Rossi X-ray Timing Explorer

Proposal to the 2004 Senior Review of
Astrophysics Mission Operations & Data Analysis Programs

J. H. Swank (Project Scientist), F. E. Marshall, (SOC Director) and the *RXTE* User's Group

Summary

The prime objective of the *Rossi X-ray Timing Explorer (RXTE)* is the study of astrophysical compact objects: black holes (galactic and extragalactic), many types of neutron stars, and accreting white dwarfs. *RXTE*'s capability for rapid timing is unique among all past and present X-ray observatories, and no other rapid timing instrument is planned for more than a decade. The qualitatively new discoveries made with *RXTE* about dynamical timescale phenomena related to neutron stars and black holes would have been impossible otherwise, and such discoveries in the next several years will also require *RXTE*. These phenomena probe basic physics in the most extreme environments of gravity, density, and magnetic fields, addressing key objectives of NASA's Strategic Plan. The last two years have seen *RXTE* continue to achieve many dramatic new scientific milestones, especially in the realm of kilohertz timing results. In addition to its unparalleled timing capability, the ability to re-point *RXTE* quickly has led to breakthroughs in many areas of compact object astrophysics. The current high level of productivity, unique capabilities, and capacity for multi-observatory programs with ground- and space-based telescopes such as *Chandra*, *XMM-Newton*, and *INTEGRAL* all argue strongly for continuing the *RXTE* mission at this time.

1. Science Proposal

1.1. Introduction and Overview

Neutron stars and black holes are the only known laboratories where we can directly witness the motion of matter in regions of strong-field, relativistic gravity. Neutron stars provide our only look at macroscopic nuclear density matter. Their magnetic fields are the highest known. *RXTE* studies of these objects provide a unique probe of physics at the extremes of theory.

Since beginning observations in 1996, *RXTE* has had a tremendous impact on high energy astrophysics. In 2002–2003, *RXTE*-related results appeared in 310 papers from refereed journals, and 710 abstracts in total (over the mission lifetime, these quantities are 1017 and 2800, respectively). Timely results in IAU Circulars and Astronomer's Telegrams have increased from 88 to 139 between 2000–2001 and 2002–2003. Some of the many new discoveries made with *RXTE* are listed below and discussed in some detail throughout this proposal. These discoveries are probing a broad range of physics in extreme environments: direct measurement of neutron star magnetic fields, constraints on the equation of state (EOS) of nuclear-density matter, the physics of thermonuclear burning and nucleosynthesis on neutron stars, the evolution and composition of ultra-compact binary systems, the nature of accretion flows, the masses and spins of black holes, and the relativistic outflow of matter in jets and winds. The proceedings of the workshop "X-Ray Timing 2003: Rossi and Beyond", held in November 2003, includes many reviews of these results.

Our primary goal in this proposal is to demonstrate how and why, at this point in its mission, *RXTE* is still making key progress on its most fundamental science questions. We do this by describing the new discoveries and their importance. However, we first describe some of the practical reasons why continued observations with *RXTE* are essential to further breakthroughs in our understanding of compact objects.

Many of the most important targets for *RXTE* science are transient, meaning that they appear suddenly, must be identified and then studied or the opportunity is lost, perhaps forever. *RXTE* uses its All Sky Monitor (ASM), as well as dedicated monitoring with the Proportional Counter Array (PCA), to mine the sky for new and recurrent transients. For example, transient sources of key importance to *RXTE* are the accreting millisecond pulsars. Indeed, *RXTE* has discovered pulsations from all five of these objects. A new goal for the next 4 years of operations will be to attempt to double their discovery rate. We discuss below how this is achievable.

Many transient sources enter important states in which, for example, they produce pairs of kilohertz oscillations or X-ray bursts, only rarely, so that persistent searches, followed by careful monitoring are required to obtain the crucial new discovery. Moreover, it may take looks at several outbursts of a source to find an especially vital piece of information. From the last two years of operation it is clear that such discoveries continue to be made. It simply requires *RXTE*'s unique capabilities to unearth them. Without the *RXTE* mission many such discovery opportunities will be lost.

