Abstract

The Rossi X-ray Timing Explorer (RXTE) satellite was launched on 30 December 1995. It has made substantial contributions pertaining to compact objects and their environs. Broad-band spectral and short-time-scale temporal studies are exploring the effects of General Relativity in the regime of strong gravity. We present a brief outline of the principal contributions and then give a general overview of two new areas of x-ray astronomy that have proven by RXTE to be very fruitful: accreting neutron stars with millisecond spin periods and microquasars. The former pertains to the spin evolution of low-mass x-ray binaries and the equations of state of neutron stars while the latter lends insight to disk-jet interactions in galactic black-hole binary systems.

1 Mission status

The Rossi X-ray Timing Explorer (Bradt, Rothschild & Swank 1993) was launched on 30 December 1995. Since then it has carried out a diverse observing program that has been open to the entire astronomical community since a month after launch. It carries an All-Sky Monitor (Levine et al. 1996; Levine 1998) which, together with a flexible spacecraft pointing capability, permits rapid (hours) acquisition of new or recurrent
transient sources, sources entering new or interesting states, and gamma-ray burst afterglows. The pointed instruments are a large Proportional Counter Array (PCA; 2 – 60 keV; Jahoda et al. 1996) and a rocking High Energy X-ray Timing Experiment (HEXTE; 15 – 200 keV; Rothschild et al. 1998). All three instruments continue to operate close to their design state. It is hoped that operations can continue for several more years. There are no on-board expendables which would limit the spacecraft life.

Information about the mission as well as data products may be accessed on the web through: [http://heasarc.gsfc.nasa.gov/docs/xte/](http://heasarc.gsfc.nasa.gov/docs/xte/). The source intensities from the ASM are posted every few hours on: [http://heasarc.gsfc.nasa.gov/xte_weather/](http://heasarc.gsfc.nasa.gov/xte_weather/).

2 Scientific accomplishments: overview

The RXTE was designed to study compact objects and the material in their environs with emphasis on temporal studies with high statistics together with broad band-band spectroscopy. Over 150 papers had been accepted in the refereed literature by the summer of 1998. RXTE has been highly influential in conduct of science in many wavebands. Over 120 IAU Circulars had announced RXTE discoveries of immediate interest and these have been followed by numerous reports from other observatories, gamma-ray, x-ray, radio and optical. At [http://heasarc.gsfc.nasa.gov/whatsnew/xte/papers.html](http://heasarc.gsfc.nasa.gov/whatsnew/xte/papers.html), circulars and papers may be found.

The areas in which RXTE has made important contributions are listed here, with a few sample references. They are extracted from the Proposal to the 1998 Senior Review of NASA Astrophysics Missions Operations and Data Analysis authored by J. Swank, F. Marshall & the RXTE Users’ Group. Thereafter, I will give brief overviews, from my perspective, of two areas wherein RXTE has broken substantial new ground, namely, kiloHertz oscillations and microquasars.

1. Behavior of matter in regimes of strong gravity through the temporal and spectral signatures of kiloHertz pulsars and variability in microquasars (see refs. below).

2. Spinup evolution of neutron stars through the characteristics of kHz pulsars and the discovery of the first accretion powered millisecond pulsar (see refs. below).

3. Formation of relativistic astrophysical jets through the multiwavelength study of (galactic) microquasars (see refs. below).

4. AGN unified models and emission mechanisms through multiwavelength (esp. TeV) studies (e.g., Cantanese et al. 1997), detection of iron line and reflection components in individual Sy1 and Sy2 galaxies (e.g., Weaver, Krolik & Pier 1998, Nandra et al. 1998), and temporal studies with long term sampling with both the PCA and the ASM instruments. See for example the variability of the BL Lac objects Mkn 501 and Mkn 421 in Fig. 1.

