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Publication date
1996

Published in
Symposium - International Astronomical Union

Citation for published version (APA):
van der Klis, M. B. M. (1996). Low-mass x-ray binaries: recent developments. *Symposium - International Astronomical Union*, *165*, 301.

LOW-MASS X-RAY BINARIES—RECENT DEVELOPMENTS

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Abstract. Recent developments in the field of low-mass X-ray binaries are briefly reviewed, with particular emphasis on a comparison between the systems that contain accreting low magnetic-field neutron stars and those that contain black-hole candidates. The possibility that inclination effects play a role in black-hole candidate phenomenology is explored.

1. Introduction

Low-mass X-ray binaries (LMXB) are defined as X-ray binary systems in which the mass donor stars have a mass $M < 1\,\mathrm{M}_\odot$. The donor star mass is very significant from the point of view of binary evolution, but from the point of view of the compact objects the LMXB are a mixed bag. They include persistent and transient black-hole candidates, low magnetic-field neutron stars such as bright bulge sources, persistent as well as transient bursters and dippers, and even a few accretion powered pulsars. For this paper, in the spirit of my assignment to review recent developments in the field of LMXB, I shall mostly ignore the pulsars and focus on a comparison between systems containing low magnetic-field accreting compact objects, i.e., black-hole candidates and low magnetic-field neutron stars, as some of the more exciting recent developments have to do with the comparison between neutron stars and black-hole candidates. 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 will briefly summarize the status of this in Section 5. For more extensive reviews I refer to Van der Klis (1994b,d).

J. van Paradijs et al., (eds.), Compact Stars in Binaries, 301–312.

In the process of accretion onto compact objects, 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. Stellar-mass black holes and neutron stars have similar masses and dimensions, and therefore the phenomena accompanying accretion onto them may be expected to show similarities. Indeed, in practice, similarities have emerged that indicate that a unified description of these accretion phenomena may be possible. The fact that a phenomenon is seen in both neutron star and black-hole candidate systems is in itself very revealing, as it shows that the phenomenon 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 studying the similarities of neutron stars and black holes, furthermore, some characteristics have emerged that may indeed be unique to black holes.

The power spectra of accreting compact objects can be described in terms of a small number of simple shapes (see Van der Klis 1994b,d). *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. Z and Atoll Sources

Z and atoll sources (Hasinger & Van der Klis 1989, hereafter HK89) are low magnetic-field neutron stars. They have been extensively described previously (Van der Klis 1989, 1994b and references therein), and only a summary of their properties is presented here. The X-ray spectral changes are usually subtle, and *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 CDs and HIDs, and source position in the track is used as an indication for $\dot{M}$.

Six *Z sources* are known. They produce Z-shaped tracks in X-ray CDs and HIDs. $\dot{M}$ 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. In Sco X-1 and GX 17+2, their frequency has been observed to increase from ~6 to ~20 Hz when $\dot{M}$ increases.

The most successful HBO model is the *magnetospheric beat frequency model* (Alpar & Shaham 1985; Lamb *et al.* 1985), which requires Z sources to have a magnetosphere. Some pulsars show QPO that may be caused by a similar mechanism (Angelini *et al.* 1989; Finger *et al.* in these proceedings). 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 & 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 $L_{\rm Edd}$. Lamb (1991) proposed a comprehensive model for the QPO and X-ray spectral properties of Z sources that uses the above ingredients.

A dozen *atoll sources* are known (HK89; Van der Klis 1994b). They 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% 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 $\dot{M}_{\rm Edd}$ (van der Klis 1991; Oosterbroek *et al.* 1994). As will be discussed in Section 4, Cir X-1 also shares some characteristics with black-hole candidates.

3. Black-Hole Candidates

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. 1 summarizes the power spectra in the three states. The LS power spectrum shows strong (30–50% amplitude) band-limited noise with $\nu_{\rm cut}$ 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 $\nu_{\rm cut}$ sometimes vary, whereas the power spectrum above $\nu_{\rm cut}$ remains approximately unchanged (Belloni & 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. 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 ($\nu_{\rm cut}$~1–10 Hz), and power law shaped (α~1). CD/HID branches occur in the VHS, and the power spectral parameters seem to depend on position in the branches, but