Highlights of *RXTE* Discoveries 2002–2003

- Three new accreting millisecond pulsars (Figure 1), showing an unexpected preference for very short binary periods.
- Burst oscillations in *two* accreting millisecond pulsars, that identify the oscillations as the spin.
- The first harmonic signals in burst oscillations, constraining the neutron star mass and radius (Figure 3)
- Twin kilohertz (quasiperiodic oscillations) QPOs in *two* accreting millisecond pulsars (Figure 2), showing the spin is related to the QPO frequency separation.
- The first measurement of accretion disk properties during a superburst, measuring the inner disk radius.
- Discovery of a transient magnetar, implying a hidden population.
- Flux changes in a bursting Anomalous X-ray Pulsar (AXP), like those of Soft Gamma Repeaters (SGRs).
- A young pulsar-like glitch in an AXP (Figure 5).
- A new black hole system with high frequency QPOs in a 3:2 ratio, strengthening the case for a relativistic resonance interpretation (Figure 6).
- A cyclotron line in a transient pulsar, detected by HEXTE, bringing to 14 the number of cyclotron lines indicating magnetic fields, temperatures, and optical depths (Figure 4).
- Discovery of new outbursts from two historical black hole transients, providing information about the distribution of recurrence times.
- A Seyfert (AGN) with strong X-ray/optical correlation, suggesting that the emissions are cospatial for a high mass nucleus (Figure 9).

The Focus for 2005–2008 *RXTE* Observations

In the sections that follow we discuss in more detail the implications and importance of the new results, summarized in the box above. These new insights on millisecond variability, which only *RXTE* can obtain, provide a focus for the next four years of operations. We describe remaining goals for future observations throughout, but emphasize the most important of these here.

Accreting millisecond pulsars provide perhaps the most important and unique *RXTE* science opportunities. The five known sources represent the beginnings of a statistically meaningful sample, however, in order to understand the formation and evolution of such systems, the spin and orbital period distributions need to be much better sampled. To systematically probe the masses and radii of neutron stars new examples of pulsar burst oscillations need to be found. Two examples of kilohertz oscillations in pulsars have settled key questions, but more examples are needed to better clarify the relation between the QPO frequencies and the spins. In order to maximize this opportunity, we plan to increase our millisecond pulsar monitoring programs, in terms of area of the sky probed, in order to increase the discovery rate, with a goal a factor of ~ 2 improvement. This will be accomplished by extending dedicated PCA monitoring to more of the Galactic plane.

So far *RXTE* has discovered seven black hole systems with high frequency QPOs (Figure 6), four of them with at least two high frequencies. These have been significant findings, and have allowed the first suggestive correlations with mass (Figure 7) using the three for which there are dynamical mass measurements, but three is not yet enough to accurately define the QPO frequency – mass relation. The occurrence of these QPOs is not yet fully predictable, but correlations with the early, bright phases of transients and so-called steep power law (SPL) states are very suggestive. In order to obtain more QPO detections, longer observations of such states will be a high priority for future observations. Transient black hole candidates will continue to be pursued even when they do not exhibit very-high states or high frequency QPOs. Radio emission and jet production have been seen at the onset, at state transitions, and in the low hard state. Sensitive radio coverage is now available to further enable exploration of this connection. Thus, all black hole transient outbursts will receive increased priority.

1.2. Neutron Stars

1.2.1. Spins

Millisecond Pulsars. Since the last Senior Review *RXTE* has discovered three new accreting millisecond pulsars; XTE J0929−314, XTE J1807−294, and XTE J1814−338, with spin frequencies of 185 Hz, 191 Hz, and 314 Hz, respectively. In addition to these discoveries, a new outburst of SAX J1808.4−3658 (the first accreting millisecond pulsar) was detected and monitored extensively. These new observations have had an enormous impact on our understanding of the high frequency variability seen in accreting neutron stars, the formation of millisecond pulsars, and the evolution of ultra-compact binary systems.

The new observations of SAX J1808.4−3658 and XTE J1814−338 led to the detections of both persistent pulsations and oscillations during thermonuclear bursts (“burst oscillations”) *in the same source*. This has established beyond any doubt that burst oscillations are produced by spin modulation of the burst flux from the neutron star surface, and therefore provide a direct measure of the spin frequency of neutron stars. The first detections were made in SAX J1808.4−3658 (Chakrabarty *et al.* 2003; in ’t Zand *et al.* 2001). Four bursts were observed, each of which showed oscillations consistent with the 401 Hz spin frequency measured from the persistent pulsations. Indeed, the relative phasing of the oscillations during the bursts is very close to that of the persistent

