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QUASI-PERIODIC OSCILLATIONS AND NOISE IN LOW-MASS X-RAY BINARIES

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1. INTRODUCTION

Power spectra of the X-ray intensity variations of low-mass X-ray binaries (LMXB) show dramatic changes in shape as a function of X-ray intensity and spectral hardness. At least five different power spectral components have now¹ been identified whose characteristics change in complex, but consistent, ways in correlation with other source parameters.

These power spectral variations are for the first time providing an observational handle on the bright LMXB, Galactic X-ray binary systems that, in spite of being the brightest and longest-known (25) extrasolar celestial X-ray sources, have long defied interpretation owing to a lack of diagnostic properties. An intricate phenomenology has been revealed, probably involving two different populations among bright LMXB, each having its own pattern of correlated X-ray/power spectral behavior. Comparative power spectral studies of other types of X-ray binaries inspired by and modeled on techniques developed for bright LMXB suggest links with “classical” accreting X-ray pulsars and black hole candidates.

The large amplitudes and short time scales of the observed intensity variations suggest that they are a diagnostic of the accretion process in the innermost regions of LMXB, close to the compact object. It seems likely

¹ This review was completed in November 1988, a few weeks after the Fifth Los Alamos Space Physics/Astrophysics Workshop “Quasi-Periodic Oscillations in Luminous Galactic X-Ray Sources” in Santa Fe, New Mexico.

that “power spectroscopy” of these sources, combined with X-ray spectral studies, is providing insight into such topics as neutron star magnetic field decay, disk-magnetosphere interaction, inner radiation-pressure-dominated accretion disks near the Eddington limit, and the evolutionary connection between LMXB and millisecond radio pulsars.

All power spectral components seen in bright LMXB are broad, which indicates aperiodic variability. Some exhibit a very wide power distribution over typically several decades in frequency; others form a more localized peak (see Figure 1). It is generally assumed (and there is evidence; see 136) that the variations underlying all of these power spectral components are stochastic, but only those with very wide power distributions are called “noise” components, whereas those causing peaks are called quasi-periodic oscillations (QPO). Note that this definition differs from the mathematical

Figure 1 Power spectra of the X-ray intensity variations of two bright LMXB. Note the presence of low-frequency noise in addition to the QPO peak in GX 5–1 and its absence in Sco X-1.

one (e.g. 19). The reason for a separate treatment of power spectral peaks is that with their well-defined preferred frequency (the peak centroid frequency), they are supposedly more amenable to interpretation than the noise components. Some components always form clear peaks; others are more ambiguous and only occasionally appear peaked. Thus, sometimes the choice as to what to call QPO and what to call noise is somewhat arbitrary. In this review I refer to QPO in the case of roughly symmetric peaks with widths not much exceeding their centroid frequencies, and to noise in all other cases. Noise of which the power spectrum monotonically decreases as a function of frequency is, in an obvious analogy, called “red noise.”

The occurrence of a broad power spectral component (QPO peak or otherwise) does not tell us what is the underlying signal or physical process. Therefore, QPO and noise could be caused by a variety of phenomena, and indeed observational evidence suggests that more than one process is at work. In spite of this, the X-ray intensity variations are discussed in terms of their power spectra; the reason is that photon counting statistics usually make the data too noisy, at the millisecond time scales most interesting in the context of stellar-mass compact objects, to observe the variations directly, and thus it is necessary to calculate the average power spectrum of large amounts of data in order to detect the signals.

The potential ambiguities inherent in this approach are illustrated by the confusion that arose when, after the discovery of QPO in GX 5–1, Sco X-1, and Cyg X-2 (see Section 1.3), attempts were made to explain all observed power spectral peaks in the same terms. In hindsight, we know that two qualitatively different QPO phenomena had been found in rapid succession, very likely requiring two entirely different explanations. The resolution of the puzzle came from an approach in which QPO properties were considered in relation to (a) other power spectral components and (b) X-ray spectral properties. This approach—to look for patterns of correlated power spectral and X-ray spectral behavior in order to remove ambiguities remaining when power spectra or X-ray spectra are considered in isolation—has proven to be a very powerful one, and its results have provided a large amount of new insight into LMXB phenomenology.

The QPO peaks that are the main subject of this review (Figure 1; Section 2) typically display the following characteristics:

- centroid frequencies between 5 and 60 Hz,
- peak widths of roughly half the centroid frequency,
- amplitudes between 1 and 10% of the total intensity,
- persistence for typically $> 10^5$ QPO cycles,
- recurrence.

Note that these characteristics, typical of QPO in persistently bright LMXB, may not explore the entire parameter space accessible to the underlying physical phenomena; see, in particular, Section 4 for a discussion of some (possibly closely) related power spectral peaks with properties that are somewhat different from the above.

The study of aperiodic variability in bright LMXB is a field that is very much in flux. In this review, I stress the general patterns of QPO phenomenology and attempts at understanding these patterns rather than detailed differences between individual sources and models for one single aspect of the observed behavior of QPO sources. A comprehensive review of the properties of QPO sources complete up to December 1987 is provided in (58). Discussions of early QPO models can be found in (48, 53), and methods of Fourier spectral analysis relevant to QPO sources are discussed in Chapter 2 of (58) and in (136). For earlier reviews on aspects of QPO sources and models, see also (30, 31, 104–106, 132–135).

1.1 *Signal Analysis Aspects of QPO and Noise*

Many different types of stochastic signals could in principle give rise to the power spectral components observed in LMXB (see, e.g., 136). The type of signal that on physical grounds has been by far the most popular in modeling X-ray binary power spectra in general is random shot noise (127; see also 110, and references therein), and this preference has propagated into the description of the recent results on QPO and noise (1, 2, 20, 21, 47, 50, 100–102).

Power-law red noise with a power spectrum $P(\nu)$ described by $P(\nu) = A\nu^{-\alpha}$, where ν is the frequency, α the power-law slope, and A a normalization constant, is often encountered in practice. Physically, to avoid infinite integrated power, when $\alpha > 1$ such a spectrum must turn over (become flat) below some frequency ν_{to} , and when $\alpha < 1$ it must break (become steeper) above some frequency ν_{break} . A shot-noise signal consisting of sharp-edged shots has a power-law spectrum with $\alpha = 2$ for large ν (128).

QPO spectra can be modeled with signals containing wave trains or “oscillating shots” (50, 143)—short-lived oscillations whose amplitude as well as frequency can vary during the lifetime of the shot (50). The width of the QPO peak is determined by both the range of frequency variation and the shot’s lifetime. An example of an oscillating shot is a signal of the form $I(t) = [A + B\cos(2\pi\nu_{\text{QPO}}t)]\exp(-t/\tau_{\text{decay}})$ ($t > 0$), where A and B are positive constants. For such a shot, oscillating with a constant frequency ν_{QPO} and decaying exponentially on a time scale τ_{decay} , the QPO peak has a Lorentzian shape centered on ν_{QPO} with a full width at half maximum of $\Delta\nu = 1/\pi\tau_{\text{decay}}$ (102). The coherence time of the QPO is usually defined as

$\tau_{\text{coh}} \equiv 1/\pi\Delta\nu$. It reflects frequency changes as well as the shot's lifetime. Unless oscillating shots are fine-tuned to have a zero mean [positive and negative contributions of the oscillation cancel out on time scales longer than $1/\nu_{\text{QPO}}$ (in our example, $A \equiv 0$)], they cause not only a QPO peak but also an associated red noise component, the shape of which is determined by the oscillating shot's envelope (in our example, an exponential). For random positive-definite shots ($B < A$), the integrated power in red noise and in QPO peak are similar (50).

The integrated power in a power spectral component is a measure of the variance of the underlying signal in the time series. This means that we can estimate the strength of the signal in terms of its root-mean-square (rms) deviation from the mean of the time series. Usually this "rms amplitude" is expressed as a fraction of the mean intensity. When the signal is not always present, the largest deviations from the mean that actually occur can be much larger than the measured rms amplitude.

The rules governing the detection of broad power spectral components are different from those in the case of coherent oscillations, such as from pulsars (see 58, 136). In particular, there is no advantage in using very high power spectral resolutions; in fact, spreading out the power of a broad feature over many power spectral resolution elements makes the feature harder to find (see 132), although formally its significance is not affected. Usually, advantage is taken of this by calculating many low-resolution power spectra of successive short data segments, which saves computing time and in addition allows the monitoring of spectral variations (143). The significance n_σ (in standard deviations) by which a broad feature stands out against the noise is given by $n_\sigma = \frac{1}{2}Ir^2(T/\Delta\nu)^{1/2}$, where I is the mean intensity, r the fractional rms amplitude, T the observing time, and $\Delta\nu$ the feature's width. This means that a small drop in r can be sufficient to make a very significant feature drop below the detection limit, so that observational reports of a power spectral component suddenly appearing or disappearing can well be consistent with only moderate variations in its strength.

1.2 *Low-Mass X-Ray Binaries and Millisecond Radio Pulsars*

Observationally, LMXB are distinguished from massive X-ray binaries (MXB) in a number of ways (see 55, 95, 146). LMXB are part of an older Galactic population than MXB (see also 16), usually lack the X-ray pulsations and eclipses often seen in MXB, show X-ray bursts (always absent in MXB), have soft X-ray spectra, and emit optical light dominated by an accretion disk rather than by a massive companion star. These differences are attributed to LMXB containing low-mass ($\lesssim 1 M_\odot$) rather

than massive ($\gtrsim 10 M_{\odot}$) mass-losing companion stars, which allows them to be on average older (usually $> 10^9$ yr) than MXB ($\lesssim 10^7$ yr) (e.g. 130); this in turn has allowed the magnetic field of the accreting neutron star to decay to values much below the 10^{12} – 10^{13} G believed to be characteristic of MXB (see 120). That neutron star surface magnetic field strengths decay on time scales of $\lesssim 10^7$ yr is suggested by observations of radio pulsars (see 43, and references therein). A few LMXB systems may contain a black hole rather than a neutron star (see 67).

The brightest LMXB tend to be located in the Galactic bulge and are less likely to show X-ray bursts than fainter ones (e.g. 156), but there is no evidence for a bimodal luminosity (150) nor, from existing sky surveys (69, 153, 154), for a bimodal *intensity* distribution. Table 1 lists the brightest LMXB in order of decreasing time-averaged X-ray intensity. Except for the black hole candidate GX 339–4, these sources are all “persistently bright” (9). Among the top ten sources in Table 1, eight are located in the Galactic bulge and only one (GX 3+1) has shown regular X-ray bursts, on one single occasion when its luminosity dropped considerably (62). It is among these ten brightest LMXB that most QPO have so far been found. None of them regularly shows X-ray bursts; “reliable” bursters are only found among the bottom eight in the list. The distances to the brightest LMXB are usually not well known, but as a group the X-ray luminosities of the “top ten” are of the order of the Eddington limit (1.5 – 3×10^{38} erg s $^{-1}$ for hydrogen accretion onto a 1 – $2 M_{\odot}$ neutron star).

The type of companion star may influence the average luminosity of a LMXB (119, 155). Main sequence companions transferring mass through Roche lobe overflow caused by orbital angular momentum loss induced by gravitational radiation and/or magnetic braking would provide low rates of mass transfer and would hence be found in less luminous LMXB. Companions evolving off the main sequence toward the giant branch could drive much larger mass transfer rates by their evolutionary expansion and produce highly luminous LMXB (see 149 for a review). If this is correct, then the most luminous sources should have long ($\gtrsim 10$ hr) orbital periods. This is not easy to check observationally. Fainter LMXB often show periodic X-ray dips (84) that reveal their orbital periods to be mostly below ~ 10 hr. However, the brightest LMXB do not show X-ray dips, and as most of them cannot be observed optically owing to their location in the bulge, the orbital period is not known. Two of the brightest LMXB located outside the bulge (Sco X-1 and Cyg X-2) have optically been found to have long orbital periods; GX 9+9 has a short period (see Table 1).

