The Astrophysical Journal, 534:L31–L34, 2000 May 1

ON THE DISAPPEARANCE OF KILOHERTZ QUASI-PERIODIC OSCILLATIONS AT A HIGH MASS ACCRETION RATE IN LOW-MASS X-RAY BINARIES

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Received 2000 February 11; accepted 2000 March 16; published 2000 April 27

ABSTRACT

For all sources in which the phenomenon of kilohertz quasi-periodic oscillation (kHz QPO) is observed, the QPOs disappear abruptly when the inferred mass accretion rate exceeds a certain threshold. Although the threshold cannot at present be accurately determined (or even quantified) observationally, it is clearly higher for bright Z sources than for faint atoll sources. Here we propose that the observational manifestation of kHz QPOs *requires* direct interaction between the neutron star magnetosphere and the Keplerian accretion disk and that the cessation of kHz QPOs at a high accretion rate is due to the lack of such an interaction when the Keplerian disk terminates at the last stable orbit and yet the magnetosphere is pushed farther inward. The threshold is therefore dependent on the magnetic field strength—the stronger the magnetic field, the higher the threshold. This is certainly in agreement with the atoll/Z paradigm, but we argue that it is also generally true, even for individual sources within each (atoll or Z) category. For atoll sources, the kHz QPOs also seem to vanish at a low accretion rate. Perhaps the "disengagement" between the magnetosphere and the Keplerian disk also takes place under such circumstances because of, for instance, the presence of quasi-spherical advection-dominated accretion flow (ADAF) close to the neutron star. Unfortunately, in this case, the estimation of the accretion rate threshold would require a knowledge of the physical mechanisms that cause the disengagement. If the ADAF is responsible, the threshold is likely dependent on the magnetic field of the neutron star.

Subject headings: accretion, accretion disks — binaries: general — relativity — stars: oscillations — X-rays: stars

1. INTRODUCTION

The detection of kilohertz quasi-periodic oscillation (kHz QPO) in low-mass X-ray binaries is arguably the greatest discovery that the *Rossi X-Ray Timing Explorer* (*RXTE*) has made to date. Such signals almost certainly originate in the immediate vicinity of central neutron stars, given that the fastest oscillations are observed to occur on dynamical timescales near such objects (see review by van der Klis 2000). The prospect of using kHz QPOs to probe the effects of strong gravity near neutron stars is therefore very exciting.

Various models (e.g., Klein et al. 1996; Miller, Lamb, & Psaltis 1998; Stella & Vietri 1999; Osherovich & Titarchuk 1999) have been proposed to explain kHz QPOs that, in nearly all cases, come in pairs (note that we choose not to discuss the QPOs observed during thermonuclear bursts). Except for the "photon-bubble model" (Klein et al. 1996), all other models invariably associate one of the pair to the Keplerian motion of clumps of matter or "hot spots" at the inner edge of a geometrically thin accretion disk (although the "sonic-point model" differs in detail; e.g., Miller et al. 1998; however, see Lai 1998). The inner edge of the disk is determined by the pressure balance between the accreted matter and the magnetic field of the neutron star. As the mass accretion rate increases, the ram pressure of the accreted matter increases, which squeezes the magnetosphere more, and thus the accretion disk extends farther toward the neutron star. Therefore, we expect that the frequency of the "Keplerian QPO" increases with the accretion rate, which agrees with the observations (van der Klis 2000). Since no Keplerian flow can exist inside the last stable orbit, we expect that there is an upper limit to the frequency of this QPO—any further increase in the accretion rate cannot result in an increase in the frequency of the QPO. Observing this limit would provide strong observational evidence for the presence of the last stable orbit around neutron stars, a natural consequence of strong gravity.

However, due to the lack of detailed knowledge on how the signals are produced in the first place, it is still not clear how kHz QPOs would behave when the accretion disk reaches the last stable orbit. Without considering any physical mechanisms responsible for modulating the X-ray emission, one might take it for granted that the frequency of the Keplerian QPO would saturate at a sufficiently high accretion rate (e.g., Zhang et al. 1998b; Lai 1998). On the other hand, Cui et al. (1998) emphasized the importance of the disk-magnetosphere interaction in producing the QPOs, based on a detailed study of the evolution of a kHz QPO observed in Aquila X-1, a transient atoll source, throughout the rising phase of an X-ray outburst. In this Letter, we generalize the ideas proposed by Cui et al. to all kHz QPO sources.

