Since the initial discoveries with the Rossi X-ray Timing Explorer (RXTE) in 1996 of kilohertz quasi-periodic oscillations (kHz QPOs) and burst oscillations in a number of low-mass X-ray binaries (LMXBs) containing low-magnetic-field neutron stars, a very active field has developed. I briefly summarize some of the developments since those early days, which include the discovery of the first accreting millisecond pulsar, further claims of the detection of strong-field general-relativistic effects, intriguing correlations of the kHz QPO properties with QPOs at lower frequencies, strong challenges for the beat-frequency interpretation of the twin kHz QPO peaks and a number of new theoretical ideas, some of which involving frame dragging. Twenty LMXBs have now been seen to exhibit periodic or quasi-periodic phenomena with frequencies exceeding $10^{2.5}$ Hz. Although the commensurabilities between the observed frequencies that suggest a beat-frequency interpretation have conclusively been shown to be not precise, the preponderance of the evidence still is in favour of the idea that there exists some kind of beat-frequency relation between the twin kHz peaks. However, that evidence is only coming from 4 of the 17 sources showing twin kHz QPOs.

1 Introduction

In this review, I attempt to summarize what happened in the field of millisecond X-ray variability from accreting low-magnetic field neutron stars in the period of slightly over one year since I submitted my review for the proceedings of the Lipari NATO ASI (van der Klis 1998). So, for anything that happened before October 1997 and for much of the introductory material, I refer to that article. As in that article, I refer to the tables summarizing the phenomenology for most of the references. A brief account of what went before:

Twin kilohertz quasi-periodic oscillation (QPO) peaks began to be discovered with the Rossi X-ray Timing Explorer (RXTE) early 1996, briefly after its launch. The peaks had associated rms amplitudes of $\lesssim 1\%$ up to several $10\%$ of the total source flux, peak separations of $\sim 250$–$360$ Hz, coherences between $Q \sim 1$–$10^2$, and their frequencies (of the higher-frequency peak of the two) varied between $500$ and $1200$ Hz with mass accretion rate $\dot{M}$. Only a short time later another series of RXTE discoveries began, of a different type of rapid oscillations. These came from some of the same sources, but only during type 1 X-ray bursts, and had frequencies between $330$ and $590$ Hz, depending
on the source. These burst oscillations were interpreted in terms of the spin frequency of a layer in the neutron star atmosphere that is presumably close to the neutron star spin frequency itself. Finally, quite recently, the first true spin frequency was detected (at 401 Hz) in an accreting low-magnetic field neutron star. In several sources it was found that the twin kHz peak separation was equal to the frequency of the burst oscillations, or half that, to within a few percent. This strongly suggested a beat-frequency interpretation, where the higher-frequency peak (hereafter the upper peak) is identified with orbital motion at some preferred radius in the disk and the lower-frequency kHz QPO peak (hereafter the lower peak) is at the beat frequency between this orbital frequency and the spin frequency of the neutron star: \( \nu_{lo} = \nu_{upp} - \nu_s \). It was immediately realized that if we are indeed seeing the signature of orbital motion around neutron stars with orbital frequencies of up to 1200 Hz, then we are probing a region of space-time where strong-field general relativity is required to describe orbital motion, and constraining the mass-radius relation of neutron stars and thereby the equation of state (EOS) of supranuclear-density matter. This spurred a large amount of both observational and theoretical work on these phenomena, some of which I will summarize here.

