**X-Ray Observations of Low-Mass X-Ray Binaries: Accretion Instabilities on Long and Short Time-Scales**

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**Abstract.** X-rays trace accretion onto compact objects in binaries with low mass companions at rates ranging up to near Eddington. Accretion at high rates onto neutron stars goes through cycles with time-scales of days to months. At lower average rates the sources are recurrent transients; after months to years of quiescence, during a few weeks some part of a disk dumps onto the neutron star. Quasiperiodic oscillations near 1 kHz in the persistent X-ray flux attest to circular motion close to the surface of the neutron star. The neutron stars are probably inside their innermost stable circular orbits and the x-ray oscillations reflect the structure of that region. The long term variations show us the phenomena for a range of accretion rates. For black hole compact objects in the binary, the disk flow tends to be in the transient regime. Again, at high rates of flow from the disk to the black hole there are quasiperiodic oscillations in the frequency range expected for the innermost part of an accretion disk. There are differences between the neutron star and black hole systems, such as two oscillation frequencies versus one. For both types of compact object there are strong oscillations below 100 Hz. Interpretations differ on the role of the nature of the compact object.

**INTRODUCTION**

Low-mass X-ray binaries (LMXB) are the binaries of a low-mass “normal” star and a compact star. The compact star could be a white dwarf, a neutron star, or a black hole. The Rossi X-Ray Timing Explorer (*RXTE*) has been observing since the beginning of 1996 and has obtained qualitatively new information about the neutron star and black hole systems. In this paper I review the new results briefly in the context of what we know about these sources. The brightest, Sco X–1, was one of the first non-solar X-ray sources detected, but only with *RXTE* have sensitive measurements with high time resolution been made that could detect dynamical time-scales in the region of strong gravity. *RXTE* also has a sky monitor with a time-scale of hours that keeps track of the long term instabilities and enables in depth observations targeted to particular states of the sources.
The LMXB have a galactic bulge or Galactic Population II distribution. The mass donor generally fills its Roche lobe, is less than a solar mass, and is optically faint, in contrast to the early type companions of pulsars like Cen X–3 or the black hole candidate Cyg X–1. In many cases the optical emission is dominated by emission from the accretion disk, and that is dominated by reprocessing of the X-ray flux from the compact object [1]. The known orbital periods of these binaries range from 16 days (Cir X–1) to 11 minutes (4U 1820–30). The very short period systems (< 1 hr) are expected to have degenerate dwarf mass donors and probably the mass transfer is being driven by gravitational radiation. The different properties of the sources indicate several populations. The longer period systems with more massive companions are probably slightly evolved from the main sequence.

There are about 50 persistent neutron star LMXB [2]. Distances can be estimated in a variety of ways. The hydrogen column density indicated by the X-ray spectrum should include a minimum amount due to the interstellar medium. Many of the sources emit X-ray bursts associated with thermonuclear flashes that reach the hydrogen or helium Eddington limits. In some cases the optical source provides clues. The resulting luminosity distribution appears to range from several times the Eddington limit for a neutron star down below the luminosity of about $10^{38}$ ergs s$^{-1}$, corresponding to $\approx 10^{-11} \ M_\odot \ yr^{-1}$ [3]. The lower limit has come from instrument sensitivity, but it may also reflect the luminosity below which the accretion flow is not steady, so that the source must be a transient.

“X-Ray Novae” that are among the brightest X-ray sources for a month to a year are sufficiently frequent that they were seen in rocket flights in the beginning of X-ray astronomy. The X-ray missions that monitored parts of the sky during the last three decades found that on average there are 1–2 very bright transient sources each year (e.g. [4]) with durations of a month to a year. In 5 years of RXTE operations, we know of 20 transient neutron star sources and and an equal number of transient black hole sources. If they have a 20 yr recurrence time we have seen only a quarter of them and if we have only been watching a third of the region in the sky, 20 observed sources implies more than 240 sources exist. In reality there is a distribution of the recurrence times, some as short as months, others longer than 50 years, if optical records are good. On the basis of such estimates, the number of potential black hole transients is estimated to be on the order of thousands [5].

The separation of sources into persistent and transient sources is a very gross simplification. One of the discoveries of recent missions, and especially of the All Sky Monitor (ASM) [6] has been that the persistent sources have cycles of variations with time-scales ranging from many months to days. If the transient outbursts originate in accretion instabilities, perhaps these variations are related. In the next section I show some of the kinds of behavior being observed.

