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QUASI-PERIODIC VARIABILITY AND THE INNER RADII OF THIN ACCRETION DISKS IN GALACTIC BLACK HOLE SYSTEMS

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ABSTRACT

We calculate upper bounds on the inner radii of geometrically thin accretion disks in galactic black hole systems by relating their rapid variability properties to those of neutron stars. We infer that the inner disk radii do not exhibit large excursions between different spectral states, in contrast with the concept that the disk retreats significantly during the soft–to–hard-state transition. We find that, in the hard state, the accretion disks extend down to radii $\lesssim$6–25 GM/c^2 and discuss the implications of our results for models of black hole X-ray spectra.

Subject headings: accretion, accretion disks — black hole physics — X-rays: stars

1. INTRODUCTION

X-ray spectra and rapid variability provide discriminating signatures for the properties of accreting compact objects. Correlating these characteristics in the case of weakly magnetic neutron stars has provided strong constraints on physical models for their accretion flows (see van der Klis 1998 for a review). The detailed timing studies of galactic X-ray sources with the *Rossi X-Ray Timing Explorer* (*RXTE*) now make possible the extension of similar analyses to the case of accreting black holes.

Accreting black holes show a variety of X-ray spectral states (Tanaka & Lewin 1995). The majority of sources are usually observed in the so-called hard/low and soft/high states named after the relative hardness of the X-ray spectra and the luminosity in the soft (~0.5–2 keV) X-ray band. In the standard paradigm, the soft and hard X-ray spectral components are attributed, respectively, to a geometrically thin accretion disk and a hot Comptonizing medium, with their relative contribution determining the source state (as is the case for coronal models [see, e.g., Haardt & Maraschi 1993, Zdziarski et al. 1998, Poutanen & Coppi 1998, and Dove et al. 1997 for recent studies], advection-dominated accretion flows [e.g., Esin, McClintock, & Narayan 1997], etc.). In most cases, the X-ray spectra of the hard/low state show no evidence for soft blackbody emission (e.g., Esin et al. 1997) or strong reflection features (i.e., the backscattered emission from the putative accretion disk; see, e.g., Gierliński et al. 1997). Based on this, it has been argued that, in the hard state, the geometrically thin disks do not extend down to the innermost stable orbit but are truncated at tens or hundreds of Schwarzchild radii.

The rapid variability properties of black holes can be used in assessing the accretion-flow geometries inferred from spectral models. Various types of quasi-periodic oscillations (QPOs) and peaked noise features have been observed from many persistent and transient black hole sources (e.g., van der Klis 1995). The frequencies of these variability components follow correlations that are consistent with the ones observed in neutron star systems (Wijnands & van der Klis 1999; Psaltis, Belloni, & van der Klis 1999a). They are, therefore, likely to be produced by similar physical mechanisms. In particular, the QPO properties in both black hole and neutron star systems vary systematically and reproducibly with spectral state and can have fractional widths down to $\delta\nu/\nu \lesssim 0.2$ (see van der Klis 1995). For this reason, although they are related to the hard (>2 keV) component of the X-ray spectrum, their frequencies are believed to be determined by modulations in the geometrically thin component of the accretion flow.

In this Letter, we use the empirical correlations between QPO frequencies in neutron star and black hole systems to infer the fastest variability timescales for specific black hole spectral states. This information allows us to place upper bounds on the inner radii of the geometrically thin components of the accretion flows and compare them to those inferred by the spectral models of galactic black holes. Even though we use the empirically determined correlations, our results are supported by the recent identification of the various observed QPO frequencies with fundamental general relativistic frequencies around compact objects (Stella & Vietri 1999; Stella, Vietri, & Morsink 1999; Psaltis & Norman 1999).

2. SPECTRA AND RAPID VARIABILITY OF ACCRETING BLACK HOLES

We use previously published data for a sample of four persistent and six transient galactic black hole systems. These include the best-studied sources for which QPOs have been detected, and the corresponding spectral states have been identified and reported in the literature. Following Wijnands & van der Klis (1999) and Psaltis et al. (1999a), we include the QPOs observed in the microquasars GRS 1915+105 and GRO J1655−40 only when these sources show canonical black hole spectral states.