A few ballpark numbers are useful to keep in mind. Orbital motion around a \( M=1.4M_\odot \) neutron star with a frequency \( \nu_K \) of 1200 Hz takes place at an orbital radius of \( r_K = 15 \text{ km} \); the expressions are

\[
\nu_K = \left( \frac{GM}{4\pi^2 r_K^3} \right)^{1/2} \approx 1200 \text{ Hz} \left( \frac{r_K}{15 \text{ km}} \right)^{-3/2} \left( \frac{M}{1.4M_\odot} \right)^{1/2},
\]

or

\[
r_K = \left( \frac{GM}{4\pi^2 \nu_K^2} \right)^{1/3} \approx 15 \text{ km} \left( \frac{\nu_K}{1200 \text{ Hz}} \right)^{-2/3} \left( \frac{M}{1.4M_\odot} \right)^{1/3},
\]

(this is exact for a Schwarzschild geometry and as measured at infinity; for realistic neutron stars the frame dragging corrections are moderate). The radius of the innermost stable circular orbit (ISCO) calculated in the same geometry is \( R_{ISCO} = 6GM/c^2 \), which for 1.4M_\odot works out to 12.5 km.

2 Phenomenology

2.1 Millisecond pulsar

The first accreting millisecond pulsar was finally discovered, more than two years after RXTE’s launch, by Rudy Wijnands using RXTE on April 13, 1998 in the soft X-ray transient SAX J1808.4−3658 (Fig. 2). Wijnands and van der Klis 1998a,b). The pulse frequency is 401 Hz.
Figure 1: The discovery power spectrum of the first accreting millisecond X-ray pulsar. (Wijnands and van der Klis 1998b)

This discovery, a long sought after “Holy Grail” of X-ray astronomy, had been anticipated for nearly 20 years, because magnetospheric disk accretion theory as well as the example of the non-accreting millisecond radio pulsars indicated that such rapid spin frequencies had to exist among accreting low-magnetic field neutron stars – yet despite numerous searches such rapid pulsars had not turned up in observations of LMXBs. Now that one such accreting millisecond pulsar is known, of course, the question becomes “why only one?”.

The pulsations in SAX J1808.4−3658 are not particularly weak and we know for sure that pulsars of similar amplitude and observed (as opposed to intrinsic) coherence are not present in many other LMXBs observed in a similar (rather standard) way as SAX J1808.4−3658 was with RXTE. The answer to this question may lie in part in the orbital characteristics of the source. The 2.0-hr orbital period was discovered, and the orbit measured, with admirable speed by Chakrabarty and Morgan (1998a,b). With a projected orbital radius $a \sin i$ of only 63 light milliseconds and a mass function of $3.8 \times 10^{-5} M_\odot$, the companion is either very low mass, or we are seeing the orbit nearly pole-on.

If we see the orbit pole-on, then this may be what allows us to see the pulsations in this system, and a different orientation of the orbit what hides them in many other LMXBs. The fact that the pulse profile of SAX J1808.4−3658 (Fig. 2) is nearly sinusoidal might be related to this pole-on orientation. In any case, of course, the low radial-velocity amplitude of the orbit reduces the Doppler shifts and keeps the pulsar more nearly coherent, facilitating its discovery without the use of special deacceleration techniques (which are, however, being used to try and discover other pulsars; e.g., Vaughan et al. 1994; van der Klis et al. 1999, in prep.).
Another possibility is that SAX J1808.4−3658 is a different type of system from the other well-studied LMXBs. Perhaps the fact that it is an unspectacular little transient is related to an accretion history that favours the preservation of a magnetic field configuration (strength, orientation) that produces a pulsar, and some other unspectacular little transients (with, perhaps, low-mass companions) will turn out to be millisecond pulsars as well.

It would be of enormous interest to find burst oscillations (§2.2) or kHz QPOs (§2.3) in SAX J1808.4−3658, as this would allow right away to confirm or reject various models for these phenomena involving the neutron star spin, which in SAX J1808.4−3658, uniquely among accreting low-magnetic field neutron stars, is known accurately and with certainty. However, the RXTE observations during the first few days of the April 1998 outburst, when the source was brightest, were relatively limited. Perhaps for this reason, although SAX J1808.4−3658 is known from its September 1996 SAX discovery observation (in ’t Zand et al. 1998) to be a type 1 X-ray burster, no bursts were seen in the RXTE observations of the April 1998 outburst (the source was unobservable for SAX during that time), nor were kHz QPOs detected. Early in the outburst, when from comparing to other LMXBs the chances of seeing kHz QPOs were best, due to the limited observing time RXTE was not very sensitive to them (Wijnands and van der Klis 1998c). Plans are in place to spend a large amount of observing time with RXTE on SAX J1808.4−3658 during its next outburst, which should allow us to do a good job with respect to this and various other issues related to this interesting source.
2.2 Burst oscillations