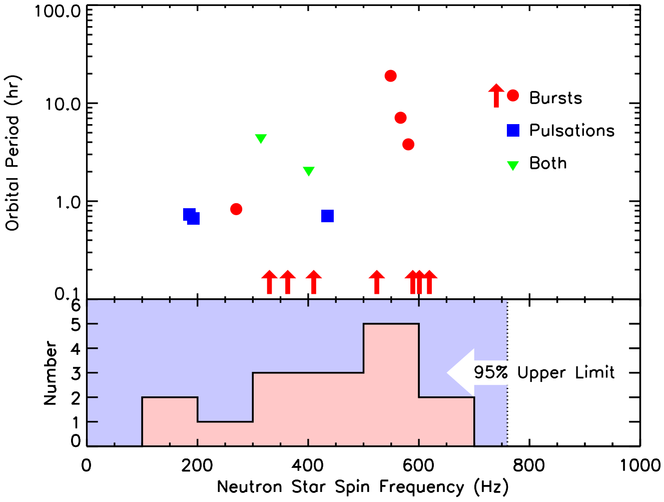

Fig. 1.— Distributions of low mass X-ray binary neutron star spins. (upper) Frequencies and binary periods of 5 millisecond pulsars and 11 bursters with oscillations. (lower) Histogram of spin frequencies, showing the 95% population upper limit for neutron star spin derived by Chakrabarty *et al.* (2003).

pulsations, suggesting a common source of the asymmetry which produces the modulations, perhaps the stellar magnetic field. The oscillations during one burst showed a 4 Hz frequency drift during the burst rise.

RXTE monitoring of the outburst of XTE J1814−338 led to the observation of 27 X-ray bursts. All the bursts showed oscillations at the 314 Hz spin frequency. The burst oscillations in XTE J1814−338 are strongly phase locked to the persistent pulsations, again, indicative of a dynamically important magnetic field (Strohmayer *et al.* 2003). The bursts from XTE J1814−338 led to another new discovery, the first detection of harmonic structure in the pulse profiles of burst oscillations. This is important because the harmonic content of the pulse profiles encodes important information on the mass and radius of the neutron star, and therefore the equation of state (EOS) of super-dense matter. Modeling of the burst oscillation profiles from XTE J1814−338, and the derived neutron star constraints, are described in more detail below (Section 1.2.3). Additional detections of burst oscillations with harmonic content from newly discovered pulsars would enable more comprehensive studies of neutron stars and their exotic interiors.

Burst Oscillations. With confirmation that burst oscillations reflect the spin rates of neutron stars, the observed distribution of burst oscillation frequencies gains added importance, because it can be used to set constraints on the maximum spin rates of neutron stars. This is exciting because the maximum spin rate of a neutron star also depends directly on the EOS. Chakrabarty *et al.* (2003) argued that the observed distribution, which spans the range from 270–619 Hz, more or less uniformly, indicates an upper limit of about 760 Hz. Figure 1 shows the distribution of frequencies. Unlike radio observations, *RXTE* is not biased against ∼millisecond spin frequencies, hence the observed upper limit provides direct evidence for a braking mechanism such as magnetic torque (Ghosh & Lamb 1979) or gravitational radiation (Wagoner 1984; Bildsten 1998).

Evolution of Ultra-Compact Binaries. From the new pulsar discoveries it is now clear that a population of transient, low luminosity, ultra-compact binaries exists in the Galaxy and that these systems are a likely channel for the formation of isolated millisecond radio pulsars. Of the 5 systems now known, 3 have minimum companion masses in the $\sim 0.01 M_\odot$ range. This is in the range of massive planetary bodies ($\sim$ 10 Jovian masses). The ultra-compact systems are too small to contain hydrogen-rich companions, so the donor stars in these systems are almost certainly helium-rich and the product of evolution with mass transfer after a common envelope phase (Nelson & Rappaport 2003) which determines the minimum orbital period. The existence of such systems was unknown prior to 2002 observations by *RXTE.* The binary periods of the millisecond pulsars and the burst sources (where known) are also shown in Figure 1.

1.2.2. Strong Gravity and Accretion Flows

Kilohertz QPO. Discovered with *RXTE* in 1996, kilohertz (kHz) QPOs have now been detected in 25 neutron star (Low Mass X-ray Binaries) LMXBs. Two QPO peaks at frequencies ν_1 and ν_2 are seen in the power spectra of X-ray flux variations. The QPOs are strongly correlated with variations in X-ray flux. On time scales of hours the peaks move together in frequency by hundreds of Hz while maintaining a separation, $\Delta\nu = \nu_2 - \nu_1$, that varies by a few tens of Hz at most. The phenomenon is *never seen* in black holes and is a new neutron star signature on a par with pulsations and X-ray bursts. With frequencies up to $\sim$ 1300 Hz—equivalent to the orbital frequency mere kilometers above the surface of a $1.4 M_\odot$ neutron star—kilohertz QPOs provide direct information about the motion of matter in the strong gravity near neutron stars.