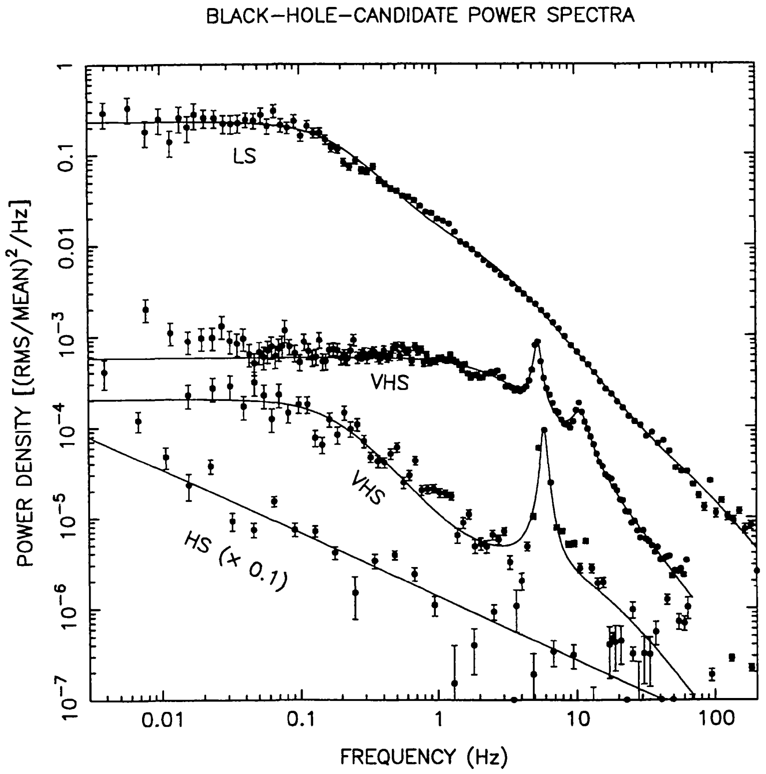


Figure 1. **Power spectra from GINGA data of black-hole candidates in the low (LS; Cyg X-1), high and very high (HS and VHS; GS 1124−68) states.**

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 one relation (Van der Klis 1994c), suggesting that they form one 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 $\dot{M}$. In the bright low magnetic-field neutron-star systems the assumption of strict dependence on $\dot{M}$ worked very well. Recent evidence indicates that some black-hole transients, even when they are very luminous, remain in the "low" state; see Section 5.

4. 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).

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 from those of black-hole candidates in the low state, and the 1–20 keV (Langmeier *et al.* 1987; Yoshida *et al.* 1993) and 13–80 keV (Van Paradijs & 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 $\dot{M}$. 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 BHCs). Another difference is that Z sources do not show the fast changes in broad-band noise shape seen in black-hole candidates.

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. 2). 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 (BHC characteristics). The reason, then, 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