5. High magnetic fields in neutron stars through the study of (1) the magnetosphere/disk boundary with low-frequency QPOs (e.g., Kommers, Chakrabarty & Lewin 1998), Type II bursts, the propeller effect (e.g., Cui 1997), and cyclotron lines (Kreykenbohm et al. 1999); (2) the discovery of the fastest rotation powered pulsar ($P = 16$ ms; Marshall et al. 1998), and (3) the discovery of x-ray pulsations supporting the identification of a magnetar, a neutron star with an extraordinarily high magnetic field ($2 \times 10^{10}$ T), as a soft gamma-ray repeater (Kouveliotou et al. 1998).

6. Transient sources through PCA slews and ASM monitoring which have revealed
~15 previously unknown sources and numerous recoveries of previously known sources, together with follow-on studies with the PCA and other observatories. Several new examples of radio-jet systems have been revealed (see below). Sample light curves from the RXTE/ASM extending over 2.5–yr are shown in Fig. 1.

7. State changes in binary systems through temporal/spectral tracking during major changes in x-ray flux and spectrum. In the case of Cyg X–1, a change of corona size is indicated (Cui et al. 1997).

8. Superorbital quasi periodicities in high and low mass binaries as well as in black-hole binaries through their discovery or confirmation with the ASM. (e.g., $P \approx 60$ d in SMC X1; See Fig. 1). Some are most likely due to precessing accretion disks similar to the 35–d period in the well known Her X–1. However, the evolution of wave forms and periods indicates relatively complex underlying physics (Levine 1998).

9. Gamma-ray burst afterglows through rapid position determinations with the ASM and PCA. Five burst positions with positions accurate to a few arcminutes in one or two dimensions have been reported to the community within hours of the event (Smith et al. 1999). One of the three known GRB with measured extragalactic red shifts (GRB 980703) was first located with the ASM on RXTE (Levine, Morgan & Muno 1998, Djorgovski et al. 1998). Another (GRB 970828) had a very bright afterglow in x rays but no discernable optical or radio afterglow (Remillard et al. 1997; Groot et al. 1998).

10. X-ray emission regions in cataclysmic variables through PCA tracking of eclipse transitions with precisions of tens of kilometers (e.g., Hellier 1997), and wind-wind collisions in Eta Carina through repeated PCA spectral observations (Corcoran et al. 1997).

11. Diffuse source spectra from the galactic plane (Valinia & Marshall 1998), supernova remnants (e.g., Allen et al. 1997), and clusters of galaxies (e.g., Rephaeli & Gruber 1999) to high energies (> 10 keV) with PCA and HEXTE.

3 KiloHertz oscillations in low-mass x-ray binaries

The most prominent area of RXTE accomplishment is that of kiloHertz oscillations. Relatively high-Q quasiperiodic oscillations (QPO) at kHz frequencies (up to 1230 Hz) in Low-Mass X-ray Binaries (LMXB) have been found in the persistent flux of 18 sources (as of this writing, Dec. 1998). Five of these, and one other, exhibit quite coherent, but transient, oscillations in the frequency range 290 – 590 Hz during Type I (thermonuclear) bursts. One additional source, a transient, exhibited sustained coherent pulsations at 401 Hz with Doppler shifts characteristic of a binary orbit. Reviews of the field may be found in van der Klis (1998, 1999).

These new phenomena are probing the processes taking place close to the neutron stars where the effects of General Relativity are important. For example, if the highest-frequency kHz QPO observed in a given source is interpreted as the Kepler frequency of the inner accretion disk, it should be limited by the frequency of the innermost stable orbit allowed in general relativity ($r = 6GM/c^2$ for Schwarzschild geometry). Since 17 of the sources exhibit maximum frequencies in the relatively narrow 1000–1200 Hz range, these frequencies may indeed represent the innermost stable orbits. The phenomenon is also placing constraints on the equations of state of neutron stars.
as we illustrate below.

The first discovered examples of the quasi-periodic oscillations at kHz frequencies were in Sco X-1 (van der Klis et al. 1996) and 4U 1728–34 (Strohmayer et al. 1996). These QPO usually occur in pairs. As the source intensity increases, the two QPO generally increase in frequency with a frequency difference that remains approximately constant (Strohmayer et al. 1996); see Fig. 2.

