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SIMILARITIES IN NEUTRON STAR AND BLACK HOLE ACCRETION

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ABSTRACT

In this paper, I compare the X-ray properties of accreting low magnetic field neutron stars and accreting stellar mass black hole candidates. Rather than looking for signatures that are unique to black holes, I use the similarities in the observed properties of accreting neutron stars and black hole candidates in order to see whether it is possible to find a common pattern of phenomenology across the two groups. Following this purely phenomenological approach, I propose as a working hypothesis that three different states are common to the accretion process onto low magnetic field neutron stars and black holes. In a given source, the instantaneous accretion rate determines the state; between sources, other parameters, such as compact object mass and magnetic field strength, may also play a role.

Subject headings: accretion, accretion disks — black hole physics — stars: neutron

1. INTRODUCTION

X-ray binaries are commonly divided into low-mass X-ray binaries (LMXBs), defined as all X-ray binary systems in which the mass donor stars are less massive than 1 $M_\odot$, and high-mass X-ray binaries (HMXBs), which constitute the rest. This classification is very significant from the point of view of binary evolution. However, from the point of view of the compact objects these groups are mixed bags. LMXBs include persistent (GX 339−4) and transient (many soft X-ray transients such as A0620−00 and GS 1124−68) black hole candidates, low magnetic field neutron stars (bright bulge sources, bursters, dippers) and a few accretion-powered pulsars (GX 1+4, 4U 1626−67). HMXBs also include black hole candidates (Cygnus X−1), and many pulsars, but no low magnetic field neutron stars or soft X-ray transients are known among them (no Be transients are known to contain a black hole). For this paper, I shall mostly ignore the pulsars and focus on a comparison between systems containing black hole candidates and those containing low magnetic field neutron stars.

The historical record of black hole "signatures" that were subsequently associated with neutron star systems (bimodal spectral states, rapid variability; see, e.g., Tanaka 1989) testifies to the fact that the accretion process onto neutron stars and black holes has much in common. This is perhaps to be expected, since the characteristics that make accreting compact objects unique, namely, the very high, and thinly shielded, energy density (the origin of the high-energy emission) and the short dynamical and radiative timescales (underlying the rapid [millisecond] variability), are common to neutron stars and black holes. Naively, one would expect most of the accretion flow onto these two types of compact object to be very similar; only in the very innermost region (a few gravitational radii from the center) would one expect the differences between neutron stars and black holes (such as the presence or absence of a material surface or relativistic frame dragging) to become noticeable. It should be kept in mind, however, that this innermost region is the region where most of the gravitational energy is released, and that at least in principle the effects of what happens in the middle could propagate outward and affect the accretion flow at larger distances.

It might be expected, then, that the phenomena displayed by accreting neutron stars and black holes are similar, but that the parameters needed in describing these phenomena differ: phenomenologically the differences between the two groups might be more quantitative than qualitative. In the following, I review the X-ray observations of the black hole candidates and the low magnetic field neutron stars with this in mind. In §§ 2 and 3, I deal with spectroscopic and in § 4 with variability measurements. In § 5, I introduce a scheme to place the phenomenology of accreting neutron stars and black hole candidates on common ground, in § 6, I discuss a variability component that may serve as a phenomenological link between the neutron stars and the black holes, and in § 7, I summarize my conclusions. Throughout, I shall be using the expression "black hole candidate" not only for compact objects that (from orbit measurements) have a mass too high for a neutron star (the black hole candidates proper), but also for those that phenomenologically appear to fall in the same group as these sources (e.g., Tanaka 1992; Grebenev et al. 1993), the "candidate black hole candidates" or black hole candidates "by association."

2. 20–500 keV X-RAY SPECTRA

Accreting black holes are widely believed to have harder 20–500 keV spectra than accreting low magnetic field neutron stars. According to Sunyaev et al. (1991), based on the *Kvant* observations, a power-law spectrum with a hard tail extending out to several 100 keV is a black hole signature. The SIGMA observations of X-ray burst sources (which are, of course, low magnetic field neutron stars) reported by Barret & Vedrenne (1994), however, show that hard 20–200 keV spectra can also occur in neutron stars (Fig. 1). In two sources Barret & Vedrenne (1994) find power-law slopes with a photon index[1] $\alpha \sim 3$ in the hard X-ray band; in a third case, Terzan 2, the

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[1] Photon spectral indices (α) are used throughout this paper.