2. SATURATION OF kHz QPO FREQUENCY AT HIGH X-RAY FLUX?

Using data from the *RXTE* observations of 4U 1820−30, which spanned over almost 1 yr, Zhang et al. (1998b) found that the kHz QPOs detected in the source evolved strongly in frequency at low X-ray fluxes but reached a plateau at high fluxes. They attributed such a saturation in the QPO frequency to the presence of the last stable orbit. In other words, the plateau frequency of one of the kHz QPOs would represent the Keplerian frequency at the last stable orbit, if the interpretation is correct.

However, for atoll or Z sources, the X-ray flux is not always a reliable indicator for the mass accretion rate (e.g., Méndez et al. 1999; Méndez 2000; Ford et al. 2000), which fundamentally determines the magnetospheric radius of the neutron star and thus the location of the inner edge of the accretion

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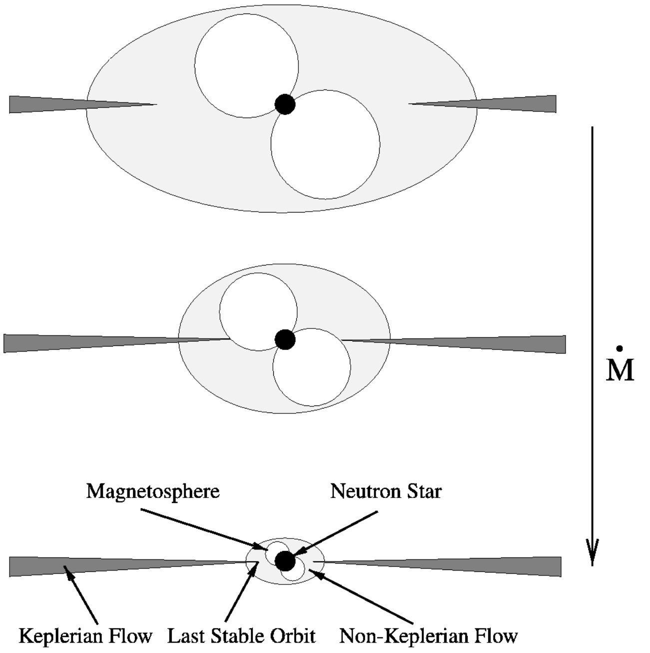

FIG. 1.—Schematic illustration of the geometry and evolution of accretion flows in a low-mass X-ray binary (not to scale). In the proposed scenario, the inner edge of the Keplerian disk pushes the magnetosphere of the neutron star inward, and the region of non-Keplerian flow (e.g., ADAF) becomes smaller as the mass accretion rate increases (from top to bottom). Note that kHz QPOs are produced when the disk begins to interact with the magnetosphere, and they persist until the disk reaches the last stable orbit.

disk. Moreover, it is now well established that the frequency of kHz QPOs is *not* well correlated with X-ray flux over a long period of time, although short-term linear correlations seem to be present (Zhang et al. 1998a; Méndez 2000 and references therein). Therefore, for 4U 1820−30, the observed evolution of the kHz QPOs with X-ray flux may not be a good representation of that with accretion rate. The saturation of the QPO frequencies could simply be an artifact caused by poor sampling of the data (M. Méndez 1999, private communication). Unfortunately, there is no reliable way of determining (or even quantifying) the accretion rate for atoll or Z sources at present. One empirical approach that is often taken is to use the position along the distinctive tracks in the color-color or color-intensity diagrams (which define atoll or Z sources) as a qualitative measure of the accretion rate (van der Klis 1995). The approach seems effective since the frequency of kHz QPOs is shown to be uniquely correlated with such a "color track position" for a number of sources (Méndez et al. 1999; Méndez 2000; van Straaten et al. 2000).