Six sources have now shown burst oscillations. The frequencies are listed in Table 1. These oscillations are not detected in each burst. In four of these sources (the top four in Table 1), twin kHz peaks in the persistent emission have also been observed (see §2.3). It turns out that in each case, the burst QPO frequencies are close to the frequency differences between the twin peaks, or twice that. These frequencies have been listed in Table 1 in the columns labeled Frequency 1 and Frequency 2, respectively.

| Source        | Frequency 1 (Hz) | Frequency 2 (Hz) |
|---------------|-----------------|-----------------|
| 4U 1636–53    | 290             | 581             |
| 4U 1702–43    | 330             | —               |
| 4U 1728–34    | 363             | —               |
| KS 1731–260   | —               | 524             |
| MXB 1743–29   | 589             | —               |
| Aql X-1       | 549             | —               |

References see Tables 2, 3 and 4. Source identification of MXB 1743–29 is uncertain. Frequency 1 is close to the kHz QPO peak separation frequency, frequency 2 to twice that. For MXB 1743–29 and Aql X-1 this separation frequency is unknown.

The burst QPOs have a relatively large coherence. In KS 1731–260 a Q of 900 was reported (Smith, Morgan and Bradt 1997). However, usually drifts by a few Hz are observed in the QPO frequency (Strohmayer et al. 1998c; Fig. 3). These drifts are suggestive of the bursting layer slightly expanding and then contracting, changing its rotation rate to conserve angular momentum and thus modulating the QPO frequency. In 4U 1728–34 the QPO amplitude decreases and the fitted black-body radius increases during the burst rise in a way that is very suggestive of a modulation caused by an expanding hot spot (Strohmayer, Zhang and Swank 1997b). The high Q value, the small frequency drifts and the amplitude variations of the burst QPOs therefore support the view that their origin lies in the neutron star spin, and that their frequency is close to the spin frequency.

In addition to this evidence, it has been shown by Strohmayer et al. (1998b) that the frequency to which the oscillation approaches near the end of the burst (Fig. 3) is constant to within about 0.01% between bursts far apart in time. In the above interpretation this asymptotic frequency is the rotation frequency of the bursting layer when it approaches its quiescent rotation state, one that may be more nearly in corotation with the underlying star. This is another argument in favour of the near-constant neutron star spin as the
process underlying the observed, slightly drifting frequencies.

Miller (1998), from an analysis of five bursts in 4U 1636−53, reports the presence of a 290 Hz burst oscillation at half the frequency of, and simultaneous with, the stronger 580 Hz oscillation, and interprets this in terms of the presence of two antipodal hot spots on the surface. If correct, this would indicate a neutron star spin frequency of 290 Hz (more nearly equal to the kHz peak separation, see \( \text{§2.3} \)), and strongly suggests we are seeing the signature of the presence of two magnetic poles. As the oscillation frequency drifts, we can not be looking at the magnetic poles themselves, which are of course fixed in the frame corotating with the spin of the star. Perhaps we are seeing the effect of
the accumulation of extra nuclear fuel at the poles, which becomes decoupled from the magnetic field lines by convection during the bursts (Bildsten 1996, priv. comm.). The required near-simultaneous ignition of both poles at the burst onset may be a problem for this interpretation.

