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RAPID X-RAY VARIABILITY IN GALACTIC BLACK HOLE CANDIDATES

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ABSTRACT

The rapid X-ray variability of galactic accreting black-hole candidates is compared to that of accreting neutron stars with low magnetic fields. The power spectra of these objects can be described in terms of a small number of simple power spectral shapes: power law noise, band limited noise, and quasi-periodic oscillations (QPO). In a given source, the properties of these power spectral components seem to depend, to first order, only on mass flux. Similarities in the power spectral properties between source types strongly suggest that similar physical mechanisms underlie power spectral components seen in black-hole candidates and in neutron stars with various magnetic-field strengths. Two rapid ($\gtrsim 1$ Hz) QPO and two band limited noise components appear to occur across all types of X-ray binaries; the situation with respect to the ubiquitous power law components, as well as with respect to slow ($\lesssim 1$ Hz) QPO is as yet unclear. One QPO and one band limited noise component appear to be magnetospheric as they are not seen in black-hole candidates and atoll sources (which are inferred to be neutron stars with a very low magnetic field). Another QPO and band limited noise component may be related to the presence of an inner, radiation pressure dominated accretion disk, as they do not occur in X-ray pulsars. It is discussed to what extent the relatively small *quantitative* differences between the rapid X-ray variability properties of neutron stars and black-hole candidates can be used to identify black holes, and whether there exist any *qualitative* differences (*i.e.*, black hole signatures) in the rapid X-ray variability.

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1. INTRODUCTION

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 to be expected, as 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 time scales (underlying the rapid [millisecond] variability), are common to neutron stars and black holes. To first order one would expect 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. With this in mind, in the following I review the X-ray observations of the black-hole candidates and compare them to the low

magnetic-field neutron stars, with particular emphasis on the observations of their rapid X-ray variability. Indeed, similarities have emerged that indicate that a unified description of some of the accretion phenomena may be possible. If a phenomenon is seen in both neutron star and black-hole candidate systems this tells us quite a bit about the phenomenon, as then it can not be due to any property that is unique to either neutron stars or black holes, such as the presence or absence of a surface, or the presence or absence of a strong non-aligned magnetic field. In addition, some source characteristics are emerging from the studies of the similarities of neutron stars and black holes, that may indeed be unique to black holes.

Fig. 1. Power-spectral shapes. The synthetic time series (right) were calculated by inversely transforming a synthetic Fourier transform with amplitudes given by the square root of the assumed power spectrum (left) and random phases. No counting noise was included.

In the process of accretion onto a compact object, the X-ray spectrum and the rapid X-ray variability originate in the same physical region (near the compact object), so that these X-ray properties are expected to be coupled. The hypothesis that the mass flux $\dot{M}$ towards the compact object governs both the X-ray spectrum and the power spectrum, so that when $\dot{M}$ varies these observables will show correlated variations works well in explaining the data. A very recent development is that maybe we are beginning to understand some of the effects of binary inclination in the non-dipping LMXB; I'll briefly discuss how the results from these sources might be applied to black-hole candidates in Section 4. For more extensive reviews I refer to van der Klis (1994b, d).

In the following I shall use 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".

The power spectra of accreting compact objects can be described in terms of a small number of simple shapes (Fig. 1). *Power law noise* has a power distribution $\propto \nu^{-\alpha}$, *band limited noise* one that steepens towards high ν and flattens towards low ν . Band limited noise that has a maximum at $\nu > 0$ is called *peaked*; if the maximum is at $\nu = 0$ the component is called *flat-topped*. The same power spectral component can be at one time flat-topped and at another time peaked. *Quasi-periodic oscillations* (QPO) are a type of peaked noise. Usually, the term QPO is reserved for relatively narrow peaks.

2. BLACK HOLE STATES

Three source states are distinguished in black-hole candidates (Tananbaum et al. 1972, Oda et al. 1976, Miyamoto et al. 1991). In the *low state* (LS) the X-ray spectrum is a flat power law with photon spectral index 1.5–2. In the *high state* (HS) the 1–10 keV flux is much higher due to a soft component; the power law is sometimes "sticking out" from under the soft component at higher energies. In the *very high state* (VHS) the X-ray spectrum is similar to that in the high state (at higher 1–10 keV flux), with perhaps an additional hard power law component. The VHS is mainly distinguished from the HS by the properties of its rapid X-ray variability.

