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BARDEEN-PETTERSON EFFECT AND QUASI-PERIODIC OSCILLATIONS IN X-RAY BINARIES

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ABSTRACT

The Bardeen-Petterson effect around a rapidly rotating compact object causes a tilted accretion disk to warp into the equatorial plane of the rotating body. Viscous forces cause the accretion flow to divide into two distinct regions—an inner aligned accretion disk and an outer tilted accretion disk. The transition between these two occurs at a characteristic radius that depends on the mass and angular momentum of the central object and possibly on the accretion rate through the disk. We propose that accreting material passing through the transition region may generate quasi-periodic brightness oscillations such as have been observed in a number of X-ray binaries. We show that this effect may be present in the black hole X-ray binary GRO J1655−40. We also argue that the quasi-periodic oscillation (QPO) frequency range predicted by this model is consistent with observed QPO frequencies in both black hole and neutron star low-mass X-ray binaries.

Subject headings: accretion, accretion disks — black hole physics — stars: individual (GRO J1655−40) — stars: neutron — X-rays: stars

1. INTRODUCTION

Since their discovery in the mid-1980s (van der Klis et al. 1985), quasi-periodic oscillations (QPOs) have been observed in the X-ray brightness of a number of neutron star (NS) and black hole (BH) X-ray binaries. In so-called Z sources, which are high-luminosity NS low-mass X-ray binaries (LMXBs), there are typically four distinct QPO frequencies observed: (1) the $\simeq$5–20 Hz normal/flaring branch oscillation, (2) the $\simeq$15–60 Hz horizontal-branch oscillation, and (3) and (4) two "kilohertz" QPOs in the range $\simeq$200–1200 Hz (van der Klis et al. 1996). Atoll sources, which are less luminous NS LMXBs, typically display two kilohertz QPOs in the range $\sim$500–1330 Hz as well as low-frequency ($\sim$20–60 Hz) QPOs and broad noise components (Strohmayer et al. 1996). Not as many detections exist for QPOs in BH X-ray binaries. However, several low-frequency ($\sim$0.1–50 Hz) QPOs have been observed, and higher frequency QPO components have been identified in the spectra of at least three BH candidates ($\simeq$67 Hz in GRS 1915+105: Morgan, Remillard, & Greiner 1997; $\simeq$300 Hz in GRO J1655−40: Remillard et al. 1999b; and $\sim$160–280 Hz in XTE J1550−564: Remillard et al. 1999a; Homan et al. 2001). (See, e.g., van der Klis 1995, 2000 and Wijnands 2000 for recent summaries.)

These QPOs may provide a useful probe into the inner accretion flows around NSs and BHs. Consequently, a number of theoretical models have been proposed to explain the observations. For example, QPOs have been modeled as general relativistic Lense-Thirring precession (e.g., Stella & Vietri 1998; Morsink & Stella 1999), geodesic motion of gas clumps (e.g., Stella & Vietri 1999; Stella, Vietri, & Morsink 1999; Karas 1999), trapped oscillation modes in the disk (e.g., Marković & Lamb 1998; Nowak & Wagoner 1991, 1992), interruption of the gas flow at the centrifugal barrier (e.g., Titarchuk, Lapidus, & Muslimov 1998), and various beat-frequency interpretations (e.g., Alpar & Shaham 1985; Lamb et al. 1985; Miller, Lamb, & Psaltis 1998). Some of these models depend explicitly on the existence of a stellar surface and may therefore be valid only for QPOs in NS systems. Furthermore, none of the models proposed thus far have been able to simultaneously explain all of the QPOs observed in individual systems.