In stars where kHz QPOs and burst oscillations occur together (Section 1.2.1), $\Delta\nu$ is within a few tens of Hz of the burst oscillation frequency ν_{burst} (for $\nu_{burst} < 400$ Hz) or near half that frequency (for $\nu_{burst} > 400$ Hz). To account for this a spin-orbit beat frequency interpretation was proposed shortly after their discovery in which the burst oscillations occur at once or twice the spin frequency ν_{spin}; ν_2 is an orbital frequency ν_{orb} in the inner accretion disk; and ν_1 is the beat frequency $\nu_{orb} - \nu_{spin}$ of the orbital frequency with the spin frequency (Miller *et al.* 1998). To account for observed variations of $\Delta\nu$ from the burst oscillation frequency (or half it), other models were proposed. These attempted to explain not only the kHz QPOs but also the 10–80 Hz low-frequency

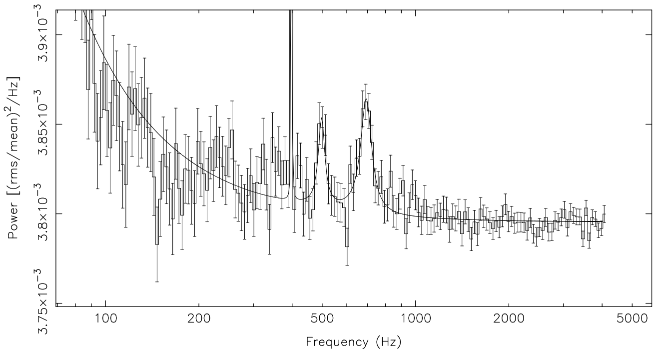

Fig. 2.— Power spectrum of SAX J1808.4−3658 showing the pulsar spike at 401 Hz and twin kHz QPO peaks near 500 and 700 Hz. After Wijnands *et al.* 2003 Nature.

QPOs (whose frequencies vary in correlation with ν_1 and ν_2) in terms of general relativistic orbital and epicyclic frequencies in the accretion disk (Stella & Vietri 1999, Stella *et al.* 1999). These relativistic precession models required neutron star spins up to 900 Hz, much higher than those inferred from the beat frequency model or the burst oscillations.

A key breakthrough since the last Senior Review has been the discovery of twin kHz QPOs and burst oscillations in an accreting millisecond pulsar, SAX J1808.4−3658, which has definitively settled the relationship between $\Delta\nu$ and the neutron star spin.

New Results. New observations in 2002 of the 401 Hz accreting millisecond pulsar SAX J1808.4−3658 show twin kHz QPOs with a peak separation $\Delta\nu$ of 195 ± 6 Hz, consistent with half the spin frequency (Figure 2; Wijnands *et al.* 2003). This confirms that kHz QPO frequencies are commensurate with the neutron star spin frequency. Moreover, it shows the original spin-orbit beat frequency interpretation to be incorrect, as that interpretation can not explain a $\Delta\nu$ equal to *half* the spin frequency. These observations also falsify the relativistic precession models mentioned above as these require a much faster spin. Twin kHz QPOs have also recently been found in a second accreting millisecond pulsar, the 191 Hz spin XTE J1807−294 (Markwardt *et al.* 2004). In this object, with $\nu_{spin} < 400$ Hz, the peak separation is consistent with the spin frequency, not half it.

These new results appear to restrict possible kHz QPO mechanisms to those in which the spin imposes commensurate motions in the accretion flow, perhaps by resonance. As spin is rotational, these disk motions must have azimuthal dependency. It has been proposed that at least some of the kHz QPOs are a result of resonances between the spin frequency and general relativistic orbital and epicyclic frequencies at specific radii in the disk (Wijnands *et al.* 2003, Kluzniak *et al.* 2003, Lamb & Miller 2003, Lee *et al.* 2004). In contrast, the models that have been proposed for black hole high frequency QPOs with 3:2 frequency ratios (Kluzniak and Abramowicz 2001, Abramowicz *et al.* 2003) involve resonances between orbital and epicyclic motions at specific radii in the disk (Section 1.3). Lamb and Miller (2003) have proposed a model which involves a beat interaction between the frequencies at the resonant radius and the orbital frequency at the inner edge of the disk (an orbit–orbit beat frequency), which explain the high tunability of the frequencies.

The new discoveries show that the link between kHz QPOs, burst oscillations and spin is very suggestive of interpretation in terms of a resonant interaction in the disk between orbital, epicyclic and spin frequencies.