If the higher-frequency peak of the pair is the Kepler velocity of a blob of orbiting disk material, the lower-frequency peak could arise from the interaction of the blob with the magnetosphere which is co-rotating with the spinning neutron star. The observed lower frequency would thus be a beat frequency, such as that postulated for QPOs at much lower frequencies (≤ 60 Hz) in the 1980’s (Alpar and Shaham 1985, Lamb et al. 1985). The difference of the two frequencies would be the neutron-star spin frequency. For the 17 sources that exhibit two frequencies, the differences range from ~250 to ~350 Hz, indicating neutron-star spins in this range. (See Table 1 in van der Klis 1999.)

The increase of frequency of the oscillations with intensity (Fig. 2) can be understood in this picture as being due to an increase in the Kepler frequency arising from a decrease in the size of the magnetosphere caused, in turn, by the increased ram pressure of the accreting material (Ghosh & Lamb 1992). In fact, the source 4U 1820–30 exhibits frequencies that increase with flux until they saturate at about 1060 Hz and 800 Hz (Fig. 3). This suggests that the innermost stable orbit has been reached (Zhang et al. 1998b). But since this plot is a compilation of data from different observations that might have differing intensity-frequency relations (see below), the effect could be an artifact (Mendez et al. 1999).

If indeed the maximal frequencies represent the innermost stable orbits, the highest observed frequency seen to date (1228 Hz) yields a neutron star mass of ~2.0 $M_\odot$, which is significantly above the canonical 1.4 $M_\odot$. Further, the radius of the neutron star must not exceed the radius of the Kepler orbit corresponding to the maximum observed frequency in a given source. This limit, together with the marginally stable orbit just discussed above, places constraints on allowed equations of state for neutron stars (Miller, Lamb & Psaltis 1998, see Fig. 4). The current limits do not yet distinguish among the plotted equations of state, but the potential for doing so is clearly there.

The interpretation that the difference frequency is the neutron-star spin frequency gains credence from the discovery of nearly coherent pulsing during x-ray bursts in several sources at about, or at about twice, the difference frequency (e.g., Strohmayer et al. 1996). The frequency of the burst oscillations in 4U 1728–34 is stable from burst to burst within about 0.01% over a period of 1.6 years (Strohmayer et al. 1998; Fig. 5). This stability is a strong indicator that these pulsations directly represent the neutron-star spin. They could arise from a transient hot spot (or hot spots) in the runaway thermonuclear burning on the neutron-star surface (Bildsten 1995). If there were a hot spot at each of two opposed magnetic poles, the detected frequency would be twice the spin frequency.

This picture needs refinement or modification for several reasons: (1) the frequency difference as a function of intensity (or of one of the two frequencies) is not constant in Sco X–1 (van der Klis et al. 1997), 4U 1608 (Mendez et al. 1998), 4U 1735–44 (Ford et al. 1998), and possibly in all sources (Psaltis et al. 1998); (2) the frequencies in bursts are not strictly 1.0 or 2.0 times the difference frequencies in all sources, especially in 4U
1636–536 (Mendez, van der Klis & van Paradijs 1998), (3) there are small frequency drifts during a single burst (Fig 5), and (4) although there are correlations between source intensity and QPO frequency on short time scales (hours), the correlations do not hold up over long periods (days); very different intensities can yield the same QPO frequency, e.g., in Aql X–1 (Zhang et al. 1998a). These problems are not necessarily fatal to the basic picture; there are various proposed scenarios to explain the discrepancies. Alternatively, the answers could lie in very different directions, see, e.g., Stella & Vietri (1999).