Most recent theoretical attention has focused on the high-frequency kilohertz QPOs. In this paper, however, we wish to instead address moderate-frequency ($\sim$1–300 Hz) QPOs. Specifically, we propose the Bardeen-Petterson effect (Bardeen & Petterson 1975) as a potential mechanism for generating such QPOs in X-ray binaries. This new mechanism derives from the possible existence of a well-defined transition radius in tilted accretion disks around rapidly rotating compact objects. This transition radius is a result of the Bardeen-Petterson effect, which will be explained further in § 2. In § 3, we consider the likelihood that this effect is present in BH and NS X-ray binaries. We also discuss mechanisms by which accreting material passing through this transition radius may generate observable quasi-periodic brightness oscillations. In § 4, we discuss the BH X-ray binary GRO J1655−40. We find that our estimated QPO frequency range is consistent with either of two QPOs observed in that system. In § 5 we consider NS LMXBs and argue that our model is consistent with the $\sim$100 Hz peaked noise component seen in some of these systems.

2. THE BARDEEN-PETTERSON EFFECT

The Bardeen-Petterson effect is illustrated schematically in Figure 1. This effect causes a tilted accretion disk around a rapidly rotating compact object to warp into the equatorial plane of the central object (Bardeen & Petterson 1975; Kumar & Pringle 1985; Scheuer & Feiler 1996). The effect is the combined result of differential Lense-Thirring precession and internal viscosity. The Lense-Thirring precession causes the disk to "twist up." Damping of the fluid motion by viscosity limits this twisting. Close to the accreting BH or NS, where the Lense-Thirring precession is strongest, viscosity allows the misaligned angular momentum of the tilted disk to be transported outward. This allows the inner region to settle into the rotation plane of the BH or NS.

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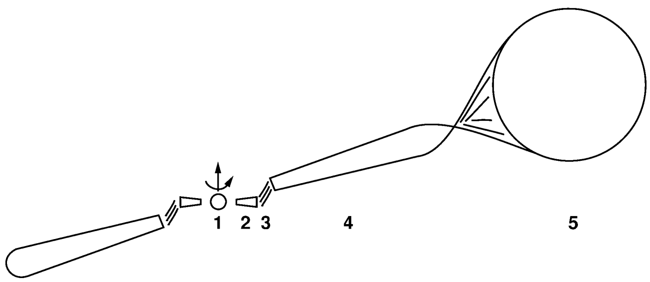

FIG. 1.—Schematic diagram of the Bardeen-Petterson effect showing (1) the central rotating BH or NS, (2) the inner, aligned accretion disk, (3) the transition region, (4) the outer, tilted accretion disk, and (5) the companion star.

Farther out, the disk remains in its original plane because the Lense-Thirring precession rate drops off rapidly with increasing radial distance ($\sim r^{-3}$; Lense & Thirring 1918). Internal pressure and viscous stress in the outer regions are thus able to limit its effects. The end result, as shown in Figure 1, is an aligned inner accretion disk (region 2), a tilted outer accretion disk (region 4), and a transition region (3) between the two.

2.1. *Transition Radius*

The Bardeen-Petterson transition radius is expected to occur approximately where the rate of twisting up by differential precession is balanced by the rate at which warps of the disk are diffused or propagated away by viscosity. Using thin-disk theory, in which the effects of pressure are neglected and an isotropic viscosity is assumed, the transition radius was first estimated as (Bardeen & Petterson 1975; Hatchett, Begelman, & Sarazin 1981)

$$R_{\rm BP} = \left(\frac{6a_*}{\alpha\delta^2}\right)^{2/3} R_{\rm GR} \ . \tag{1}$$

Here α is the standard viscosity parameter associated with the radial accretion (Shakura & Sunyaev 1973), δ is the aspect ratio of the disk, a_* is the dimensionless specific angular momentum parameter of the BH or NS ($a_* = Jc/GM^2$, where J is the angular momentum), and $R_{\rm GR} = GM/c^2$, where M is the gravitational mass of the BH or NS.