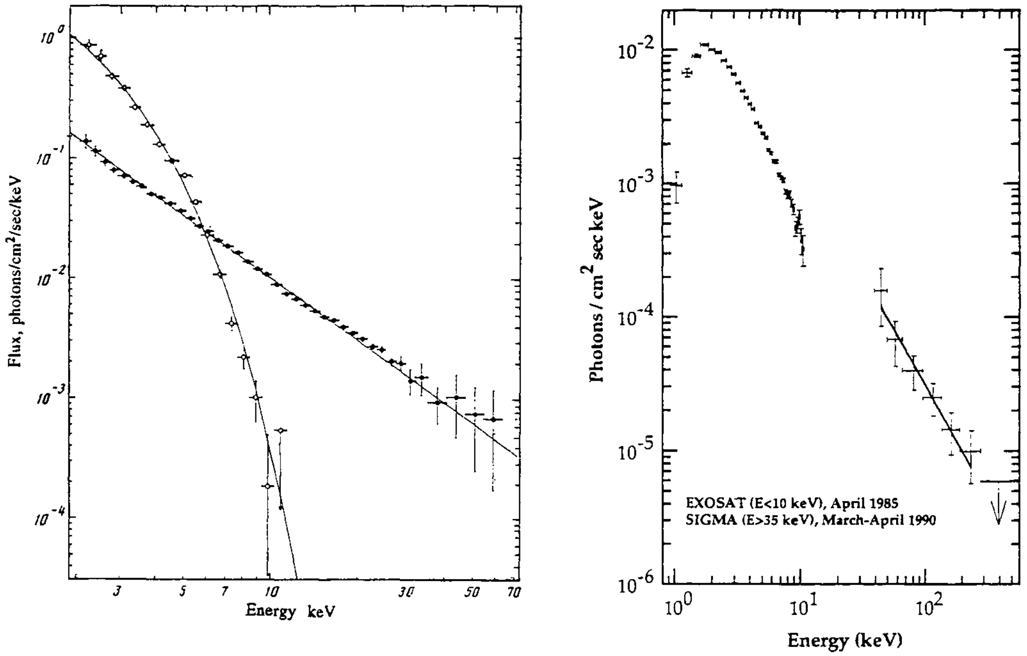

FIG. 1.—Hard X-ray spectra of a probable black hole, GX 339−4 (*left*), and a probable neutron star, Terzan 2 (*right*). From Grebenev et al. (1991) and Barret et al. (1991).

spectrum is even harder, with $\alpha \sim 1.7$. In black hole candidates in the low, hard state (see § 3) the photon spectral index is about 1.5–2 in this energy range (Sunyaev et al. 1991; Grebenev et al. 1993). The case of Terzan 2 is less than ironclad, since sources other than the known X-ray burst source in this globular cluster might be contributing to the X-ray spectrum. Therefore, it is still possible that hard tails with power-law slopes as hard as $\alpha \lesssim 2$ are unique to black holes (this would mean that Terzan 2 contains an accreting black hole), but clearly making the distinction between black holes and neutron stars is not as simple as measuring the mere presence or absence of a hard tail out to 100 keV.

It is perhaps possible that hard tails occur in black hole candidate systems up to higher (total) luminosity levels than in neutron star systems, as all neutron star hard tails occurred in relatively low accretion rate systems, and stringent upper limits were set on hard tails in bright sources such as Scorpius X-1 (Barret & Vedrenne 1994). Note, however, that also in black hole candidates, when the accretion rate becomes high, the hard tail can disappear (Fig. 1; Grebenev et al. 1991).

Clearly, what is needed is a more sensitive survey of the hard X-ray spectra of neutron stars and black hole candidates over a range of luminosity levels. This would allow to quantify any differences between them for what concerns the dependence of the X-ray spectrum on luminosity. The *INTEGRAL* mission, with its increased sensitivity, can play a key role in this. At present, all we can say is that the black hole candidate spectra may be harder in the 20–500 keV band than the low magnetic field neutron star spectra, but that it is also possible that hard spectra similar to those emitted by black hole candidates are (perhaps at lower luminosity levels) emitted by neutron stars. It may be possible to find a scaling law with, for example, the compact-object mass as a parameter that governs the dependence of spectral hardness on luminosity.

3. 1–30 keV X-RAY SPECTRA

It is now well established (e.g., Tanaka 1992) that in the 1–30 keV band the X-ray spectra of the black hole candidates are well described by the sum of two X-ray spectral components, an "ultrasoft" component with roughly a bremsstrahlung shape with a kT of $\sim$1–2 keV, and an $\alpha \sim 1.5$–3 power-law component. The X-ray spectral changes of these sources are quite spectacular (Fig. 2). In the "low" (hard) state only a flat ($\alpha \sim 1.5$–2) power-law component is seen; often it is stronger than in the high state. In the "high" (soft) state the ultrasoft component dominates below 10 keV, but the flat power law can still be visible, projecting from the spectrum above 10 keV; sometimes the power law does not stick out visibly from the spectrum, but in some descriptions of the X-ray spectrum it is still required ($\alpha \sim 2$–3). In the "very high" state (see § 4.1) the spectrum is also soft, but a similarly steep power law to that in the high state may occasionally reemerge (see Miyamoto et al. 1993).

By following the decay of black hole candidate soft X-ray transients, it seems clear that in a given source the ultrasoft component is a good (roughly monotonic) indicator of the mass accretion rate, and that $\dot{M}$ decreases from the very high through the high to the low state. The power-law component has a less simple relation to $\dot{M}$, so that a capability to observe below 10 keV is necessary to know what the accretion rate is doing, a fact that should be weighed in planning *INTEGRAL*'s low-energy capabilities.

The low magnetic field neutron stars, by contrast, usually show only very subtle X-ray spectral changes (Fig. 3) when the X-ray intensity varies between roughly 1 and 0.01 times the maximum observed value. X-ray color-color diagrams, which are sensitive to changes of a few percent in flux ratios between energy bands, help to see what is going on in these systems. By

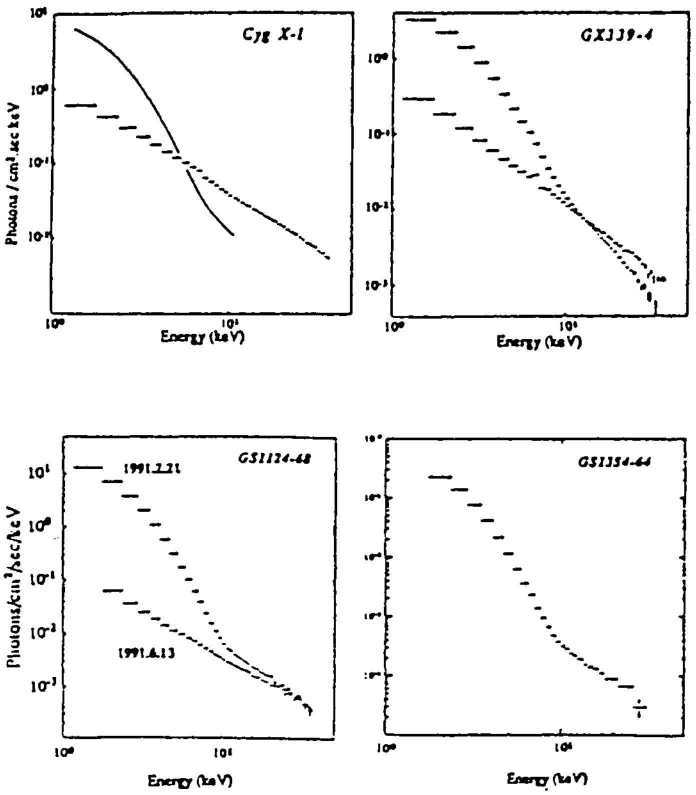

FIG. 2.—1–20 keV X-ray spectra from black hole candidates. From Tanaka (1992).