2.3 Kilohertz quasi-periodic oscillations

The number of sources that have shown kilohertz quasi-periodic oscillations (kHz QPOs) is now eighteen. Together with the one source that showed burst oscillations (§2.2) but no kHz QPOs, and the millisecond pulsar (§2.1), which so far showed neither, this brings the total number of sources that has shown kilohertz periodic or quasi-periodic phenomena (here defined as phenomena at frequencies exceeding $10^{2.5}$ Hz) to twenty. All but one of the kHz QPO sources have shown twin kHz peaks in their power spectrum (Fig. 5); the exception with only a single peak so far is Aql X-1. Tables 2, 3, and 4 summarize the results on these sources.

![Figure 5: Twin kHz peaks in Sco X-1. (van der Klis et al. 1997b)](image)

The two kHz QPO peaks increase in frequency with inferred mass accretion rate $\dot{M}$ both in Z and in atoll sources (see Hasinger and van der Klis 1989 or the review by van der Klis 1995 for the introduction of these subtypes of LMXBs). In Z sources, the QPOs are nearly always seen down to the lowest inferred $\dot{M}$ levels these sources reach, in atoll sources the QPOs tend to occur in the middle of the $\dot{M}$ range of each source (Fig. 6). Kilohertz QPOs are seen in a similar frequency range (500–1200 Hz for the upper peak) in sources that differ in average X-ray luminosity $L_x$ by 2.5 orders of magnitude (where $L_x$ is here defined simply as $4\pi d^2 f_x$ with $f_x$ the X-ray flux and $d$ the distance),

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December 21, 1998

[1] December 21, 1998
| Source   | Lower freq. (Hz) | Upper freq. (Hz) | Peak freq. (Hz) | Burst freq. (Hz) | References                                      |
|----------|-----------------|-----------------|----------------|-----------------|------------------------------------------------|
| Sco X-1  | 565±5           | 870±5           | 307±5          | Van der Klis et al. 1996a,b,c,1997b |
|          | ↓ 845±5         | ↓ 1080±5        | ↓ 237±5        |                  |
|          |                 |                 | 1130±5         |                  |
| GX 5−1  | 215±5           | 505±5           | 298±11         | Van der Klis et al. 1996c |
|          | ↓ 660±5         | ↓ 890±5         | ↓ 294±8        | Wijnands et al. 1998c |
|          |                 |                 | 700±5          |                  |
| GX 17+2 | 645±5           | 783±5           | 294±8          | Van der Klis et al. 1997a |
|          | ↓ 480±5         | ↓ 1080±5        | ↓ 346±29       | Wijnands et al. 1997b |
|          |                 |                 | 1085±5         |                  |
| Cyg X-2 | 730±5           | 855±5           | 346±29         | Wijnands et al. 1998a |
|          | ↓ 530±5         | ↓ 1005±5        | ↓ 625±13       |                  |
|          |                 |                 | 625±13         |                  |
| GX 340+0| 250±5           | 570±5           | 325±10         | Jonker et al. 1998 |
|          | ↓ 250±5         | ↓ 820±5         | ↓ 1020±5       |                  |
|          |                 |                 | 1020±5         | Kuulkers and van der Klis 1997 |

These notes refer also to Tables 3 and 4. Frequencies with no quoted errors were rounded to the nearest 5, or, for burst QPOs, 1 Hz. Arrows indicate ranges over which the frequency was observed or inferred to vary; these can be made up of several overlapping ranges from different observations. Frequencies not connected by arrows are measurements at different epochs. Frequencies in the same row were observed simultaneously (except for burst QPOs). Entries straddling the upper and lower peak columns are of single, unidentified peaks. **Marginal detection.** Special detection method; Méndez et al. (1998a,b,c). Source identification uncertain. **Pulsar.**

and the kHz QPO frequency seems to be determined more by the difference between average and instantaneous $L_x$ of a source than by $L_x$ itself. This is unexplained and must mean that another parameter than $\dot{M}$, related in some way to the average $L_x$, affects the QPO frequency (van der Klis 1997). Perhaps
Table 3: Observed frequencies of kilohertz QPOs in atoll sources - Part I