Ivanov & Illarionov (1997) obtained an alternative expression for a characteristic radius analogous to the Bardeen-Petterson transition radius by considering the scale of oscillations in a twisted accretion disk around a Kerr BH:

$$R_{\rm BP} = \left(\frac{384a_*}{25\delta^2}\right)^{2/5} R_{\rm GR} \ . \tag{2}$$

Most recently, Nelson & Papaloizou (2000) obtained a slightly different estimate by considering separate horizontal and vertical shear components of viscosity. Their expression for the transition radius depends on the relative strength of the dimensionless vertical shear viscosity parameter, α_1:

$$R_{\rm BP} = \begin{cases} (24\alpha_1\, a_*/\delta^2)^{2/3} R_{\rm GR} & \text{if } \alpha_1 > \delta \ , \\ (24a_*/\delta)^{2/3} R_{\rm GR} & \text{if } \alpha_1 \lesssim \delta \ . \end{cases} \tag{3}$$

Typical values for the viscosity parameters α and α_1, and the aspect ratio δ, are $0.04 \lesssim \alpha \lesssim 0.2$, $\alpha_1 \sim \alpha$, and $0.03 \lesssim \delta \lesssim 0.3$. These are based on numerical calculations (e.g., Nelson & Papaloizou 1999; Bryden et al. 1999). In hydrodynamic simulations, Nelson & Papaloizou (2000) found the transition radius to lie consistently below the analytic estimates in equation (3) by a factor of $\sim$2–3. This correction is included in the following analysis, although it does not qualitatively change the results.

In the present work, we will adopt the following expression for the Bardeen-Petterson transition radius motivated largely by equation (3) and the numerical results of Nelson & Papaloizou (2000):

$$R_{\rm BP} = A a_*^{2/3} R_{\rm GR} \ , \tag{4}$$

where the scaling parameter A lies in the range $10 \lesssim A \lesssim 300$. The corresponding Keplerian orbital frequency is therefore

$$\nu_{\rm Kep,BP} = \frac{c^3}{2\pi G A^{3/2} a_* M} \ . \tag{5}$$

3. BARDEEN-PETTERSON EFFECT IN X-RAY BINARIES

As noted above, the Bardeen-Petterson effect requires a tilted accretion disk around a rapidly rotating compact object. In the context of our present study, we must evaluate the likelihood that this condition is met in observed X-ray binaries. To do this, we must consider the probability that tilted-disk systems are formed and how long they last relative to the overall lifetime of X-ray binaries. These factors are not well known, but we can make some estimates.

3.1. *X-Ray Binary Formation*

X-ray binaries can possibly form in one of four ways (e.g., Canal, Isern, & Labay 1990; Verbunt & van den Heuvel 1995). The most likely paradigms for Galactic sources are core collapse of a massive star in a binary or accretion-induced collapse of a white dwarf or NS in a binary. Less likely possibilities (except perhaps in dense globular clusters) are binary capture or binary replacement. In the first two mechanisms, one member of a preexisting binary must explode as a supernova in order to form the required NS or BH. During this violent event, even a small asymmetry in the explosion will impart substantial momentum to the newly formed remnant (e.g., Dewey & Cordes 1987; Bailes et al. 1989). Even if an initially aligned system remains bound, it is unlikely that the two stellar spin axes will remain aligned with the orbital spin axis after the supernova. Detailed Monte Carlo modeling by Brandt & Podsiadlowski (1995) of this evolutionary path for LMXBs indicates that only $\sim$20% of the progenitor systems remain bound after a supernova explosion. Furthermore, the resultant median of tilt angle for the systems that remain bound is approximately 20°, with roughly 60% of them having tilt angles in the range of 5°–45°. Hence, a large fraction ($\sim \frac{1}{2}$) of such systems should be born as candidates for the Bardeen-Petterson effect.

In the other two mechanisms, which are unlikely except perhaps in globular clusters, a NS or BH must pass close enough to another star or binary system to become gravitationally bound. Here the collapsed star and its new companion evolved separately until the time of their encounter. There is, therefore, no preferred orientation for the angular momenta of the stars relative to the angular momentum axis of the forming binary. Hence, the majority of such systems would also be Bardeen-Petterson effect candidates. Thus, it appears likely that many, if not most, X-ray binaries form with misaligned angular momenta (one such observed system is discussed in § 4).