Fig. 2 summarizes the power spectra in the three states. The LS power spectrum shows strong (30–50% amplitude) band-limited noise with ν_{cut} between 0.03 and 0.3 Hz. This LS noise is usually flat-topped, but sometimes peaked (Vikhlinin et al. 1994). The level of the flat top and, in anti-correlation with this, the cut-off frequency ν_{cut} sometimes vary, whereas the power spectrum above ν_{cut} remains approximately unchanged (Belloni and Hasinger 1990, Miyamoto et al. 1992a). In the HS power law noise with $\alpha \sim 1$ and an amplitude of a few % is present. Sometimes LS noise is present in the hard X-ray spectral component seen in the HS, and this is taken as evidence that the LS noise is a property of the hard power-law X-ray spectral component. Slow QPO with frequencies similar to the LS noise cut-off frequencies (~ 0.08 – 0.8 Hz; Motch et al. 1983, Ebisawa et al. 1989, Grebenev et al. 1991) and possibly related to peaked LS noise sometimes occur in LS and HS. The rare VHS shows 3–10 Hz QPO and rapidly variable broad-band noise. The QPO show second harmonics and possible subharmonics. The noise in the VHS alternates in shape, sometimes within 1 s, between band-limited ($\nu_{\text{cut}} \sim 1$ – 10 Hz), and power law shaped ($\alpha \sim 1$). CD/HID branches occur in the VHS, and the power spectral parameters seem to depend on position in the branches, but these branch structures are not very similar from one epoch to the next ("messy" branches). The LS and VHS band limited noise cut-off frequency and amplitude fit a single relation (van der Klis 1994c), suggesting that they part of a single phenomenon. The VHS power law noise is similar to that in the HS.

The transient black-hole candidate GS 1124–68 (Nova Mus '91) in its decay went through all three states (Miyamoto et al. 1992b, Kitamoto et al. 1994), strongly suggesting that the states directly follow $\dot{M}$, an assumption that works very well in the bright low magnetic-field neutron-star systems. Recent evidence indicates that some black hole transients, even when they are very luminous, remain in the "low" state; see Sunyaev, these proceedings.

BLACK-HOLE-CANDIDATE POWER SPECTRA

Fig. 2. Power spectra from Ginga data of black-hole candidates in the low (LS; Cyg X-1), high and very high (HS and VHS; GS 1124-68) states.

3. SIMILARITIES BETWEEN BLACK HOLE CANDIDATES AND LOW MAGNETIC FIELD NEUTRON STARS

There is a number of striking similarities between black-hole candidate and neutron star phenomenology (see van der Klis 1994a, d). To describe these similarities it is necessary to briefly review the phenomenology of the accreting low magnetic-field neutron stars, the Z and atoll sources.

Z and atoll sources (Hasinger and van der Klis 1989, hereafter HK89, see also van der Klis 1989, 1994b and references therein) show rather subtle X-ray spectral changes. *Colour-colour diagrams* (CDs) and *hardness-intensity diagrams* (HIDs), plots of X-ray hardness ratios vs. each other or vs. count rate are used to describe the X-ray spectral variations. The sources produce a characteristic track in the CD/HIDs, and source position in the track is used as an indication for $\dot{M}$.

Z sources produce tracks in the CD/HIDs that are Z-shaped. $\dot{M}$ is inferred to increase following the Z track from upper left to lower right. Z source power spectra show three broad noise components, *very low frequency noise* (VLFN), *low frequency noise* (LFN) and *high frequency noise* (HFN) and two QPO components, *horizontal branch oscillations* (HBO) and *normal and flaring branch oscillations* (N/FBO). VLFN is 1-6% amplitude power law noise that gets stronger with $\dot{M}$. HBO and LFN are a QPO and a band limited noise component that appear and disappear together, and are likely physically related. They are strongest at low $\dot{M}$ and disappear at high $\dot{M}$. HBO frequency (13-55 Hz) and LFN cut-off frequency (2-20 Hz) increase with $\dot{M}$. LFN can be flat topped or peaked, depending on the source. N/FBO have a preferred frequency near 6 Hz, increasing to ~ 20 Hz when $\dot{M}$ increases.

The most successful HBO model is the *magnetospheric beat frequency model* (Alpar and Shaham 1985, Lamb et al. 1985), which requires Z sources to have a magnetosphere. In most models for the N/FBO,

radiation pressure plays the key role (van der Klis et al. 1987, Hasinger 1987, Lamb 1989, Fortner et al. 1989, Miller and Lamb 1992, Alpar et al. 1992). Z sources have near-Eddington luminosities, and the NBO frequency is roughly similar in each Z source, in accordance with the idea that the frequency is determined by the Eddington critical luminosity L_{Edd} . Lamb (1991) proposed a comprehensive model for the QPO and X-ray spectral properties of Z sources that uses the above ingredients.