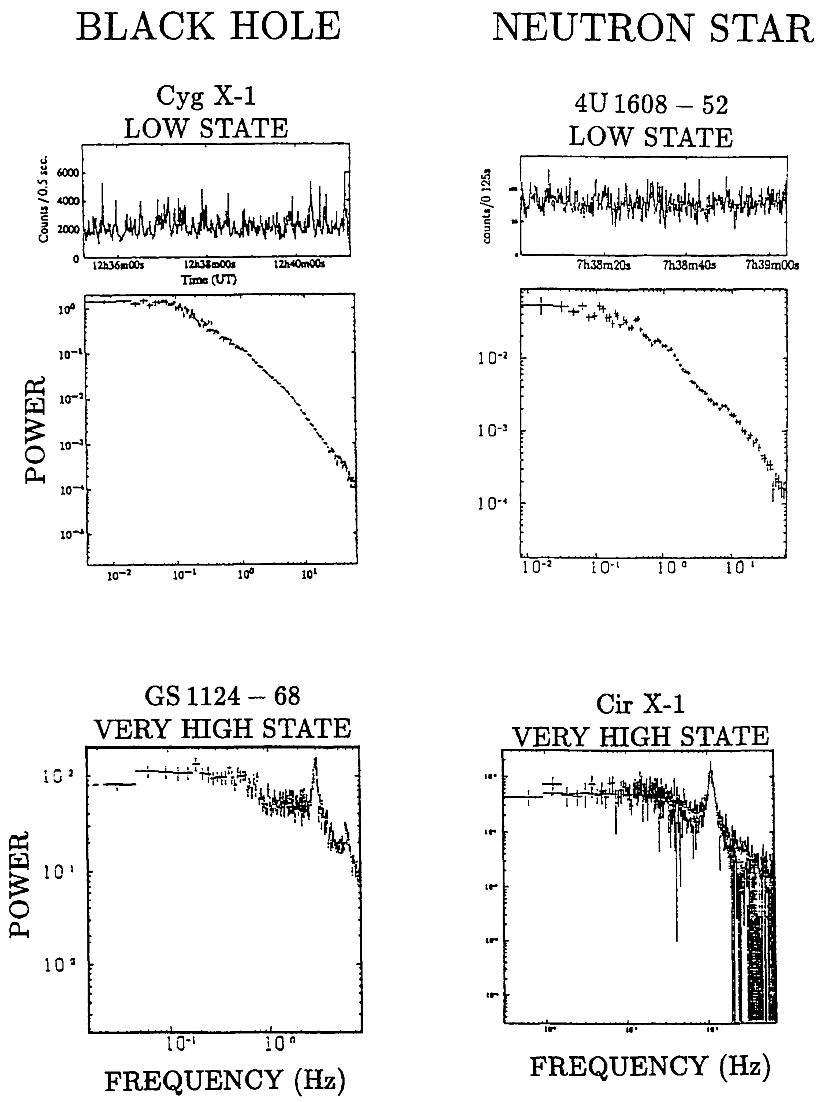
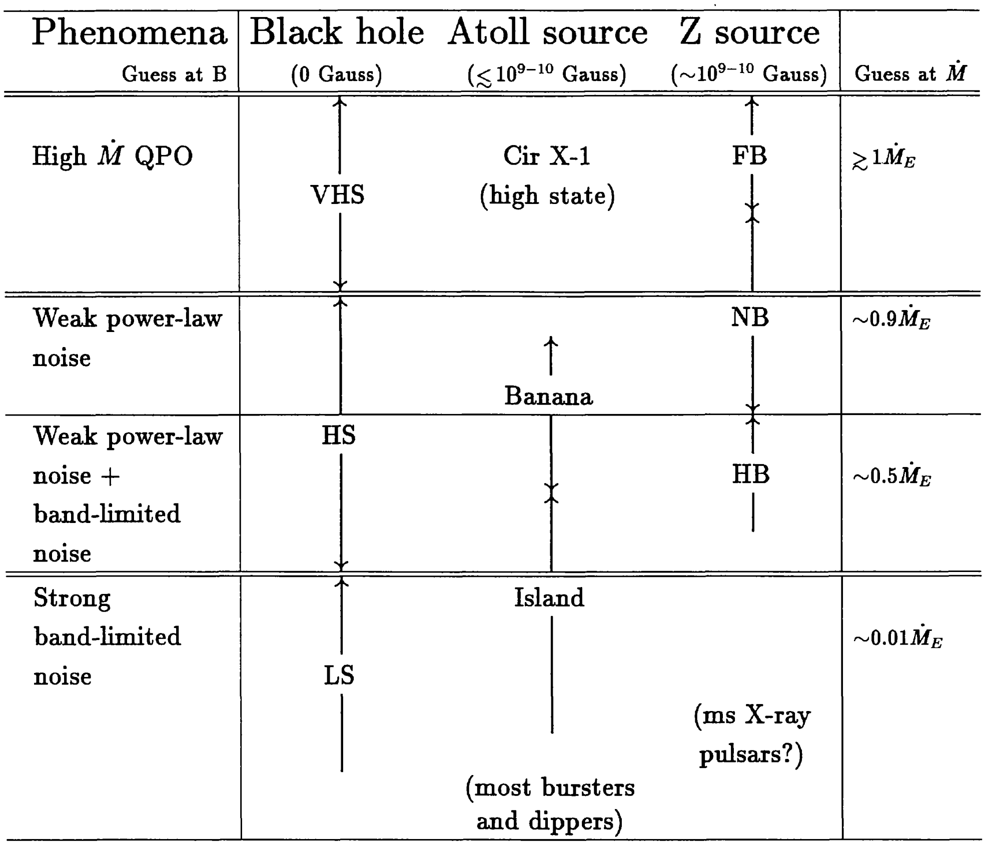


Figure 2. Power spectra from the black-hole candidates Cyg X-1 (*top left*) and GS 1124–68 (*bottom left*) in the low state and the very high state, respectively, and from the low magnetic-field neutron stars 4U 1608–52 (*top right*) and Cir X-1 (*bottom right*) in the atoll island state and a very high 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).

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



Phenomena Guess at B	Black hole (0 Gauss)	Atoll source ($\lesssim 10^{9-10}$ Gauss)	Z source ($\sim 10^{9-10}$ Gauss)	Guess at $\dot{M}$
High $\dot{M}$ QPO	VHS	Cir X-1 (high state)	FB	$\gtrsim 1\dot{M}_E$
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 (most bursters and dippers)	(ms X-ray pulsars?)	$\sim 0.01\dot{M}_E$

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

Figure 3. 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 might affect the $\dot{M}/\dot{M}_{\rm Edd}$ levels at which state transitions occur.

$\dot{M}$ 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. 3 presents a line-up of the three common states of black-hole candidates and low magnetic-field neutron stars.

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). If correct, then the amplitude of this noise is constrained by the ratio of nuclear burning to accretion energy (times a correction factor dependent on the wave form of the noise). For hydrogen, this is ~0.04; for helium only ~0.01. Note that 4U 1820−30, which is believed to accrete hydrogen-poor matter, sometimes shows VLFN with a strength of 4.5% (HK89), in apparent violation of this. The power law noise of black-hole candidates in the HS could not be caused by the same mechanism.