Importance of Observing Flexibility to Discovery. The importance of finding both kHz QPOs and burst oscillations in an accreting millisecond pulsar had been foreseen. Thus, *RXTE* observing plans were in place in the event SAX J1808.4−3658 would have another outburst. When that outburst finally occurred in October 2002, *RXTE* observed the source essentially all the time it was visible. It only once went into the state where twin kHz QPOs are normally observed, for less than a day, and indeed twin kHz QPOs were then seen (only one kHz peak was observed in numerous additional observations). If we had not had the opportunity to wait for the next outburst, or if the observing schedule had been less persistent, we would not have had this advance in understanding.

Non-pulsing kHz QPO sources. Of the 25 kHz QPO sources now identified, 4 have shown a third kHz QPO peak. For three bright non-pulsars a weak sideband is seen about 50 Hz above the lower-frequency kHz peak, and in the 401 Hz pulsar a feature is observed 10 Hz above the pulsar spike. In all cases the sideband moves away from the main peak when QPO frequencies increase. Large observing programs are required to determine whether this increase remains consistent, as it is up to now, with being proportional to ν_{orb}^2, as predicted for Lense-Thirring precession (Jonker *et al.* 2004).

If the kHz QPOs reflect the frequency of orbital motion then detection of a ceiling in their frequency variations could be indicative of the (depending on disk model) marginally stable or marginally bound orbital radii predicted by general relativity. Early work on 4U 1820−30 suggested such a ceiling near 1060 Hz (Zhang *et al.* 1998, Kaaret *et al.* 1999), which was reached at accretion rates exceeding a certain level. It now appears that there is a saturation of frequency as a function of a spectral parameter, but which is not uniquely related to luminosity (Mendez 1999; Bloser *et al.* 2000; Mendez 2002).

We have so far not obtained a clear picture of how so-called "parallel tracks" of frequency versus luminosity form; in particular, we have only identified one apparent case of transitions between two parallel tracks (Mendez 2002). In order to test ideas for their formation and the relation to a frequency ceiling, very long observations minimizing gaps are required.

The power density spectra of most LMXB have several low frequency features in addition to the two kHz QPO. The features are temporally correlated. The correlation between the strongest low frequency QPO and the lower kHz QPO has been linked to a similar relation in black hole candidates at lower frequencies (Psaltis *et al.* 1999). Recently the relation has been extended to even lower frequency oscillations in dwarf novae (Warner & Woudt 2002). Whether these correlations (covering 5 decades in frequency) actually imply the same physical phenomena across all these objects is subject to debate. If they were the same, the relativistic precession interpretation where ν_{LF} is Lense-Thirring precession would be tenable, as it cannot apply to white dwarfs. This does *not* disqualify ν_2 from being an orbital frequency nor ν_1 from being a relativistic spin/orbit epicyclic resonance as has been proposed.

1.2.3. High Density Physics

Extreme Physics On and Near Neutron Stars. The X-ray emissions of millisecond accreting pulsars bear the signatures of emitting matter which is confined at high densities. In the past two years, detailed physical modeling of the waveforms of persistent pulsations and thermonuclear burst oscillations has provided a new path to constraining neutron star masses, radii, and the dense matter equation of state (EOS), a quantity of fundamental importance to physics.

Poutanen & Gierlinski (2003) have investigated the energy dependent persistent pulse profiles observed from the 401 Hz accreting pulsar SAX J1808.4−3658. They model the observed profiles with a two component spectrum: a soft profile (2–4 keV) dominated by blackbody emission, presumably from the accretion hot spot on the neutron star surface; and a second, hard component (12–18 keV), due to Compton emission from a plane parallel shock in the accretion stream. The result is a phase- and energy-dependent model of the pulse profile, which was then fitted to the observed folded pulse profile for an entire outburst of the pulsar. According to the model, the allowed masses and radii of SAX J1808.4−3658 fall in a tightly constrained region of parameter space (Figure 3).

Bhattacharyya *et al.* (2004) have used a similar approach to model the phase dependent spectra of X-ray bursts from XTE J1814−338, the most recently detected pulsar system. These models include self-consistent calculations of the neutron star structure and realistic photon propagation. Such modeling has only become possible because XTE J1814−338 was a prolific burster with oscillations, and the oscillations had significant harmonic content (Strohmayer *et al.* 2003). Within the context of the model, the oscillation profiles constrain the allowed neutron masses and radii, as shown in Figure 3. It is exciting that the two constraints are both mutually consistent, and jointly constrain the allowed equation of state parameter space. Observations by *RXTE* of one or two new outbursts similar to the first one could lead to very stringent joint constraints, and investigate possible systematic effects.