3.2. *Alignment Timescale*

Since the Bardeen-Petterson effect causes the accretion flow to lie in the equatorial plane of the accreting body out to a disk radius of $R_{\rm BP}$, the material actually accreted by the stellar remnant will not change the orientation of the remnant's angular momentum. However, as pointed out by Rees (1978), the torque exerted by the BH or NS as it aligns the disk with its own spin axis also has the effect of aligning the BH or NS with the angular momentum of the disk. A number of authors have addressed this issue (e.g., Rees 1978; Scheuer & Feiler 1996; Natarajan & Pringle 1998), particularly with respect to misaligned accretion disks around BHs. The alignment angle decreases exponentially with a characteristic timescale, $t_{\rm align}$, given by (Scheuer & Feiler 1996)

$$t_{\rm align} \approx 3a_* \frac{M}{\dot{M}} \left(\frac{2R_{\rm GR}}{R_{\rm BP}}\right)^{1/2} , \qquad (6)$$

where $\dot{M}$ is the mass accretion rate through the disk. For illustration, we consider a 1.4 $M_\odot$ NS and a 7 $M_\odot$ BH, each with $a_* = 0.1$ and $A = 100$. We derive a lower limit for $t_{\rm align}$ by setting $\dot{M}$ at the respective Eddington accretion limits. These values give minimum alignment timescales of 3×10^6 and 7×10^6 yr, respectively. However, a more realistic long-term accretion rate for LMXBs is $\dot{M} = 0.01\dot{M}_{\rm Edd}$ (van der Klis 1995). This gives alignment timescales comparable to the estimated lifetime of X-ray binaries (10^8–10^9 yr; Verbunt & van den Heuvel 1995). These long timescales for alignment imply that the typical distribution of tilt angles in LMXBs should be close to the distribution estimated by Brandt & Podsiadlowski (1995) for LMXB formation. Thus, a large fraction ($\sim\frac{1}{2}$) of LMXBs may be candidates for observation of the Bardeen-Petterson effect.

3.3. *X-Ray Modulation Mechanism*

We now wish to consider possible mechanisms by which the Bardeen-Petterson effect could generate observable QPOs. We begin with the findings of Nelson & Papaloizou (2000) that for moderate angles ($\theta \gtrsim 30°$) between the disk midplanes, the inner and outer accretion disks are nearly disconnected. For larger angles, the separation between the two disks becomes even more pronounced. In such cases, accretion between the outer and inner disks presumably occurs along a tenuous bridge of material or in the form of gas clumps that periodically break off from the outer disk and collide with the inner disk. Whether accretion takes place along a bridge or in discrete clumps, there is likely to be significant shock heating at the point where this accreting material impacts the inner disk. As the shock-heated gas continues to orbit the BH or NS, it may generate periodic brightness oscillations at the orbital frequency for that radius. We expect this radius to lie just inside the Bardeen-Petterson transition radius, so that the QPO frequency should be very close to the Keplerian orbital frequency given in equation (5). Using $\theta \gtrsim 30°$ as a guide, we may expect $\sim$30% of LMXBs to be susceptible to this mechanism based on the tilt-angle distribution predicted by Brandt & Podsiadlowski (1995).

4. GRO J1655−40

The BH binary GRO J1655−40 is a very important target for studies such as this one since many of the relevant system parameters have been measured or inferred. There is also evidence that the angular momentum axis of the BH in this system is not aligned with the angular momentum of the binary.