At radii close to the compact objects the dynamical time-scale gets shorter, till it is the milliseconds of the neutron star or black hole. RXTE’s large area detectors detect oscillations on these time-scales which must reflect the dynamics at the innermost stable circular orbit (ISCO) of these neutron stars and black holes.

The neutron stars of this sample are expected to have magnetic dipole moments
and surface fields about $10^8 - 10^9$ gauss. Of course the neutron stars have a surface such that matter falling from the accretion disk to the neutron star crashes into the surface and generates X-ray emission. In the case of the black holes matter could fall through the event horizon and disappear with no further emission of energy. Thus the X-rays produced and the dynamics that dominates in the two cases (neutron star versus black hole) could be different. However, a number of similarities appear in the signals we receive.

**LONG TIME-SCALE VARIABILITIES**

**High Accretion Rate - Persistent Sources**

Among the persistent LMXB there are characteristic variations on time-scales of months in some sources and days in others [6]. Quasiperiodic modulations were pointed out at 37 days for Sco X–1 (IAUC 6524), 24.7 days for GX 13+1 (IAUC 6508), 77.1 days for Cyg X–2 (IAUC 6452), 37 days for X 2127+119 in M15 (IAUC 6632). The obviously important, but not strictly periodic modulations in 4U 1820–30 and 4U 1705–44 at time-scales of 100–200 days are shown in Figure 1. For Sco X–1, the changes in activity level occur in a day and the activity time-scale is hours. The hardness is often correlated with the rate, although this measure does not bring out more subtle spectral changes.

These time-scales are less regular than the 34 day cycle time of Her X-1, and similar modulations in LMC X-4 and SMC X-1, which are thought to be due to the precession of a tilted accretion disk. The latter sources are high magnetic field pulsars in which the disk is larger than in the LMXB, and is truncated by the magnetosphere at a radius as large as $10^8$ cm. The LMXB spectral changes are also different than those of the pulsars. In the LMXB case the changes are thought to be real changes in the accretion onto the neutron star, at least the production of X-rays, rather than a change in an obscuration of the X-rays that we see.

The spectral changes are captured in the color-color diagrams that give rise to the names “Z” and “Atoll” for subsets of the LMXB. These were identified with EXOSAT observations by Hasinger and van der Klis [7]. Characteristics of the bursts from 4U 1636–53 depended on the place of the persistent flux in the atoll color-color diagram [8]. This implied that the real mass accretion rate was correlated with the position on the diagram (although other possibilities such as the distribution of accreted material on the surface of the neutron star may play a role). That the position in the diagram is not uniquely correlated to the flux is as yet not understood. Transients atoll sources like Aql X–1 and 4U 1608–52 go around the atoll diagram during the progress of the outburst.
FIGURE 1. \textit{RXTE ASM Rates from Four Atoll Bursters.} Modulations are typically a factor of two, although sometimes more. Many properties vary with these modulations.

\textbf{Low Average Accretion Rate - Transients}

There are only a few persistent LMXB in which the compact object is a black hole. Black hole binaries are for some reason more likely to be transients. Perhaps the binaries harboring them are not being driven to have as much mass exchange, so that it happens that these systems are in the range of mass flow through the disk that makes them transient. There are also neutron star transients with low average mass exchange rates. Figure 2 shows on the left two neutron star transients, a well known atoll burster Aql X–1 and the pulsar GRO J1744–28, which had two outbursts a year apart, but has otherwise not been seen. On the right are two black hole candidates, 4U 1630–47, which recurs approximately every two years, and XTE J1550–564, which like GRO J1744–28, had a dramatic outburst, with a weaker recurrence after a year’s hiatus. Black hole candidates can get brighter than the transient bursters, consistent with the Eddington limit for more massive compact objects and they probably go through more different spectral and timing “states”, but there are also similarities in the kinds of behavior that are exhibited.

From both BeppoSAX and RXTE results it is clear that there is a population of systems which have transient episodes, but which are an order of magnitude less luminous at peak. BeppoSax has seen bursts from a number of sources for which the persistent flux is below their sensitivity limit. RXTE has seen a dozen sources which may not rise above $10^{36}$ ergs s$^{-1}$ during transient episodes. Several of these are believed to be neutron stars because Type I (cooling) bursts were observed.
They include the source SAX J1808.4-3658, unique to date, that both pulses (2.5 msec) and has Type I bursts.

Some sources have spectral and timing properties consistent with black hole candidates which go into the black hole “low hard” state, with strong white noise variability below 10 Hz and hard spectra. One of these was V4641 Sgr, which went into much brighter outburst, with a radio jet, before disappearing.

