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Kilohertz Quasi-Periodic Oscillations in Low-Mass X-Ray Binaries

Abstract

In early 1996 a series of discoveries began with NASA's Rossi X-ray Timing Explorer of a new, up to then unknown astrophysical phenomenon. It turned out that accreting low magnetic-field neutron stars show quasi-periodic oscillations in their X-ray flux at rates of up to more than a kilohertz. These kHz QPO, now reported from eleven different systems, are among the fastest phenomena in the sky and can provide us with new information about the fundamental properties of neutron stars and help testing general relativity in the strong-field regime. If, for example, their frequencies can be identified with the Keplerian frequencies of matter in orbit around a $1.4 M_{\odot}$ neutron star, then the radius of the star would have to be less than 15 km, which directly constrains the equation of state of bulk nuclear-density matter, and for an only slightly tighter orbit or slightly more massive neutron star the orbital radius would equal the Schwarzschild-geometry general-relativistic marginally stable orbit (12.5 km for a $1.4 M_{\odot}$ object). So far all models that have been put forward for explaining the new phenomenon have encountered problems. In this paper I review the relatively simple and highly suggestive phenomenology as it has emerged from the data up to now, and discuss some of the proposed models.

I Introduction

There are two places in the universe where we can study neutron stars. In radio pulsars, which form the main theme of this meeting, nature performs for us the experiment of spinning a magnetized neutron star, and this allows us to derive interesting conclusions about the fundamental properties of these objects by making it possible to measure their spin rates with very high precision. In X-ray binaries a completely different experiment is performed: take a neutron star (or a black hole) and throw large amounts of matter at it. Analysis of the results of this experiment provides information about the nature of neutron stars and the properties of the space-time around them that can not be obtained from radio pulsars. So, in my view the main motivation for studying X-ray binaries is not that they exhibit a wide range of complex phenomenology, which they do, but that they contain neutron stars (and black holes), objects of fundamental physical interest,

and allow to derive information about the equation of state of high-density matter and perform tests of general relativity in the strong-field regime. In this talk, I shall be discussing low-mass X-ray binaries (LMXBs) containing neutron stars exclusively, as it is in the understanding of the physics of these systems that great progress has recently become possible by the discovery, with NASA's Rossi X-ray Timing Explorer (RXTE), of a new phenomenon, kilohertz quasi-periodic oscillations (kHz QPO).

In these X-ray binary systems matter is transferred from a low-mass ($\lesssim M_{\odot}$) star to a neutron star by way of an accretion disk. The X-rays originate from the hot ($\sim 10^7$ K) plasma comprising the inner few 10^1 kilometers of the flow. This is very close to the neutron star, which itself has a radius, R , of order 10 km, so that by studying the properties of this flow one expects to be able to derive information about the star.

The high temperatures in the inner flow are caused by the release of large amounts of gravitational energy when the matter descends into the neutron star's very deep gravitational potential well ($GM/R \sim 0.2c^2$; here and below I assume $M = 1.4 M_{\odot}$ for the neutron star's mass). The characteristic velocities near the star are of order $(GM/R)^{1/2} \sim 0.5c$. Therefore the dynamical time scale, the time scale for motion of matter through the emitting region, is short; $\tau_{\text{dyn}} \equiv (r^3/GM)^{1/2} \sim 0.1$ ms for $r = 10$ km, and ~ 2 ms for $r = 100$ km.

Up to less than a year ago, no direct information existed about the properties of these flows at these time scales. In this paper I report on how, since February 1996, we are for the first time actually observing time variability from accretion flows onto neutron stars at the expected millisecond time scales. A new rapid-variability phenomenon has been discovered, namely quasi-periodic oscillations in the X-ray flux with amplitudes of up to several 10% of the total flux, quality factors $Q \equiv \Delta\nu/\nu$ (see §II) of up to several 100, and frequencies of up to ~ 1200 Hz. I shall call this phenomenon "kHz QPO" (kilohertz quasi-periodic oscillations) throughout the rest of this paper.