The low magnetic field strength of the neutron star in a LMXB allows the star to be spun up to millisecond rotation rates by the torques exerted by the accreting matter, and it is believed that radio pulsars with millisecond spin rates are produced through spin-up in binary systems (see 131 for a

Table 1 Bright low-mass X-ray binaries^a

Source name(s)	$l^{\text{II}}, b^{\text{II}}$ ($^{\circ}$)	I_x^b			P_{orb}^c (hr)	Type ^d	Phenomenology ^e
		Mean (μJy)	Min. (μJy)	Max. (μJy)			
Sco X-1 (1617–155)	359+24	12,400	9300	16,300	19.2	Z	QPO
GX 5–1 (1758–250)	5–1	1200	1070	1410	—	Z	QPO
GX 349+2 (1702–363) ^f	349+3	780	620	980	—	Z	QPO
GX 17+2 (1813–140)	16+1	680	600	780	19.8? ^g	Z	QPO, (bu)
GX 9+1 (1758–205)	9+1	650	550	720	—	A	—
GX 340+0 (1642–455)	340–0	490	400	620	—	Z	QPO
GX 3+1 (1744–265)	2+1	430	230	550	—	A	QPO, (Bu)
Cyg X-2 (2142+380)	87–11	430	290	730	235	Z	QPO, (bu), Mo
GX 13+1 (1811–171)	14+0	340	240	430	—	A	—
GX 9+9 (1728–169)	8+9	290	230	340	4.2	A	Mo
4U 1820–30 (NGC 6624)	3–8	260	94	360	0.2	A	QPO, (Bu), Mo
4U 1705–44	343–2	260	39	440	—	A	Bu
4U 1636–53	333–5	220	100	320	3.8	A	Bu
Ser X-1 (1837+049)	36+5	200	150	290	—	—	Bu
GCX-1 (1742–294)	0–0	170	130	270	—	—	Bu?
4U 1728–33	354–0	170	140	190	—	A	Bu
GX 339–4 (1659–487)	339–4	160	36	250	14.8?	—	QPO, BH? ^h
4U 1735–44	346–7	160	110	210	4.6	A	Bu

^a All variable objects in 3A Catalogue (69, 153) with an average flux $\geq 100 \mu\text{Jy}$ not identified with an early-type star (excluding Cyg X-3).

^b Converted from *Ariel V* ASM counts into μJy (2–11 keV) according to 1 ASM c/s = 2.6 μJy (9).

^c See (84).

^d Z or A(toll) source; see text. After (36).

^e QPO: all reported quasi-periodic oscillations are indicated here (see Section 3 for an evaluation of QPO reports in atoll sources); Bu: regular X-ray bursts; (Bu): has shown an episode of regular X-ray bursts; (bu): occasional X-ray bursts reported; BH?: black hole candidate, Mo: shows periodic X-ray modulation (9, 55, 64).

^f “Sco X-2.”

^g Reference: (37).

^h References: (77, 157).

review). Likely progenitors of some millisecond radio pulsars are LMXB containing an evolved companion star (see 131; the evolution of these systems may involve the accretion-induced collapse of a white dwarf into a neutron star). Millisecond radio pulsars have magnetic fields in the 10^8 – 10^{10} G range; however, in apparent conflict with an evolutionary connection, the magnetic field of an LMXB neutron star, decaying on the canonical time scale of $\lesssim 10^7$ yr, would be expected to drop much below these values within the system’s lifetime. It has been argued on various grounds [see 131 and (in particular) 43, and references therein] that neutron star magnetic field decay may “bottom out” at field strengths somewhere in the 10^8 – 10^{10} G range rather than continuing all the way to zero.

The related issues of magnetic field decay in accreting and nonaccreting neutron stars, neutron star formation, neutron star spin-up in LMXB, and the presence and possible observational consequences of evolved companion stars in LMXB are subjects of lively debate (see, e.g., 44). Direct observational information (neutron star surface fields and spin rates, evidence for different populations of LMXB) would help enormously in settling these issues, and consequently the observational diagnostic provided by QPO and noise could be useful here.

In MXB the magnetic field of the neutron star disrupts the accretion disk far ($\sim 10^8$ cm) above the surface; in LMXB, with their low magnetic field, the disk extends much farther down, and an “inner” radiation-pressure-dominated accretion disk can form (see 46, 160, and references therein for views of accretion disk–magnetic field interactions). For luminosities near the Eddington limit these inner disks are likely unstable (e.g. 94), and it is not clear from theory how they behave. Possibly the inner disk is puffed up by radiation pressure and forms a thick accretion torus; relativistic jets could form, maybe producing a triple radio source such as observed in Sco X-1 (38). Bright LMXB are a laboratory of inner-disk physics, and QPO likely are a direct diagnostic of what happens there. In Section 2.4.1 some attempts at interpreting QPO in these terms are described.

Perhaps the most fundamental reason why we would like to obtain information about the conditions in the inner regions of LMXB is that these sources provide us with a different view of neutron star physics. The neutron stars in LMXB probably have low magnetic field strengths, are the only neutron stars spinning at millisecond rates undergoing accretion torques, and [having accreted considerable amounts of matter (up to $0.8 M_{\odot}$; e.g. 120)] likely exceed the canonical mass of $1.4 M_{\odot}$ (in MXB; 95). In all of these aspects they differ from neutron stars in massive X-ray binaries, and observation of the consequences of these differences would help in our understanding of neutron star physics.

1.3 *History and Prehistory of QPO and Noise in LMXB*

Noise in the X-ray intensity variations of what we now call the persistently bright LMXB has been studied since the early days of X-ray astronomy, initially mainly in the extremely bright source Sco X-1 (54; see also 40, 79, 89) but later also in many other sources (see 23, 85, 90 for surveys; 8 for a review; also 110). However, after the discovery of the rapid variability in Cyg X-1 (82) and periodic X-ray pulsations in Cen X-3 (24), the bulk of the effort with respect to *stochastic* variations went to black hole candidate Cyg X-1 (see 60 for a review) and other “rapidly variable” sources believed to be related (but see also Section 4.3), such as Cir X-1

(Section 4.1.1), GX 339–4 (Section 4.3), and V0332+53 (see also Section 4.3); consequently, the persistently bright LMXB were somewhat neglected. It was not until after the discovery, with *EXOSAT*, of QPO and associated red noise from these sources that systematic power spectral studies of the *shape* of the noise components got underway.

Slow QPO, in the sense of broad power spectral peaks and/or recurrent flares in the 1–20 mHz range, were reported from a number of sources [~ 1 mHz in 4U 1626–67 (42, 59); 0.7–20 mHz in Cyg X-3 (138); 20 mHz in 4U 1820–30 (110); 5–10 mHz in GX 349+2 (66; see also 77)]. In some cases these reported oscillations may have been the result of chance occurrences in a (red) noise signal (127). It seems unlikely that they are related to the QPO that are the main subject of this review, although this possibility cannot yet be totally excluded. Slow QPO have recently also been reported from LMC X-1 (see Section 4.3).

Short oscillation trains during or near several Type I (thermonuclear flash; see 55) X-ray bursts have been reported [36 Hz (65); 82 Hz (96); 1.5 Hz (78); 7.6 Hz (R. L. Kelley²)]. The unique character of these oscillation events makes comparison with QPO seen in the persistently bright LMXB difficult; “Type I burst QPO” usually are more coherent.

Oscillations with a frequency of ~ 2 Hz were seen by Tawara et al. (122) during two flat-topped Type II (accretion event; see 55) X-ray bursts in the peculiar “Rapid Burster” (Section 4.1.2). The frequency of the QPO differed between the bursts and drifted within each burst, so it was concluded that they could not be a direct manifestation of neutron star rotation. The relation of Rapid-Burster QPO to QPO in persistently bright LMXB is not clear. In general, Rapid Burster QPO are more coherent and less persistent. It has been argued on the basis of later extensive *EXOSAT* studies (108, 109; see Section 4.1.2) that a relation [with “normal branch” QPO (see Section 2.3)] exists.

In 1985 it was announced that 20–36 Hz QPO and associated red noise, designated “low-frequency noise” (LFN), had unexpectedly been observed from GX 5–1 during a search with *EXOSAT* for periodic millisecond pulsations; the QPO frequency was strongly correlated with X-ray intensity (140, 143). Alpar & Shaham (3, 4) proposed that these QPO were caused by an interaction between a rapidly spinning neutron star’s magnetic field and matter circulating in an accretion disk, the characteristic frequency of this interaction being the beat frequency between the Keplerian frequency at the disk’s inner edge and the star’s spin frequency.³ They pointed out

² Paper presented at Santa Fe Workshop (see Note 1).

³ A similar idea had been considered previously for QPO in cataclysmic variables (86; see also 152). Apart from some very general considerations (143), research on LMXB QPO has not benefited much from the earlier cataclysmic variable work. QPO in these accreting white dwarf systems appear to be even more complex than in LMXB.

that spin rate and magnetic field strength derived in this “beat-frequency” model (Section 2.4.1) fitted with the idea that bright LMXB evolve into millisecond radio pulsars (Section 1.2). Modulation of the accretion rate through magnetic gating was proposed as a feasible mechanism for causing the X-ray intensity variations, and it was shown that the observed red noise was a natural consequence of this accretion-modulation mechanism (50).

However, QPO discovered subsequently from Sco X-1 by Middleditch & Friedhorsky (70, 71) had quite different properties.⁴ Their frequency was sometimes low (near 6 Hz) and approximately constant or even slightly anticorrelated with X-ray intensity (71); at other times it was high (between 10 and 20 Hz) and either positively correlated or varying erratically as a function of X-ray intensity, depending on the source state (144). Red noise was weak as compared with the QPO (71, 139). Both results seemed to pose a problem for the beat-frequency model.

In a third source, Cyg X-2, QPO were discovered (33, 34) with very similar properties to GX 5–1, but further QPO observations [Cyg X-2 (80, 81); GX 349+2 (14, 57); GX 17+2 (111); Rapid Burster (113); 4U 1820–30 (115)] presented a confused picture. Stella (104) proposed, based on the analogy with the QPO in Sco X-1, to distinguish between “low-frequency” (< 10 Hz), “high-frequency” (> 10 Hz), and “erratic” QPO, having, respectively, a negative (or no), a strongly positive, and an erratic frequency-intensity correlation.

The observational situation was rather bewildering at this point, as a large variety of behavior seemed possible for the QPO phenomenon. As the beat-frequency model was unable to explain everything observed, alternative QPO models were being considered (7, 26, 68, 76, 145), and ways were worked out to broaden the range of phenomena that could be explained within the modulated-accretion beat-frequency model (1, 2, 10, 20, 98, 102, 118).

Progress in unraveling the complex QPO phenomenology came from comparing power spectral and X-ray spectral data and from paying attention to the noise components in addition to the QPO peaks. Three of the newly discovered QPO sources were known to exhibit two different X-ray spectral states (11, 103, 158), distinguishable as branches in an X-ray hardness vs. intensity plot, and *EXOSAT* observations confirmed this (Figure 2). For Sco X-1, the suspicion that QPO properties might be

⁴ As a historical aside, the first observed consequence of the 6-Hz QPO in Sco X-1 may have been the transient narrow power spectral spikes in the 1–10 Hz range reported in 1971 by Angel et al. (5). These were likely statistical fluctuations pushed over the detection limit by the increased average power in the broad QPO peak, which remained unnoticed.