INSTABILITIES CLOSE TO THE COMPACT OBJECT

Kilohertz Oscillations for Neutron Stars - near the ISCO

More than 22 LMXB have now exhibited a signal at kilohertz frequencies in the power spectra of the x-ray flux (See [9]). Figure 3 (thanks to T. Strohmayer) shows results for samples of data from an atoll and a Z source. Usually this signal is two peaks at 1–15 % power. They indicate quasi-periodic oscillations with coherence (mean frequency/frequency width) as much as 100. The centroid frequencies are not constant for a source, but vary. Over a few hours the frequency is correlated with the X-ray flux, increasing with the flux. The flux variations of a factor of two are correlated with changes of frequency between 500 Hz and 1000
FIGURE 3. RXTE Power Density Spectra. (left) Atoll Source 4U1728-34. (right) Z Source Sco X-1. For each the grey scale plot of power as a function of frequency and time is shown for sequential observing intervals. The average PDS is shown above and the count rate during the observations on the right. One burst occurred during the 4U 1728-34 observation. The power spectra used are for 32 s data intervals.

Hz, approximately [10]. The highest reported is 1330 Hz, from 4U 0614+09. Considering that for a circular orbit at the Kepler radius \( r_K \), the observed frequency is

\[ f_K = \frac{2183}{M_1} \left( \frac{r_{ISCO}}{r_K} \right)^{3/2}, \]

where \( r_{ISCO} = 6GM/c^2 \) is the innermost stable circular orbit for a spherical mass \( M = M_1M_0 \) of smaller radius, neutron stars of masses \( M_1 = 1.6–2.0 \) would have Kepler frequencies at the ISCO of just such maximum frequencies as are observed.

While the luminosities of the sources exhibiting these QPO range from \( 10^{36} \) ergs s\(^{-1} \) to above \( 10^{38} \) ergs s\(^{-1} \), the maximum values of the upper frequency range only between 820 Hz and 1330 Hz. This suggests [11,12] that it represents a characteristic of the neutron stars fairly independently of the accretion rate. The ISCO and the neutron star radius are candidates. For lower fluxes, the frequencies, at least locally in the light curve, decline, as if the Kepler orbit were further out. Which is more likely, that the inner radius is then at the ISCO or at the radius of the neutron star? In the latter case the neutron star is outside the innermost stable circular orbit. Understanding the boundary requires consideration of the radiation pressure, the magnetic fields, and the optical depth of the inner disk. For sources with flux near the Eddington limit, the optical depth of the material near the surface should be much larger than the optical depth of the material accreting
at rates 100 times less. For the inner disk being at the ISCO, and fairly compact neutron stars, this plausibly does not matter. For the inner disk at the surface or a large neutron star, it seems hard to explain the similarity of appearance between luminous Z sources and fainter atoll sources. There are in fact differences in the appearance of the QPOs: one is that the amplitude of the QPOs is larger for the atoll sources than for the Z sources. So the situation is not completely clear.

If a disk is truncated at an inner radius which moves in toward the neutron star as the mass flow through the disk increases and a QPO is generated near this inner edge, the frequency would be likely to increase with the luminosity. The frequency would not be able to increase beyond the value corresponding to the minimum orbit in which the disk could persist. Miller, Psaltis, and Lamb [13] argued that if radiation drag was responsible for the termination of the disk, optical depth effects would lead to the sonic point radius moving in as the accretion rate increases. There would be a highest frequency corresponding to the minimum possible sonic point radius. In the cycles of 4U 1820-30 the frequency approached a maximum which it maintained as the flux increased further before the feature became too broad to detect. This kind of behavior would arise from a sonic point explanation.

From Figure 4, it can be seen that if the equation of state (EOS) of the nuclear matter at the center of a neutron star is very stiff, near the L equation of state, for \(1.4 - 2M_\odot\) neutron stars the radius of the star is close to its own ISCO; whether it is inside or outside it is depends sensitively on the mass. If the equation of state is softer, closer to the FPS EOS, interpretation of the maximum frequencies observed as a Kepler frequency at the surface would imply a mass significantly less than the \(1.4M_\odot\) with which many neutron stars are probably formed. In either case, moderately stiff EOS and maximum frequency at the ISCO, or stiff equation of state and maximum frequency either at the ISCO or the surface, the frequency would be from near the ISCO, if not just outside it. Accurate considerations require the rotation rate of the neutron star to be taken into account.