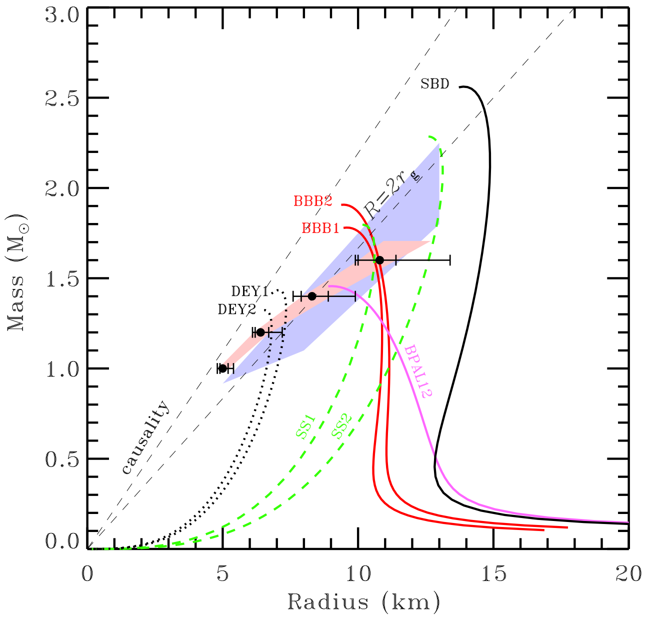

Fig. 3.— Constraints on the high density neutron star equation of state by *RXTE* measurements. Theoretical equations of state (thick lines) are shown, along with derived constraints from pulse profile fitting of SAX J1808.4−3658 (pink region) and XTE J1814−338 (blue region).

Extreme Irradiation. Unique *RXTE* observations of the "superburst" from 4U 1820−30 have recently provided new insights into accretion disk structure and evolution. This event was observed with the PCA instrument in September, 1999. Strohmayer & Brown (2002) studied its spectral evolution and detected an emission line and edge consistent with that expected from fluorescence of iron in the accretion disk surrounding the neutron star. Ballantyne & Strohmayer (2004) have successfully analyzed these spectra using state of the art models of the spectrum produced by reflection of an incident black body spectrum off an accretion disk. They reveal the ionization state of the disk as well as the real-time response of the disk to the large X-ray flux from the superburst. The data indicate that the inner disk is disrupted by the superburst, perhaps being heated and "puffed up" into a geometrically thick, but tenuous flow, perhaps as far out as ∼100–200 GM/c^2. The disk then recovers, and fills back in as the burst progresses.

The *RXTE* superburst observations continue to spark new theoretical work. Recently, Cumming & Macbeth (2004), have presented the first detailed calculations of the flow of heat from a superburst through the surface layers of a neutron star. They show that detailed model-

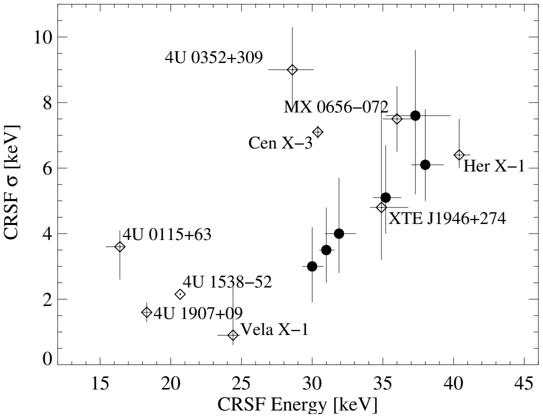

Fig. 4.— Correlation of cyclotron line width vs. energy. Open points are for phase-averaged spectra, while the filled points are phase-resolved spectra of just GX 301−2.

ing of the observed light curves should allow the thickness of the superburst fuel layer and the energy released to be inferred.

1.2.4. High Magnetic Fields

Accreting Binary Pulsars.

RXTE addresses important outstanding questions about accreting binary pulsars with high magnetic fields (10^{11-13}G).

The first glitch ever detected in the spin frequency of an accreting pulsar was seen in KS 1947+300 (Galloway, Morgan & Levine, 2004). The data clearly show a sudden increase of spin frequency by 1.83 μHz, a significant fraction of the neutron star's rotational energy. If the glitch mechanism is the same as in rotation powered pulsars, with the faster spinning core suddenly coupling to the crust, the discovery raises several questions. Could it have been triggered by the accretion event? The last time the pulsar spin frequency was observed higher than at the time of the glitch was in 1994, implying that the time-scale to reach spin equilibrium between the crust and the core is decades or more. If so, then accretion torques in transient outbursts act mainly on the moment of inertia of the crust, and many previous conclusions based on measured spin-up rates should be reconsidered in this light.