comparing such diagnostics with the rapid X-ray variability properties (§ 4), it has been possible to detect the presence of two distinct groups among these systems (Fig. 4), which are called the Z and the atoll sources (Hasinger & van der Klis 1989, hereafter HK89). The number of sources exhibiting Z source characteristics is six (various predicted but previously unobserved phenomena and states turned up in these sources, since HK89 identified them as a group); the number of probable atoll sources has by now risen from 10 to 14 (van Paradijs et al. 1990; Oosterbroek et al. 1991; Kitamoto, Tsunemi, & Roussel-Dupré 1992; Jongert et al. 1994). Optical and UV observations and X-ray burst properties have made it possible to determine the sense of $\dot{M}$ in the X-ray color-color diagrams of Z and atoll sources (Hasinger et al. 1990; van der Klis et al. 1990). In order of increasing $\dot{M}$ (Fig. 4, *arrows*), the spectral/variability states of the Z sources are called the "horizontal branch," the "normal branch," and the "flaring branch," and those of the atoll sources the "island state" and the "banana branch." Crucially, during the subtle X-ray spectral changes defining these states, the X-ray intensity I_x is *not* a measure of

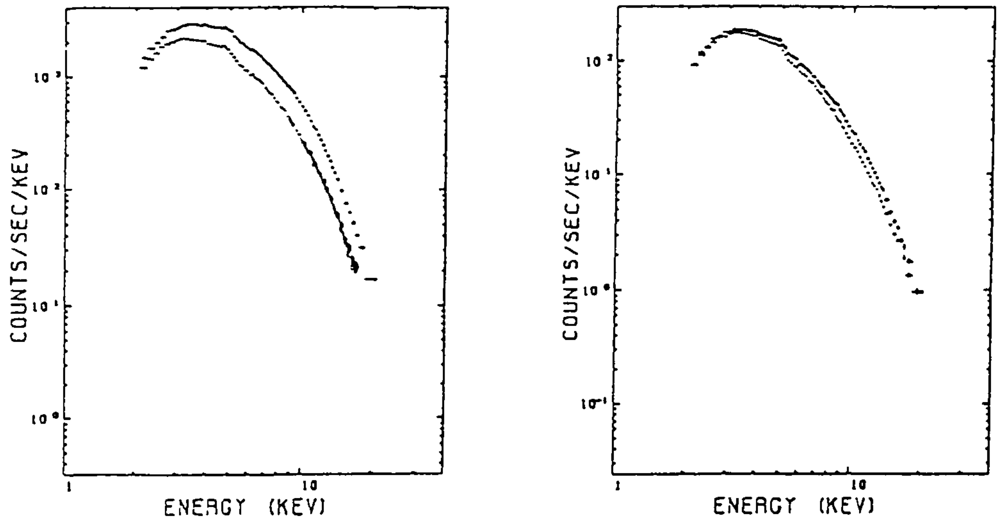

FIG. 3.—1–20 keV X-ray spectra from a Z source, Scorpius X-1 (*left*), and an atoll source, 4U 1608–52 (*right*). From Inoue (1992).