| Source | Lower peak freq. (Hz) | Upper peak freq. (Hz) | Peak separation freq. (Hz) | Burst oscillation freq. (Hz) | References |
|--------|-----------------------|-----------------------|----------------------------|-----------------------------|------------|
| 4U 0614+09 | 485                   | 840                   | ↓                          | ↓                           | Mendez et al. 1997 |
|         |                       |                       | ↓                          | 323±4                       | Vaughan et al. 1997, 1998 |
|         | 800                   | 1145                  |                            |                             | Kaaret et al. 1998 |
| 4U 1608−52 | 440                   | 765                   | ↓                          | ↓                           | Berger et al. 1996 |
|         | 475                   | 800b                  | ↓                          | ↓                           | Yu et al. 1997 |
|         | 865                   | 1090b                 | ↓                          | ↓                           | Mendez et al. 1998a,b,d |
|         |                       |                       |                            |                             | Kaaret et al. 1998 |
| 4U 1636−53 | 830                   | 900                   | ↓                          | ↓                           | Zhang et al. 1996, 1997a |
|         |                       | 1150                  | ↓                          | 257±20                       | Van der Klis et al. 1996d |
|         |                       | 950                   | ↓                          | 276±10                       | Wijnands et al. 1997a |
|         |                       | 1228                  | ↓                          |                             | Vaughan et al. 1997 |
|         |                       | 830                   | ↓                          | 251±4b                       | Mendez et al. 1998c |
|         |                       | 1190b                 | ↓                          | 290,581                      | Strohmayer et al. 1998b |
| 4U 1702−43 | 625                   | 825                   | ↓                          | 1058b                       | Markwardt et al. 1998 |
|         | 655                   | 1000b                 | ↓                          | 344±7b                       | Ford et al. 1997a |
|         | 700                   | 1040b                 | ↓                          | 337±7b                       | Ford et al. 1998a |
|         | 770                   | 1085b                 | ↓                          | 315±11b                      | Ford et al. 1998a |
| 4U 1705−44 | 775                   | 902                   | ↓                          | 1075a                       | Ford et al. 1998a |

Notes: see Table 2.

this parameter is the neutron star magnetic field strength.

In 4 sources, both twin kHz peaks and burst oscillations are seen, and the fact that the burst oscillation frequency is near 1 or 2 times the kHz peak
Table 4: Observed frequencies of kilohertz QPOs in atoll sources - Part II

| Source     | Lower peak freq. (Hz) | Upper peak freq. (Hz) | Peak freq. (Hz) | Burst separation freq. (Hz) | References                                      |
|------------|-----------------------|-----------------------|----------------|---------------------------|------------------------------------------------|
| 4U 1728−34 | ↓                     | ↓                     | 325±7          | 640−990, 355±5, 364        | Strohmayer et al. 1996a,b,c, 1997b, 1998b, Ford and van der Klis 1998 |
| KS 1731−260| ↓                     | ↓                     | 900−1205       | 260±10, 524                | Morgan and Smith 1996, Smith et al. 1997, Wijnands and Van der Klis 1997 |
| 4U 1735−44 | ↓                     | ↓                     | 640−980        | 341±7, 296±12, 249±15      | Wijnands et al. 1996, 1998b, Ford et al. 1998b |
| MXB 1743−29c|                        |                        | 900−1150       | 249±15                    | Strohmayer et al. 1996d, 1997a                   |
| SAX J1808.4−3658 |                  |                        | 401±4          | 850−1110, 261±10          | Wijnands and van der Klis 1998                    |
| 4U 1820−30 | ↓                     | ↓                     | 660−860        | 358±43, 275±8              | Smale et al. 1996, 1997, Zhang et al. 1998b      |
| Aql X-1   | ↓                     | ↓                     | 677−871        | 549                       | Zhang et al. 1998c, Cui et al. 1998, Yu et al. 1998 |
| 4U 1915−05 | ↓                     | ↓                     | 820−555        | 555−935, 355±7             | Barret et al. 1997, 1998                        |
| XTE J2123−058|                   |                        | 850−110±7      | 1110±7, 211±10             | Homan et al. 1998a,b                             |