The so-called discrepancies are actually excellent probes with which to verify or discard theoretical models. For example, the frequency difference as a function of intensity in Sco X–1 requires quantitative understanding; see, for example, Stella & Vietri 1999. Also, the frequency vs intensity dilemma (item 4 above) has been clarified by the discovery of monotonic mapping of frequency with position in the color-color diagram of 4U 1608–52 (Mendez et al. 1999).

Finally, as noted above, the beat-frequency model was originally introduced to explain some of the lower-frequency quasi-periodic oscillations (~ 6 - 60 Hz) in LMXB in the 1980’s. One cannot explain both kinds of oscillations (low-frequency and kHz) in the same source with this one model. Attempts to rationalize these phenomena include (1) a sonic-point model to explain the kHz oscillations as arising from interactions between radiation and orbiting blobs at the sonic-point radius (Miller, Lamb & Psaltis 1998), (2) nodal precession of the inner disk, dominated by the Lense-Thirring effect, to explain the lower-frequency oscillations (Stella & Vietri 1998), and (3) periastron precession to explain the lower-frequency peak of the kHz twin peaks (Stella & Vietri 1999). The latter model can reproduce the changes in the frequency difference but does not attempt to explain the apparent coincidences with the frequencies of the kHz QPO during bursts in some sources. Strong-field GR is required to calculate the periastron-precession frequency. Thus, as pointed out by the authors, if their model is validated, the kHz QPO phenomenon provides an unprecedented testbed for strong-field General Relativity.

These indicators of the neutron-star spin are only indirect (through the beat frequency) or fleeting (during bursts). The detection of coherent, persistent, accretion-powered pulsing at millisecond periods had so far eluded RXTE researchers. This elusive goal was reached with the recent (April 1998) RXTE discovery of highly coherent 401–Hz x-ray pulsing in the persistent flux of a transient source (Wijnands & van der Klis 1998). A binary orbit was easily tracked with the Doppler shifts of the 401–Hz pulsations (Chakrabarty & Morgan 1998, Fig. 6). The orbital period is 2.01 hr which indicates a companion mass less than 0.1 $M_\odot$.

The Doppler variation demonstrated without doubt that the pulsations arose from the neutron-star spin. The source thus became the first known accretion-powered millisecond pulsar. The source had been detected in a previous transient episode (September 1996) with the SAX Wide Field Camera (and also in RXTE/ASM data retrospectively) and two x-ray bursts were observed from it (in ’t Zand et al. 1998). It is known as SAX J1808.4–3658. The rapid pulsing discovery occurred during a later outburst (April 1998) that was revealed in RXTE/PCA data during a spacecraft slew (Marshall 1998).

These discoveries of millisecond-period x-ray sources fill an important link in the spin evolution of neutron stars. It had long been postulated that millisecond radio
pulsars are spun up in x-ray binaries (Radhakrishnan & Srinivasan 1982, Alpar et al. 1982), and LMXB were prime candidates because of their lack of coherent pulsations at lower frequencies. This long-sought evolutionary link has now been established. This is the successful attainment of one of RXTE’s major goals.

4 Microquasars

Another area of major accomplishment by RXTE is that of “microquasars”. The discovery of transient galactic x-ray emitting objects with superluminal radio jets, GRO 1655–40 and GRS 1915+105 (e.g., Tingay et al. 1995, Mirabel & Rodriguez 1994), and the well-determined high mass ($7.0 \pm 0.2 M_\odot$) of the compact object in GRO 1655–40 (Orosz & Bailyn 1997) focused attention on the fact that counterparts of (black-hole) quasars are close by in the Galaxy. Their proximity allows studies with much higher statistics, and their lower (stellar) masses lead to much smaller time constants for motions of matter in the vicinity of the compact object. The time constants scale linearly with mass, e.g., the orbital period of Kepler matter in the innermost stable orbit. Thus a 1–year intensity variation in the vicinity of a $10^8 M_\odot$ quasar would occur in 3 s in a galactic $10 M_\odot$ microquasar.