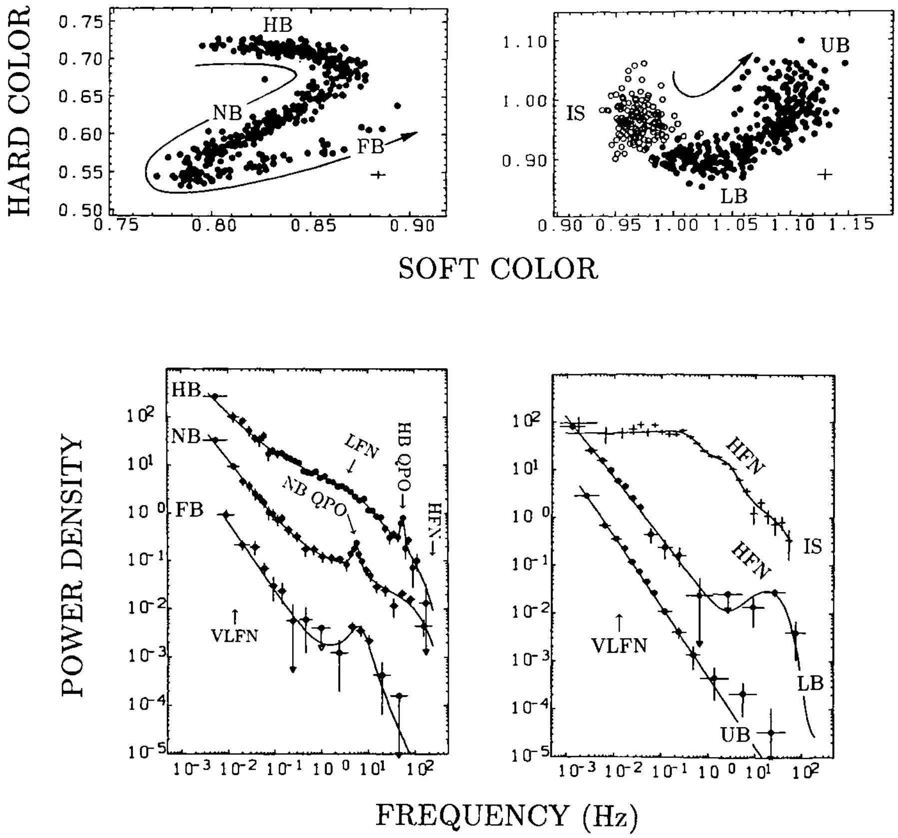

FIG. 4.—X-ray color-color diagrams and power spectra of Z (*left*) and atoll (*right*) sources in their horizontal (HB), normal (NB), and flaring (FB) branches, and island state (IS) and lower (LB) and upper (UB) banana branches, respectively. The arrows in the upper diagrams indicate the direction of increasing mass accretion rate.

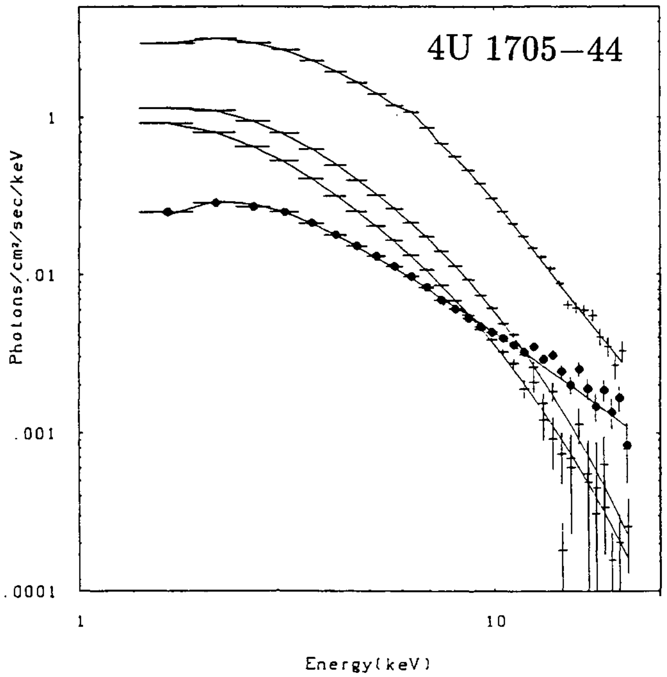

FIG. 5.—X-ray spectra from the atoll source (and X-ray burst source) 4U 1705−44. The filled circles show the source in a low state. From Langmeier et al. (1987).

the mass accretion rate $\dot{M}$; both positive and negative correlations between these two quantities occur.

For the comparison with the black hole candidates it is of particular interest to note that, when changes in X-ray intensity larger than a factor of $\sim 10^2$ are considered, the X-ray spectral changes of the low magnetic field neutron stars become considerably less subtle, and that at the low end of the intensity (and, no doubt, $\dot{M}$) range, power-law spectra similar to those in the black hole candidates occur, with $\alpha \sim 1.5$–2 (White & Mason 1985; Langmeier et al. 1987; Gottwald et al. 1987; White, Stella, & Parmar 1988) (Fig. 5). As we shall see in the next section, in these low-$\dot{M}$ states the rapid X-ray variability also resembles that of the black hole candidates.

4. RAPID X-RAY VARIABILITY

4.1. *Black Hole Candidates*

Three distinct rapid X-ray variability states are clearly distinguishable in the black hole candidates (Fig. 6). In the *low state* (when the $\alpha \sim 1.5$ power-law component dominates the X-ray spectrum) the famous large-amplitude (up to 40% rms of the mean flux) fluctuations occur that were discovered in Cygnus X-1 by Oda et al. (1971). The power spectrum of these fluctuations roughly resembles a Lorentzian with a FWHM of 0.1–1 Hz centered on zero frequency, consistent with the fact that it can be approximately fitted with an exponential shot-noise

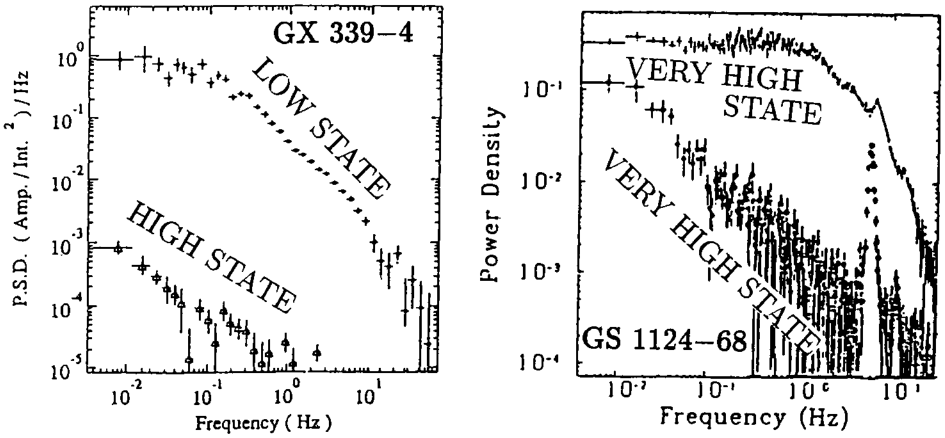

FIG. 6.—Power spectra of black hole candidates in their low, high, and very high states. From Inoue (1992) and Dotani (1992).

model with a decay time of 0.3–3 s. For historical reasons I shall call these variations "the shot noise," although there is no conclusive evidence that a shot-noise process in the classical sense of randomly occurring identical shots really causes it.