Notes: see Table 2.

separation frequency is the main argument for the beat frequency interpretation of kHz QPOs. The evidence for this is summarized in Table 3. In
Figure 6: X-ray color-color diagram of 4U 1608−52. Mass accretion rate is inferred to increase counterclockwise, approximately along the drawn curve. kHz QPO detections are indicated with filled symbols. (Méndez et al. 1998d)

4U 1636−53, Méndez et al. (1998c) have shown that the correspondence is not exact. Yet, although we would dearly like to have a few more examples, the preponderance of the evidence still seems to indicate that at least an approximate beat-frequency relation exists between the three frequencies in those sources where they are all observed.

Table 5: Commensurability of kHz QPOs and burst oscillation frequencies

| Source       | Burst oscillation frequency (Hz) | kHz QPO separation frequency (Hz) | Ratio (burst/separation frequency) |
|--------------|---------------------------------|-----------------------------------|-------------------------------------|
| 4U 1636−53   | 290                             | 251±4                             | 1.155±0.018                         |
| "           | 581                             | "                                 | 2.315±0.037                         |
| 4U 1702−43   | 330                             | 333±5                             | 0.991±0.015                         |
| 4U 1728−34   | 364                             | 355±5                             | 1.025±0.014                         |
| KS 1731−260  | 524                             | 200±10                            | 2.015±0.078                         |

References see Tables [3] and [4].

In an interpretation where the burst oscillations and the kHz peak separation are both close to the neutron star spin, this peak separation is predicted to be approximately constant. It is clear that this is not always the case: both in Sco X-1 and in 4U 1608−52 this separation decreases systematically when
the kHz QPO frequencies increase (Fig. 7), and indications for this exist in 4U 1735−44 and 4U 1702−43 as well (see Tables 3 and 4).

Figure 7: The variations in kHz QPO peak separation in Sco X-1 and 4U 1608−52 as a function of the lower peak frequency. (Méndez et al. 1998b)

The possibility to detect evidence in kHz QPOs for the existence of the innermost stable circular orbit (ISCO) predicted by general relativity, which would constitute the first direct detection of a strong-field general-relativistic effect, has fascinated since the beginning (Kaaret, Ford and Chen 1997; Zhang, Strohmayer and Swank 1997). It has been conjectured that when the inner edge of the accretion disk reaches the ISCO, the QPO frequency might level off and remain constant while $\dot{M}$ continues rising. For this reason, the recent measurement of an apparent leveling off of the increase of QPO frequency with X-ray count rate in 4U1820−30 (Zhang et al. 1998b; Fig. 8) attracted considerable attention.

The difficulty in measurements of this kind is not in measuring the frequency, but in measuring $\dot{M}$. We have known since the days of EXOSAT that variations in X-ray count rate or even X-ray flux in the band accessible to our instruments do not necessarily track $\dot{M}$ (Hasinger and van der Klis 1989, van der Klis et al. 1990, Hasinger et al. 1990), and RXTE observations have confirmed this beautifully. A clear example of this is seen in 4U 1608−52 (Méndez et al. 1998d; Fig. 9 left). This figure, containing many more measurements, looks much less nice than Fig. 8. With sparser coverage it could easily have happened to give a similar impression of leveling off. When plotting frequency vs. X-ray color, which in this case may be a better measure of $\dot{M}$ (though not a perfect one either), there is no sign of any saturation (Fig. 10).
Figure 8: Evidence for a leveling off of the kHz QPO frequency with count rate in 4U 1820–30. (Zhang et al. 1998b)

Figure 9: In 4U 1608–52 a QPO frequency vs. count rate plot shows no clear correlation. When plotted vs. X-ray color it is clear there is no saturation of QPO frequency. (Méndez et al. 1998d)