Other galactic x-ray sources are known to exhibit evidence for radio jets through episodic non-thermal radio emission and/or diffuse emission or resolved jets. These include the long-known Cyg X–3, GX 339–4, Cir X–1, SS433 and Cyg X–1 (see van Paradijs 1995 for references), and also the RXTE discovered or recovered transients XTE J1748–288 (Rupen & Hjellming 1998), GRS 1739–278 (Hjellming et al. 1996, Durouchoux et al 1996) and CI Cam (Hjellming & Mioduszewski 1998). One of these sources, Cir X–1 most likely contains a neutron star (Tennant, Fabian & Shafer 1986, Shirey, Bradt & Levine 1999), and another, CI Cam, is a symbiotic system. Altogether these sources are a rich resource for the understanding of the role accretion disks play in jet formation.

It is fortunate that the superluminal sources GRS 1915+105 and GRO 1655–40 have exhibited extensive activity during the RXTE mission. GRO 1655–40 was active for about 16 months beginning in April 1996, and GRS 1915+105 has been active since the beginning of the mission. The latter source exhibits a variety of states in its long-term variability as measured with the RXTE/ASM (Fig. 7). In the high-statistics data from the RXTE/PCA, its x-ray variability is dramatic and varied, including rapid oscillations, sudden dips, sharp spikes, etc., all accompanied with spectral changes (Fig. 8; Greiner, Morgan & Remillard 1996, Morgan, Remillard & Greiner 1997, Taam, Chen & Swank 1997).

Next, I present briefly three areas of substantive progress in microquasar studies.

4.1 Initiation of accretion

The sudden turn-on of GRO 1655–40 in x rays was fortuitously monitored in BVRI during the week just prior to the x-ray turn on (Fig. 9; Orosz et al. 1997). A linear increase of flux was seen in all four bands. It began first in the I band, 6.1 d before the commencement of the linear x-ray rise. The increases in the R, V and B bands commenced systematically later with the latter occurring 5.0 days before the
x-ray commencement. This sequence suggests that the initiating event of a transient outburst was a wave of instability propagating inward in the disk (Lasota, Narayan & Yi 1996). This is an important breakthrough in the determination of the causes of x-ray nova outbursts.

4.2 Accretion-jet correlations

There have been clear coincidences between radio/infrared non-thermal flares and x-ray events, both on the longer time scales of the ASM data (Pooley & Fender 1997) and shorter-term events in the PCA data (Pooley & Fender 1997, Eikenberry et al. 1998, Mirabel et al. 1998). The latter type of x-ray event consists of a large x-ray dip (~15 minutes) that contains a pronounced spike (Fig. 8, bottom panel). Such an event is associated with an infrared flare and a delayed radio flare as shown in an event captured by Mirabel et al. (1998, Fig. 10). Five and possibly six IR/x-ray coincidences of this type were reported by Eikenberry et al. (1998) and in no case was the coincidence violated!

These x-ray dips are repetitive, occurring irregularly at intervals of a half hour or so (Fig. 8). The source may reside in this state for hours to days. This is only one of several oscillatory states in which the source can find itself; see Fig. 8. The spectral evolution of an infrared/radio flare has been shown to represent a single relativistically expanding plasmoid (Eikenberry & Fazio 1997, Mirabel et al. 1998, Fender & Pooley 1998). These IR/radio events are small, i.e., mini flares. A series of them emitted when the source is in this state could give rise to a single large superluminal outburst. It thus appears that the jets are quantized, not continuous, and that RXTE is seeing the “pump” that creates them!

X-ray spectral fits (Fig. 11, Swank et al. 1997) during these events show a softening of the disk-black body component, which can be interpreted as the disappearance of the inner part of the disk as proposed by Belloni et al. (1997a,b). Thereafter, the gradually increasing temperature and decreasing radius of the disk component would represent the refilling of the disk. The power-law component suddenly softens at a sharp x-ray spike near time 1600 s when the disk is nearly full. Mirabel et al. (1998) suggest that this spike is the initiating event of the flare (see the IR flare in Fig. 10). The frequency of the associated low-frequency QPO (Fig. 11) appears qualitatively to track the disk radius as if it were the Kepler frequency at this or an associated radius. But the situation is not this simple given the existence of other QPOs, e.g., 67 Hz, in the system (see Remillard et al. 1999).