A great deal of information is available about the properties of LMXBs and the physics of accretion onto a neutron star. The last pre-kHz-QPO overview of rapid X-ray variability in X-ray binaries can be found in the Lewin et al. book *X-Ray Binaries* (Van der Klis 1995; look here if you wish to find out about atoll sources, Z sources and the latter's 16–60 Hz horizontal-branch oscillations and the 6–20 Hz normal-flaring branch oscillations). For understanding what follows, it is useful to remind the reader of the usual terminology with respect to the subclasses of LMXBs (Hasinger & Van der Klis 1989): Z sources are near-Eddington accretors and probably have somewhat stronger ($1\text{--}5 \cdot 10^9$ G) magnetic fields, atoll sources are often X-ray burst sources, have luminosities between $10^{-3} L_{\text{Edd}}$ and a few $10^{-1} L_{\text{Edd}}$, and are thought to have somewhat weaker magnetic fields ($10^8\text{--}10^9$ G).

X-ray astronomers are presently scrambling to try and make sense of the phenomenology of kHz QPO, which turn out to be at the same time highly suggestive of interpretation and very restrictive of possible models, and theorists have already begun working out sophisticated models. None of this has reached an equilibrium

state yet, and what I report in this paper will necessarily be of a “snapshot” nature. What is clear at this point is that for the first time we are seeing a rapid X-ray variability phenomenon that is directly linked with a neutron star’s most distinguishing characteristic (only shared among macroscopic objects with stellar-mass black holes): its compactness. This is particularly evident if the phenomena are in some way related to orbital motion. After all, a Keplerian orbital frequency $\nu_K = P_{\text{orb}}^{-1} = (GM/4\pi^2 r_K^3)^{1/2}$ of 1200 Hz around a $1.4 M_{\odot}$ neutron star as seen from infinity corresponds to an orbital radius $r_K = (GM/4\pi^2 \nu_K^2)^{1/3}$ of 15 km, directly constraining the equation of state of the bulk nuclear-density matter, and only just outside the general-relativistic marginally stable orbit. Whatever the model, for the first time we have to seriously worry about general-relativistic effects in describing the observable dynamics of the physical system.

II Observations and interpretation

Kilohertz QPO have now¹ been reported from 11 LMXBs, 3 of which are Z sources and 8 of which are atoll sources and probable atoll sources (see Van der Klis 1995; hereafter I shall use “atoll source” for LMXBs that probably fall in this class as well as for those that definitely do so), together covering nearly three orders of magnitude in X-ray luminosity ($\sim 10^{-3}$ to $\sim 1 L_{\text{Edd}}$). Table 1 summarizes some of these results, and provides an overview of the literature that is approximately complete as of this writing. Rather than getting into an exhaustive description of the phenomenology or following the historical line, I shall concentrate on what I consider at this point to be the main clues. I refer to the table for all kHz QPO observational references in the remainder of this section.

A clear pattern of systematic behavior has emerged. In most sources (8 out of 11) two simultaneous kHz peaks (hereafter: twin peaks) are observed in the power spectra of the X-ray count rate variations (Figure 1). The lower-frequency peak (hereafter the *lower peak*) has been observed at frequencies between 325 and 920 Hz, the higher-frequency peak (hereafter the *upper peak*) has been observed at frequencies between 500 and 1207 Hz. When the accretion rate \dot{M} increases, both peaks move to higher frequency. In atoll sources \dot{M} is inferred to correlate with X-ray count rate, and kHz QPO frequency increases with count rate. In Z sources in their so-called “normal branch” (NB), \dot{M} is inferred to *anticorrelate* to count rate, and indeed in Z sources in the NB kHz QPO frequency increases when the count rate drops.

¹March 21, 1997

Table 1: Observed frequencies of kilohertz QPO.

Source (in order of RA)	Lower peak freq. (Hz)	Upper peak freq. (Hz)	Peak sepa- ration (Hz)	“Third” freq. (Hz)	References
4U 0614+091	480 ↓ 800	520 ↓ 750 ↓ 1150	327±4	328	Ford et al. 1996, 1997 Van der Klis et al. 1996d Méndez et al. 1997 Vaughan et al. 1997
4U 1608–52		691 830 ↓ 890			Van Paradijs et al. 1996 Berger et al. 1996 Vaughan et al. 1997
Sco X-1	570 ↓ 800 ↓ 830	870 ↓ 1050 ↓ 1080 ↓ 1130	292±2 ↓ 247±3		Van der Klis et al. 1996a,b,c, 1997b
4U 1636–53	898 ↓ 920	1147 ↓ 1183 ↓ 1193 835 ↓ 897	249±13	581	Zhang et al. 1996, 1997 Van der Klis et al. 1996d Wijnands et al. 1997 Vaughan et al. 1997
4U 1728–34	640 ↓ 790	500 ↓ 990 ↓ 1100	355±5	363	Strohmayer et al. 1996a,b,c
KS 1731–260	898	1159 ↓ 1207	260±10	524	Morgan & Smith 1996 Smith et al. 1997 Wijnands & Van der Klis 1997
4U 1735–44		1150			Wijnands et al. 1996