Figure 2 Spectral branches in X-ray spectral hardness vs. intensity diagrams. QPO frequencies in each branch are indicated. After Priedhorsky et al. (93) and Hasinger (28).

related to these X-ray spectral states arose during the initial discoveries and crystallized at the 1985 Workshop on X-ray Time Variability in Taos, New Mexico, when comparing the apparently conflicting data on the source (71, 72, 139, 144). Further work on GX 5–1 and Sco X-1 (93, 141, 142; this work was discussed at the 1985 Cambridge Discussion Meeting on *EXOSAT* Results) and on Cyg X-2 (29, 32) showed conclusively that QPO modes and X-ray spectral states were strongly correlated. The red noise in GX 5–1 was shown to consist of two components: the above-

mentioned LFN, which only appeared in the spectral state where the intensity-dependent QPO were seen; and a second, power-law component dominating at frequencies below 0.01–1 Hz that was seen in all states, independent of the QPO, and was designated “very low frequency noise” (VLFN; 142). It was noted that the red noise in Sco X-1 seemed to contain no LFN but apparently only VLFN. [After the first reports on QPO, an extensive study of the red noise in a number of sources was made by Makishima (61); it referred mostly to this VLFN, as it dealt with frequencies below ~ 1 Hz.]

However, the situation was still confusing. True, bimodal patterns of QPO and X-ray spectral behavior were observed in GX 5–1, Cyg X-2, and Sco X-1, with high-frequency, intensity-dependent QPO in one spectral state and ~ 6 -Hz (nearly) intensity-independent QPO in the other, but Sco X-1 did not fit in with the other two sources. Its X-ray spectral hardness vs. intensity diagram was different (Figure 2), and LFN was absent even when intensity-dependent QPO appeared. The proposed classification of Stella (104), which combined the high-frequency QPO of GX 5–1 and Cyg X-2 with those of Sco X-1 into one class, was criticized on these grounds (132, 142).

The resolution of the puzzle came from Hasinger (28), who, on the basis of the data summarized in Figure 2 and using the ~ 6 -Hz QPO seen in all three sources as the main clue, proposed that the behavior of the QPO sources was in fact *trimodal* and characterized by a Z-shaped pattern in the X-ray hardness vs. intensity diagram, of which we had been seeing the upper half in GX 5–1 and Cyg X-2 and the lower half in Sco X-1. Furthermore, he noted that each of the three branches of the Z had its own characteristic power spectral behavior. These conjectures were beautifully confirmed from further observations, and the class of the “Z sources” is now very well established (see Section 2).

With this clarification of the phenomenology, modeling QPO became a more feasible task. Attempts to explain all observed QPO behavior within the framework of the modulated-accretion magnetospheric beat-frequency model, which had been criticized for being unconvincing (53, 109, 132–134, 142) were abandoned, and the model became the dominant one for the phenomenon it had been conceived for: the intensity-dependent high-frequency QPO and associated LFN originally found in GX 5–1 and later also observed in other sources (Section 2.2).

Millisecond time lags were discovered in these high-frequency QPO signals between X-ray spectral bands (29, 134, 137), suggesting that the X-rays were Compton scattered in a hot plasma before emerging from the vicinity of the neutron star. This was in line with earlier suspicions (159, and references therein) based on the shape of the X-ray spectrum. This

result was pleasing, as the temporal smearing caused by such a scattering process had been quoted earlier as one of the possible reasons why periodic pulsations were not observed from these rapidly rotating magnetic neutron stars (50). The problem of accounting for the effect of the scattering on QPO and (hypothetical) beamed pulsar radiation stimulated a great deal of theoretical effort (10, 12, 45, 100, 151). The suggestion from the beat-frequency model that the magnetosphere was very small in these systems (tens of kilometers in radius, rather than thousands as in the accreting pulsars) stimulated a reassessment of magnetospheric theories, and it was pointed out that magnetospheric formation might be qualitatively different in these systems from that in massive X-ray binaries, as for such a small magnetosphere the magnetospheric boundary was located in the radiation-pressure-dominated part of the disk (160).

Further observations produced further puzzles, such as sources that should have shown QPO according to the Z scheme but did not (56, 87), and persistently bright LMXB that exhibited QPO with properties that did not seem to fit well into the scheme (17, 51, 52, 116). Recently, it was proposed (36) that in addition to the Z sources, there exists a second class of slightly fainter bright LMXB, including some of the brightest nonbursting LMXB as well as some bright X-ray burst sources (see Table 1; Section 3), that shows another pattern of correlated X-ray spectral and power spectral behavior. It was argued that these so-called atoll sources do not exhibit QPO similar to those seen in the Z sources. All persistently bright LMXB may be classifiable as either a Z or an atoll source; however, some peculiar LMXB that are not persistently bright (Section 4.1) exhibit different QPO properties.

Recent power spectral studies of other types of X-ray binaries have produced interesting results. In two accreting X-ray pulsars (Section 4.2) (A. Tennant, see Note 2; L. Angelini, see Note 2) QPO peaks were detected at frequencies consistent with the magnetospheric beat-frequency model (but other models are also possible), noise components in accreting pulsars were found to be very strong but otherwise quite similar to those in LMXB (T. Belloni, see Note 2), and QPO were detected with the *Ginga* satellite from two black hole candidates (18, 63; Section 4.3).

2. THE Z SOURCES

The Z sources are named after the pattern (Figure 3, *top*) they trace out, when varying, in an X-ray hardness vs. intensity ($H-I$) or X-ray color-color diagram. Recently, the use of the color-color diagrams, in which two different measures for X-ray spectral hardness are used (83, 157) has been preferred, as in these diagrams the source tracks are more repeatable

Figure 3 Z source behavior. X-ray color-color diagrams (*top*) are roughly Z shaped; horizontal branch (HB), normal branch (NB), and flaring branch (FB) are indicated. Note the difference in slope of the HB between the two sources. Power spectra (*bottom*) of the X-ray intensity variations refer to HB, NB, and FB (downward), respectively. Various power spectral components are indicated (see Section 2); note the difference in shape of the LFN. After Hasinger & van der Klis (36).

(29, 97). The three branches in the Z correspond to three distinct X-ray spectral/power spectral states. The upper branch is named the “horizontal branch” (HB; 103), the middle one the “normal branch” [NB (61); the positive $H-I$ correlation in this branch was considered “normal” as opposed to the more exceptional HB behavior], and the lower one the “flaring branch” [FB (28), after the flaring shown by Sco X-1 in this branch]. This terminology is not particularly appropriate to the phenomenology as known today; whether the HB is really horizontal depends on source and spectral band, NB behavior is not more common than HB

or FB behavior, and in the FB some sources' intensity actually *decreases* rather than flares [Cyg X-2 (30, 97); GX 340+0 (W. Penninx, see Note 2)]. However, the names are generally used, and therefore I shall employ them here as well.

Figure 3 (*top*) shows two examples of the color-color diagrams of Z sources. Note that the HB is well developed and really horizontal in Cyg X-2 (*left*) and short and almost vertical in GX 17+2 (*right*). The sources always follow the Z (11, 97, 103); they do not “jump” between branches. Typically, sources move up and down irregularly in a given branch or around the HB-NB or NB-FB transition point for hours to days before transitioning to another section of the Z (31, 72, 93, 97, 145). There is no evidence that a source spends more time in a particular section of the Z. The parameter varying along the Z is most likely the accretion rate $\dot{M}$, but there is no direct evidence for this, nor for the sense in which $\dot{M}$ varies (see Section 2.4). Optical, UV, and radio emission correlate to X-ray spectral state [see 79 (and references therein), 88; G. Hasinger, see Note 2).

On each branch the power spectra show characteristic structures (Figure 3, *bottom*), discussed in detail below. A total of six power spectral components has been detected. Two (“very low frequency noise” and “high-frequency noise”) occur in all three spectral branches. These universal components are discussed in Section 2.1. In Section 2.2, horizontal branch QPO (HB-QPO) and the associated LFN are discussed. These components are strongest in the HB but have also been reported from the NB. Section 2.3 deals with normal branch QPO and flaring branch QPO (NB-QPO and FB-QPO). These two components clearly differ, but there is strong evidence that they are in fact manifestations of the same phenomenon. Universally *absent*, up to now, have been periodic pulsations. Upper limits of fractions of a percent have been obtained (58, and references therein; see also 35).

Table 2 lists the six sources that show Z behavior. References listed there are not repeated below when parameter ranges are quoted. For five of the sources, the Z character seems indisputable in that at least two branches together with the associated power spectral behavior have been observed; the sixth (GX 349+2) has so far only been observed in the FB and in the lowest portion of the NB. Table 3 lists typical power spectral properties of these sources.

2.1 Universal Noise Components: VLFN and HFN

VLFN (“very low frequency noise”; 142) and HFN (“high-frequency noise”; 36) are detected in all three branches (35, 36, 145), with no clear variations in strength or shape as a function of position in the Z. Com-

Table 2 Evidence for Z behavior^a

Source	Any branch			Horizontal branch			Normal branch		Flaring branch			References
	VLFN	HFN	Branch ^b	QPO	LFN	Branch ^b	QPO	Branch ^b	QPO	Branch ^b	QPO	
GX 17+2	•	•	•	•	•	•	•	•	•	•	•	36, 51, 87a, 88, 112
GX 340+0	•	•	•	•	•	•	•	•	•	•	—	36, 147 ^c
Cyg X-2	•	•	•	•	•	•	•	•	•	•	—	17, 27, 29, 33, 36, 73, 81, 107, 137
Sco X-1	•	•	•	—	•	•	•	•	•	•	•	35, 36, 71, 93, 145
GX 5-1	•	•	•	•	•	•	•	•	•	—	—	17, 22, 36, 74, 137, 142, 143
GX 349+2	•	•	—	—	—	•	— ^d	•	— ^d	•	— ^d	36, 91

^a •: detected; —: not detected.
^b Refers to detection of spectral branch in X-ray hardness-intensity or color-color diagram.
^c W. Penninx (see Note 2).
^d Very broad peaks were reported (36, 91).

Table 3 Power spectral properties of Z sources^a

Component	Shape	Strength ^b (rms)	Other properties		Time lags
<i>All branches</i>					
VLFN	Power law ^c	0.5–3%	α	1.5–2	
HFN	Cutoff power law ^d	1.5–4%	ν_{cut}	40–80 Hz	
<i>HB</i>					
LFN	Cutoff power law ^d	3–4%	α	−1 to +0.3	
			ν_{cut}	5–10 Hz ⁱ	10-ms soft lags
QPO	Lorentz ^e	2–7%	ν_{QPO}	15–55 Hz ^f	4-ms hard lags
<i>NB</i>					
QPO	Lorentz ^e	1–5%	ν_{QPO}	5–7 Hz ^g	150° hard lags
<i>FB</i>					
QPO	Lorentz ^e	? ^h	ν_{QPO}	10–20 Hz ^f	

^a Typical values. See Table 2 for references.^b $\sim (1\text{--}20 \text{ keV})$.^c $\nu^{-\alpha}$.^d $\nu^{-\alpha} e^{-\nu/\nu_{\text{cut}}}$.^e $[(\nu - \nu_{\text{QPO}})^2 - (\Delta\nu/2)^2]^{-1}$.^f Strongly correlated with position in spectral branch.^g Approximately constant.^h Only reported in 5–35 keV range in Sco X-1, then 5–10% (rms) (93, 145).ⁱ 1–2 Hz for $\alpha < 0$ (peaked LFN).

ponents of similar shape are also seen in atoll sources (Section 3) and even in accreting pulsars (Section 4.2) and black hole candidates (Section 4.3).

VLFN is a power-law component with a total strength of a few percent, usually dominating the power spectra below 0.01–0.1 Hz. It has mostly been studied at frequencies above 1 mHz, and therefore it is not yet clear whether it can be identified with the well-known variability of bright LMXB on time scales of hours to days (23, 85, 90). No evidence for a turnover has been reported. VLFN power-law slopes have been reported between 1.2 and 2.3. It is likely that both the lowest and the highest values in this range are unreliable. Some of the lower values were derived from power spectra not extending to sufficiently low frequencies or from analyses not properly distinguishing between VLFN and other components; the highest values may have suffered from low-frequency leakage (see 16a).