In the *high state* (when the ultrasoft component dominates the X-ray spectrum), variability is very much less. The power spectrum has a power-law shape $P \propto \nu^{-\gamma}$, $\gamma \sim 1$; the associated variability has an amplitude of only a few percent rms (0.01–100 Hz). Sometimes the shot noise is detected also in the high state; it has been reported that then it is stronger at higher photon energies, where the power-law component in the X-ray spectrum dominates, than at lower energies, where the ultrasoft component dominates (Oda et al. 1976). All this suggests that the shot noise is a property of the power-law component and the few percent variability with the $\gamma \sim 1$ power-law power spectral shape is a property of the ultrasoft component. I note that this conclusion stands in need of quantitative verification.

In the "*very high state*" (only seen in GX 339−4 and GS 1124−68 so far; Miyamoto et al. 1991; Dotani 1992; Miyamoto et al. 1993; Grebenev et al. 1993) when the ultrasoft component dominates but an $\alpha \sim 2$–3 power-law component may also be (at least sometimes) present in the X-ray spectrum, quasi-periodic oscillations (QPOs) with frequencies between 3 and 10 Hz occur in combination with broad-band noise that sometimes resembles the above high-state $\gamma \sim 1$ power-law component, and at other times resembles a version of the low-state shot noise from which the longest correlated timescales have been removed (see also § 6). The presence or absence of the shot noise in the very high state has been reported to correlate (Miyamoto et al. 1993) with the presence or absence of the power-law X-ray spectral component, suggesting that indeed a similar process to that in the high state may be responsible.

Much slower ($\lesssim$1 Hz) QPOs have been seen in several cases in black hole candidates in their low and high states (Frontera & Fuligni 1975; Motch et al. 1983; Ebisawa, Mitsuda, & Inoue 1989; Grebenev et al. 1991; Vikhlinin et al. 1992a, b; Kouveliotou 1992a, b). Some of the reported QPO peaks are very broad, and most resemble the "peaked high-frequency noise" seen in the neutron star atoll sources (§ 4.2, Fig. 4). The rather narrow peaks near 1 Hz detected in LMC X-1 and GX 339−4 may be similar to the 1.4 Hz QPO seen in Circinus X-1 (Tennant 1988). It seems plausible that several different phenomena are contained among the "slow" black hole candidate QPOs.

4.2. *Neutron Stars*

The Z and atoll systems (HK89; Fig. 4 above) are thought to contain neutron stars, since many of the atoll sources and at least one Z source show X-ray bursts (Tawara et al. 1984; Sztajno et al. 1986). These sources have two rapid X-ray variability components in common. A power-law component with an index γ of about 1–1.5 in the atoll sources and 1.5–2 in the Z sources with a strength of 0.5 to a few percent rms is called "very low frequency noise" (VLFN). It is strongest at high accretion rates. A component called "high-frequency noise" (HFN) resembling the black hole candidate shot-noise component is strongest at low accretion rates. The strongest examples of HFN have been seen at the lowest luminosities (in 4U 1705−44 [Langmeier, Hasinger, & Trümper 1989] and 4U 1608−52 [Inoue 1992]).

In the Z sources, two QPO components occur in addition to these noise components. At relatively lower $\dot{M}$ the frequency-tunable 13–55 Hz so-called horizontal-branch oscillations (HBOs) appear, and at higher $\dot{M}$ the 6 Hz so-called normal-branch oscillations (NBOs) and the closely related 6–20 Hz flaring-branch oscillations (FBOs) are seen. There is some overlap in the $\dot{M}$ ranges of the two first-mentioned types of QPOs: HBOs and NBOs are sometimes seen simultaneously (Hasinger et al. 1990). NBOs and FBOs never occur simultaneously; there is a gradual transition from one type to the other as the accretion rate changes, indicating that NBOs and FBOs are part of one phenomenon. The HBOs are most likely magnetospheric in origin (the "beat-frequency model"; Alpar & Shaham 1985; Lamb et al. 1985). The NBOs and FBOs have been proposed to be an aspect of accretion at near-Eddington (NBOs) and super-Eddington (FBOs) rates (Fortner, Lamb, & Miller 1989; Alpar et al. 1992). A comprehensive model explaining the various types of QPOs and spectral branches of the Z sources has been proposed by Lamb (1991).

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5. SIMILAR STATES IN NEUTRON STARS AND BLACK HOLES

Our current working hypothesis for explaining the combined properties of the neutron star Z and atoll sources (due to HK89) is that the Z sources have higher magnetic field strengths B and accretion rates $\dot{M}$ than the atoll sources. The difference in magnetic field explains why Z sources show HBOs and atoll sources do not; the difference in accretion rate explains why Z sources have NBOs and FBOs and atoll sources do not. Of the eight brightest persistent X-ray binaries, six are Z sources (see van der Klis 1989), supporting a difference in average accretion rate between the two groups. The alternative hypothesis, that Z and atoll sources differ only in $\dot{M}$, is unattractive, as there is no evidence that Z sources at low $\dot{M}$ in any way tend to become similar to atoll sources at high $\dot{M}$ or vice versa. The correlation between $\dot{M}$ and B that this classification implies (Fig. 7) may originate in the different evolutionary history of Z and atoll systems that is suggested by what is known so far about their orbital period distributions (Z sources tend to have longer periods and subgiant companions, atoll sources shorter periods and dwarf companions; HK89).

Predictions from this working hypothesis are that an atoll source that becomes bright will show Z-source normal-branch/flaring-branch properties (NBOs and FBOs and spectral branches), but never HBOs, and that a Z source that becomes faint will show millisecond pulsations (as the accreting matter can no longer hide the pulsations). The properties of Circinus X-1 (which is a neutron star; Tennant 1986) fit the first prediction (Tennant 1987; Makino, Kitamoto, & Miyamoto 1992; Oosterbroek et al. 1994). The second prediction has not yet been tested, as no Z source has ever been seen to go dim.