The observational constraints on the orientation of this system are summarized in Figure 2. Orosz & Bailyn (1997) found the inclination of the binary orbit of this partially eclipsing system to be $i = 69.5° \pm 0.1°$ (measured from the plane of the sky). This means that the angular momentum axis of the binary, $\boldsymbol{J}_{\rm binary}$, is tilted by the same amount from the line of sight of an observer. However, the orientation of the binary orbit (i.e., position angle) in the sky is not known. Thus, $\boldsymbol{J}_{\rm binary}$ is only constrained to lie somewhere on a 69.5° cone about the line of sight as shown in Figure 2. Hjellming & Rupen (1995) observed two highly collimated relativistic jets expanding from opposite sides of this source during a period of hard X-ray activity (Harmon et al. 1995). The position angle on the sky of the approaching jet was $47° \pm 1°$, and its inclination was $i = 5° \pm 2°$ (i.e., almost in the plane of the sky). This means that the axis through the center of the radio jets was tilted with respect to $\boldsymbol{J}_{\rm binary}$ by between 15.5° and 90°, as illustrated in Figure 2. Depending on the model used to describe the radio jets, their orientation should reflect the angular momentum axis of either the BH or the inner accretion disk. On the other hand, the orientation of the binary orbit should define the orientation of the outer accretion disk. Altogether this implies that the outer accretion disk is probably tilted with respect to the equatorial plane of the BH by between 15.5° and 90°. This makes GRO J1655−40 a strong candidate for the occurrence of the Bardeen-Petterson effect.

In order to estimate the Bardeen-Petterson transition radius using equation (4), we need to know the mass and

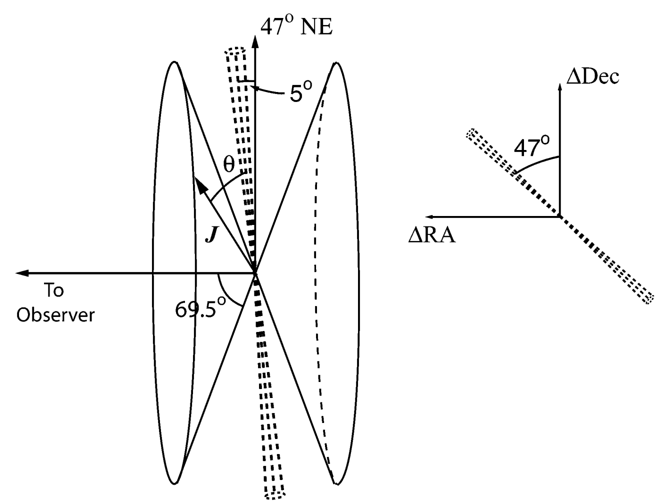

FIG. 2.—Illustration of the relative orientation between the radio jets and the binary angular momentum axis, $\boldsymbol{J}$, of GRO J1655−40. The observed orientation of the radio jets is shown by the dashed cones (Hjellming & Rupen 1995); $\boldsymbol{J}$ is restricted to lie on either of two 69.5° cones about the line of sight of the observer (Orosz & Bailyn 1997), as shown by the solid cones. The tilt angle, θ, between the radio jets and $\boldsymbol{J}$ is between 15.5° and 90°.

angular momentum of the BH. Optical investigations of the binary give a mass of $M_{\rm BH} = 6.7 \pm 1.2\ M_\odot$ (Orosz & Bailyn 1997; Shahbaz et al. 1999). Modeling of the X-ray spectra from this system (Sobczak et al. 1999) gives a probable angular momentum of $a_* \approx 0.5$, with an upper limit of $a_* < 0.7$. Other authors, however, give values as high as $a_* = 0.95$ (Cui, Zhang, & Chen 1998). Moreover, the exact value of a_* is not critical to our conclusions. We simply require an upper limit, which we take as $a_* \lesssim 0.95$. This gives us an upper limit on the transition radius of $R_{\rm BP} \lesssim 290 R_{\rm GR}$, based on our adopted constraints on the scaling parameter A. The physical constraint that the transition region lie outside the innermost stable circular orbit gives us a firm lower limit on the transition radius of $R_{\rm BP} \gtrsim 6R_{\rm GR}$ for a nonrotating or slowly rotating BH. The resultant range is $6R_{\rm GR} \lesssim R_{\rm BP} \lesssim 290R_{\rm GR}$, or 60 km $\lesssim R_{\rm BP} \lesssim$ 2900 km. We caution, however, that these estimates of $M_{\rm BH}$ and a_* derive from models that have assumed a single continuous accretion disk, whereas we have shown that the Bardeen-Petterson effect creates an inner and outer disk component inclined relative to one another. This point may require further analysis; however, the size of the inner accretion disk is extremely small compared to the estimated size of the outer accretion disk (4.2×10^6 km; Orosz & Bailyn 1997), so that this correction is likely to be small.