HFN has a shape that can be described as a flat power law with an exponential cutoff: $P(\nu) = \nu^{-\alpha} \exp(-\nu/\nu_{\text{cut}})$. A similar shape usually fits the LFN component in the HB (Section 2.2), but in HFN the cutoff frequency is higher: 25 to > 100 Hz. The distinction between HFN and LFN becomes apparent in the HB, where both components are sometimes detected simultaneously (35, 36). Strengths between 1.6 and 8% (rms) have been reported; a similar component in atoll sources and accreting pulsars can be considerably stronger (Sections 3 and 4.2).

2.2 *The Horizontal Branch: QPO and LFN*

Among the five sources exhibiting a HB in their X-ray color-color diagram, four have shown intensity-dependent QPO. [The exception is Sco X-1, whose HB is least developed (35).] The total observed QPO frequency range is 15–55 Hz, with some variation from source to source. QPO frequency ν_{QPO} and X-ray intensity I_x are strongly positively correlated; their relation is consistent with being either linear or a power law (Figure 4). Power-law slopes $-(d \log \nu_{\text{QPO}} / d \log I_x)$ of between 0.8 and 2 have been reported. [The slope of 4 quoted in (112) is defined differently.] Obviously, this result depends on the X-ray spectral band (here roughly 1–20 keV) and interstellar absorption. In view of the difficulties in finding the correct model for the X-ray spectra, not much work has been done yet in relating HB-QPO frequency to physically meaningful X-ray spectral components (see, however, 27, 33) or even X-ray luminosity. In all cases, QPO frequency increases along the HB toward the NB.

HB-QPO peaks fit to Lorentzian or Gaussian shapes; the quality of the data usually is not sufficient to strongly reject either of the two [or more complex shapes (20, 101, 102; see, however, 73)]. Determining the precise shape of the peak is complicated by its variations with intensity. The relative peak widths ($\Delta \nu / \nu_{\text{QPO}}$) are between 0.12 and 0.4, implying coherence times of 2.6 to only 0.8 cycles (see Section 1.1). No clear relation between peak width and HB-QPO frequency applying to all sources has been established.

Fractional rms amplitudes between 2 and 6.5% (1–20 keV) have been reported for HB-QPO, where the lower limit is probably set by observational limitations. In GX 5–1 and Cyg X-2 there is a tendency for fractional amplitude to drop as a function of frequency (and intensity; 33,

Figure 4 HB-QPO frequency vs. X-ray intensity in GX 5–1. After van der Klis et al. (143).

143), while in absolute terms, QPO amplitude has a maximum halfway across the HB.

Possible second harmonics to the main HB-QPO peak, indicating non-sinusoidal oscillation profiles, have been reported (29, 74, 107, 112; W. Penninx, see Note 2). They are relatively weak and not much is known about them.

LFN is seen in all sources when they are in the HB. Its shape has been described with an exponential (13, 33, 143), which fits well only at frequencies above ~ 1 Hz, and with power laws (107) and Lorentzians centered on zero frequency (22, 74, 112). However, over a wide frequency range, a flat power law with an exponential cutoff (similar to that used for HFN) usually provides better fits (28, 36). Cutoff frequencies (and the roughly equivalent Lorentzian half-widths) vary between 5 and 15 Hz. LFN is not always “red” (monotonic); sometimes it shows a broad peak [e.g. in GX 17+2 (51; Figure 3, *bottom right*) and Sco X-1 (35)]. In a cutoff power-law description, this LFN shape is accommodated by allowing ascending power laws (36). There seems to be a correlation between peak LFN shapes, low HB-QPO amplitudes, and short, vertical HBs (36).

The LFN strength is similar to that of HB-QPO, with their rms amplitude ratio (LFN/QPO) in the range 1–2. In GX 5–1, LFN and HB-QPO strength go up and down hand in hand; their ratio remains close to 1 (143). In Cyg X-2, HB-QPO and LFN strength are anticorrelated (33). On time scales of seconds, HB-QPO and LFN strength in GX 5–1 may vary more or less independently (J. Norris, see Note 2).

Not much detail has emerged as yet about the X-ray *spectrum* of HB-QPO and LFN, other than that it is harder than that of the time-averaged flux (29, 132; K. Mitsuda, see Note 2).

Time lags of up to 4 ms exist in the HB-QPO of Cyg X-2 (29, 137) and GX 5–1 (73, 134, 137) between very roughly the 1–6 and 6–20 keV bands. (Hard X rays lag the soft ones.) Cross-spectral analysis allows the measurement of time lag as a function of frequency and shows that this “hard lag” is a property of the HB-QPO only; in the LFN, *soft* lags are seen (137). It is not clear yet how the time lags depend on frequency inside each of the broad power spectral components. In Cyg X-2 time lag and oscillation frequency are anticorrelated (29, 74, 137). No measurements were reported of the dependence of time lag on photon energy.

HB-NB transitions involve only minor changes in X-ray intensity and spectrum but are quite spectacular in the power spectra: In particular the LFN appears and disappears very suddenly (within 100–200 s; 31) when the source changes state. HB-QPO have been reported to persist together with NB-QPO in Cyg X-2 (73, 81). As state changes can be rapid, confusion between branches could occur. However, recent work (G. Hasinger, see

Note 2 and personal communication) makes it likely that HB-QPO indeed occur in the NB together with NB-QPO.

2.3 Normal and Flaring Branch QPO

QPO in the NB with frequencies between 5 and 7 Hz have been reported from all five Z sources that have shown a full NB in the color-color diagram. Very broad peaks near 6 Hz have also been seen in GX 349+2 (91). (QPO in the 4–8 Hz range reported from other source types may or may not be similar; see Sections 3 and 4.) In Cyg X-2, GX 5–1, and GX 340+0, NB-QPO are only seen in the middle of the NB (29, 73, 147). In Sco X-1, QPO are absent in the upper part of the NB (35), appear in the middle of it, and persist all the way into the FB. Reported NB-QPO relative peak widths are usually between 0.2 and 0.6, but wider peaks are also seen (91, 112). No higher harmonics to the main peak were reported.

QPO frequency ν_{QPO} varies only a small amount in the NB. In Sco X-1 a slight increase (by $<10\%$; 71, 145) is observed along the NB in the direction of the FB; the X-ray intensity I_x decreases in the NB in this direction, and therefore ν_{QPO} and I_x are here anticorrelated.

In Sco X-1, ν_{QPO} gradually increases from ~ 6 to ~ 10 Hz when the source moves from the NB through the NB-FB transition region (Figure 5). In the FB, ν_{QPO} varies strongly between 10 and 20 Hz correlated with position of the source in the branch (higher frequency as the source moves “up” the FB away from the NB; see Figure 2). Because intensity increases up the FB, ν_{QPO} correlates positively with I_x here. Up the FB, the QPO peak becomes wider and finally dissolves into the HFN (35; see also 71).

Figure 5 Dynamic power spectrum (*top*; darker pixels indicate higher power) and X-ray light curve (*bottom*) of Sco X-1 exhibiting NB-FB behavior. A gradual transition between FB-QPO (~ 20 Hz) and NB-QPO (~ 6 Hz) is observed near 18:15 UT. After Priedhorsky et al. (145).

In a description of the X-ray spectrum in terms of two spectral components [a “blackbody” and a “Comptonized” one (see 161)], it was found that ν_{QPO} in the NB and FB jointly relate approximately linearly with the luminosity of the blackbody component (145). FB-QPO with intensity-correlated frequencies up to 20 Hz have recently also been seen from GX 17+2 (W. Penninx, see Note 2); from the same FB observation, an additional peak near 125 Hz was reported (see also Section 4.1.1).

An X-ray spectrum of NB-QPO in Cyg X-2 was reported by Mitsuda (73, 75; Figure 6, *top*). The fractional QPO amplitude reaches a minimum near 6 keV. This observation reconciles earlier reports about NB-QPO being soft in Cyg X-2 in the 1–6 keV band (29) and hard in Sco X-1 between 1 and 35 keV (93, 145). Large time delays of up to 80 ms occur in Cyg X-2 between QPO in spectral bands above and below 6 keV (hard photons lag the soft ones by $\sim 150^\circ$, or precede them by 210° in phase; 73, 75). The time lag spectrum shows a large jump between 5 and 10 keV (Figure 6, *bottom*).

2.4 Understanding the Z Sources

2.4.1 PHENOMENOLOGY Sufficient data have been accumulated for some general patterns in the properties of Z sources to become evident.

HB-QPO are qualitatively different from NB-QPO. In the HB, QPO frequency is high and strongly correlated with position in the branch (and hence with intensity); in the NB, it is low and hardly varies. In the HB, there is a strong noise component (LFN) associated with the QPO. NB-QPO have no such associated component, which implies a different shape for the signal underlying the power spectrum. There is a discontinuous change in QPO frequency when moving from the HB into the NB: from high and rising up to ~ 55 Hz in the HB to low and approximately constant

Figure 6 Relative amplitude (*top*) and time lag (*bottom*) spectra of the NB-QPO in Cyg X-2. A large discontinuity in the time lag spectra near 6 keV coincides with a minimum in relative amplitude. After Mitsuda (73).

at ~ 6 Hz in the NB. HB-QPO may persist into the NB and coexist with NB-QPO—this confirms that they are different phenomena.

The FB-QPO, on the other hand, are probably the same phenomenon as NB-QPO, even though their frequency (like that of HB-QPO) is higher than in the NB and strongly correlated with position in the branch. The main argument for identifying them is that gradual transitions between them are observed in Sco X-1 (Figure 5). A secondary argument is that no LFN is observed in association with either of them.

For these reasons, it is now nearly universally accepted that we are dealing with two physically distinct phenomena: HB-QPO/LFN and NB/FB-QPO (but see 106). Observations provide a number of direct clues to the nature of each of these two types of rapid time variability.

In the HB, the simultaneous presence of QPO and LFN fits in with oscillating-shot models (Section 1.1) in which the shots are positive definite. The “hard” millisecond time lag in HB-QPO could be caused by a simple time shift between hard and soft signals (e.g. caused by Comptonization; see below), whereas X-ray spectral softening during a shot could cause the simultaneous soft lag in the LFN (22, 135, 137).

In the NB the fractional amplitude spectrum of the QPO has a minimum in the 5–10 keV range, and there is a phase lag of close to half a cycle between NB-QPO below 5 keV and above 10 keV (Figure 6). This suggests that NB-QPO can be described in terms of “rocking” of the X-ray spectrum around a pivot point in the 5–10 keV range (49; see, however, 73 for a different interpretation). When the high-energy end of the spectrum goes up, nearly simultaneously the low-energy end goes down, and vice versa, causing larger QPO amplitudes at high and low energies than near the pivot point and a large phase shift between high and low energy QPO (as observed). The absence of red noise implies that this rocking occurs symmetrically around an equilibrium position (see Section 1.1).

Much attention has been given to the relation of QPO frequency ν_{QPO} with X-ray intensity I_x . However, if the parameter varying along the Z is accretion rate $\dot{M}$, then clearly I_x is not proportional to $\dot{M}$, and thus the correlation of ν_{QPO} with position in the Z seems more relevant. In some sources [Cyg X-2 (30); GX 340+0 (W. Penninx, see Note 2)], X-ray intensity begins to decrease when the source moves up the FB. In such a case, one predicts ν_{QPO} to strongly *anticorrelate* with X-ray intensity. However, no FB-QPO have been reported from these sources yet.

2.4.2 MODEL SCENARIOS Attempts to model the geometry of the emitting regions in bright LMXB using their X-ray spectrum only have been inconclusive. Two-component spectral models have been discussed (161, and references therein), but no universally accepted physical model has

emerged. The recognition of the Z sources as a separate class, as well as the additional constraint provided by their rapid temporal variations, may make modeling these sources a more hopeful enterprise. Recently, attempts were begun to provide scenarios for the entire Z behavior (31, 49). Quantitative modeling within the framework of such scenarios has started (49). In the following, I sketch some considerations relevant to such scenario building.