Cyg X-1.—This persistent source spends most of its time in the hard state but occasionally shows a transition to the soft state (Cui et al. 1997, and references therein). We use the results of the joint *Ginga*/OSSE observation of Cyg X-1 during its hard state, in which ≃1–3 Hz QPOs were observed (Rutledge et al. 1999, and references therein). In a recent transition to the soft state, ≃4–12 Hz QPOs were also detected with *RXTE*, but no spectral analysis has been reported for this observation (Cui et al. 1997).

GX 339−4.—This is one of the few sources in which five distinct spectral states have been observed (Wilms et al. 1999, and references therein). An ≃0.3–0.4 Hz QPO has been recently detected during the hard state with *RXTE* (Nowak,

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Wilms, & Dove 1999), as has a $\simeq$6–7 Hz QPO during the very high state with *Ginga* (Miyamoto et al. 1991).

1E 1740.7−2942 and GRS 1758−258.—These two sources have only been observed in their hard states. Recent *RXTE* observations have revealed the presence of a 2.0 and a 0.4 Hz QPO in 1E 1740.7−2942 and GRS 1758−258, respectively (Smith et al. 1997). No detailed spectral analysis is available for these observations, but a canonical hard-state photon index of $\simeq$1.6 was reported for both sources by Smith et al. (1997).

GRO J1655−40.—During the decay phase of the recent outburst of this superluminal source, four canonical black hole spectral states were identified (Méndez, Belloni, & van der Klis 1998a). In the hard and intermediate states, an $\simeq$0.8 and an $\simeq$6.5 Hz QPO were detected, respectively.

GS 1124−683 (*Nova Muscae 1991*).—During the 1991 outburst of this source, five distinct spectral states were observed with *Ginga* and OSSE (see, e.g., van der Klis 1995 and references therein). When the source was probably in the very high state, an $\simeq$4–6 Hz QPO was detected (Miyamoto et al. 1994; Belloni et al. 1997).

4U 1630−47.—This recurrent transient has been recently observed again in outburst with *RXTE*. While the source was in the hard state, an ~0.8 Hz QPO was detected (McCollough et al. 1999).

GRO J0422+32.—OSSE and *ASCA* have observed this transient source in both the hard and soft states. An ~0.23 Hz QPO was detected during the OSSE observation, while the source was in the hard state (Grove et al. 1998a, 1998b).

XTE J1755−324.—*RXTE* observations of this X-ray nova revealed characteristic spectral states of black hole sources (Revnivtsev, Gilfanov, & Churazov 1998). During the decay of the outburst, an $\simeq$2–3 Hz QPO was detected.

XTE J1550−564.—This newly discovered X-ray transient shows QPOs with frequencies that vary in the range ~0.1–10 Hz as its energy spectrum softens (Cui et al. 1999). Here we use only the data points with QPO frequencies $\gtrsim$1 Hz, for which the energy spectral indices were reported in the literature (Sobczak et al. 1999).

Figure 1 shows the photon spectral indices and the corresponding QPO frequencies for the sources in our sample.