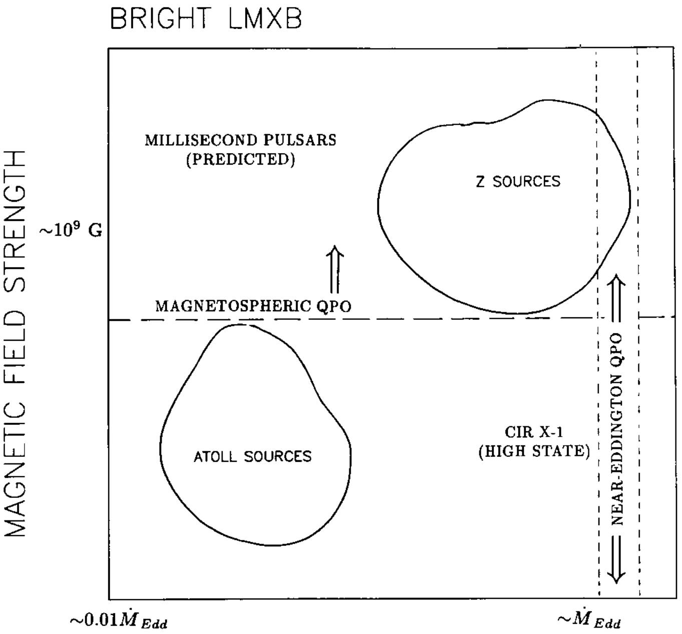

FIG. 7.—Proposed (HK89) relative locations of the Z and atoll sources in the accretion rate/neutron star magnetic field strength plane. The probable location of Circinus X-1 in the high state is also indicated.

There is a striking similarity in the rapid X-ray variability properties of the black hole candidates and the atoll sources. At low accretion rates the power spectra are nearly identical in shape (Fig. 8; roughly a zero-centered Lorentzian) and fractional rms amplitude (several times 10%): the black hole candidate shot noise and the atoll source HFN appear to be the same low-state phenomenon. At higher accretion rates, both black hole candidates and atoll sources have lower fractional rms amplitudes (a few percent) with a rather flat ($\gamma \sim 1$–1.5) power-law slope in the power spectrum. Although they never reach accretion rates sufficiently low for the HFN to become stronger than ~10%, the Z sources show HFN and VLFN properties similar to this.

Other similarities exist between neutron star and black hole candidate phenomenology. The 6–20 Hz neutron star NBOs and FBOs (in Z sources and Circinus X-1) and the 3–10 Hz black hole candidate very high state QPOs might be similar phenomena. It is interesting to note that both appear at the very highest accretion rates. If we can apply the Eddington-limited radial-flow model (Fortner et al. 1989) designed for the neutron star NBOs (which is by no means clear), and if scaling by compact-object mass is the only scaling that needs to be done, then the lowest reported QPO frequencies in GX 339−4 and GS 1124−68 of ~3 Hz would imply black hole masses of about 3 $M_\odot$. Finally, the strong shot noise that is occasionally displayed by black hole candidates in the very high state may be similar to a comparable component seen in Circinus X-1 when it becomes very bright (Oosterbroek et al. 1994).

By combining the above clues, I come to an extended working hypothesis that puts the phenomenology of the neutron star Z and atoll sources and the black hole candidates into one common scheme (Fig. 9). The scheme contains three rapid-variability regimes ("states") that are common to neutron stars and black hole candidates; in a given source $\dot{M}$ determines the state, but it is possible that the critical values of $\dot{M}$ at which a source changes state depend on other source parameters (e.g., on compact-object mass; a scaling with $\dot{M}_{\rm Edd}$ seems natural, but more complex scaling laws might apply). This could explain why GS 2023+338 remains in its "low state" (power-law X-ray spectrum, and probably strong shot noise) at high luminosities: this is the stellar black hole candidate with the highest mass function (Casares, Charles, & Naylor 1992).

In this scheme, the *very high state* of the black hole candidates (3–10 Hz QPOs) corresponds to the normal branch/flaring branch of the Z sources (6–20 Hz QPOs). In analogy with the Z sources (§ 4.2), I suggest that the black hole candidates are also accreting near the Eddington limit in this state. Atoll sources do not usually attain such high accretion rates, but Circinus X-1 in its high state fits in (6–20 Hz QPOs). Occasional strong shot noise is seen in this state in the black hole candidates and in Circinus X-1 (but not in the Z sources, perhaps due to their magnetosphere). The *high state* of the black hole candidates corresponds to the horizontal branch of the Z sources and the banana branch of the atoll sources. Only Z sources show the 13–55 Hz HBO (and associated noise) here, as they have a magnetosphere, which is absent in the other source types. Otherwise this state is characterized by little variability, with a power spectrum showing a $\gamma \sim 1$–1.5 power law of a few percent rms. The *low state* of the black hole candidates