Considering Z phenomenology, the key questions seem to be the following: What drives source motion through the Z? What happens at the branch transitions? What causes HB-QPO/LFN and NB/FB-QPO? Answering these questions likely entails resolving the older problem of explaining the color-color diagrams in terms of X-ray spectral models.

As a model for HB-QPO/LFN, the modulated-accretion magnetospheric beat-frequency model (4, 50) stands strong. In this model, plasma in near-Keplerian orbits at the inner edge of an accretion disk interacts with a neutron star magnetosphere. Plasma inhomogeneities ("clumps") enter the magnetosphere more readily at some point(s) (e.g. near the magnetic poles) than at others. As the magnetosphere spins (with the star) at a rate ν_s , a given clump in the plasma, circulating with a frequency ν_K , will periodically pass by a given point of easier entry into the magnetosphere with a frequency $\nu_B = |\nu_K - \nu_s|$ (the beat frequency between Keplerian disk and neutron star spin frequencies). The clump's accretion, modulated at ν_B by its interaction with the field, contributes an oscillating shot (Section 1.1) to the X-ray intensity I_x ; the time it takes for the clump to accrete corresponds to the duration of the shot, the oscillation frequency ν_B is the QPO frequency, and because the shots are positive-definite, QPO and LFN strength are predicted to be similar (Section 1.1; this is also why the model is hard to apply to NB/FB-QPO).

The magnetosphere is defined as the region where the Keplerian disk flow is disrupted and the plasma is forced to corotate. Its radius r_M is determined by a balance between material and magnetic stresses originating in accreting plasma and magnetic field, respectively. In most models (see 46, 160; and references therein) the magnetosphere is quite "stiff," so that the change of r_M in response to variations in $\dot{M}$ is small. The fact that ν_{QPO} varies by factors of 2 or 3 whereas $\dot{M}$ likely only varies by factors of order unity, too (the sources remain at luminosities of the order of the Eddington luminosity L_{Edd}), then suggests that ν_s and ν_K are relatively closely matched, so that a small variation in r_M (and hence, with Kepler's law, in ν_K) can cause a relatively large change in their difference ν_B (4). This means that ν_K must be at least several times as large as ν_B , so that for frequencies as observed in HB-QPO (again, with Kepler's law) r_M can be at most several tens of kilometers. The magnetospheric boundary is

therefore in the inner, radiation-pressure-dominated region of the disk (160). Magnetospheric formation there is not well understood, but that such radii imply neutron star field strengths of $\lesssim 10^{10}$ G seems very likely. Such field strengths are also expected from evolutionary considerations (Section 1.2).

Within r_M the plasma corotates, so it is likely that $\nu_s < \nu_K$; otherwise, centrifugal forces would probably inhibit accretion. The neutron star spin frequency ν_s is practically constant, so an observed increase in $\nu_{\text{QPO}} = |\nu_K - \nu_s|$ must imply an increase in ν_K . With Kepler's law, this implies a decrease in r_M . It is very plausible on general grounds that r_M decreases when $\dot{M}$ increases (but see 160). From the sense of ν_{QPO} in the HB, we then derive that $\dot{M}$ increases in the HB toward the NB and is therefore positively correlated with I_x in this branch. This seems consistent, as deviations from a positive $\dot{M}$ - I_x correlation are expected for the highest accretion rates (where more accreting matter might get into the line of sight), while in the picture sketched here, $\dot{M}$ would be lowest in the HB.

In the absence of a definitive theory of accretion onto a magnetized neutron star, the relations between r_M and $\dot{M}$ and between $\dot{M}$ and I_x are uncertain, and it is not possible to estimate the neutron star spin frequency ν_s from the slope of the ν_{QPO} vs. I_x relation. However, the "matching" argument given above implies that ν_s is at least several tens of hertz. Thus the question arises [and has indeed been asked from the early days of the beat-frequency model (e.g. 4, 143)]: If there is a rapidly spinning magnetized neutron star, why are we not seeing a rapid pulsar in these systems?

Some mechanisms might suppress pulsar modulation (50, 143). A particularly effective one may be scattering. A region of scattering plasma can suppress pulsar modulation caused by beamed radiation while *transmitting* much of the isotropic QPO signal, even if their frequencies are similar (10, 45, 151). Such plasma can also cause millisecond time lags in the QPO signal between energy bands: Compton scattering in a hot plasma would result in a situation where photons that have undergone many scattering events emerge with higher energies, but delayed (owing to a longer light travel time) with respect to those scattered only a few times (29; see, e.g., 99). The size of the scattering region required to explain the observed time lags of up to 4 ms is relatively large (10^2 – 10^3 km; 12, 117, 162). Since most gravitational energy is released in the inner few kilometers from the neutron star surface, it is unlikely that a large fraction of the luminosity could be provided by hot electrons in a cloud of this size (100, 117). However, if one allows the oscillating flux incident on the cloud (before Comptonization) to have a different X-ray spectrum from the non-oscillating incident flux, there may be ways out of this energy problem

(49). Simultaneous measurements of X-ray flux, QPO amplitude, and time lags (all as a function of photon energy) combined with quantitative modeling will provide strong constraints on models of this kind.

The modulated-accretion magnetospheric beat-frequency model apparently allows one to account for most of the observed properties of the HB-QPO/LFN. Its basic strong points are (a) a natural preferred frequency (ν_B) whose value (and range of variation) fits with observations without stretching model parameters, and (b) the fact that the model involves modulation of the basic accretion process and has therefore no problem in producing strong oscillations. These strong points have not been matched by competing models for HB-QPO (Section 1.3). However, the model should be confirmed by detection of the predicted low-level periodic pulsations. Provisionally accepting the model, we know the parameter varying along the Z and its sense: It is $\dot{M}$, increasing toward the FB. This points to where we may have to look for answers to the other key questions: What happens at the branch transitions, and what is the nature of the NB/FB-QPO?

In early proposals, the HB-NB transition has been attributed to a switch from magnetically channeled polar cap to more uniform accretion (6), and the NB-FB transition to a drop in the amount of rotational energy fed back from a rapidly spinning neutron star into the disk (92; see, however, 35). In all recent scenarios radiation pressure plays the key role. As a group, Z sources are near the Eddington luminosity L_{Edd} , so when $\dot{M}$ increases in a given source, one expects to see the effects of radiation pressure at some point. The NB-QPO frequency is nearly the same between sources; this suggests that it is determined by some parameter not varying much between sources, e.g. L_{Edd} (28). Two possible consequences of approaching L_{Edd} —a transition to a thick accretion disk and a spherical accretion regime (28, 30, 31, 35, 48, 49, 145), and a decrease in inflow velocity (28, 49)—have been exploited in recent explanations for spectral and temporal behavior in the NB and FB.

The HB-NB transition may be caused by the onset of an inner disk instability that leads to a geometrically thick disk (30, 48, 49). The X-ray spectrum seemingly pivots around a point between 3 and 6 keV when the source moves up and down the NB, which suggests that the X-ray spectral changes in the NB are due to changes in the degree of Comptonization, caused by a changing scattering optical depth of the plasma in the line of sight (29, 49). A transition to a super-Eddington regime may explain the NB-FB transition (30, 31, 35, 49), with outflow and lower scattering optical depth causing spectral changes in the FB similar to those in the NB, but in the opposite direction along the branch (49). Sco X-1 flares and Cyg X-2 dips up the FB; this behavior may be due to differences in inclination (35).

HB-QPO/LFN become much weaker at the HB-NB transition point, which might indicate that the plasma clumps disappear there (31). This disappearance might be caused by a slowdown of the fall velocity of the accreting plasma sufficient for processes occurring at the speed of sound to have the opportunity to smooth out plasma inhomogeneities (49).

Oscillations in a geometrically thick, toruslike inner accretion disk partially obscuring the X rays were proposed to explain NB/FB-QPO [145 (cf. 7), but see also 48]. Hasinger (28) proposed that a standing sound wave in a radiation-pressure-supported plasma layer close to the neutron star surface provides the correct frequency for NB-QPO (see, however, 49, 91). This proposal may have been the first to exploit the fact that at near-Eddington luminosities, radiation pressure slows down the falling plasma sufficiently for sound-speed effects to become important (see also 69a).

Lamb (49) recently proposed that an instability can occur in the slowed-down accretion flow, which originates in the fact that the flow needs a finite time to react (with its reduced fall speed) to changes in luminosity. The resulting optical depth changes in the accreting plasma cause the quasi-periodic rocking of the X-ray spectrum particular to NB-QPO (Section 2.4.1). Preliminary results from quantitative modeling of the flow (G. Miller & F. Lamb, see Note 2) show spectral variations that in an X-ray color-color diagram are reminiscent of HB-NB behavior. The angular momentum of the accreting plasma is neglected in this model; it is likely that more realistic descriptions would involve accretion tori, as earlier invoked in more qualitative scenarios for the spectral changes (47) and QPO (145). In models of the type discussed above, the X-ray luminosity on the NB is always close to L_{Edd} , so that sources in the NB might provide standard candles (28, 49).

Much of the preceding discussion is in a sketchy state. However, a general framework seems to be emerging that has the magnetospheric beat-frequency mechanism and Eddington-limited flows as its two key ingredients. Possibly, for the first time we are dealing with models for the brightest LMXB that can be tested with data obtainable with presently available instrumentation.

3. ATOLL SOURCES

The proposal that there exists a class of bright LMXB that has a pattern of correlated X-ray and power spectral behavior fundamentally different from that of the Z sources is recent (36). Not much is known as yet about the relation of this new class of “atoll” sources to Z sources, and it is still conceivable that the classification is not one of sources, but of source states. However, as a framework within which to discuss the phenomenology of

bright LMXB, the division between Z and atoll sources is extremely useful, and this is why I use it here. Sources identified as exhibiting atoll behavior are indicated with an “A” in Table 1. As a group, they are somewhat fainter than the Z sources and, contrary to these, some of them are reliable X-ray bursters. Table 4 summarizes which aspects of atoll behavior were detected in each source.

3.1 *Islands and Bananas*

Two different structures, provisionally labeled “islands” and “bananas” (36), occur in the color-color diagrams of the atoll sources.

Curved, relatively fuzzy branches such as in Figure 7 (*top left*) are the bananas; the isolated clump in Figure 7 (*top right*) is an example of an island. Both types of structure can occur in a single source, and together they sometimes form a kind of atoll in the color-color diagram. The reason for these fragmented color-color diagrams is observational: In an island state a source apparently does not move much during a typical observational interval of hours to days. Thus, atoll sources in the island state are less active in the color-color diagram than are Z sources, which in the same time trace out large segments of the Z. One transition from an island to the left end of a banana has been observed. It is not clear that islands appear at any fixed position in the diagrams with respect to the bananas, but the bananas recur in a given source in roughly the same place. The X-ray intensity is low in the island state, and this state is characterized by regular X-ray burst behavior; less regular bursting can also occur in the bananas.

Two power spectral components have been identified in atoll sources.

Table 4 Atoll behavior^a

Source	“Banana” state			“Island” state		
	Branch ^b	VLFN	HFN	Branch ^b	VLFN	HFN
4U 1820–30	●	●	●	●	●	●
4U 1705–44	●	●	●	●	—	●
4U 1636–53	●	●	●	●	—	●
GX 9+1	●	●	●	—	—	—
GX 3+1	●	●	●	—	—	—
4U 1735–44	●	●	●	—	—	—
GX 9+9	●	●	●	—	—	—
GX 13+1	●	●	—	—	—	—
4U 1728–33	—	—	—	●	—	●

^a ●: detected; —: not detected (36).
^b Refers to detection of spectral branch in X-ray hardness vs. intensity or color-color diagram.

Figure 7 Atoll source behavior. Color-color diagrams (*top*) show elongated “banana” branches (*left*) and isolated “islands” (*right*); power spectra (*bottom*) are nearly pure power laws in the banana state (*left*) and show a clear break in the island state (*right*). Both types of behavior can be observed in the same atoll source at different epochs. After Hasinger & van der Klis (36).