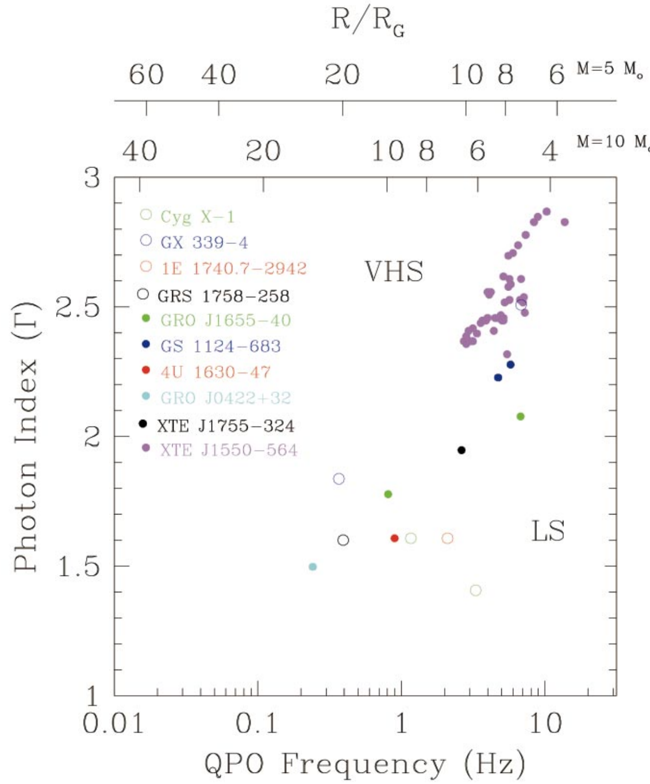

FIG. 1.—Photon spectral index vs. QPO frequency ν_1 for different spectral states (hard/low state: LS; very high state: VHS) of galactic black hole sources. The top axis shows the inferred upper bounds on the inner radii of geometrically thin accretion disks for different black hole masses.

3. THE INNER RADII OF THE ACCRETION DISKS

The observed QPOs in accreting compact objects are typically narrow ($\delta\nu/\nu \lesssim 0.2$), with properties that vary systematically and reproducibly with spectral state. Although QPOs are associated with the hard X-ray spectral components (see, e.g., Berger et al. 1996), the above characteristics can be accounted for in a physical model only if the timing properties of the QPOs are associated with the geometrically thin component of the accretion flow. Indeed, for all frequencies in the flow, $\delta\nu/\nu \sim (H/R)^2$, and hence $H/R \ll 1$. This argument is model-independent and has been the basis of most theoretical models for neutron star and black hole QPOs (see Psaltis et al. 1999a for a recent review of QPO models). In such models, Comptonization in a hot medium that surrounds the accretion disk typically amplifies the oscillations (see, e.g., Lee & Miller 1998), possibly accounting for the fact that strong QPOs are observed only when the hot component of the accretion flow is present.

The centroid frequency $\nu_{\rm QPO}$ of the QPO provides an upper bound on the inner radius $R_{\rm in}$ of the geometrically thin component of the accretion flow. Since the fastest variability timescale at any radius around a compact object is the Keplerian orbital frequency, then

$$\nu_{\rm QPO} \leq \frac{1}{2\pi}\left(\frac{GM}{R_{\rm in}^3}\right)^{1/2}$$

and hence

$$\left(\frac{R_{\rm in}}{R_g}\right) \leq 220\nu_{\rm QPO}^{-2/3}\left(\frac{M}{10\ M_\odot}\right)^{-2/3}, \qquad (1)$$

where $R_g \equiv GM/c^2$ and M is the mass of the compact object. In this section we deduce the fastest variability timescales during different black hole spectral states and use equation (1) to place upper bounds on the inner radii of the accretion disks.

The power-density spectra of accreting black holes typically show a broad noise component that is flat-topped up to a break frequency ν_b and decreases as a power law above it. Often, a narrow QPO at a frequency ν_1 and a broader peaked noise component at a frequency ν_2 are also detected (typically $\nu_2 \sim 10\nu_1 \sim 10^2\nu_b$). When present, the QPO at ν_1 is typically narrow ($\delta\nu/\nu \lesssim 0.2$) and unambiguously detected; this is the QPO we discuss in § 2 for the sources in our sample.

In accreting, weakly magnetic neutron stars, the same variability components are observed in the power spectra, together with a third QPO peak at a frequency $\nu_3 > \nu_2$ (van der Klis 1998; Psaltis et al. 1999a). In such systems, the QPOs with frequencies ν_1, ν_2, and ν_3 are often called the HBO, lower kilohertz QPO, and upper kilohertz QPO, respectively (see van der Klis 1998). The frequencies of all these power-spectral components vary over wide ranges, often by a factor of 10^2 in a given source, and yet ν_1 follows simple power-law relations (χ^2/degrees of freedom $\sim$ 1; see Psaltis et al. 1998, 1999b for a thorough statistical analysis) with ν_b, ν_2, and ν_3 (Wijnands & van der Klis 1999; Psaltis et al. 1999a). These correlations depend only weakly (if at all) on the other properties of the sources, thus demonstrating that they are produced in the accretion flows and not by the compact objects.