Kaaret et al. (1999) reanalyzed the data of Zhang et al. (1998b) and added data from more recent observations. They seemed to confirm that the QPO frequencies leveled off at high X-ray fluxes, although this result was *not* reproduced in other studies (van der Klis 2000). When they plotted the frequencies against the inferred accretion rate (as indicated by the color track position in the color-intensity diagram that they defined), however, the frequencies varied *monotonically* over the entire range. The authors noted an apparent deviation in the correlation at high accretion rates, with very limited dynamical range, from that extrapolated from low accretion rates. They then interpreted the deviation as evidence for the last stable orbit. We would like to note, however, that the color track position of the source is only an *empirical* indicator for the accretion rate. It is not clear at all how the two are *quantitatively* related; there is certainly no compelling reason to expect that they are necessarily *linearly* correlated. Consequently, the correlation between the QPO frequency and the color track position is expected to be complex (but is not known). A more serious question regarding the interpretation is why no other sources show a similar behavior (i.e., the claimed saturation of kHz QPO frequencies at a high accretion rate) if the phenomenon were to originate in something so fundamental. It seems unlikely that the uniqueness of 4U 1820−30 can be the answer to this question.

3. CLUES FROM TRANSIENT ATOLL SOURCES

Transient atoll sources are nearly ideal systems for a detailed study of the evolution of kHz QPOs with mass accretion rate because of the large dynamical range that they provide during an X-ray outburst. Unfortunately, they are very few in number, and even fewer undergo outbursts on timescales short enough that they can be observed. Nevertheless, high-quality data is available for some of these sources.

Aql X-1 is known for experiencing frequent outbursts (van Paradijs & McClintock 1995). During an outburst in 1998, the source was intensively monitored throughout the rising phase of the outburst (Cui et al. 1998). Although the origin of X-ray outbursts is generally unknown, there appears to be some consensus now that thermal instability causes a sudden surge in the mass accretion rate through the disk and thus initiates an X-ray outburst (see review by King 1995). Therefore, we know, at least qualitatively, how the mass accretion rate evolves during an outburst. Cui et al. found that the rising phase seems to be quite simple (at least for Aql X-1): the X-ray flux correlates fairly well with the color track position, compared with the decaying phase in which no correlation exists between the two quantities on long timescales (Zhang et al. 1998ba; Méndez 2000). Perhaps during the rising phase of an outburst, the X-ray flux is simply proportional to the mass accretion rate, as usually expected.

The evolution of a kHz QPO (not a pair) detected in Aql X-1 was carefully followed during the rising phase of the outburst (Cui et al. 1998). The QPO was not detected at the beginning of the outburst, when the accretion rate was presumably low; it then appeared and persisted through the intermediate range of the accretion rate; and it vanished again when the accretion rate exceeded a certain threshold ($\dot{M}_h$) near the peak of the outburst. To account for such an evolution of the kHz QPO, Cui et al. proposed the following physical scenario, as illustrated in Figure 1.

In the quiescent state, the mass accretion takes place in the form of advection-dominated accretion flow (ADAF) close to the central neutron star and in the forms of a standard Keplerian disk farther away (e.g., Narayan & Yi 1994, 1995; see also Menou et al. 1999 for discussions of neutron star systems). Therefore, there is no direct interaction between the Keplerian disk and the magnetosphere of the neutron star in this state. Such an interaction was argued to be essential for producing X-ray modulation associated with kHz QPOs; consequently, there would be no kHz QPOs in the quiescent state. At the onset of an X-ray outburst, the mass accretion rate begins to increase rapidly, so the ADAF region shrinks and the Keplerian disk moves inward (Narayan 1997). As soon as the disk starts to interact with the magnetosphere, kHz QPOs are produced. The accretion rate continues to increase as the outburst proceeds, so the magnetosphere is pushed farther toward the neutron star and the disk extends farther inward. After the disk has reached the last stable orbit, any increase in the mass accretion rate disengages the disk from the magnetosphere, causing the QPOs to disappear. For Aql X-1, assuming the X-ray flux is proportional to the accretion rate, the inferred low and upper limits on the magnetic field strength are certainly consistent with our expectation of an atoll source (Cui et al. 1998).