They are similar in shape to the VLFN and HFN discussed in Section 2 and bear the same names; there is no formal evidence that they are related—in fact, in some respects the atoll HFN may be more similar to Z source LFN (see below).

VLFN is strongest in the bananas. Its power-law slope is less than in Z sources; usually it is close to 1 (“1/f noise”). Its strength is typically 2–3% (rms) in the bananas and less than 1% in the islands. HFN dominates the island power spectra; strengths can be large [up to 20% (rms)]. The HFN shape shows more or less the same range of variation as seen in LFN in Z sources: between strictly “red” and a broad peak (17, 36).

Both components have additional structure superimposed on their overall shapes; wiggles, such as those visible in Figure 7 (*bottom*), abound. Some have the character of QPO peaks (56, 74, 116). It has been argued (36) that they are not similar to QPO seen in Z sources. There is a tendency for gradual power spectral changes when a source moves from the island state to the left end of the banana, and from there to the upper right of the banana: VLFN becomes stronger and HFN weaker.

3.2 *Understanding the Atoll Sources*

No explanation has been proposed for atoll behavior. However, something can be said about the relation between atoll and Z sources (36). The division between atoll and Z sources does not coincide with earlier proposed groupings of bright LMXB (see 148, and references therein). Because, as a group, atoll sources are fainter than Z sources, they may have lower accretion rates. Interestingly, all four orbital periods measured in atoll systems are short (< 5 hr), whereas both periods measured in Z sources are long (> 10 hr). Thus the data are consistent with Z sources containing evolved companion stars, while atoll sources do not; this might account for different accretion rates (see Section 1.2; cf. 148). If the only difference between Z and atoll sources is accretion rate, then transitions between Z and atoll behavior are expected in LMXB that show a large range in $\dot{M}$. It is not clear, however, that a lower accretion rate alone explains all differences—in particular, the absence of HB-QPO in atoll sources. Possibly, the atoll neutron stars have lower magnetic fields, so that the beat-frequency mechanism does not work (36).

4. RELATED OBJECTS

The phenomena discussed in this section form in a sense the loose ends of the phenomenology of QPO and noise in X-ray binaries. Their relation with QPO and noise in the Z and atoll sources, of which they are in some cases very reminiscent, is in all cases uncertain.

4.1 *Nonpersistently Bright LMXB*

4.1.1 CIRCINUS X-1 Cir X-1 is a peculiar recurrent transient source showing large transitions in X-ray intensity related to a (probably orbital) period of 16.6 days (see 123, and references therein). During a bright X-ray outburst, 5–17 Hz QPO were seen for approximately 7 hr (123, 124). Their frequency was weakly correlated with X-ray intensity between 5 and 6 Hz and was strongly correlated between 7 and 17 Hz. This behavior is reminiscent of NB/FB-QPO, and spectral variations during this episode suggested the presence of two connected branches (125) in a hardness-

intensity diagram; however, the exact relation to Z behavior is unclear. Excess power in the 30–300 Hz range detected simultaneously was described as a QPO broad peak (123); it may be an HFN component.

A very narrow (0.03–0.05 Hz) 1.4-Hz QPO peak was detected during another outburst (125). The QPO frequency did not significantly vary when the X-ray intensity changed by a factor of six. Very strong [40–80% (rms) down to 0.05 Hz] red noise was observed in this observation.

4.1.2 THE RAPID BURSTER The Rapid Burster (MXB 1730–335; see 55) is unique in showing transient episodes during which the source exhibits Type II X-ray bursts, which are probably sudden increases in accretion rate lasting from seconds to minutes and recurring with intervals between 10 s and ~ 1 hr. Long Type II bursts often have flat tops. Three different types of QPO were reported.

During long, flat-topped bursts, strong [up to 20% (rms)] QPO with frequencies in the 2–5 Hz range occur (109, 122). QPO peaks are narrow ($\Delta\nu/\nu$ down to 0.05; 109, 122), and red noise is weak (rms amplitude down to 10% of that of QPO; 109). L. Stella (see Note 2) argues that these QPO can be identified with NB-QPO in Z sources (see also 28). This is based on (a) similar QPO frequencies, (b) an anticorrelation between ν_{QPO} and I_x (109) also seen in Sco X-1 in the NB, and (c) the shape of the X-ray color-color diagram.

Even stronger [up to 35% (rms)] 2–4.5 Hz QPO sometimes occur in the persistent (i.e. nonburst) flux, after short (1–2 min) Type II bursts. They often show a characteristic frequency evolution from ~ 4 to ~ 2 Hz within 3 to 6 min, correlated to a simultaneous X-ray spectral hardness evolution (109). In these QPO, time lags have been detected: For oscillation frequencies > 3.6 Hz, the soft (1–5 keV) signal lags the hard (5–20 keV) one by ~ 8 ms (108).

The third kind of QPO has frequencies between 0.4 and 1 Hz and also occurs in the persistent flux, preferentially before short Type II bursts. A strong second harmonic was observed in one case (109).

Recent observations with the *Ginga* satellite [F. Makino et al., reported by K. Mitsuda (see Note 2)] show QPO switching between frequencies of 5, 10, and 15 Hz during two long Type II bursts; the higher frequencies are consistent with their being harmonics of the lowest frequencies. The quality of the data is sufficient to see the oscillations directly in the X-ray light curve.

4.2 *Accreting Pulsars*

Two cases of a QPO peak in MXB accreting pulsars have recently been reported. In Cen X-3 (A. Tennant, see Note 2) the QPO frequency is

between 35 and 68 mHz for a pulsar frequency of ~ 210 mHz. In EXO 2030+337 (L. Angelini, see Note 2) the QPO frequency is between 190 and 210 mHz for a ~ 24 -mHz pulsar. The QPO frequency of the latter was reported to decrease by $\sim 10\%$ when the X-ray intensity dropped by $\sim 25\%$.

These observations are of great interest, as QPO caused by a beat-frequency mechanism (Section 2.4.2) in a source whose neutron star spin frequency is known allow us to measure the magnetospheric radius r_M . In both cases, the QPO frequency is consistent with a magnetospheric beat-frequency model with $r_M \approx 4000$ km, which indicates a magnetic field strength appropriate for an accreting pulsar (10^{12} – 10^{13} G). In the case of EXO 2030+337, the slope of the correlated frequency-intensity change fits as well. However, in this case the data are also consistent with the QPO frequency being the Kepler frequency at the magnetospheric boundary. With a pulsar beam sweeping the surroundings, a beat-frequency model involving reflection or obscuration of X rays by circulating blobs in the disk is a possibility that should be considered in addition to an accretion-modulation mechanism.

Noise components have been reported from each of a sample of eight accreting pulsars by T. Belloni (see Note 2). The shape of the power spectrum of the noise is usually very reminiscent of HFN in atoll sources (it could also be LFN), including the power spectral wiggles. Cutoff frequencies are in the 0.1–10 Hz range. The strength of the noise can be large [up to 30% (rms)] and is quite variable.

4.3 *Black Hole Candidates*

Strong [$\gtrsim 20\%$ (rms)], rapid (> 1 Hz) variability is no longer a good argument for black hole candidacy; Cir X-1 (Section 4.1.1) and V0332+53 were both suspected to be a black hole on these grounds (41, 121) and then later shown to be a burst source (126) and a pulsar (114), respectively. Many pulsars are now known to be strongly and rapidly variable (Section 4.2), and LMC X-3 [a strong black hole candidate on the basis of its companion star's orbital optical radial velocity curve (15)] does not show strong, rapid variability (129). The well-known rapid variability of another good black hole candidate, Cyg X-1 (see 60), has a noise power spectrum similar to that of pulsars (T. Belloni, see Note 2).

LMC X-1, a “tentative” black hole candidate on the basis of a relatively low-quality optical radial velocity curve (39; see also 67) and its so-called ultra-soft X-ray spectrum (157), shows slow (0.075 Hz) QPO (18). Slow QPO were earlier observed (77) in GX 339–4, a black hole candidate solely on the basis of its ultra-soft spectrum and its bimodal spectral behavior reminiscent of Cyg X-1 (see 157). It is unclear whether these two

cases of slow QPO are related, as is their relation with the slow QPO mentioned in Section 1.3.

The full pattern, if there is one, has not yet emerged. Very recently, the surprising discovery of ~ 6 -Hz 3–4% (rms) QPO peaks with widths between 0.5 and 1.5 Hz was reported (63) from GX 339–4. Strong second harmonics and a broad noise component of strongly variable shape were observed as well. As noted by K. Mitsuda (see Note 2), if these QPO can be identified with NB-QPO in Z sources, then either the source is a black hole, and thus a neutron star surface and magnetic field are not required for NB-QPO, or it is a neutron star and then ultra-soft spectra are not a sign of black holes. However, the QPO in GX 339–4 are similar but not identical to NB-QPO: The frequency is the same, but harmonic content and red-noise strength are clearly larger.

5. CONCLUSIONS

Our understanding of the phenomenology of the bright LMXB has increased enormously over the last few years. Most progress was made in unraveling the properties of the very brightest among them, which are now called the Z sources (Section 2). These sources show three distinct X-ray spectral states, and two patterns of rapid temporal variability whose occurrence strongly correlates.

The “horizontal branch” quasi-periodic oscillations and associated low-frequency noise (HB-QPO/LFN) have properties that suggest a magnetospheric origin. The modulated-accretion magnetospheric beat-frequency model, involving a rapidly spinning neutron star with a surface field of roughly 10^{9-10} G has been successful in accounting for these variations. A prediction of this model is that at some (low) level, millisecond pulsations due to the magnetized neutron star’s rotation are present.

The “normal-” and “flaring-branch” quasi-periodic oscillations (NB/FB-QPO) in Z sources are less easy to interpret, but the similar frequencies between sources in the NB state, the X-ray spectral variations to which the QPO correlate, and general considerations concerning the X-ray luminosity of the sources hint at Eddington-limited accretion flows as an important ingredient in their description.

Observations of subtle differences (time lags, amplitude variations) in the rapid variability between X-ray spectral bands provide links between X-ray spectroscopy and X-ray timing of Z sources. Compton-scattering models for this kind of data appear successful, and the data are of sufficient quality to test them at a detailed level.

The observational data on the atoll sources (Section 3) are as yet less constraining. However, the fact that there are two populations among

bright LMXB is in itself important information. Present evidence is consistent with the two classes having different companion star types.

Broad noise components of very similar shape are observed in virtually all stellar-mass accreting compact objects out to relatively high frequencies (> 1 Hz), and various QPO phenomena are seen in the more distant cousins of Z sources, such as pulsars and black hole candidates. Caution is indicated, however, in the interpretation of these results. As we have seen in the Z sources, apparently similar timing phenomena can turn out to be physically quite different. Although there are basic similarities, the detailed physical circumstances in these sources differ greatly. Even if a beat-frequency mechanism is at work, it might be physically quite distinct from that believed to operate in Z sources.

A few tasks that lie ahead can be clearly defined at this point. Further observational work on the apparently universal broad noise components is needed to clarify their relation to source type. The properties of accreting-pulsar and black-hole candidate QPO should be further investigated: Are they like those in Z sources, or are the observed similarities only superficial? The relation of atoll sources to Z sources needs to be clarified: Are they similar sources at a lower accretion rate, or are they in some respect qualitatively different? Observations of LMXB varying over a large range in X-ray luminosity (e.g. soft X-ray transients) could be crucial here.

It should be attempted, finally, to construct comprehensive models for the entire pattern of correlated temporal and spectral behavior of the Z sources. The observations have reached a level where it is possible to quantitatively test such models. This will in any case improve our understanding of poorly grasped physics, such as magnetospheric formation and near-Eddington accretion flows, and if successful, the models will allow us to estimate basic quantities of compact objects in LMXB, such as neutron star spin rates and magnetic field strengths.