Atoll sources (HK89, van der Klis 1994b) show one curved branch in the CD, often fragmented due to observational effects. $\dot{M}$ increases from left to right along the branch. Their power spectra show two broad noise components called *very-low-frequency noise* (VLFN) and *high-frequency noise* (HFN). Atoll source VLFN is power law noise similar to that in Z sources. Atoll source HFN has a cut-off frequency of 0.3–20 Hz and depends strongly on $\dot{M}$. At low $\dot{M}$ it is strong (up to 22%); when $\dot{M}$ increases this decreases to <2% (HK89) while the cut-off frequency increases (Yoshida et al. 1993, Prins et al. 1994). Atoll HFN is sometimes flat-topped and sometimes peaked.

HK89 proposed that the neutron stars in atoll sources have lower magnetic field strengths than Z sources, and are constrained to lower mass fluxes $\dot{M}$. The lower field explains why the (magnetospheric) HBO are not seen in atoll sources, and the lower $\dot{M}$ why the same is true for the (near-Eddington) N/FBO. The implied relation between $\dot{M}$ and magnetic field strength may have an evolutionary origin (van der Klis 1991). Predictions are that an atoll source that becomes bright will show Z source high- $\dot{M}$ properties (N/FBO and appropriate spectral branches), but never HBO, and that a Z source that becomes faint will show millisecond pulsations.

The properties of Cir X-1 fit the first prediction. This source is a low magnetic-field neutron star (it shows type 1 X-ray bursts; Tennant et al. 1986a, b) with a complex phenomenology that most likely originates in the large variations in mass transfer that the system undergoes as a function of its 17-d period. Sometimes (at intermediate brightness levels and away from periastron) its power-spectrum and CD behaviour are very similar to those of an atoll source on the banana branch (Oosterbroek et al. 1994). When the source becomes very bright, at periastron, it sometimes shows 6–20 Hz QPO and spectral branches that are reminiscent of Z source N/FBO behaviour (Tennant 1987; Makino et al. 1992; Oosterbroek et al. 1994). The source is apparently an example of an atoll source that can reach $\dot{M}_{Edd}$ (van der Klis 1991; Oosterbroek et al. 1994). As will be discussed below Cir X-1 also shares some characteristics with black-hole candidates.

I now turn to the comparison of the above-described neutron star properties with those of the black-hole candidate systems described in the previous section.

The black-hole candidate LS is very similar to the atoll source low $\dot{M}$ ("island") state. Both states occur at the lowest 1–10 keV count rates and inferred $\dot{M}$ levels. Both are dominated by strong (several 10%) band limited noise (LS noise and atoll HFN) which is sometimes flat-topped and sometimes slightly peaked. When an atoll source becomes really faint, the power spectra are nearly indistinguishable (Fig. 3) from a black-hole candidate in the low state and the 1–20 keV (Langmeier et al. 1987, Yoshida et al. 1993) and 13–80 keV (Van Paradijs and van der Klis 1994) X-ray spectra become hard, just as in black-hole candidates in the LS. Even the inverse correlation between cut-off frequency and flat-top level, characteristic for black-hole candidates in the LS, was seen in an atoll source, 4U 1608–52, at low $\dot{M}$ (Yoshida et al. 1993). Z source LFN fits in with black-hole candidate LS noise and atoll HFN: it is also stronger at lower $\dot{M}$, disappears at higher $\dot{M}$, can be peaked and flat-topped, and has a higher ν_{cut} at higher $\dot{M}$. The absence of a similar band-limited noise component in pulsars, and also the beat-frequency model as applied to Z sources, suggest that such noise arises through inhomogeneities in the inner, radiation pressure dominated part of the disk, which in pulsars is disrupted by magnetic stresses.

The black hole candidate VHS has strong similarities to the Z source high $\dot{M}$ ("normal/flaring branch") state. Both occur at the highest inferred $\dot{M}$ levels, and both show QPO, with similar frequencies (6–20 Hz in the neutron star systems, 3–10 Hz in the black-hole candidates), that depend on the position of the source in branched tracks in the HID/CDs. Clearly different is the harmonic content of the QPO (black-hole candidate VHS QPO show strong harmonics, Z source N/FBO do not) and the character of the HID/CD branches (much "messier" in black-hole candidates). Another difference is that Z sources do not show the fast changes in broad band noise shape seen in black-hole candidates.