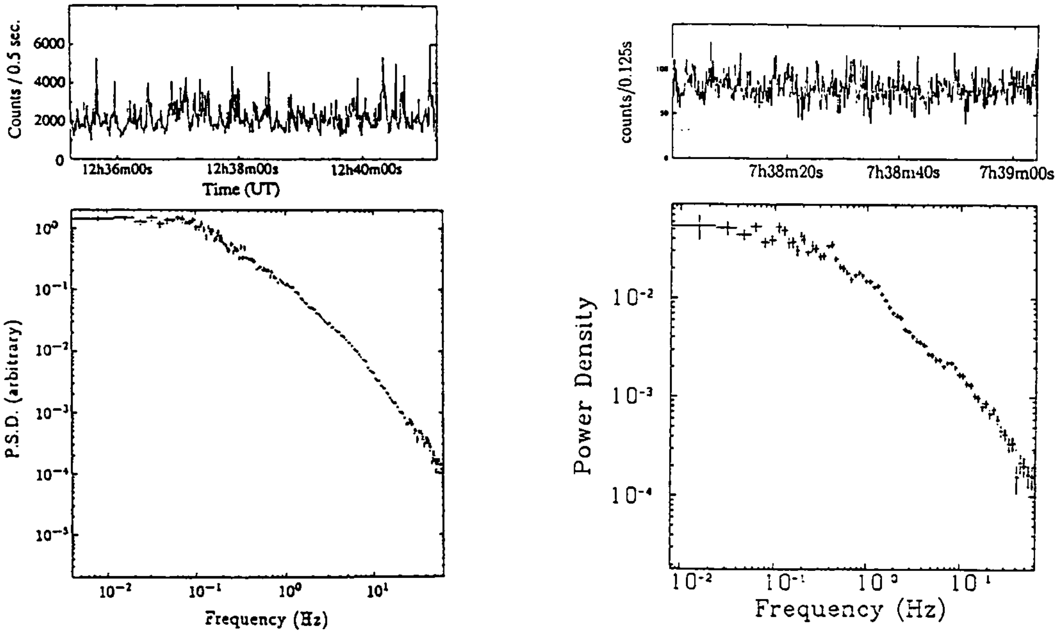

FIG. 8.—Power spectra and X-ray light curves from the black hole candidate Cygnus X-1 (*left*) and the neutron star 4U 1608−52 (*right*) in the low state illustrating the similarity between neutron star and black hole candidate low states. Adapted from Inoue (1992).

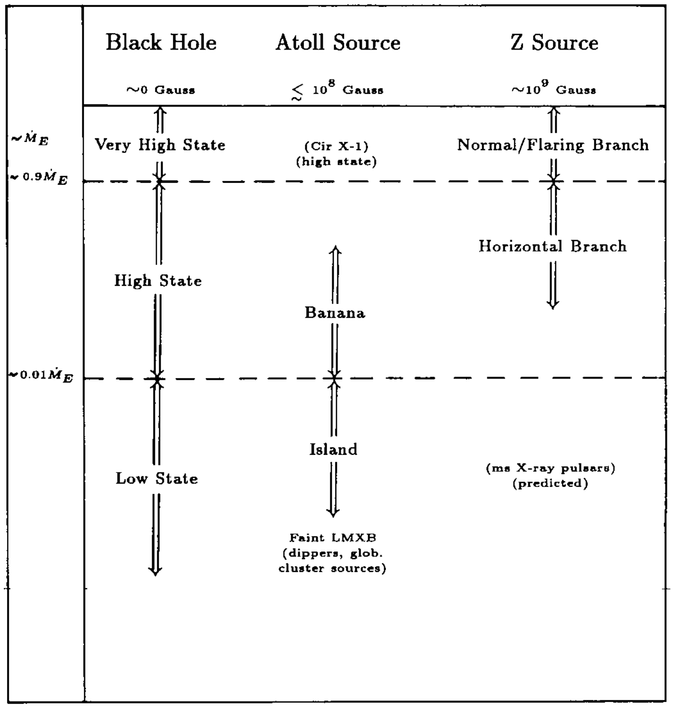

FIG. 9.—Proposed classification scheme for neutron star and black hole accretion phenomenology. There are three states that are common to black holes and neutron stars; $\dot{M}$ determines which state a given source is in. The values of the accretion rate (in terms of the Eddington rate $\dot{M}_E$) at which the state transitions might occur are indicated. These values are intended as rough order-of-magnitude indications only. Other source parameters might affect these values of $\dot{M}$, and so the state transitions may occur at different values of $\dot{M}/\dot{M}_E$ for different source types.

corresponds to the island state of the atoll sources. Both show *very* similar HFN, with large amplitude (up to a few times 10% rms) and similar power spectral shapes. The similarity of the atoll sources to the black hole candidates in the low state is largest in the faintest observed atoll island states (Langmeier et al. 1989; Inoue 1992). Z sources have never been seen to attain accretion rates that are this low; if they did, then one would expect to see millisecond pulsations in them.

The X-ray spectral properties of neutron stars and black hole candidates may also have similarities across compact-object type that conform to this scheme. In particular, flat power-law 1–20 keV spectra similar to those of black hole candidates in their low state occur in atoll sources when they become faint (§ 3).

6. THE HFN/SHOT NOISE; "FLAT-TOPPED NOISE"

No satisfactory model exists for the black hole candidate shot noise/neutron star HFN. In view of the fact that this variability component provides a phenomenological link between the black hole candidates and the low magnetic field neutron stars (and perhaps even with the high magnetic field neutron stars; see Belloni & Hasinger 1990b), it would be of great interest to construct such a model. Comparative studies of neutron stars and black hole candidates can help in this task by, for example, uncovering a property that scales with compact-object mass. If black hole candidate shot-noise and neutron star HFN are due to the same physical process (I shall refer to these two phenomena together as "flat-topped noise"), then it seems likely that this process takes place in the inner accretion disk, a structure common to black hole and neutron star accretion in which sufficient energy is released to create comfortably fluctuation amplitudes of more than several times 10% rms. Note that a model that identifies the variability frequencies of the flat-topped noise with Kepler frequencies at certain radii in the disk is not attractive, as the "business part" of the disk (where most of the gravitational energy is released) has characteristic Kepler frequencies of 100–1000 Hz, whereas the flat-topped noise breaks between 1 and 0.01 Hz. The radial flow time through the part of the inner disk where most of the energy is liberated might, depending on the disk model and the value of the viscosity, be of the right magnitude. Disk inhomogeneities arriving at the outer radius of this disk annulus would be quickly sheared into rings but would still cause a fluctuation (shot) in the X-ray output lasting for the time it takes for the matter to flow through the region (Miyamoto et al. 1992). The fact that the flat-topped noise is seen in the low state, disappears in the high state, and occasionally reemerges in the very high state (§ 4), possibly in correlation with the X-ray spectral power-law component, may be related to the visibility of the inner region where these phenomena originate. In the low state, the inner region is in full view; in the high state accreting material above and below the plane of the disk may shield this region from being seen, whereas in the very high state, where the Eddington luminosity is reached, radiation pressure occasionally blows away enough matter to temporarily once again reveal the inner region. A source with a low inclination might avoid this shielding in all states and would consequently never exhibit high-state behavior. This is another possible explanation for the properties of GS 2023+338.