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Literature Cited

1. Alpar, M. A. 1986. *MNRAS* 223: 469–78
2. Alpar, M. A. 1987. In *High Energy Phenomena Around Collapsed Stars*, NATO ASI Ser. C, ed. F. Pacini, 195: 359–66. Dordrecht: Reidel
3. Alpar, M. A., Shaham, J. 1985. *IAU Circ. No. 4046*
4. Alpar, M. A., Shaham, J. 1985. *Nature* 316: 239–41
5. Angel, J. R. P., Kestenbaum, H., Novick, R. 1971. *Ap. J. Lett.* 169: L57–61

6. Berman, N. M., Stollman, G. M. 1988. *MNRAS* 232: 487–95
7. Boyle, C. B., Fabian, A. C., Guilbert, P. W. 1986. *Nature* 319: 648–49
8. Bradt, H. V., Kelley, R. L., Petro, L. D. 1982. In *Galactic X-Ray Sources*, ed. P. W. Sanford, P. Laskarides, J. Salton, pp. 89–112. Chichester, Engl: Wiley
9. Bradt, H. V. D., McClintock, J. E. 1983. *Annu. Rev. Astron. Astrophys.* 21: 13–66
10. Brainerd, J., Lamb, F. K. 1987. *Ap. J. Lett.* 317: L33–38
11. Branduardi, G., Kylafis, N. D., Lamb, D. Q., Mason, K. O. 1980. *Ap. J. Lett.* 235: L153–57
12. Bussard, R. W., Weisskopf, M. C., Elsner, R. F., Shibazaki, N. 1988. *Ap. J.* 327: 284–93
13. Collmar, W., Kendziorra, E., Staubert, R. 1988. *Adv. Space Res.* 8(2): 411–14
14. Cooke, B. A., Stella, L., Ponman, T. 1985. *IAU Circ. No. 4116*
15. Cowley, A. P., Crampton, D., Hutchings, J. B., Remillard, R., Penfold, J. E. 1983. *Ap. J.* 272: 118–22
16. Cowley, A. P., Hutchings, J. B., Crampton, D. 1988. *Ap. J.* 333: 906–16
- 16a. Deeter, J. E. 1984. *Ap. J.* 281: 482–91
17. Dotani, T., Mitsuda, K. 1988. In *Physics of Neutron Stars and Black Holes*, ed. Y. Tanaka, pp. 143–48. Tokyo: Universal Acad. Press
18. Ebisawa, K., Mitsuda, K., Inoue, H., Dotani, T. 1988. In *Physics of Neutron Stars and Black Holes*, ed. Y. Tanaka, pp. 149–53. Tokyo: Universal Acad. Press
19. Eckmann, J.-P., Ruelle, D. 1985. *Rev. Mod. Phys.* 57: 617–56
20. Elsner, R. F., Shibazaki, N., Weisskopf, M. C. 1987. *Ap. J.* 320: 527–36
21. Elsner, R. F., Shibazaki, N., Weisskopf, M. C. 1988. *Ap. J.* 327: 742–49
22. Elsner, R. F., Weisskopf, M. C., Darbro, W., Ramsey, B. D., Williams, A. C., et al. 1986. *Ap. J.* 308: 655–60
23. Forman, W., Jones, C., Tananbaum, H. 1976. *Ap. J.* 208: 849–62
24. Giacconi, R., Gursky, H., Kellogg, E., Schreier, E., Tananbaum, H. 1971. *Ap. J. Lett.* 167: L67–73
25. Giacconi, R., Gursky, H., Paolini, F. R., Rossi, B. B. 1962. *Phys. Rev. Lett.* 9: 439–43
26. Hameury, J.-M., King, A. R., Lasota, J.-P. 1985. *Nature* 317: 597–99
27. Hasinger, G. 1986. In *The Evolution of Galactic X-Ray Binaries, NATO ASI Ser. C*, ed. J. Truemper, W. H. G. Lewin, W. Brinkmann, 167: 139–49. Dordrecht: Reidel
28. Hasinger, G. 1987. *Astron. Astrophys.* 186: 153–58
29. Hasinger, G. 1987. In *The Origin and Evolution of Neutron Stars, IAU Symp. No. 125*, ed. D. J. Helfand, J.-H. Huang, pp. 333–45. Dordrecht: Reidel
30. Hasinger, G. 1988. *Adv. Space Res.* 8(2): 377–81
31. Hasinger, G. 1988. In *Physics of Neutron Stars and Black Holes*, ed. Y. Tanaka, pp. 97–115. Tokyo: Universal Acad. Press
32. Hasinger, G., Langmeier, A., Sztajno, M., Pietsch, W., Gottwald, M. 1985. *IAU Circ. No. 4153*
33. Hasinger, G., Langmeier, A., Sztajno, M., Trümper, J., Lewin, W. H. G., et al. 1986. *Nature* 319: 469–71
34. Hasinger, G., Langmeier, A., Sztajno, M., White, N. 1985. *IAU Circ. No. 4070*
35. Hasinger, G., Friedhorsky, W. C., Middleditch, J. 1988. *Ap. J.* 337: 843–48
36. Hasinger, G., van der Klis, M. 1989. *Astron. Astrophys.* In press
37. Hertz, P. 1988. In *Physics of Neutron Stars and Black Holes*, ed. Y. Tanaka, pp. 211–14. Tokyo: Universal Acad. Press
38. Hjellming, R. M., Wade, C. M. 1971. *Ap. J. Lett.* 164: L1–7
39. Hutchings, J. B., Crampton, D., Cowley, A. P. 1983. *Ap. J. Lett.* 275: L43–47
40. Ilovaisky, S. A., Chevalier, C., White, N. E., Mason, K. O., Sanford, P. W., et al. 1980. *MNRAS* 191: 81–93
41. Jones, C., Giacconi, R., Forman, W., Tananbaum, H. 1974. *Ap. J. Lett.* 191: L71–74
42. Joss, P. C., Avni, Y., Rappaport, S. 1978. *Ap. J.* 221: 645–51
43. Kulkarni, S. R. 1988. *Adv. Space Res.* 8(2): 343–50
44. Kundt, W., ed. 1989. *Neutron Stars, AGN and Jets, NATO ASI Ser. C*. In press
45. Kylafis, N. D., Klimis, G. S. 1987. *Ap. J.* 323: 678–84
46. Lamb, F. K. 1984. In *High Energy Transients in Astrophysics, AIP Conf. Proc.*, ed. S. E. Woosley, 115: 179–214. New York: AIP
47. Lamb, F. K. 1986. In *The Evolution of Galactic X-Ray Binaries, NATO ASI Ser. C*, ed. J. Truemper, W. H. G. Lewin, W. Brinkmann, 167: 151–71. Dordrecht: Reidel
48. Lamb, F. K. 1988. *Adv. Space Res.* 8(2): 421–47
49. Lamb, F. K. 1988. *Ap. J.* In press

50. Lamb, F. K., Shibazaki, N., Alpar, M. A., Shaham, J. 1985. *Nature* 317: 681–87
51. Langmeier, A. 1988. PhD Thesis. Ludwig-Maximilians-Univ. München, Germ. (In German)
52. Langmeier, A., Hasinger, G., Sztajno, M., Trümper, J., Pietsch, W. 1985. *IAU Circ. No. 4147*
53. Lewin, W. H. G. 1986. In *The Physics of Accretion onto Compact Objects*, *Lect. Notes Phys.*, ed. K. O. Mason, M. G. Watson, N. E. White, 266: 177–93. Berlin: Springer-Verlag
54. Lewin, W. H. G., Clark, G. W., Smith, W. B. 1968. *Ap. J. Lett.* 152: L55–61
55. Lewin, W. H. G., Joss, P. C. 1983. In *Accretion-Driven Stellar X-Ray Sources*, ed. W. H. G. Lewin, E. P. J. van den Heuvel, pp. 41–115. Cambridge: University Press
56. Lewin, W. H. G., van Paradijs, J., Hasinger, G., Penninx, W. H., Langmeier, A., et al. 1987. *MNRAS* 226: 383–94
57. Lewin, W. H. G., van Paradijs, J., Jansen, F., van der Klis, M., Sztajno, M., et al. 1985. *IAU Circ. No. 4101*
58. Lewin, W. H. G., van Paradijs, J., van der Klis, M. 1988. *Space Sci. Rev.* 46: 273–377
59. Li, F. K., Joss, P. C., McClintock, J. E., Rappaport, S., Wright, E. L. 1980. *Ap. J.* 240: 628–35
60. Liang, E. P., Nolan, P. L. 1984. *Space Sci. Rev.* 38: 353–84
61. Makishima, K. 1986. *ISAS Res. Note 313*, ISAS, Tokyo. 29 pp.
62. Makishima, K., Mitsuda, K., Inoue, H., Koyama, K., Matsuoka, M., et al. 1983. *Ap. J.* 267: 310–14
63. Makishima, K., Miyamoto, S., and the Ginga Team. 1988. *IAU Circ. No. 4653*
64. Mason, K. O. 1986. In *The Physics of Accretion onto Compact Objects*, *Lect Notes Phys.*, ed. K. O. Mason, M. G. Watson, N. E. White, 266: 29–57. Berlin: Springer-Verlag
65. Mason, K. O., Middleditch, J., Nelson, J. E., White, N. E. 1980. *Nature* 287: 516–18
66. Matsuoka, M. 1985. In *Catalysmic Variables and Low-Mass X-Ray Binaries*, ed. D. Q. Lamb, J. Patterson, pp. 139–42. Dordrecht: Reidel
67. McClintock, J. E. 1986. In *The Physics of Accretion onto Compact Objects*, *Lect. Notes Phys.*, ed. K. O. Mason, M. G. Watson, N. E. White, 266: 211–28. Berlin: Springer-Verlag
68. McDermott, P. N., Taam, R. E. 1987. *Ap. J.* 318: 278–87
69. McHardy, I. M., Lawrence, A., Pye, J. P., Pounds, K. A. 1981. *MNRAS* 197: 893–919
- 69a. Meyer, F. 1986. In *Radiation Hydrodynamics in Stars and Compact Objects*, *Lect. Notes Phys.*, ed. D. Mihalas, K.-H. A. Winkler, 255: 249–67. Berlin: Springer-Verlag
70. Middleditch, J., Friedhorsky, W. 1985. *IAU Circ. No. 4060*
71. Middleditch, J., Friedhorsky, W. C. 1986. *Ap. J.* 306: 230–37
72. Mitsuda, K. 1984. *ISAS Res. Note 251*, ISAS, Tokyo
73. Mitsuda, K. 1988. In *Physics of Neutron Stars and Black Holes*, ed. Y. Tanaka, pp. 117–31. Tokyo: Universal Acad. Press
74. Mitsuda, K., Dotani, T., Yoshida, A. 1988. In *Physics of Neutron Stars and Black Holes*, ed. Y. Tanaka, pp. 133–42. Tokyo: Universal Acad. Press
75. Mitsuda, K., and the GINGA Lac Team. 1988. *Adv. Space Res.* 8(2): 391–95
76. Morfill, G. E., Truemper, J. 1986. In *The Evolution of Galactic X-Ray Binaries*, *NATO ASI Ser. C*, ed. J. Truemper, W. H. G. Lewin, W. Brinkmann, 167: 173–81. Dordrecht: Reidel
77. Motch, C., Ricketts, M. J., Page, C. G., Ilovaisky, S. A., Chevalier, C. 1983. *Astron. Astrophys.* 119: 171–76
78. Murakami, T., Inoue, H., Makishima, K., Hoshi, R. 1987. *Publ. Astron. Soc. Jpn.* 39: 879–86
79. Miyamoto, S., Matsuoka, M. 1977. *Space Sci. Rev.* 20: 687–755
80. Norris, J. P., Wood, K. S. 1985. *IAU Circ. No. 4087*
81. Norris, J. P., Wood, K. S. 1987. *Ap. J.* 312: 732–38
82. Oda, M., Gorenstein, P., Gursky, H., Kellogg, E., Schreier, E., et al. 1971. *Ap. J. Lett.* 166: L1–7
83. Ostriker, J. P. 1977. *Ann. N.Y. Acad. Sci.* 302: 229–43
84. Parmar, A. N., White, N. E. 1988. In *X-Ray Astronomy with EXOSAT*, *Mem. Soc. Astron. Ital.*, ed. R. Pallavicini, N. E. White, 59: 147–68
85. Parsignault, D. R., Grindlay, J. E. 1978. *Ap. J.* 225: 970–87
86. Patterson, J. 1979. *Ap. J.* 234: 978–92
87. Penninx, W., Hasinger, G., Lewin, W. H. G., van Paradijs, J., van der Klis, M. 1988. *MNRAS*. In press
- 87a. Penninx, W., Lewin, W. H. G., Mitsuda, K., van der Klis, M., van Paradijs, J., et al. 1989. *Astron. Astrophys.* In press
88. Penninx, W., Lewin, W. H. G., Zijlstra, A. A., Mitsuda, K., van Paradijs, J., et al. 1988. *Nature* 336: 146–48