Another transient atoll source, 4U 1608−52, showed a remarkably similar pattern, based on the inferred mass accretion rate from the color-color diagram, in the evolution of its kHz QPO during the decaying phase of an outburst (Méndez et al. 1999). Therefore, we propose that *it is the disappearance of kHz QPOs at a high mass accretion rate that provides evidence for the presence of the last stable orbit.*

4. APPLICATION TO ALL kHz SOURCES

Without an exception, the kHz QPOs vanish at a high mass accretion rate for all sources (van der Klis 2000). For different sources, however, this seems to occur at a different accretion rate. For instance, $\dot{M}_h$ is certainly higher for Z sources than for atoll sources, perhaps suggesting a critical role that the magnetic field plays (according to the atoll/Z paradigm; van der Klis 1995). This would be naturally explained by our model since the model requires that the stronger the magnetic field, the higher the threshold (see § 5 for a quantitative treatment). Moreover, extending the model to all kHz sources would solve a long-standing observational puzzle as to why the kHz QPOs disappear at a higher accretion rate for a brighter source (van der Klis 2000). It is interesting to note that no kHz QPOs have ever been detected in a group of bright atoll sources (GX 3+1, GX 9+1, GX 13+1, and GX 9+9; Wijnands, van der Klis, & van Paradijs 1998; Strohmayer 1998; Homan et al. 1998). Perhaps, for these sources, the accretion rate always remains above $\dot{M}_h$.

At a low mass accretion rate, with the exception of 4U 1728−34, kHz QPOs become undetectable when the accretion rate is below a certain threshold ($\dot{M}_l$) for all atoll sources; for Z sources, on the other hand, the QPOs are detected down to the lowest inferred mass accretion rate (van der Klis 2000). Perhaps the ADAF scenario can also be applied to persistent atoll sources or even Z sources. If so, $\dot{M}_l$ would likely depend sensitively on the magnetic field strength, as we will demonstrate in the next section.

5. DISK-MAGNETOSPHERE INTERACTION

One of the critical issues that the kHz QPO models do not explicitly address is the physical mechanism that modulates the X-ray emission. The models are presently still at the level of simply associating the natural frequencies in a low-mass neutron star binary to the kHz QPOs observed. However, a mechanism is clearly needed for the natural frequencies to manifest themselves observationally. An obvious candidate is the interaction between the Keplerian disk and the magnetosphere of the neutron star, as was proposed in the original formulation of the beat-frequency model (Alpar & Shaham 1985). Such an interaction can create inhomogeneity or warping in the accretion flow (Vietri & Stella 1998; Lai 1999), which may cause X-ray emission to be modulated at the orbital frequency.

Assuming a dipole field, the radius of the magnetosphere, in units of the Schwarzschild radius ($\equiv 2GM/c^2$), is approximately given by (Frank, King, & Raine 1992)

$$r_m \approx 2.19\dot{m}^{-2/7} m^{-10/7} B_8^{4/7} r_6^{12/7}, \tag{1}$$

where m is the mass of the neutron star in solar units, $\dot{m}$ is the mass accretion rate in Eddington units ($1.39 \times 10^{18} m$ g s^{-1}), B_8 is the dipole field of the neutron star in units of 10^8 G, and r_6 is the radius of the neutron star in units of 10^6 cm. To derive $\dot{M}_h$, therefore, we set $r_m = 3$ (ignoring the effects of the slow rotation of the neutron star). We have

$$\dot{M}_h = 0.33 m^{-5} B_8^2 r_6^6. \tag{2}$$

For neutron stars with $m = 2$ and $r_6 = 1$, $\dot{M}_h \approx 0.01$ for $B = 10^8$ G or ∼1 for $B = 10^9$ G, which is roughly what we expect of atoll or Z sources, respectively (van der Klis 1995).

At a low mass accretion rate, if the ADAF is responsible for truncating the Keplerian disk, we can derive $\dot{M}_l$ by setting $r_m = r_{\rm tr}$, where $r_{\rm tr}$ is the radius at which the Keplerian disk makes a transition to the quasi-spherical ADAF. However, the physical origin of the transition is still poorly understood. Observationally, $r_{\rm tr}$ is clearly a function of $\dot{m}$—the higher the mass accretion rate, the smaller the transition radius (Narayan 1997). Assuming $r_{\rm tr} \propto \dot{m}^{-\alpha}$ (where $\alpha > 0$), equating $r_{\rm tr}$ to r_m yields

$$\dot{M}_l^{\alpha-2/7} \propto m^{10/7} B_8^{-4/7} r_6^{-12/7}. \tag{3}$$

If $\alpha > \frac{2}{7}$, the stronger the magnetic field is, the lower $\dot{M}_l$ will be; the converse is true for $\alpha < \frac{2}{7}$. The former appears to be supported by observations, given that the kHz QPOs persist down to the lowest mass accretion rate for Z sources while they seem to disappear at some point for atoll sources. Of course, the ADAF scenario might break down entirely for Z sources; i.e., the mass accretion process always takes the form of a Keplerian disk, so the kHz QPOs are always detectable at low mass accretion rates.