The range of Keplerian frequencies corresponding to our derived range of $R_{\rm BP}$ is 1 Hz $\lesssim \nu_{\rm Kep,BP} \lesssim$ 300 Hz. This range of frequencies is consistent with three of the four QPOs observed in GRO J1655−40 (Remillard et al. 1999b): the variable 14–28 Hz QPO and the relatively stable 9 and 300 Hz QPOs. However, identification of the 300 Hz QPO with the Bardeen-Petterson transition radius would require that the transition region lie just outside the innermost stable circular orbit, which would make it difficult for an inner, aligned disk to form. It seems more likely that the Bardeen-Petterson effect might be associated with either the 9 Hz or the 14–28 Hz QPO. This conclusion seems to be supported by the spectral modeling of Remillard et al. (1999b), who identified the 300 Hz and the 14–28 Hz QPOs with the power-law component of their model rather than the disk component. Only the 9 Hz QPO appeared to have the X-ray spectral characteristics expected for a purely disk-based oscillation (Remillard et al. 1999b). Hence, we tentatively identify the 9 Hz QPO in GRO J1655−40 as perhaps the best potential observation of the Bardeen-Petterson transition radius in an X-ray binary. However, there is an ongoing debate as to whether the 9 Hz QPO is definitely disk related and the other QPOs are not. Hence, it is premature to definitively exclude the 14–28 or the 300 Hz QPOs as possible candidates.

5. NEUTRON STAR X-RAY BINARIES

For NS X-ray binaries, the parameter space available is much narrower than for BH binaries. Both the mass and the angular momentum of NSs are tightly constrained by theory and observation. Models for the NS equation of state give the following upper limits (Salgado et al. 1994; Cook, Shapiro, & Teukolsky 1994): $M_{\rm NS} \lesssim 2.6\ M_\odot$ and $a_{*,\rm NS} \lesssim 0.7$. Observed radio pulsars in binary systems are all consistent with $1.35\ M_\odot \le M_{\rm NS} \le 1.45\ M_\odot$ (Thorsett & Chakrabarty 1999). If we consider these upper limits of $M_{\rm NS}$, $a_{*,\rm NS}$, and the parameter A, then we can use equation (5) to set a lower limit for the Bardeen-Petterson orbital frequency in NSs: $\nu_{\rm Kep,BP} \gtrsim 3$ Hz. The upper limit for the Bardeen-Petterson orbital frequency is fixed by the orbital frequency at the inner edge of the accretion disk. For a putative $1.4\ M_\odot$ NS with $a_* = 0.1$, the orbital frequency at the innermost stable circular orbit is $\approx$1700 Hz. This range of frequencies (3–1700 Hz) is consistent with most of the QPOs observed in NS LMXBs. In Z sources, it is consistent with the normal/flaring and horizontal-branch oscillations and kilohertz QPOs. In atoll sources, it is consistent with the low-frequency QPOs, the peaked noise components, and the kilohertz QPOs.

However, in order for the Bardeen-Petterson effect to be a consistent interpretation, we should expect all the QPOs associated with this effect to show similar properties. Tentatively adopting the 9 Hz QPO in GRO J1655−40 as our most likely example, we can use it as a template with which to identify other Bardeen-Petterson–generated QPOs. Toward this end, this QPO has at least two noteworthy features: it has a relatively low coherence parameter ($Q = \nu/\Delta\nu < 3$), and its frequency appears to be independent of the count rate in the detector (Remillard et al. 1999b), although this conclusion is based on only a few observations. Another peculiar feature of the QPO is that it is only present during some observations but is mostly absent. This transient behavior is presumably related to the accretion dynamics, e.g., in our model, whether or not clumps happen to be crossing the transition region during an observation. We hope this aspect can be better understood with future hydrodynamic simulations.