89. Petro, L. D., Bradt, H. V., Kelley, R. L., Horne, K., Gomer, R. 1981. *Ap. J. Lett.* 251: L7–11
90. Ponman, T. 1982. *MNRAS* 201: 769–99
91. Ponman, T. J., Cooke, B. A., Stella, L. 1988. *MNRAS* 231: 999–1009
92. Priedhorsky, W. 1986. *Ap. J. Lett.* 306: L97–100
93. Priedhorsky, W., Hasinger, G., Lewin, W. H. G., Middleditch, J., Parmar, A., et al. 1986. *Ap. J. Lett.* 306: L91–95
94. Pringle, J. E. 1981. *Annu. Rev. Astron. Astrophys.* 19: 137–62
95. Rappaport, S. A., Joss, P. C. 1983. In *Accretion-Driven Stellar X-Ray Sources*, ed. W. H. G. Lewin, E. P. J. van den Heuvel, pp. 1–39. Cambridge: University Press
96. Sadeh, D., Byram, E. T., Chubb, T. A., Friedman, H., Hedler, R. L., et al. 1982. *Ap. J.* 257: 214–24
97. Schulz, N. S., Hasinger, G., Trümper, J. 1988. *Astron. Astrophys.* In press
98. Shaham, J. 1987. In *The Origin and Evolution of Neutron Stars, IAU Symp. No. 125*, ed. D. J. Helfand, J.-H. Huang, pp. 347–61. Dordrecht: Reidel
99. Shapiro, S. L., Lightman, A. P., Eardly, D. M. 1976. *Ap. J.* 204: 187–99
100. Shibazaki, N., Elsner, R. F., Bussard, R. W., Ebisuzaki, T., Weisskopf, M. C. 1988. *Ap. J.* 331: 247–60
101. Shibazaki, N., Elsner, R. F., Weisskopf, M. C. 1987. *Ap. J.* 322: 831–37
102. Shibazaki, N., Lamb, F. K. 1987. *Ap. J.* 318: 767–85
103. Shibazaki, N., Mitsuda, K. 1984. In *High Energy Transients in Astrophysics, AIP Conf. Proc.*, ed. S. E. Woosley, 115: 63–71. New York: AIP
104. Stella, L. 1986. In *Plasma Penetration into Magnetospheres*, ed. N. Kylafis, J. Papamastorakis, J. Ventura, pp. 199–214. Iraklion: Crete Univ. Press
105. Stella, L. 1988. *Adv. Space Res.* 8(2): 367–76
106. Stella, L. 1988. In *X-Ray Astronomy with EXOSAT, Mem. Soc. Astron. Ital.*, ed. R. Pallavicini, N. E. White, 59: 185–211
107. Stella, L., Chiappetti, L., Ciapi, A. L., Maraschi, L., Tanzi, E. G., Treves, A. 1986. *Proc. Marcel Grossman Meet., 4th*, ed. R. Ruffini, pp. 861–66. Amsterdam: North-Holland
108. Stella, L., Haberl, F., Lewin, W. H. G., Parmar, A. N., van der Klis, M., et al. 1988. *Ap. J. Lett.* 327: L13–16
109. Stella, L., Haberl, F., Lewin, W. H. G., Parmar, A. N., van Paradijs, J., et al. 1988. *Ap. J.* 324: 379–90
110. Stella, L., Kahn, S. M., Grindlay, J. E. 1984. *Ap. J.* 282: 713–18
111. Stella, L., Parmar, A. N., White, N. E. 1985. *IAU Circ. No. 4102*
112. Stella, L., Parmar, A. N., White, N. E. 1987. *Ap. J.* 321: 418–24
113. Stella, L., Parmar, A. N., White, N. E., Lewin, W. H. G., van Paradijs, J. 1985. *IAU Circ. No. 4110*
114. Stella, L., White, N. E., Davelaar, J., Parmar, A. N., Blissett, R. J., et al. 1985. *Ap. J. Lett.* 288: L45–49
115. Stella, L., White, N. E., Priedhorsky, W. 1985. *IAU Circ. No. 4117*
116. Stella, L., White, N. E., Priedhorsky, W. 1987. *Ap. J. Lett.* 315: L49–53
117. Stollman, G. M., Hasinger, G., Lewin, W. H. G., van der Klis, M., van Paradijs, J. 1987. *MNRAS* 227: 7P–12P
118. Stollman, G. M., Kuperus, M. 1988. *Astron. Astrophys.* 203: 104–10
119. Taam, R. E. 1983. *Ap. J.* 270: 694–99
120. Taam, R. E., van den Heuvel, E. P. J. 1986. *Ap. J.* 305: 235–45
121. Tanaka, Y., and the Tenma Team. 1983. *IAU Circ. No. 3891*
122. Tawara, Y., Hayakawa, S., Kunieda, H., Makino, F., Nagase, F. 1982. *Nature* 299: 38–41
123. Tennant, A. F. 1987. *MNRAS* 226: 971–78
124. Tennant, A. F. 1988. *Adv. Space Res.* 8(2): 397–404
125. Tennant, A. F. 1988. *MNRAS* 230: 403–14
126. Tennant, A. F., Fabian, A. C., Shafer, R. A. 1986. *MNRAS* 219: 871–81
127. Terrell, N. J. Jr. 1972. *Ap. J. Lett.* 174: L35–41
128. Terrell, J., Olsen, K. H. 1970. *Ap. J.* 161: 399–413
129. Treves, A., Belloni, T., Chiappetti, L., Maraschi, L., Stella, L., et al. 1988. *Ap. J.* 325: 119–27
130. van den Heuvel, E. P. J. 1983. In *Accretion-Driven Stellar X-Ray Sources*, ed. W. H. G. Lewin, E. P. J. van den Heuvel, pp. 303–41. Cambridge: University Press
131. van den Heuvel, E. P. J. 1988. *Adv. Space Res.* 8(2): 355–65
132. van der Klis, M. 1986. In *The Physics of Accretion Onto Compact Objects, Lect. Notes Phys.*, ed. K. O. Mason, M. G. Watson, N. E. White, 266: 157–75. Berlin: Springer-Verlag
133. van der Klis, M. 1987. In *The Origin and Evolution of Neutron Stars, IAU Symp. No. 125*, ed. D. J. Helfand, J.-H. Huang, pp. 321–31. Dordrecht: Reidel
134. van der Klis, M. 1987. In *Variability of Galactic and Extragalactic X-Ray Sources*, ed. A. Treves, pp. 185–92. Milano: Assoc. Avanz. Astron.

135. van der Klis, M. 1988. *Adv. Space Res.* 8(2): 383–89
136. van der Klis, M. 1989. In *Timing Neutron Stars*, NATO ASI Ser. C, ed. H. Ögelman, E. P. J. van den Heuvel, 262: 27–69. Dordrecht: Kluwer
137. van der Klis, M., Hasinger, G., Stella, L., Langmeier, A., van Paradijs, J., et al. 1987. *Ap. J. Lett.* 319: L13–18
138. van der Klis, M., Jansen, F. A. 1985. *Nature* 313: 768–71
139. van der Klis, M., Jansen, F. 1986. In *The Evolution of Galactic X-Ray Binaries*, NATO ASI Ser. C, ed. J. Truemper, W. H. G. Lewin, W. Brinkmann, 167: 129–37. Dordrecht: Reidel
140. van der Klis, M., Jansen, F., van Paradijs, J., Lewin, W. H. G., Trümper, J., et al. 1985. *IAU Circ. No. 4043*
141. van der Klis, M., Jansen, F., van Paradijs, J., Lewin, W. H. G., Trümper, J., et al. 1985. *IAU Circ. No. 4140*
142. van der Klis, M., Jansen, F., van Paradijs, J., Lewin, W. H. G., Sztajno, M., et al. 1987. *Ap. J. Lett.* 313: L19–23
143. van der Klis, M., Jansen, F., van Paradijs, J., Lewin, W. H. G., van den Heuvel, E. P. J., et al. 1985. *Nature* 316: 225–30
144. van der Klis, M., Jansen, F., White, N., Stella, L., Peacock, A. 1985. *IAU Circ. No. 4068*
145. van der Klis, M., Stella, L., White, N., Jansen, F., Parmar, A. N. 1987. *Ap. J.* 316: 411–26
146. van Paradijs, J. 1983. In *Accretion-Driven Stellar X-Ray Sources*, ed. W. H. G. Lewin, E. P. J. van den Heuvel, pp. 189–260. Cambridge: University Press
147. van Paradijs, J., Hasinger, G., Lewin, W. H. G., van der Klis, M., Sztajno, M., et al. 1988. *MNRAS* 231: 379–89
148. van Paradijs, J., Lewin, W. H. G. 1986. In *The Evolution of Galactic X-Ray Binaries*, NATO ASI Ser. C, ed. J. Truemper, W. H. G. Lewin, W. Brinkmann, 167: 187–93. Dordrecht: Reidel
149. Verbunt, F. 1988. In *Physics of Neutron Stars and Black Holes*, ed. Y. Tanaka, pp. 159–73. Tokyo: Universal Acad. Press
150. Verbunt, F., van Paradijs, J., Elson, R. 1984. *MNRAS* 210: 899–914
151. Wang, Y.-M., Schlickeiser, R. 1987. *Ap. J.* 313: 200–17
152. Warner, B. 1983. In *Cataclysmic Variables and Related Objects*, ed. M. Livio, G. Shaviv, pp. 155–72. Dordrecht: Reidel
153. Warwick, R. S., Marshall, N., Fraser, G. W., Watson, M. G., Lawrence, A., et al. 1981. *MNRAS* 197: 865–91
154. Warwick, R. S., Norton, A. J., Turner, M. J. L., Watson, M. G., Willingale, R. 1988. *MNRAS* 232: 551–64
155. Webbink, R. F., Rappaport, S., Savonije, G. J. 1983. *Ap. J.* 270: 678–93
156. White, N. E. 1986. In *The Physics of Accretion Onto Compact Objects, Lect. Notes Phys.*, ed. K. O. Mason, M. G. Watson, N. E. White, 266: 377–87. Berlin: Springer-Verlag
157. White, N. E., Marshall, F. E. 1984. *Ap. J.* 281: 354–59
158. White, N. E., Mason, K. O., Sanford, P. W., Ilovaisky, S. A., Chevalier, C. 1976. *MNRAS* 176: 91–102
159. White, N. E., Peacock, A., Taylor, B. G. 1985. *Ap. J.* 296: 475–80
160. White, N. E., Stella, L. 1988. *MNRAS* 231: 325–31
161. White, N. E., Stella, L., Parmar, A. N. 1988. *Ap. J.* 324: 363–78
162. Wijers, R. A. M. J., van Paradijs, J., Lewin, W. H. G. 1987. *MNRAS* 228: 17P–21P