BLACK HOLE

NEUTRON STAR

Fig. 3. Power spectra from the black-hole candidates Cyg X-1 (top left) and GS 1124-68 (bottom left) in the low state and the very high state, respectively, and from the low magnetic-field neutron stars 4U 1608-52 (top right) and Cir X-1 (bottom right) in the atoll island state and a very high X-ray brightness state respectively, illustrating the similarity between neutron star and black-hole candidate low and very high states. Compiled from Inoue (1992), Takizawa et al. (1994) and Makino et al. (1991).

The properties of Cir X-1 provide a further link between neutron stars and black holes. In some of its high states (Tennant 1987, Makino et al. 1992, Oosterbroek et al. 1994), this source shows a mix of characteristics of Z sources and black-hole candidates in high $\dot{M}$ states (see Fig. 3). It shows QPO with frequencies between 6 and 20 Hz and no second harmonics (both Z source characteristics) in combination with messy branches in the CD/HID and fast changes in the shape of the broad band noise (black-hole candidate characteristics). In the present interpretation, the reason that Cir X-1 sometimes resembles a black hole in its rapid variability characteristics, as was noted by Toor (1977) and Samimi et al. (1979), while its X-ray bursts show it to be a neutron star, is that it is the only neutron star that we know that has a magnetic field as low as in atoll sources that sometimes accretes at near- or super-Eddington rates. Cir X-1 is therefore a key object as it can help to distinguish between phenomena that are characteristic for accretion onto any compact object that has no appreciable magnetic field, and phenomena that are truly characteristic for accretion onto a black hole. Following this line of reasoning, one concludes that a high harmonic content of the high $\dot{M}$ QPO may be a black hole signature, whereas variable broad band noise and messy branches are not.

On the basis of this array of similarities it can be concluded that the phenomenology of the black-hole candidates and low magnetic-field neutron stars may be described in terms of three $\dot{M}$ -driven states that are common to accreting low magnetic-field neutron stars and accreting black holes (van der Klis 1994a). Fig. 4 presents a line-up of the three common states of black-hole candidates and low magnetic-field neutron stars.

Phenomena	Black hole	Atoll source	Z source	
Guess at B	(0 Gauss)	($\leq 10^9$ Gauss)	($\sim 10^9$ Gauss)	Guess at $\dot{M}$
High $\dot{M}$ QPO	VHS	Cir X-1 (high state)	FB	$\geq 1\dot{M}_E$
Weak power-law noise		Banana	NB	$\sim 0.9\dot{M}_E$
Weak power-law noise + band-limited noise	HS		HB	$\sim 0.5\dot{M}_E$
Strong band-limited noise	LS	Island	(ms X-ray pulsars?)	$\sim 0.01\dot{M}_E$
		(most bursters and dippers)		

VHS: very high state; HS: high state; LS: low state; FB: flaring branch; NB: normal branch; HB: horizontal branch.

Fig. 4. Proposed classification scheme for X-ray binary source states. There are three states that are common to neutron stars and black holes; in a given source the mass transfer rate $\dot{M}$ towards the compact object determines the state. The power spectral shapes that are characteristic of each state are indicated in the leftmost column. The correspondence between the source states of each source type is indicated. Magnetic field strengths and mass fluxes are rough indications only. In particular, other source parameters, in particular inclination, are expected to affect the $\dot{M}/\dot{M}_E$ levels at which state transitions occur.

It was proposed recently that the power law noise components (VLFN) seen in accreting neutron stars might be due to unsteady nuclear burning on the neutron star surface (Bildsten 1993). A prediction of the model is that no VLFN similar to that in neutron stars should be seen in black holes.

4. DIFFERENCES BETWEEN BLACK HOLE SYSTEMS: INCLINATION EFFECTS?

The situation with respect to the states of black-hole candidates, and their relation to $\dot{M}$ is not yet entirely clear. In particular, there are cases, such as GX 339-4, where the observable energy flux in the 1-200 keV band is higher in the low state than in the high state (see Fig. 3 in Grebenev et al. 1993) and of sources, such as GS 2023+338, that despite an apparently very high X-ray luminosity display clear low-state characteristics (Kitamoto et al. 1989; Inoue 1989; 1991; Terada et al. 1992; as mentioned above, there may be a class of sources that does not show a soft component at all, see Sunyaev, these proceedings).

Fig. 5. A geometrically thick inner disk could obscure a central, hot and rapidly variable emitting region for observers at high inclination. $\dot{M}$ increases from top to bottom. The regions into which the hard and soft components are emitted overlap, making it possible to observe both components at the same time.