A clue to the nature of the flat-topped noise may be the observation (Belloni & Hasinger 1990a; Miyamoto et al. 1992) that above a time-variable cutoff frequency $\nu_{\rm flat}$ the fractional amplitude of the fluctuations as a function of frequency is constant with time, whereas below this frequency the power spectrum is flat at a level that varies with $\nu_{\rm flat}$ (Fig. 10). This indicates that the longest correlated variations (perhaps shots) in the time series are of order $\tau_{\rm flat} = \nu_{\rm flat}^{-1}$. It is as if from an approximately constant process all variations on timescales *longer* than $\tau_{\rm flat}$ are removed. It seems very likely that the variations in $\nu_{\rm flat}$ (and $\tau_{\rm flat}$) occur as a function of variations in average $\dot{M}$, but from the observations it is not clear that this is the case. It is interesting to note that this "Belloni-Hasinger effect" might even hold for the flat-topped noise that is sometimes seen in the very high state of black hole candidates. If one calculates the amplitude of the flat-topped noise seen in GS 1124−68 in the very high state (reported by Miyamoto et al. 1993) as a fraction of only the power-law component in the X-ray spectrum, then its high-frequency part (>6 Hz) is similar in strength (and shape) to that of the low-state flat-topped noise; the slower variations (<6 Hz) have been removed. Possibly the effect is related to a decreasing crossing time of the radiating part of the disk for increasing $\dot{M}$. Perhaps it is not the radial flow time of a test particle through the radiating part of the disk but the passage time of an inhomogeneity of finite radial extent that is the relevant quantity. The radial extent distribution of the disk inhomogeneities might then dominate the properties of the flat-topped noise. If at higher accretion rates large radial inhomogeneities are more rapidly smoothed out than at lower accretion rates, this could explain the effect.

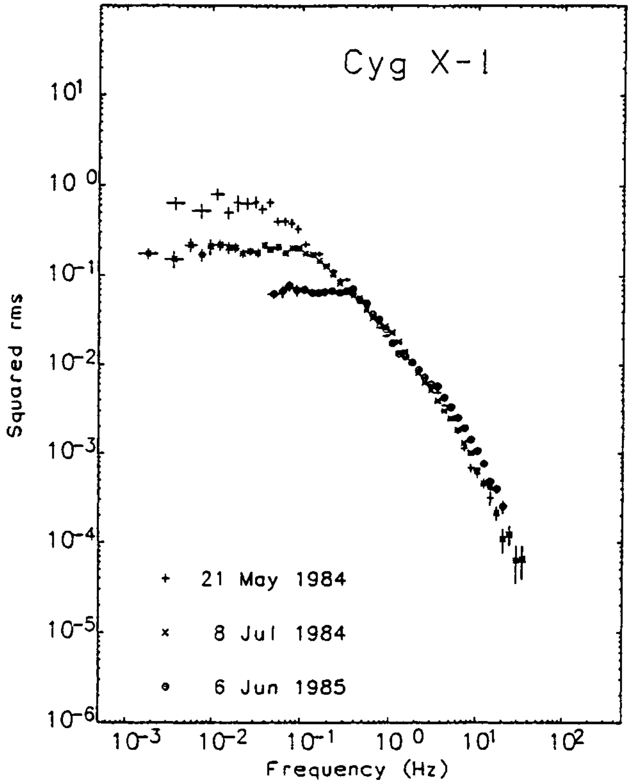

FIG. 10.—Variations in the power spectrum of Cygnus X-1 in the low state. Below a time-variable cutoff frequency $\nu_{\rm flat}$ between 0.3 and 0.03 Hz the power spectrum is flat at a level that varies as $\nu_{\rm flat}$ varies; above $\nu_{\rm flat}$ the power spectrum (normalized in such a way that integrated power equals the square of the fractional rms amplitude of the fluctuations) shows very little variation. From Belloni & Hasinger (1990a).

The Belloni-Hasinger effect seems an important clue to the nature of the flat-topped noise. Further study is required to determine to what extent this effect holds in black hole candidates in the low state, between the low state and the very high state, and between black hole candidates and neutron stars.

7. CONCLUSION

There are many similarities in the accretion phenomenology of low magnetic field neutron stars and black hole candidates. It is possible to organize the phenomena displayed by these sources into one common scheme of three $\dot{M}$-driven regimes. In addition to the search for black hole "signatures," it is of great importance to quantitatively study the *similarities* between black hole candidate and neutron star accretion. Compact-object mass can be expected to be a parameter governing the phenomena in the inner disk that likely cause these similarities, and eventually, therefore, differences by factors of a few should emerge from such quantitative comparisons between low magnetic field neutron stars and black hole candidates.

Note added in manuscript.—After this paper was completed, K. Mitsuda of ISAS kindly shared with me information about *Ginga* observations of the atoll source 4U 1608−52 in the low state (K. Yoshida et al., in preparation [1993]) which clearly show the "Belloni-Hasinger effect," previously seen only in black hole candidates. This further confirms the similarity between black hole candidates and atoll sources in the low state.

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