A number of intriguing correlations has been found between the kHz QPOs and the phenomena at lower frequencies. Wijnands and van der Klis (1998d)
point out, that the low $\dot{M}$ power-spectral similarity between BHCs and low-luminosity low-magnetic field neutron stars found with EXOSAT and Ginga (van der Klis 1994) also holds for the millisecond pulsar SAXJ1808.4-3658 (§2.1), and may even extend to Z sources in their lowest $\dot{M}$ states (the left end of the so-called horizontal branch), where by the way these sources are still quite luminous. The power spectra look very similar (Fig. 10), and with the better RXTE data it is now evident that nearly always, in addition to the break at low frequency, a QPO-like feature above the break is present. The correlation between the break frequency and the QPO frequency is excellent (Fig. 11), and encompasses both neutron stars and black-hole candidates. This suggests that both the band-limited noise component with the 0.03–30 Hz break frequency, and the 0.2–70 Hz QPO (with the possible exception of the Z sources, which are slightly off the main relation) are found in both neutron stars and black holes. This would exclude spin-orbit beat-frequency models and any other models requiring a material surface, an event horizon, a magnetic field, or their absence, for their explanation, essentially implying these phenomena are generated in the accretion flow towards any low-magnetic field compact object and are most likely disk variability features. Ford and van der Klis (1998) studied the relation between both of these features (the band-limited noise and the low-frequency QPO-like feature) and the kHz QPOs in 4U 1728−34, and find generally good correlations (there is one deviant data set), suggesting that kHz QPOs also fit into schemes of this kind in some way. This of course leaves one with the question how the absence of kHz QPOs of the type discussed in this article from black hole candidates fits in with this (the highest-frequency QPOs seen in black hole candidates have frequencies up a few 100 Hz, but although the amount of information on these QPOs is relatively limited, they appear to have properties that are different from kHz QPOs in neutron stars).

A coincidence of QPO properties pointed out by Psaltis, Belloni and van der Klis (1998) may provide an answer to this question. Power spectra of many Z and atoll sources, of Cir X-1 and of a few low luminosity neutron stars and BHCs show two QPO or broad noise phenomena whose centroid frequencies, when plotted vs. each other, seem to line up (Fig. 12). This would not only identify the low-frequency (few 10 Hz) QPOs in Z and atoll sources with even lower-frequency QPOs in Cir X-1 (3–10 Hz) and BHCs (0.3–1 Hz) as also suggested by the Wijnands and van der Klis (1998d) results, but would also indicate that the lower kHz peak in Z and atoll sources (the same argument does not hold for the upper kHz peak), the broad 20–100 Hz bumps found in Cir X-1 (Shirey et al. 1996, 1998, see also Tennant 1987), and even lower-frequency (0.2–1 Hz) bumps in some low luminosity neutron stars and BHCs are due to the same physical phenomenon. While this conjecture remains
Figure 10: Broad-band power spectra of, respectively, the millisecond pulsar, an atoll source, a black-hole candidate and a Z source. (Wijnands and van der Klis 1998d)

Figure 11: Relation between noise break frequency and QPO frequency for sources of the types shown in the previous figure. (Wijnands and van der Klis 1998d)

to be confirmed, the currently available data are suggestive. The interpretation would be similar to that mentioned above, particularly, it would imply that the lower kHz QPO is not unique to neutron star systems either, and therefore presumably a general feature of the accretion flow onto a compact object.
Of course, *orbital motion* in the disk is such an accretion flow phenomenon and remains an attractive interpretation for some of the observed frequencies. The phenomenology is quite complex; further detailed work will show to what extent these various suggestions will stand the test of additional data.