As noted, GRS 1915+105 exhibits some half dozen states with different temporal/spectral variability, not all of which fit this simple disk-depletion picture. Additional multifrequency studies are needed as are more comprehensive models.

4.3 High-frequency QPO in Microquasars

The microquasars exhibit quasi periodic oscillations (QPO) that are quite variable in frequency and also some that are relatively stable. These QPO have a large potential for probing the physics of the systems. The highest frequencies (Fig. 12), namely 67 Hz in GRS 1915+105 (Morgan, Remillard & Greiner 1997) and 300 Hz in GRO 1655–40 (Remillard et al. 1999) do not drift in frequency. They have led to intriguing
speculation about their origins. The high frequencies place them close to the central black hole, and models usually invoke General Relativity. Suggested origins include the innermost stable orbit (Morgan et al. 1987), Lense-Thirring precession (Cui, Zhang & Chen 1998), diskoseismic oscillations (Nowak, et al. 1997), and oscillations in the centrifugal barrier (Titarchuk, Lapidus, Muslimov 1998).

Some investigators are using these data and models to arrive at the angular momentum of the central black hole. The black-hole mass, $7.0 \pm 0.2 \, M_\odot$, of GRO 1655–40 and the 300–Hz oscillations in this source suggest negligible black-hole angular momentum if the oscillations are the Kepler frequency of the innermost stable orbit. On the other hand, if the 300 Hz oscillations are due to Lense-Thirring precession in the inner disk, they imply a maximally rotating black hole (Cui, Zhang & Chen 1998). The latter view gains some support from the measured high disk temperature which is indicative of the small inner disk radius expected for prograde orbital motion of a maximally rotating black hole (Zhang, Cui & Chen 1997). These conclusions are highly model dependent and therefore uncertain. Nevertheless, it is impressive to that the angular momentum of black holes is now being addressed by the community with data from RXTE. This was not dreamed of even a few years ago.

All in all, it is clear that the jet formation processes, the conditions of disk stability, and the formation of the power-law component are being explored with a powerful and effective tool, namely the temporal/spectral/statistical power of RXTE. The behavioral detail now being acquired from microquasars extends well beyond that which can be obtained from the much more distant extragalactic quasars.

### 5 Conclusions

The RXTE is making important strides in the study of compact objects, both galactic and extragalactic, in a wide variety of studies by a large international community of observers.

The discovery of 401–Hz kHz coherent pulsations in a low-mass x-ray binary has established definitively an important link in the evolution of neutron stars. The kHz QPO in 18 systems and coherent pulsations during bursts give additional strong indications of neutron-star spins at frequencies of a few hundred Hz. These QPO provide information about the behavior of matter in the immediate vicinity of the neutron star and are placing limits on the possible equations of state of neutron stars.

The temporal/spectral signatures of the various behaviors in microquasars are diverse, yet repeatable and well described with high statistics. They are powerful probes of these systems and should serve as powerful discriminators of models. At the same time, the complexity makes difficult the construction of a comprehensive model of the emission processes. The results currently point toward black-hole masses and angular momenta, the nature of disk instabilities, and the precise events that initiate the jets signifies by radio/IR flares. These results clearly have applicability to extragalactic quasars.

The temporal variability of x-ray spectra can, in principle, track the changing geometry of the several physical components of the system (e.g., disk and corona). However this requires that these physical components be securely identified with the spectral components. This is a major challenge now confronting microquasar researchers.
RXTE studies are probing phenomena where strong General Relativity is important because of the proximity of the emitting plasmas to the central gravitational object. For example, frame dragging has been invoked for some high frequency QPOs, and the orbital frequency at the innermost stable orbit may have been encountered in LMXB systems. Measurements of these and other GR effects are now within the realm of RXTE capabilities.