Among NS LMXBs, low-coherency QPOs are fairly common. However, the combination of low coherency and count rate independence seems to be most consistent with the $\sim$100 Hz peaked noise or Lorentzian component. This 100 Hz feature was first identified in 4U 1728−34 (Ford & van der Klis 1998). It has been extensively studied in SAX J1808.4−3658 by Wijnands & van der Klis (1998). These authors were also the first to identify a similar feature in 4U 0614+09 (based on observations by Méndez et al. 1997) and 4U 1705−44 (based on observations by Ford, van der Klis, & Kaaret 1998). Similar features have also been found in 4U 1820−30 (Wijnands, van der Klis, & Rijkhorst 1999), Terzan 2 (Sunyaev & Revnivtsev 2000), and GS 1826−24 (Sunyaev & Revnivtsev 2000). These observations may imply that the 100 Hz feature is fairly common in LMXBs. This might, however, become a concern if this feature proves to be too common to be consistent with the likely occurrence of the Bardeen-Petterson effect.

Irrespective of all this, we argue that the Bardeen-Petterson mechanism should produce QPOs of similar frequency in all NS LMXBs since all NS systems are characteristically very similar. We have already argued that the NS masses are similar ($M_{\rm NS} \approx 1.4\ M_\odot$). Furthermore, interpretation of the nearly coherent oscillations seen during type I X-ray bursts in 10 NS LMXBs argue for a narrow range of angular momenta for the NSs in these systems (see, e.g., Strohmayer 2001). The two remaining parameters in the estimates of the Bardeen-Petterson transition radius, the viscosity and the disk aspect ratio, are presumably similar in all LMXBs since the accretion mechanism (Roche lobe overflow) is assumed to be the same. In this context, it is interesting that $\sim$100 Hz QPOs may be quite common among NS LMXBs. This frequency is also comfortably within the range (3–1700 Hz) expected for the Bardeen-Petterson effect in NSs, as calculated above. Therefore, all of the parameters can assume typical values if the 100 Hz QPO is triggered by the Bardeen-Petterson effect.

For now, the association of the 100 Hz feature in NS LMXBs with the 9 Hz QPO in GRO J1655−40 is just a suggestion. Other authors have suggested different associations. For instance, based on a possible correlation between the 9 Hz and the 300 Hz QPO in GRO J1655−40, Psaltis, Belloni, & van der Klis (1999) suggest that these two QPOs are similar to the following QPO pairs seen in other systems: the $\simeq$10–50 Hz and the lower kilohertz QPOs in 4U 1728−34 and 4U 1608−52 and the $\sim$0.08–13 and $\sim$160–220 Hz QPOs in XTE J1550−564. However, these authors acknowledge that these identifications are very tentative and must be scrutinized carefully.

6. DISCUSSION

Positive association of a QPO in an LMXB with the orbital frequency at the Bardeen-Petterson transition radius could provide important constraints on the mass and angular momentum of the accreting body and possibly the thickness and tilt of the accretion disk. Careful study of the properties of such a QPO could also provide information about the gasdynamics near the transition radius and the role of the accretion rate in this model. Furthermore, identification of such QPOs in several LMXBs could provide information about the relative abundance of tilted accretion disk systems, which is important in understanding their formation and evolution.

We have argued that the Bardeen-Petterson effect may be a common phenomenon in LMXBs and that it provides a plausible physical explanation for at least some observed quasi-periodic brightness oscillations. The estimates of our model are consistent with a 1–300 Hz QPO in the BH X-ray binary GRO J1655−40. This system is an important test since it appears likely to have a tilted accretion disk around a rapidly rotating BH. We have also argued that this mechanism could generate a moderate-frequency QPO when applied to individual NS LMXBs.

We are currently undertaking the task of studying the Bardeen-Petterson effect numerically to follow the dynamics of the gas near the transition radius. The results of this study should provide further insight into the validity of the model we have proposed here.

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