A cyclotron line at 36 keV ($B = 3 \times 10^{12}$G) was detected in the spectra of MX0656−072 (Heindl *et al.* 2004), during a recent outburst of an old transient, now found to be a 160.7s pulsar. There are now 14 pulsars with cyclotron line measurements, 6 discovered by *RXTE* (or co-discovered with *BeppoSAX*), and 11 studied by *RXTE.* Figure 4 shows how the widths of the lines are related to the cyclotron resonance energy, a function of the electron temperature and the viewing angle. This work implies the magnetic poles are closely aligned with the rotation axes (Kreykenbohm *et al.* 2004). Only *RXTE*, using both HEXTE (15–200 keV) and the PCA (2.5–60 keV), can obtain the phase-resolved results which probe the radiative transfer.

The SMC has been regularly monitored by *RXTE* since 1997 (Corbet *et al.* 2004), resulting in a surprising total of 45 accreting pulsars (8 with binary periods known), indicating a recent burst of star formation triggered by an encounter with the LMC. Scaling by mass from our galaxy, only 3 Be/X-ray systems would be expected.

Rotation Powered Pulsars. Studies of the youngest pulsars, including some that are not observable in the radio, have characterized the spindown behavior during the tempestuous first few centuries of their lives, probing the physics of the neutron star crust and the coupling to the superfluid interior. Pulse frequency second derivatives have been measured for two pulsars; neither have the canonical "braking index," $n = 3$ expected for magnetic dipole radiation (Gavriil *et al.* 2003; Cusumano *et al.* 2003). Three others, PSR J0205+6449 (Ransom *et al.* 2004), PSR J0537−6910 (the fastest non-recycled pulsar at 16 ms; Marshall *et al.* 2004; Mineo *et al.* 2003), and PSR J1846−0258 (the youngest known pulsar; Gotthelf *et al.* 2000) are clearly perturbed by glitch activity and timing noise, and longer time baselines are required to separate the effects.

RXTE has exploited its precise absolute time calibration (better than 3 μs) to study the X-ray emission from the fastest pulsars. In PSR B1937+21 the X-ray emission comes from the same region of the magnetosphere as the giant radio pulses (Cusumano, *et al.* 2003). For the 2.3 ms period PSR J0218+4232, *RXTE* and *Chandra* (Kuiper *et al.* 2003) show that the pulsed X-ray emission extends beyond 20 keV. Such pulsars are good candidates for being unidentified gamma-ray sources that will be a major objective of NASA's upcoming GLAST mission.

Magnetars. Magnetars are highly magnetized, slowly rotating neutron stars ($P \sim$5–11 s), powered by the decay of their super-strong magnetic fields (10^{14}–10^{15} G). In an active (bursting) state, they emit hundreds of soft (kT = 30 keV), short (0.1–100 ms) X-ray bursts, often with super-Eddington luminosities.

Magnetar studies have advanced in leaps and bounds with the contributions of *RXTE*, which has established the nature of Soft Gamma Repeaters (SGRs) (Kouveliotou *et al.* 1998, 1999), the connection between SGRs and Anomalous X-ray Pulsars (AXPs) (Gavriil, Kaspi & Woods 2002; Kaspi *et al.* 2003), and the existence of transient magnetars (Ibrahim *et al.* 2004). Most importantly, the *RXTE* observations continue to produce important new scientific results.

RXTE has successfully monitored the pulse frequency evolution of two SGRs (Woods *et al.* 2002) and six AXPs (Gavriil & Kaspi 2002; Gotthelf *et al.* 2002; Kaspi *et al.* 2001; Ibrahim *et al.* 2004). As shown in the lower panel of Figure 5, for the SGRs the *RXTE* data have shown large deviations from constant spin down. Three glitches