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Figure Captions

Fig. 1. Sample of All-Sky Monitor light curves from Mar. 1996 to June 1998 showing, top to bottom, a microquasar, the flare star CI Cam, two black-hole binaries, probable disk precession in a neutron-star binary, and two faint BL Lac objects. The ordinate is count rate adjusted to the center of the field of view of a single ASM camera; the Crab nebula would yield \( \sim 75 \) c/s. (A. Levine, pvt. comm.)

Fig. 2. Power density spectra of 4U 1728–34 in three intensity states. Low frequency QPO are evident at 20–40 Hz as are two peaks at \( \sim 1 \) kHz which move to higher frequencies as the intensity increases. (From Strohmayer et al. 1996)

Fig. 3. Frequency of the two QPO’s at kHz frequencies in 4U 1820–30 as a function of intensity. The saturation suggests that the innermost stable orbit has been reached, but this conclusion has been questioned — see text. (Zhang et al. 1998)

Fig. 4. Constraints on mass and radius of neutron star in the non-rotating approximation. The highest frequencies detected limit the neutron star mass to \( \sim 1.8 \, M_\odot \). If rotation is taken into account, the limits will increase up to at most \( 2.2 \, M_\odot \). (Miller, Lamb & Psaltis 1998)
Fig. 5. Dynamic power spectra of two bursts from 4U 1728–34 separated in time by 1.6 y. In each case, the frequency settles to a stable period at 364.0 Hz with frequencies that agree within 0.03 Hz. (From Strohmayer et al. 1998)

Fig. 6. Doppler curve for the 401–Hz pulsar discovered with RXTE. The maximum delay is 63 ms, and the binary orbital period is 2.01 h. (From Chakrabarty & Morgan 1998)

Fig. 7. RXTE/ASM light curve of GRS 1915+105 with hardness ratio (5–12)/(3–5) from Mar. 1996 through Sept. 1998. The marks at the top indicate the times of PCA pointings. (R. Remillard, pvt. comm.)

Fig. 8. Three types of variability of GRS 1915+105 in RXTE/PCA data (E. Morgan, pvt. comm.)

Fig. 9. Precursor outburst activity in GRO 1655–40. The source intensity is shown in the optical (BVRI bands) and in the delayed x-ray flux. The onset times are progressively later and later as the radiation band hardens. (Orosz et al. 1997)

Fig. 10. Large x-ray dip with spike with simultaneous radio and infrared flares in GRS 1915+105. Other x-ray dips of this type are shown in the bottom panel of Fig. 8. (Mirabel et al. 1998)

Fig. 11. X-ray character of GRS 1915+105 during and near a dip+spike event, from RXTE data. Top to bottom: x-ray light curve, inner disk temperature, inner-disk radius, photon index of power-law component, dynamic power spectrum. (Swank et al. 1998)

Fig. 12. Power density spectra of two microquasars showing the high frequency and apparently stable QPOs at 67 Hz and 300 Hz. (Morgan, et al. 1997, Remillard et al. 1999)
This figure "fig1.gif" is available in "gif" format from:

http://arxiv.org/ps/astro-ph/9901174v1
SAX J1808.4−3658
Chakrabarty & Morgan (1998)

\[ \alpha \sin i = 62.809(1) \ \text{lt-ms} \]
\[ P_{\text{orb}} = 7249.119(1) \ \text{s} \]
\[ T_{\pi/2} = \text{MJD} \ 50914.899440(1) \]
\[ e < 5 \times 10^{-4} \ (2\sigma) \]

Epoch MJD 50915.0
\[ \nu = 400.9752106(8) \ \text{Hz} \]
\[ |\nu| < 7 \times 10^{-13} \ \text{Hz s}^{-1} \ (2\sigma) \]
This figure "fig7.gif" is available in "gif" format from:

http://arxiv.org/ps/astro-ph/9901174v1