There are various possible explanations for these discrepancies between observed luminosity and inferred accretion rate. One possibility is that a fourth state exists in black-hole candidates, at higher $\dot{M}$ levels than the VHS, which like the LS is characterized by strong band limited noise and a hard X-ray spectrum and which has erroneously been lumped together with the "real" low state (Nowak 1994). However, there is as yet no evidence for any phenomenological differences between these two hard and strongly variable states, as would be expected in such a model. Other explanations would involve redirecting part of the gravitational energy released in the high state into some channel where it is not observed. Again, there are several possibilities as to where the energy might be redirected (mechanical energy of jets, XUV photons; see Grebenev, these proceedings, conceivably even into the hole); here I shall discuss a possibility that is suggested by a study of the properties of neutron star systems (see also van der Klis 1994a).

A detailed examination of the properties of Z sources, in particular in their flaring branches, has led Kuulkers and van der Klis (1994) to propose that obscuration by a geometrically thick inner accretion disk plays a role in Z source phenomenology. The disk swells when $\dot{M}$ increases, and at some $\dot{M}$ the torus-like inner

disk begins to obscure the central emitting regions. In Z sources this produces a distortion of the Z pattern. For higher inclinations i , the obscuration effects set in at lower $\dot{M}$.

A similar model could explain some of the phenomenology of black-hole candidates. The reason for the disappearance of the hard LS X-ray spectral component in the HS may be obscuration of a central, hot and rapidly variable region by matter in a puffed-up inner accretion disk. For a pole-on viewing geometry no obscuration would occur and the system would be completely dominated by the hard, rapidly variable X-ray spectral component at all $\dot{M}$ levels; this might explain the behaviour of GS 2023+338 (van der Klis 1994a) and similar sources that remain always in the “low” state (really, the hard state). Such an inner disk geometry could also cause the soft, much less variable, X-ray spectral component to be more concentrated towards the equatorial plane, thus preventing high i sources from showing an appreciable soft component. The increasing concentration of the hard X-rays towards the (rotation) polar axes with increasing $\dot{M}$ would in this scenario explain why the apparent 1–200 keV luminosity in the LS seems to be sometimes higher than in its HS and VHS: most of the energy would be leaving the system in the HS and VHS along the polar axis and not be seen by us (see Fig. 5).

In the low magnetic-field neutron stars the X-ray flux is an unreliable indicator of $\dot{M}$; the same might turn out to be the case in an even stronger sense in the black-hole candidates. Note, that the mass flux $\dot{M}$ that by hypothesis determines the state is the mass flux *towards* the compact object, just as is the case in the Z sources; at near- and super-Eddington rates, not all of this matter may actually be accreted; jets might for example be formed when $\dot{M}$ becomes high enough.

5. CONCLUSIONS

A picture may be emerging where the millisecond fluctuations in black holes, and in neutron stars with high, low and very low magnetic fields can be understood in common terms. Just two structures determine the basic physics of the accretion process, namely the magnetosphere and the inner (radiation pressure dominated) disk. Z sources have the most complex phenomenology, showing HBO and N/FBO, as well as LFN and HFN, because their magnetic field is weak enough to allow the presence of a mostly undisturbed inner accretion disk (like in black holes and atoll sources) and strong enough to allow the presence of a small magnetosphere (like in pulsars). Black holes and atoll sources (including Cir X-1) have an inner disk and no appreciable magnetosphere and therefore only show an N/FBO-like and an LFN-like component. Inner disk structure causes anisotropic emission and thereby inclination effects are introduced in the phenomenology.

Similar phenomena in black hole candidates and neutron stars that could have similar underlying physical mechanisms include the low state “shot” noise, similar in character to the atoll source “high frequency” and the Z source “low frequency” noise, which could be caused by accretion of inhomogeneities in the inner disk, the very high state 3–10 Hz QPO, similar to Z source (and Cir X-1) 6–20 Hz QPO, the hardening of the X-ray spectra at low $\dot{M}$, and the existence of three source states. Black hole signatures may well exist, but it is important to be very precise and quantitative when claiming one: just the presence of hard (photon index < 1.5 in the 30–100 keV range) tails, or of strong ($> 25\%$ rms with a cut-off < 0.05 Hz) band limited noise, is probably *not* a black hole signature, the presence of such tails or such a noise component at a luminosity $> 10^{37}$ erg/s may be. The presence of strong harmonics (> 0.5 times the fundamental) in 3–10 Hz QPO seen at high ($\sim L_{\text{Edd}}$) luminosity is another possible black hole signature.

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