A characteristic of the twin kilohertz peaks is that when the frequency changes, the two frequencies approximately move together, with the difference approximately constant, at least until near the maximum frequencies (and luminosities) for which they are observed in a given source. This suggests a beat frequency and the relation between the difference frequency and the frequencies seen during bursts (See Strohmayer, this volume) suggest the neutron star spin as the origin of the beats. Miller, Lamb and Psaltis [13] explored how the two frequencies could be generated and Lamb and Miller refined the model in agreement with the 5% changes in the frequency separation, that are observed [14]. However, this varying separation between the two QPO also suggested identification as the radial epicyclic frequency of a particle moving in an eccentric orbit in the field of the neutron star. The lower of the two frequencies is then identified, not with a beat frequency, but with the precession of the periastron [15], although efforts to fit the predictions of this model in terms of particle dynamics produce implausibly large eccentricities, neutron star masses and spins [16]. Psaltis and Norman proposed that similar frequencies could be resonant in a hydrodynamic disk [17]. In these models, at least in their current
Constraints on the Neutron Star Equation of State from the kilohertz QPO. If the frequency of 1200 Hz is a Kepler frequency, the Mass of the star and the radius of the Kepler orbit are constrained. The orbit cannot be inside the ISCO. If it is at the ISCO the mass is determined and any EOS inside that radius which allow a big enough mass would support it.

forms, the difference between the two QPO peaks is not related to the spin, but to something like the radial epicycle frequency.

A quite different class of models are those in which the disk has a boundary layer with the neutron star and the plasma is excited by the magnetic field of the neutron star [18]. The magnetic pole makes a small angle with the neutron star rotation axis. In this case the lower kilohertz QPO frequency is the Kepler frequency, while both the upper frequency and the low frequency oscillation (corresponding to the Horizontal Branch Oscillations in Z sources) are related to oscillations of plasma interacting with the rotating magnetic field.

Hectohertz oscillations for Black Holes

Although accreting neutron stars and black holes should have important differences, they both presumably have an accretion disk with an inner radius, when the mass flow is high enough. Possible signals from the ISCO of black holes were discussed when accretion onto black holes was first considered [19] and anticipation of RXTE inspired detailed calculations [20]. The RXTE PCA has detected QPO in 5 black hole candidates at frequencies that are suitable to be signals from the ISCO of black holes in the range of $5 - 30M_\odot$. They have been observed only in selected
observations and are generally of lower amplitude (a few %) than the neutron star kilohertz QPO. For GRS 1915+105, the frequency has always been 67 Hz [21]. For GRO 1655–40, Remillard identified 300 Hz [22]. For XTE J1550–564, at different times it has been between 185 and 205 Hz [23]. For XTE J1859–262, a broad signal at 200 Hz is observed in the bright phases near the peak of the outburst [24]. For 4U 1630–47 as well, which has had 3 outbursts during the RXTE era, Remillard has reported 185 Hz. The black hole candidates have appeared to differ from the neutron stars in having one QPO rather than two. An obvious question is whether the second QPO is associated with the presence of a neutron star with a surface and a rotating magnetic dipole. Recent work by Strohmayer [25] casts doubt on it.

There were other black hole candidates observed with RXTE, which did not exhibit high frequency oscillations and the properties of the high frequency signal are not very well defined. Interpretation in terms of Kepler frequency at the ISCO, non-radial g-mode oscillations in the relativistic region of the accretion disk, and Lense-Thirring precession have been discussed. GRO J1655-40 is very interesting because the radial velocities of absorption lines of the secondary have given rather precise measurement of the mass. (The best estimates are so far $5.5 - 7.9 \text{M}_{\odot}$ [26].) In this case the mass well known and the black hole’s angular momentum can be the goal. The 300 Hz frequency is high enough that for a g-mode the black hole would have near maximal angular momentum, but if it represents a Kepler velocity, a Schwarzschild black hole would still be possible [27]. The question has been asked whether the microquasars GRS 1915+105 and GRO J1655-40 have powerful radio jets associated with outbursts because they have fast rotation [28].

**Decahertz Oscillations for Neutron Stars and Black Holes**

In the Z source LMXBs the first QPOs discovered were the Horizontal Branch Oscillations (HBO), first seen by EXOSAT, but then by Ginga. They occur in the range 15–50 Hz, have amplitudes as high as 30 %, increase in frequency with the luminosity, and have strong harmonic structure. With RXTE observations the atoll LMXB have also been seen to have these signals, although often the coherence is less and there are other signals (See [29]). These QPO tend to be near in frequency to the break frequency of band-limited white noise at low frequencies.