![Figure 12](image_url)

Figure 12: When plotting the frequencies of various QPO and broad noise components seen in accreting neutron stars and black holes vs. each other, a diagram emerges that suggests that similar components occur in all these sources and span a very wide range in frequency. Power-law relations describe the correlations reasonably well. The curved lines illustrate various attempts to fit these relations with spin-orbit beat-frequency models at the same spin frequency for all sources. Such models always converge to a constant frequency and therefore do not fit. (Psaltis, Belloni and van der Klis 1998)

3 Some final remarks

A number of new theoretical ideas has been proposed for explaining various aspects of the phenomenology described in the previous sections. Examples
are the papers by Alpar and Yılmaz (1997), Ghosh (1998), Kluźniak (1998), Titarchuk et al. (1998). An interesting discussion has also begun about the possibility, suggested by the beat-frequency interpretation of the kHz QPOs, that all these neutron stars spin at approximately the same rate (Bildsten 1998, Anderson et al. 1998, Levin 1998).

For the purpose of these final remarks let us concentrate on one aspect of the recent discussions and postulate that any successful model should be able to explain at least: (i) the apparent beat-frequency relation between the twin kHz peaks and the burst oscillations (Table 5), (ii) the relations between kHz QPOs and lower-frequency QPOs in Z and atoll sources described above, and (iii) the systematic variations in kHz QPO peak separation with $\dot{M}$ (Fig. 7). Here I concentrate on what may be shaping up to be two rivals: the spin-orbit beat-frequency interpretation, and the general-relativistic apsidal motion/precession interpretation. In versions of the beat-frequency model (BFM) considered by Miller et al. (1998) and Psaltis et al. (1998), the kHz QPOs are identified with the orbital frequency at the sonic radius and its beat with the neutron star spin, and the lower-frequency HBO in Z sources with the beat of the orbital motion at the magnetospheric radius with the same neutron star spin. In general-relativistic (GR) precession/apsidal motion models discussed by Stella and Vietri (1998a,b) the kHz peaks are due to orbital motion and GR apsidal motion of a slightly eccentric orbit, and the low-frequency QPO to Lense-Thirring precession of this same orbit. Both types of model may be able, with some difficulty, to explain (ii) (Psaltis et al. 1998). While of course BFM is built around, and so have no difficulty to explain, (i), in these models the question is: how to explain, in a spin-orbit beat model, the varying peak separation (iii). The GR models may be able to explain (iii) (Stella and Vietri 1998b), but seem to have no obvious way to predict a beat-frequency relation (i). Surprisingly, ways out may exist from both dilemma’s. In the sonic-point beat-frequency model, the beat interaction between spin and orbital frequencies takes place at the sonic radius by an interaction between an orbiting clump and an X-ray beam of the central, unseen, pulsar. However, the signal associated with this interaction is produced only when the matter released from this clump arrives at the neutron star surface. As pointed out by Lamb (1998, priv. comm.), if the clump is in an orbit that is gradually spiraling down, then the observed frequency will be higher than the actual beat frequency at which beam and clump interact, because the propagation time for the matter from the clump to the surface will be gradually diminishing. This will put the lower kHz peak closer to the upper one, and thus decrease the kHz peak separation, more so when due to stronger radiation drag at higher $L_x$ the spiralling-down is faster, as observed.
In the GR apsidal motion model, the upper kHz peak is at the orbital frequency and the lower one at the apsidal motion frequency of a slightly eccentric orbit. Interestingly, the difference between these two frequencies is the frequency at which the orbiting clump goes through periastron. So, perhaps in a model of this type one could explain the fact that the difference frequency between the kHz peaks is sometimes seen back during X-ray bursts by some kind of interaction at periastron with, e.g., an expanding bursting layer. Whether this would lead to a viable model remains to be seen. In particular it might be a problem to account for the apparent constancy of the burst oscillation frequency in each source.

At the conclusion of my 1997 Lipari review to which the current text is intended to be an update I said that “eventually, most LMXBs will likely exhibit the new phenomenon”, and that this would help enormously in constraining the models. Indeed, this is turning out to be the case. A further synthesis among what is now a considerable and fortunately fast-growing body of data on the properties of kHz QPOs, low-frequency QPOs and X-ray spectra observed simultaneously is likely to bring much progress in the year to come. Further long RXTE observations of these sources will be indispensible in reaching a full understanding of the systematics of the phenomenology.

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