the radius $R_{\rm ms}$ of the innermost stable circular orbit, so the actual radius of the orbit must lie on the portion of the $M^0(R_{\rm orb}, \nu^*_{\rm QPO2})$ curve that lies below its intersection with the diagonal line $M^0(R_{\rm ms})$ (the dotted line shown in Figure 4a) which relates the star's mass to $R_{\rm ms}$. As Figure 4a shows, this requirement bounds the mass and radius of the star from above. For $\nu^*_{\rm QPO2} = 1220$ Hz, the representative point of the star must lie in the pie-slice shaped region enclosed by the solid lines in Figure 4a. Thus, the mass and radius of a nonrotating star with this QPO frequency would have to be less than $1.8\,M_\odot$ and 16.0 km, respectively. Figure 4b compares the mass-radius relations for nonrotating stars given by five equations of state with the region of the radius-mass plane allowed for three values of $\nu^*_{\rm QPO2}$.

The allowed region of the R,M plane is affected by rotation (see MLP). The parameter that characterizes the importance of rotational effects is the dimensionless quantity $j \equiv cJ/GM^2$, where J and M are the angular momentum and gravitational mass of the star. For the spin frequencies ∼300 Hz inferred in the kilohertz QPO sources, j is $\sim$ 0.1–0.3, depending on the equation of state. Figure 1c illustrates the effects of slow stellar rotation on the allowed region of the R,M plane. The region allowed for a slowly rotating star is always larger than the region allowed for a nonrotating star, regardless of the equation of state. However, the region allowed for a rapidly rotating star can be smaller than that for the corresponding nonrotating star (Miller, Lamb, & Cook 1998).

If the frequency of a kilohertz QPO can be established as the orbital frequency of gas at the innermost stable circular orbit, this would be an important

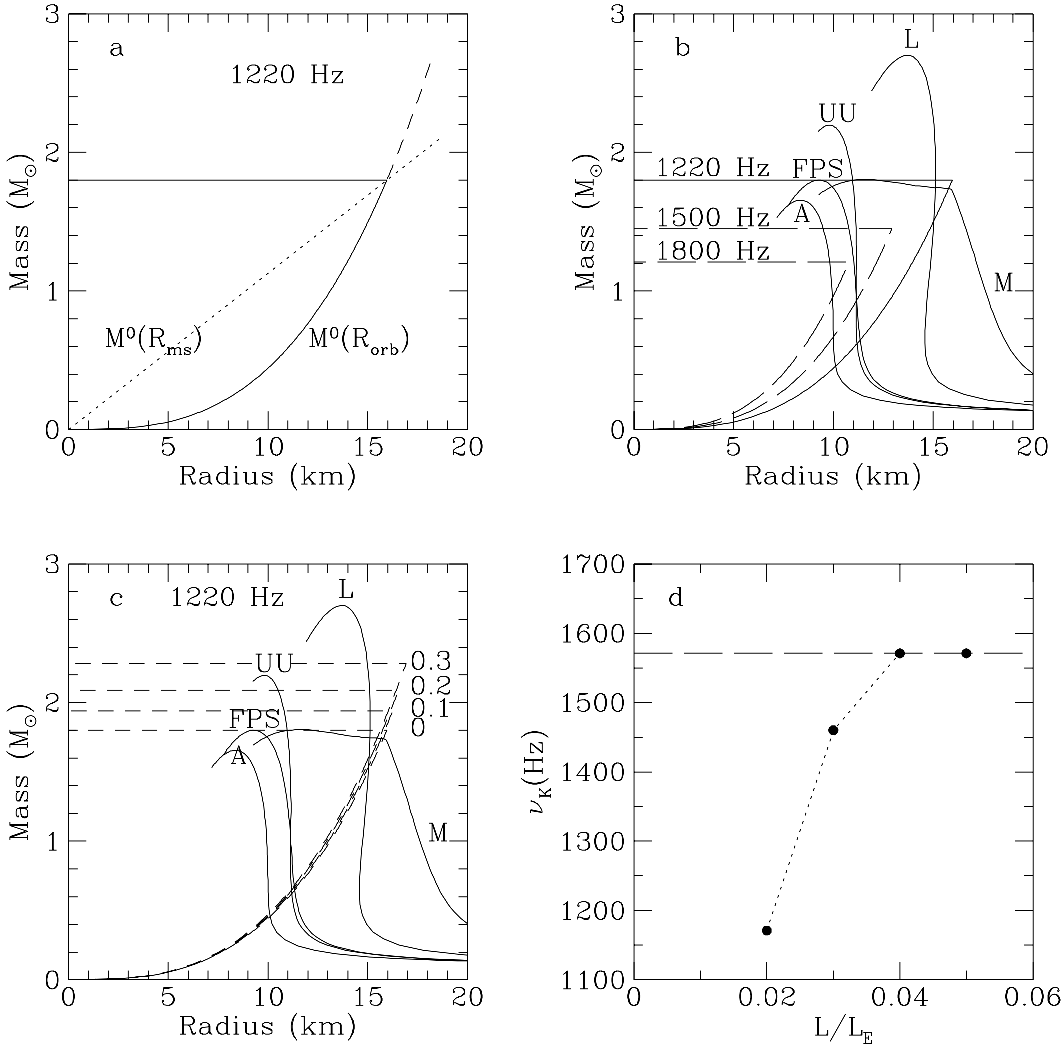

Fig. 4. (a) Radius-mass plane, showing how to construct the region allowed for a nonrotating neutron star with $\nu^*_{\rm QPO2} = 1220$ Hz (see text). (b) Comparison of the mass-radius relations for nonrotating neutron stars given by five representative equations of state with the regions of the mass-radius plane allowed for nonrotating stars with three different QPO frequencies. The light solid curves show the mass-radius relations given by equations of state A, FPS, UU, L, and M. (c) Regions allowed for rotating neutron stars with various values of j and $\nu^*_{\rm QPO2} = 1220$ Hz, when first-order effects of the stellar spin are included. (d) Illustrative Keplerian QPO frequency as a function of accretion luminosity given by the general relativistic calculations described in § 2. For details, see MLP.

step forward in our understanding of strong-field gravity and the properties of dense matter, because it would confirm one of the key predictions of general relativity in the strong-field regime and fix the mass of the neutron star in that source, for each assumed equation of state. Probably the most convincing signature would be a fairly coherent kilohertz QPO with a frequency that reproducibly increases steeply with increasing accretion rate but then becomes constant and remains nearly constant as the accretion rate increases further. This behavior emerges naturally from general relativistic calculations of the gas dynamics and radiation transport in the sonic-point model (see Fig. 4d). The constant frequency should always be the same in a given source.

This work was supported in part by NSF grant AST 96-18524, NASA grant NAG 5-2925, and NASA RXTE grants at the University of Illinois, and by NASA grant NAG 5-2868 at the University of Chicago.

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