In neutron star systems, the fastest observed timescale is given by the QPO at frequency ν_3, which follows in all sources the empirical correlation $\nu_1 \simeq 63(\nu_3/1\ \mathrm{kHz})^{1.9}$ Hz (Psaltis et al. 1999a). This correlation together with equation (1) gives an upper bound on the inner radius of the accretion disk, i.e.,

$$\left(\frac{R_{\rm in}}{R_g}\right) \le 27\nu_1^{-0.35}\left(\frac{M}{2\ M_\odot}\right)^{-2/3}. \qquad (2)$$

Observation of a narrow $\nu_1 = 70$ Hz QPO in a neutron star system, for example, constrains the inner radius of the geometrically thin accretion flow to be comparable to the radius of the innermost stable orbit.

In black hole systems, the frequencies ν_b, ν_1, and ν_2 also vary widely, but follow the same correlations (with systematic differences in the normalization of less than a factor of 2) as those exhibited by neutron star sources. This implies that the three variability components with frequencies ν_b, ν_1, and ν_2 are each produced by similar physical mechanisms in both types of compact objects. As a result, neither ν_1 nor ν_2 are likely to be associated with the highest Keplerian frequencies in the accretion disks and hence cannot be used in constraining the inner extent of the accretion disks. Moreover, QPOs at ν_3, which could provide this constraint directly, have not been detected from any black hole system.[2] We conjecture that the same physical mechanism in both neutron stars and black holes produces QPOs at ν_1 and, therefore, even in black holes, ν_1 is related to the inner radius of the accretion disk as in equation (2).

Physical motivation for this hypothesis is provided by recent modeling of the correlations between the QPO frequencies in neutron star and black hole systems (Stella & Vietri 1999; Stella et al. 1999; see also Psaltis & Norman 1999). In these models, ν_3, ν_2, and ν_1 are identified, respectively, with the orbital, periastron precession, and twice the nodal precession general relativistic frequencies of a perturbed orbit around the compact object. Given an observation of a nodal precession frequency in a source, the radius of the orbit, and hence an upper bound on the inner radius of the accretion disk, is (see Stella et al. 1999)

$$\frac{R_{\rm in}}{M} \le \left(\frac{2\alpha}{\pi}\right)^{1/3} \nu_1^{-1/3} M^{-2/3}, \qquad (3)$$

where α is the specific angular momentum of the compact object and we have set $G = c = 1$. The scaling in equation (3) is similar to the empirically inferred one, giving physical motivation to equation (2).

Equation (2) provides a bound on the inner radius of the geometrically thin accretion disk for each source in our sample. The inferred bounds are shown in Figure 1 for two different values of the black hole mass. In all spectral states in which narrow QPOs have been detected, the accretion disks appear to extend down to $\lesssim(6\text{–}25)R_g$. Note here that the inferred bounds are consistent with the inner radii of accretion disks in neutron star sources, as determined by the frequencies of the kilohertz QPOs (see, e.g., Miller, Lamb, & Psaltis 1998).

4. DISCUSSION

The upper bounds on the inner accretion disk radii derived in § 3 imply that, in general, the geometrically thin disk component extends close to the innermost stable orbit, independent of the specific spectral state that the accreting black hole displays. Our findings are complementary to the constraints on the geometry of the accretion flows around galactic black holes derived on the basis of radiation physics and spectral analysis of the different spectral states (Poutanen, Krolik, & Ryde 1997; Gierliński et al. 1997; Poutanen & Coppi 1998; Zdziarski et al. 1998; Done & Życki 1999; Esin et al. 1997; Wilms et al. 1999, and references therein). In particular, in such models it is argued that, because the reflection features in the hard state of black hole systems are much less prominent [e.g., the amplitude of Compton reflection $\Omega/(2\pi)$ is $\sim$0.2–0.3 and its associated Fe Kα lines are weak] than in Seyfert galaxies, the inner radius of the disk cannot be very close to the black hole, in order to subtend a smaller solid angle to the X-ray–emitting region (e.g., Gierliński et al. 1997; see Ross, Fabian, & Young 1999 and Beloborodov 1999 for alternative explanations of the lack of strong reflection features).