In three atoll sources (4U 1728–34, 4U 1636–53 and KS 1731–260), “third peak” oscillations have been seen during X-ray bursts whose frequencies (360–580 Hz) are consistent with being equal to the frequency *differences* between the twin peaks (in 4U 1728–34), or twice that (in the other two sources). In a fourth atoll source

Table 1: (cont.)

Source (in order of RA)	Lower peak freq. (Hz)	Upper peak freq. (Hz)	Peak sepa- ration (Hz)	“Third” freq. (Hz)	References
X 1743–29?				589	Strohmayer et al. 1996d
GX 5–1		567			Van der Klis et al. 1996e
	325	↓ 652	327±11		
	↓ 448	↓ 746			
		↓ 895			
GX 17+2	682	988	306±5		Van der Klis et al. 1997a
	↓ 880				
4U 1820–30	546				Smale et al. 1996, 1997
	↓ 796	1065	275±8		

Arrows indicate observed frequency variations.

Frequencies in the same row were observed simultaneously, except “third” frequencies. Entries straddling the upper and lower peak columns are of single, unidentified peaks.

(4U 0614+09) there is marginal evidence for a third peak at the twin-peak separation frequency which corresponds to an oscillation in the persistent emission rather than in X-ray bursts.

These cases of three commensurate frequencies very strongly suggest that some kind of beat-frequency model is at work, with the “third peaks” at the neutron star spin frequencies (or twice that), the upper kHz peak at the Kepler frequency corresponding to some preferred orbital radius around the neutron star, and the lower kHz peak at the difference frequency between these two. Strohmayer et al. (1996c) suggested that this preferred radius is the magnetospheric radius. Miller, Lamb & Psaltis (1996) proposed it is the sonic radius. In models of this kind, which involve the neutron-star spin as one of the frequencies participating in the beat-frequency process, the twin-peak separation is predicted to be constant. However, in Sco X-1 the peak separation varies systematically with inferred \dot{M} , from ~ 310 Hz when the upper peak is near 870 Hz to ~ 230 Hz when it is near 1075 Hz: the peaks move closer together by ~ 80 Hz while they both move up in frequency as \dot{M} increases. This is in strong contradiction to straightforward beat-frequency models (see §III).

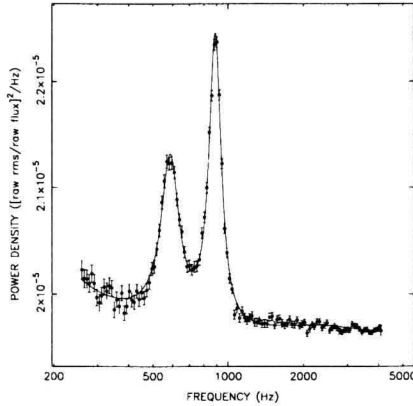


Figure 1. Power spectrum of Sco X-1 showing double kHz QPO peaks (Van der Klis et al. 1997). The sloping continuum above 1 kHz is instrumental.

In the Z sources Sco X-1, GX 5-1 and GX 17+2 twin kHz QPO peaks and the so-called horizontal-branch oscillations (HBO; Van der Klis et al. 1985) are seen simultaneously (Figure 2). HBO are thought to be a product of the magnetospheric beat-frequency mechanism (Alpar and Shaham 1985, Lamb et al. 1985). If this is correct, then this model can *not* explain the kHz QPO in these sources. It is possible in principle that the kHz QPO in the Z sources is a different phenomenon from that in the atoll sources (e.g., Strohmayer et al. 1996c), but this seems unlikely: the frequencies, their dependence on \dot{M} , the coherencies, the peak separations and the fact that there are *two* peaks, one of which sometimes becomes undetectable at extreme \dot{M} , are too similar to attribute to just coincidence. If this is correct, then the variable twin-peak separation seen in Sco X-1, the simultaneous presence of kHz QPO and HBO in Z sources, *and* the direct indications for a beat frequency in the atoll sources must all be explained within the same model, a formidable challenge.