5. Inclination Effects

Detailed examination of the properties of Z sources, in particular in their flaring branches, has led Kuulkers & 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 for higher inclination i obscuration effects set in at lower $\dot{M}$. A similar model could explain some of the differences seen between black-hole candidates (Van der Klis 1994a). Some black-hole transients, such as GS 2023+338, show only a hard power-law X-ray spectral component, even when they are very bright, and in for example GX 339−4 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).

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, *e.g.*, a puffed-up accretion disk. For a pole-on viewing geometry no obscuration would occur and the system would show only the hard, rapidly variable X-ray spectral component at all $\dot{M}$ levels; this might explain the behaviour of GS 2023+338. 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 of GX 339−4 in its LS seems to be (at least 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. 4).

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 the black-hole candidates. Note, that the mass flux $\dot{M}$ that by hypothesis determines the state is that *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.

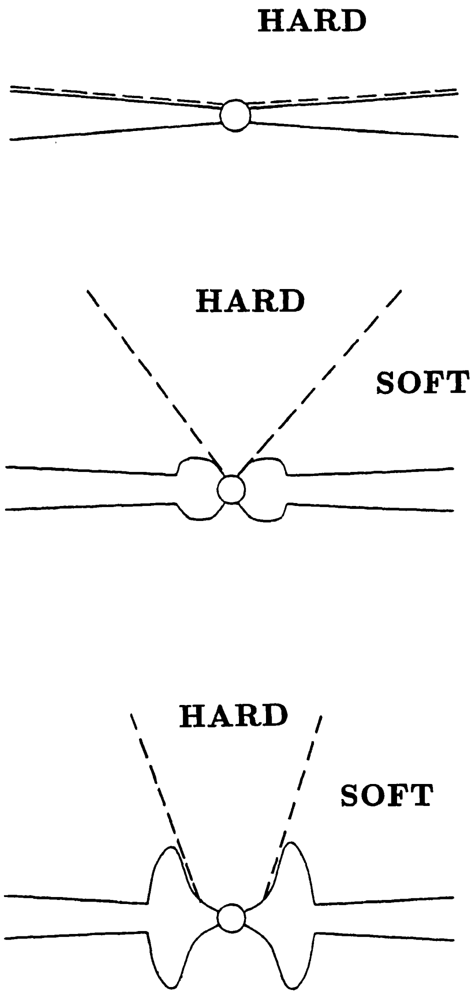


Figure 4. **A geometrically thick inner disk could obscure a central, hot and rapidly variable emitting region for observers at high inclination.**

6. Conclusion

A picture may be emerging in which 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). X-ray pulsars (not discussed here) have a magnetosphere and no inner disk and therefore show only an HBO-like and an HFN-like component, black holes and atoll sources 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.

Acknowledgements. This work was supported in part by the Netherlands Organization for Scientific Research (NWO) under grant PGS 78-277.

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Discussion

S.R. Kulkarni: 1.) The previous speaker (dr Nagase) mentioned that the orbital period change in the LMXB 4U 1820–30 to be 5 10^{-8} yr^{-1} and said you would be talking about this source. The recent determination of the center of NGC 664 and the position of the UV counterpart of 4U 1820–30 by HST (I. King et al. 1993, ApJ 413, L117) places the 4U-source within 0.6 arcsec of the cluster center. Thus all of the observed orbital periodicity can be attributed to the cluster potential.

2.) Recently, Bildsten wrote a paper (1993, ApJ 418, L21) attributing much of the LFN to incomplete burning on neutron star surface. If so, there should be considerable difference in the LFN features between LMXBs and black hole systems.

M. van der Klis: 1.) In our A&A Letter (1993, A&A 279, L21) on this source, we conclude that the variations in the shape of the light curve that we observe with ROSAT are just by themselves sufficient to explain most of the observed orbital phase changes. So, it seems we now have *two* independent ways to explain the period changes without requiring binary evolutionary efforts.

2.) Bildstens idea is that the VLFN (the power law that eliminates the power spectra at the lowest frequencies) is caused by nuclear burning, not the LFN. This is a very interesting thought and we are following up on this. The measurement of the VLFN is difficult, as it is sometimes too steep to measure with standard Fourier techniques, and also because on the relevant time scales ($>10^2$–10^3 s) the data often show gaps. However, at this stage it is already clear that black hole candidates *do* sometimes show VLFN-like power laws, which in the low state might be mashed by the presence of the strong shot noise component down to relatively low frequencies. A problem for the nuclear burning model might be the core of the atoll source 4U 1820–30. If this source is accreting H-depleted material, the energy available from nuclear burning may be too little to explain the observed VLFN amplitudes in that source.