Meyer & Meyer-Hofmeister (1994) suggested that a cool Keplerian disk could undergo a phase transition to a hot, quasi-spherical corona when the gas density in the transition region becomes too low to radiate away effectively the energy released during the mass accretion process. If such a phase transition is relevant for ADAF, then $r_{\rm tr} = 18.3 m^{0.17/1.17} \dot{m}^{-1/1.17}$ (i.e., $\alpha = 0.84 > \frac{2}{7}$; Liu et al. 1999). We would have

$$\dot{M}_l = 41.7 m^{2.76} B_8^{-1} r_6^{-3}, \tag{4}$$

which would likely be super-Eddington for atoll or Z sources. Therefore, it is not clear whether the model can be applied to neutron star systems.

6. SUMMARY

The observations of the kHz QPO phenomenon seem to suggest that the interaction between the Keplerian accretion disk and the magnetosphere of the neutron star is directly responsible for modulating the X-ray emission. For a given source, the presence (or absence) of such an interaction dictates the appearance (or disappearance) of the QPOs. At a high mass accretion rate, we argue that the presence of the last stable orbit manifests itself in the disappearance of the QPOs, as opposed to the saturation in the QPO frequency. The difference may only seem semantic since, quantitatively, both interpretations require that the neutron star is inside the last stable orbit. However, we feel that it is imperative for the models to begin to address such critical issues as modulation mechanisms for kHz QPOs, in light of the ever improving quality of the data.

One critical question is whether the neutron star magnetosphere can be disengaged from the Keplerian disk at the last stable orbit. Studies have shown that the evolution of the magnetic field configuration is very complicated as the disk approaches the last stable orbit (e.g., Lai 1998), but the exact solution is not known at present. Intuitively, as the accretion process proceeds from the inner edge of the Keplerian disk onto the surface of the neutron star, the ram pressure of the accreted matter continues to push the magnetosphere inward. In this case, the magnetosphere only interacts with the non-Keplerian accretion flow in the "gap" between the last stable orbit and the neutron star surface, but *not* directly with the Keplerian flow in the disk. The importance of such gap accretion has been studied extensively (Kluźniak & Wagoner 1985; Kluźniak & Wilson 1991).

The situation is less certain at a low mass accretion rate. In fact, observationally, it can still be argued whether or not the QPOs actually disappear, given that in nearly all cases the upper limits derived are comparable to the fractional rms amplitudes of the QPOs measured at high accretion rates (M. Méndez 2000, private communication). In the case of 4U 0614+09, however, the 95% upper limit is only about half of the measured amplitude when the source is bright (Méndez et al. 1997). Therefore, we have at least one source in which the QPOs, if present at all, are definitely much weaker at low accretion rates (i.e., below $\dot{M}_l$). Moreover, we note that often the kHz QPOs *strengthen* (relative to the average source intensity) as the accretion rate *decreases* (Wijnands et al. 1997; Wijnands & van der Klis 1997; Smale, Zhang, & White 1997). If the QPOs do disappear at a low accretion rate, some physical process, like the ADAF, could be present to truncate the Keplerian disk at a large distance from the neutron star under such circumstances. This would destroy the disk-magnetosphere interaction and thus the kHz QPOs for atoll sources. The process may also operate in Z sources: the persistence of the kHz QPOs in such cases can be attributed to a lower accretion rate threshold that is due to the stronger magnetic field of the neutron star. Alternatively, the process bears no relevance to Z sources. The disk-magnetosphere interaction is always present at low accretion rates, and so are the QPOs.

I thank Dong Lai for a stimulating discussion on the subject. Part of this work was completed when I was attending the workshop on "X-Ray Probes of Relativistic Astrophysics" at the Aspen Center for Physics (ACP) in the summer of 1999. I acknowledge helpful discussions with the participants of the workshop, in particular, with Michiel van der Klis and Mariano Méndez on several important observational issues. I also wish to acknowledge financial assistance from the ACP. This work was supported in part by NASA grants NAG5-7990 and NAG5-7484.

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