One of the distinguishing characteristics of kHz QPO is that they often show a relatively large coherence. The quality factor Q , defined as the QPO peak's centroid frequency ν divided by its full width at half maximum $\Delta\nu$ regularly reaches values of more than 100 in one or both of the twin peaks (although much lower Q 's are also common). This provides a strong constraint on "orbiting clump" type models, as lifetime broadening considerations show that the clumps must persist over hundreds of cycles. The oscillations in bursts have shown even larger coherence. They attained a record-level Q of ~ 900 in a burst in KS 1731-260 (Smith, Morgan & Bradt 1997). This high Q value supports models where these oscillations are caused by the neutron-star spin. In 4U 1728-34 (Strohmayer et al. 1996c), drifts by ~ 1 Hz have been observed in the ~ 363 Hz frequency of the QPO in bursts that are suggestive of the bursting layer slightly expanding and then recontracting, changing its rotation rate to conserve angular momentum and thus modulating the QPO frequency.

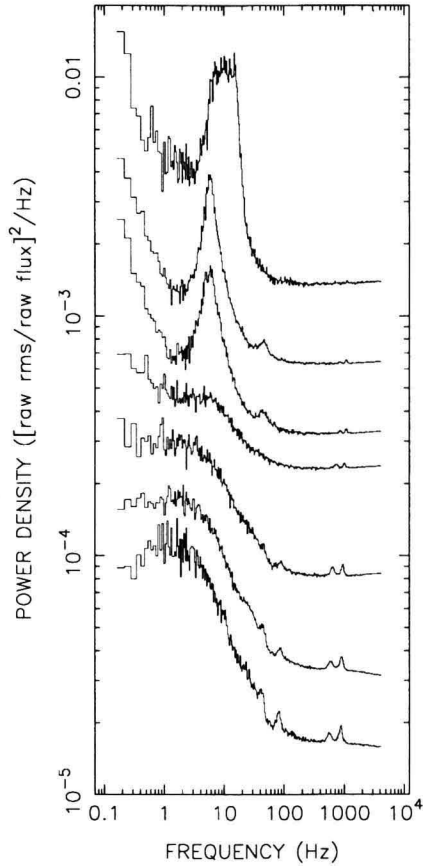


Figure 2. Power spectra of Sco X-1, with inferred \dot{M} increasing upwards. Notice the decrease in strength and increase in frequency of the kHz peaks as a function of \dot{M} . The peaks near 45 and 90 Hz are identified as horizontal branch oscillations (HBO), that between 6 and 20 Hz as normal/flaring branch oscillations (N/FBO). The large width of the N/FBO peak in the top trace is due to peak motion. The sloping continua in the kHz range are instrumental.

The amplitudes of kHz QPO have, in all cases where a check was possible, shown a strong positive dependence on photon energy (e.g., Berger et al. 1996, Zhang et al. 1996). Their amplitudes when measured in a broad photon-energy band can therefore be expected to depend strongly on details of the low-energy part of the spectrum, which contributes many photons and little kHz QPO amplitude: detector cutoff and interstellar absorption will affect the overall fractional amplitude. Reported fractional amplitudes vary between 0.5 and a few percent in Z sources and 3 and 15% (rms) in atoll sources when measured over a 2–20 keV band; for higher energies amplitudes up to 40% (rms) have been observed.

A final strong model constraint is provided by the small magnitude of any time lags between the kHz QPO signal as observed in different energy bands (Vaughan et al. 1997). Time-lag measurements require very high signal-to-noise ratios, and have so far only been made in certain single, apparently count-rate independent peaks in 4U 1608–52 and 4U 1636–53 near 850 Hz, and in a 730 Hz peak in 4U 0614+09 which was probably an upper peak. Finite lags of 10–60 μ sec were discovered in 4U 1608–52; the hard photons lag the soft ones by increasing amounts as the photon energy increases. Upper limits of 30 μ sec and 45 μ sec were set in 4U 1636–53 and 4U 0614+09, respectively. These are by far the smallest lags ever measured; they correspond to light-travel distances of 3–20 km. For rather general assumptions about the spectral formation mechanism, this limits the scale of any Compton scattering regions dominating the spectral shape to between a few and a few tens of km.