In these spectral models, it is often postulated that, inside the truncated disk, a hot central medium/corona–like structure produces the observed hard component of the spectrum. The transition to the soft state is then assumed to occur as the geometrically thin disk moves inward and the dissipated energy emerges in the form of a blackbody-like spectrum (see, however, Di Matteo, Celotti, & Fabian 1999). A dynamical model of the Comptonizing medium has been developed recently within the context of advection-dominated accretion flows (ADAFs; Esin et al. 1997); in these models, the inner Compton medium in the hard state is identified with an advection-dominated region, outside of which the thin disk exists.

Figure 1 shows that the QPO frequencies observed in the hard and very high states of all sources in our sample lie in a rather restricted range. Even though the presence of a transition in the accretion disk properties cannot be excluded, Figure 1 implies that the inner radii of the accretion disks cannot show large excursions between the different spectral states. Therefore, the concept of a geometrically thin disk retreating significantly during the soft–to–hard-state transition is not supported by our results. (Note, though, that for some sources there seems to be weak evidence for a systematic change in the QPO frequency with spectral state.) In agreement with the presence of a soft X-ray excess in the observed spectra of black hole systems in the very high state, we find that the inferred inner accretion disk radii are comparable to the radius of the innermost stable orbit. On the other hand, for all sources in our sample, the inner accretion disk radii in the hard state are inferred to be *only* $\sim(6\text{–}25)R_g$ (see Fig. 1).

To illustrate this point explicitly, we discuss specific sources for which detailed spectral modeling has been performed and compare the inferred inner disk radii to the bounds deduced here based on their rapid variability. For the hard state of Cyg

[2] It is unclear what determines the amplitudes and detectability of these QPOs in neutron star systems and hence the reason for their absence from black hole power spectra. Indeed, there is an example of a transient neutron star source (4U 1608−52; Méndez et al. 1998b) in which the QPO at ν_2 is strong and can be directly detected, but the QPO at ν_3 is revealed only after the data are analyzed using the so-called shift-and-add technique.

X-1, the truncation radius of the accretion disk is inferred to be $\sim$30–50R_g in coronal models (Poutanen et al. 1997; Poutanen & Coppi 1998; Done & Życki 1999) and $\sim$200R_g (or strictly $>$60R_g) in ADAF models (Esin et al. 1998). On the other hand, the detection of a $\gtrsim$1 Hz QPO in the same state implies $R_{\rm in} < (8–12)\, R_g$, depending on the mass of the black hole. For the hard state of GX 339$-$4, $R_{\rm in} \gtrsim 150 R_g$ for both coronal and ADAF models (Zdziarski et al. 1998; Wilms et al. 1999), whereas the rapid variability constraints imply $R_{\rm in} < (12–20)\, R_g$. In GRO J0422+32, ADAF models require $R_{\rm in} \sim 10^4 R_g$ (Esin et al. 1997), while the presence of a $\simeq$0.23 Hz QPO constrains the inner disk radius to be $R_{\rm in} < (15–25)\, R_g$.

In all the above sources, the discrepancy between the inner disk radii inferred from the rapid variability and those reported from spectral studies can be as large as a few orders of magnitude. However, in many spectral models, $R_{\rm in}$ was not necessarily chosen to be the smallest value consistent with the observed X-ray spectra. Here we have shown that rapid variability properties impose upper bounds on the inner extent of the geometrically thin accretion disks in galactic black hole systems. We therefore argue that combining both the variability and spectral properties of accreting black holes provides complementary constraints on models of their inner accretion flows. Our constraints on the inner radii will become unambiguous with the detection of quasi-periodic variability in the hard state of black hole systems with frequencies $\nu_3 \gtrsim 100$ Hz. Such a detection would also impose a strict upper bound on the mass of the compact object and possibly reveal the presence of a spinning black hole.

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