The black hole transients had already exhibited very similar features in Nova Muscae and GX 339–4 in the range 1-15 Hz. They have very similar properties to the HBO. RXTE PCA observations have found these QPO in the power spectra of most black hole candidates [30]. Different origins have been discussed for the neutron star and black hole QPOs, but their similarity is noted. Figure 5 shows examples from a Z source and a black hole candidate (See [31,32]).

The HBO were originally ascribed to a magnetic beat frequency model, assuming the Kepler frequency and the spin were both not seen. Stella and Vietri identified them with the Lense-Thirring precession (See [15]). They appear to have the correct quadratic relation to the high frequency kilohertz QPO. But the magnitude was too
FIGURE 5. Low Frequency Oscillations. (left) Horizontal Branch Oscillations in Cygnus X-2. (right) Decahertz Oscillations in the Black Hole Candidate 4U 1630-47. These are cases with similar harmonic structure, but a different relation to the break frequency of the lower frequency noise. States occur with very different harmonic structure.

high, by even a factor of about four. Assigning them to twice the nodal frequency, a reasonable possibility for the x-ray modulation, relieves the problem in some cases, but still leaves a factor of two in many. Psaltis argues that a magnitude discrepancy of a factor of two can be accommodated in situations where there is actually complex hydrodynamic flow rather than single particle orbits [33].

In the case of the black holes, the energy spectra seem to distinguish contributions of an optically thick disk and non-thermal, that is “power-law” emission, attributed to scattering of low energy photons off more energetic electrons. This division of components is not observationally so clear in the neutron star LMXB (There are many plausible reasons for this: lower central mass and smaller inner disk, X-rays generated on infall to the surface, possible spinning magnetic dipole.) For the black hole transients, this low frequency QPO is clearly a modulation of the power-law photons. However, there appear to be a variety of correlations with the disk behavior, so that the two components are clearly coupled.

In the case of the neutron stars Psaltis, Belloni, and van der Klis [34] have noted that the HBO and the lower kilohertz oscillation are correlated over a broad range of frequency (1–1000 Hz). Wijnands and van der Klis [35] showed that both the noise break and the low frequency QPO are correlated in the same way for certain neutron stars and black hole candidates. Psaltis et al. went on to point out that if some broad peaks in the power spectra of some black holes were taken to correspond to the lower kilohertz frequency in the neutron star sources, these points also fell approximately on the same relation.

While the degree to which this relation was meaningful, given the scatter in the points, selection effects, and distinctions of more than one branch of behavior, recent work is suggestive that in some way three characteristic frequencies of the disk in a strong gravitational field are significant, where these correspond to Kepler motion, precession of the perihelion and nodal precession. There remain difficulties however with specific assignments.

It has often been noted that different interpretations implied weaker features in
the spectrum, for example modulation of frequencies by the Lense-Thirring precession [16] or excitation of higher modes in the case of g-modes [27]. In the case of the neutron stars, adding together large amounts of data to build up the statistical signal, while Sco X-1 did not show sidebands [36], Jonker et al. [37] found evidence of sidebands at about 60 Hz to the lower kilohertz frequency in three sources. The frequency separation is not the same as the low frequency QPO in those sources although it is in the same range and Psaltis argues is close enough that second order effects can be responsible for the difference. It is not clear yet whether the sidebands imply a modulation of the amplitude or whether they represent a beat phenomenon and are one-sided.

CONCLUSIONS

While it has not yet been possible to fit all the properties of LMXB neatly into a model, it is hard to imagine alternatives for some important results. One of these is that in accordance with the theory of General Relativity, there is an innermost stable orbit, such that quasistatic disk flow does not persist inside it. Nuclear matter at high densities does not meet such a stiff equation of state that the neutron star extends beyond the ISCO. Instead the results suggest the neutron star lies inside the ISCO for its mass.

The accretion flows for both neutron stars and black holes have resonances which, from the observations, are apparently successfully coupled to X-ray flux. QPO are observed with high coherence. They can already be compared to assignments of various frequencies, but they do not match exactly with the identifications that have been made. However before it is possible to use it as diagnostic of gravity, it is necessary to sort out further the physics of the situations.

Extending the measurements to signals an order of magnitude fainter taxes even the abilities of RXTE. Continued observations are pushing the limits lower by reducing statistical errors, but must deal with intrinsic source variability on longer time-scales. Observations are also being sought of especially diagnostic combinations of flux and other properties.

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