The great enigma in the phenomenology right now is, in my opinion, the peculiar lack of correlation between kHz QPO frequency and average source luminosity, whereas *in each individual source* a strong correlation between frequency and \dot{M} is observed. In 4U 0614+09, at a luminosity of a few times $10^{-3} L_{\text{Edd}}$, similar QPO frequencies have been observed as in 4U 1820–30, which is near $10^{-1} L_{\text{Edd}}$, and in Sco X-1, which is inferred to be a near-Eddington accretor, yet in each of these sources the frequency changes by several 10^2 Hz in correlation with \dot{M} . In at least 6 sources, spread over this entire range of average X-ray luminosity, the upper peak has been observed to disappear below the detection limit when its frequency is somewhere between 1100 and 1200 Hz as the flux exceeds a certain limit, but this flux limit is widely different between sources. This must mean that another, compensating, parameter than just accretion rate is affecting the properties of the kHz QPO, most likely by directly affecting the frequency, although some kind of selection effect that leads to suppression of any QPO outside the 300–1200 Hz range is also a possibility. This latter possibility of course requires that in sources that go through a large decrease in accretion rate (transients) several “new” QPO peaks would successively appear near 1200 Hz, move down in frequency and disappear near 300 Hz. This has not been seen and seems somewhat unlikely, but can not be excluded at this point.

An obvious candidate for a compensating parameter is the neutron-star magnetic-field strength, but neutron-star mass or spin, either by their effects on the surrounding space-time or directly, might play a role as well. What would be required, specifically, is that there exists a correlation or an anti-correlation between, say, the magnetic field strength B of the neutron star and its mean accretion rate $\langle \dot{M} \rangle$, and that the QPO frequency depends on B in such a way as to approximately compensate the \dot{M} effect. Interestingly, it has been suggested previously (Hasinger and Van der Klis 1989, see Van der Klis 1995) on the basis of comparing Z and atoll source phenomenology that $\langle \dot{M} \rangle$ and B are correlated among LMXBs, and recently spectral modeling (Psaltis et al. 1997) has tended to confirm this. The magnetospheric beat-frequency model (Alpar & Shaham 1985), when combined with this inferred correlation, qualitatively fits the requirements sketched above, but the results on the Z sources make this model

unattractive for the kHz QPO. Perhaps the magnetic field strength affects the inner accretion flows in other ways than by just terminating the disk at the magnetospheric radius. If magnetic stresses could somehow slow down the (for example, orbital) motion responsible for the kHz QPO, that would do it. Of course, radiative stresses diminish the effective gravity and are expected to slow down orbital motion (Miller & Lamb 1993). However, the luminosity is not independent from \dot{M} , but instead is expected to vary proportionally to it, so that radiative stresses cannot fulfill this role: we know already that when in a given source \dot{M} goes up so does the luminosity, but this does not prevent the QPO frequency from going up as well.

There is a lively discussion about the nature of the observed frequencies and their potential to constrain neutron-star masses and radii and to test general relativity. Kaaret, Ford & Chen (1997) have proposed that the behavior of the single, count-rate independent QPO peaks in 4U 1608–52 and 4U 1636–53 described above is related to orbital motion near the marginally stable orbit, and from this derive neutron star masses of $\sim 2 M_{\odot}$. Zhang, Strohmayer & Swank (1997) have proposed that the narrow range of maximal frequencies (1100–1200 Hz) also mentioned above must be identified with the general relativistic marginally stable frequencies, which leads them to the conclusion that the neutron stars' masses are near $2 M_{\odot}$ as well. An alternative possibility is of course that the maximal frequencies are set by the Keplerian frequency at the neutron star surface. This requires the star to be larger than the marginally stable orbit and for $\sim 1.4 M_{\odot}$ neutron stars would favor the stiffest equations of state.

Just the assumption that the upper peak corresponds to Keplerian motion around the neutron star allows to set useful limits on neutron star parameters, a point made by Miller, Lamb & Psaltis (1996) in their paper on a model that interprets the upper peak in this way (see §III). Different from the proposals just mentioned, these limits do *not* rely on identifying any of the observed frequencies with the marginally stable orbital frequency. There are two direct constraints on the neutron-star mass and radius from the simple assertion that there is stable Keplerian motion at the frequency ν_u of the upper peak: (1) the radius of the star R must be smaller than the radius of this Keplerian orbit, in a Schwarzschild geometry $R < (GM/4\pi^2\nu_u^2)^{1/3}$, and (2) the radius of the marginally stable orbit must *also* be smaller than this: $6GM/c^2 < (GM/4\pi^2\nu_u^2)^{1/3}$, as no stable orbit is possible within this radius. Condition (1) is a mass-dependent upper limit on the radius of the star, and condition (2) provides an upper limit on the mass: $M < c^3/(2\pi 6^{3/2}G\nu_u)$. For $\nu_u = 1193$ Hz (Wijnands et al. 1997), $M < 1.9 M_{\odot}$ and $R_{\text{NS}} < 16.3$ km. Putting in the corrections for the frame dragging due to the neutron star spin requires knowledge of the spin rate (which in the sonic point model is equal to the twin peak separation, or half that; §III). The correction also depends somewhat on the neutron star model, which determines the relation between spin rate and angular momentum, so that the limits become slightly different for each EOS. Putting in these Kerr corrections (for a spin rate of 275 Hz) changes the limits quoted above only slightly, to $M < 2.1 M_{\odot}$ and $R_{\text{NS}} < 16.5$ km for a wide range of equations of state (Wijnands et al. 1997).

III Models

Space is lacking to provide a full description of the physical models that have been proposed for kHz QPO. Of course, the phenomenology as described in the previous section very strongly suggests that a beat-frequency model of some kind is at work. Neutron-star spin and disk Keplerian motion are periodic phenomena known to be present in the system and are therefore natural candidates for providing the basic frequencies. However, it is too early to declare any proposed implementation of a beat-frequency model for kHz QPO an unqualified success. Let me briefly mention other models that have been put forward.

(1) Remarkably short shrift has been given so far to *neutron star vibration models*. The short time scale variations in kHz QPO frequency and the lack of higher-frequency peaks have been cited as reasons for rejecting these models. (2) A model based on numerical radiation hydrodynamics calculations has been proposed by Klein et al. (1996) for the case of the kHz QPO in Sco X-1 and is currently being further explored. (3) The dependence between the QPO frequencies observed in Sco X-1 can be nicely explained with a model where each of the two QPO signals comes from one of two diametrically opposed *relativistic jets* emanating from the central source (Van der Klis et al. 1997b), but this model can not explain the atoll sources' kHz QPO properties.

Now let's turn to beat-frequency models. The two versions of the model that have been discussed both identify the upper peak's frequency with the Keplerian frequency of the accretion disk at some preferred radius, and the lower peak with the beat between this Keplerian frequency and the neutron star spin frequency. The magnetospheric beat-frequency model uses the magnetospheric radius r_M as this preferred radius. As HBO and kHz QPO have been seen *simultaneously* in all three Z sources where kHz QPO have so far been observed, at least *one* additional model is required. According to Miller, Lamb & Psaltis (1996), applying the magnetospheric beat-frequency model to the kHz QPO leads to several other difficulties. They propose the *sonic-point model* instead, where the preferred radius is the sonic radius r_S where the radial inflow velocity becomes supersonic.

In Z sources, applying the sonic point model for the kHz QPO, and the magnetospheric beat-frequency model for the HBO indicates $r_S < r_M$ and therefore requires a Keplerian disk flow well within the magnetosphere. The upper peak is caused in the sonic point model by a modulation of the direction into which this luminosity is emitted ("beaming"). This is similar to what is expected of an X-ray pulsar. It may require some fine-tuning of the scattering process that is thought to be smearing the pulsations to allow it to transmit the upper peak oscillations. Miller, Lamb & Psaltis (1996) suggest that as the sonic radius approaches the general-relativistic marginally stable orbit the frequency of the upper peak will hit a "ceiling" and remain stable for further increases in accretion rate. There are so far no data that have shown this. Instead it has been observed that the QPO disappear above some level of inferred accretion rate at frequencies that are mostly in the range 1100–1200 Hz (see §II). Perhaps this is

what *really* happens when R_{MSO} is reached, however, the fact that the accretion rate at which the peaks disappear is very different between sources (much higher in sources with a higher average luminosity), is yet to be explained.

Obviously, a large amount of effort is still required to make any of the models so far proposed stick. Fortunately, as it looks now the theoretical efforts that are underway at this point will be guided by a very constraining body of RXTE data. Eventually, most LMXBs will likely exhibit the new phenomenon, and many of its properties can be measured with RXTE with great precision.

Acknowledgements

This work was supported in part by the Netherlands Organization for Scientific Research (NWO) under grant PGS 78-277 and by the Netherlands Foundation for Research in Astronomy (ASTRON) under grant 781-76-017.

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