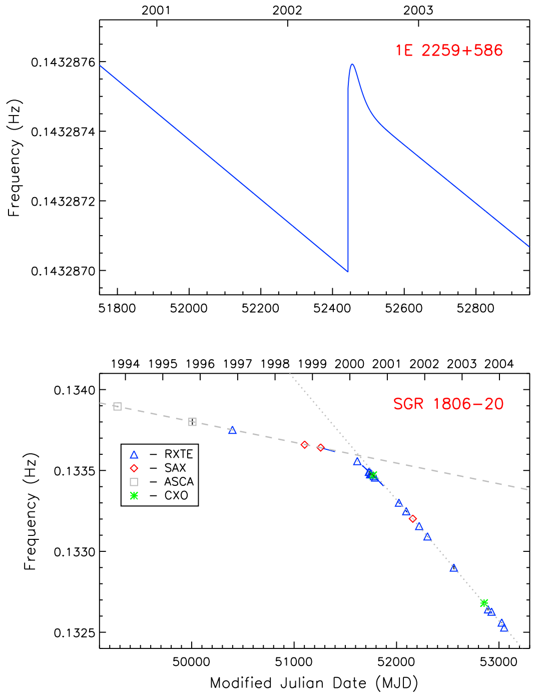

Fig. 5.— *Top* – A portion of the *RXTE* phase-connected frequency history of AXP 1E 2256+586 including the unusual glitch that coincided with burst activity in June 2002. *Bottom* – The frequency history of SGR 1806−20 covering a period of ten years shows a factor of 5.5 change *not* correlated with burst activity (Woods *et al.* 2004).

have been observed in two AXPs so far (one is shown in the upper panel of Figure 5), indicating structural similarities between magnetars and radio pulsars (See Kaspi & Gavriil 2003; Dall'Osso *et al.* 2003; Kaspi *et al.* 2003; Woods *et al.* 2004). An energy resolved study of pulse profiles of two SGRs shows that intense burst activity can result in gross changes in the pulse profile (Göğüs *et al.* 2002) as well as the flux, arguing strongly for a redistribution of the stellar magnetic field. Continuous monitoring of these sources is necessary to quantify the physical mechanisms behind their impressive activity.

The SGR-like outburst of the AXP, 1E 2259+586 (Kaspi *et al.* 2003; Gavriil *et al.* 2004, Woods *et al.* 2004) established unambiguously that AXPs and SGRs are of the same nature. In 2003, the magnetar candidate (XTE J1810−197) was discovered with *RXTE*, when its persistent emission brightened. These sources now known to be more abundant in than previously thought (Kouveliotou *et al.* 1994; Woods *et al.* 2004).

Burst afterglows have been seen, characterized by enhanced thermal emission with an approximately black body $kT \sim 4$ keV. *Swift* will be sensitive to SGR burst activity, but, as discussed below, will not provide the in-depth follow-up observations. *RXTE* PCA spectroscopy of some SGR 1806−20 bursts indicated an absorption feature that could be due to cyclotron proton resonance in a $\sim 10^{15}$ G field (Ibrahim *et al.* 2003), which, if confirmed, could provide direct measurements of magnetar magnetic fields.

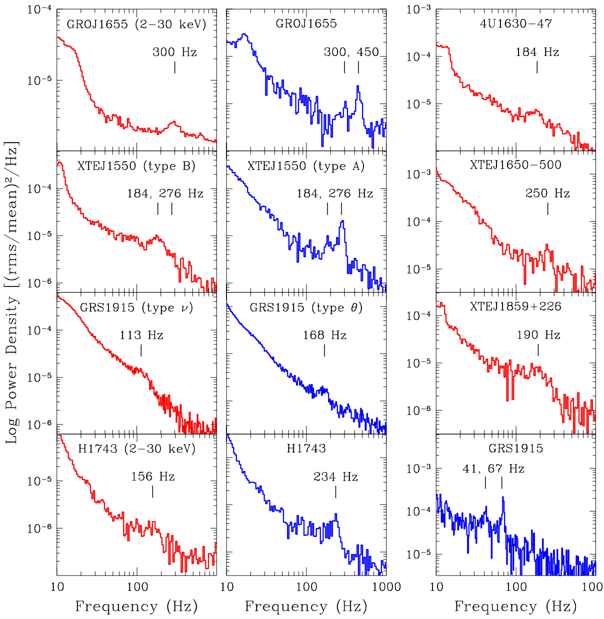

Fig. 6.— HFQPOs in seven BHB systems which show a 3:2 frequency ratio (left & central columns). The right panel shows three single-QPO sources, and a non-3:2 doublet of GRS 1915+105. Color refers energy band: 15–30 keV (blue); 2–30 keV or 6–30 keV (red).

All of these results were obtained with observations totaling 4.4 Msec, a mere 5% of the total *RXTE* exposure. Maintaining magnetar observations with *RXTE* is crucial to understanding them. Intense coverage (2 Ms) following a giant flare would be invaluable.

1.3. Black Holes

QPOs from Black Holes Binaries. Black hole binaries remain a focus for several key *RXTE* science questions: 1) how can we use X-ray variability to constrain the masses and spins of black holes, and, 2) can black hole binaries provide a laboratory for understanding accretion physics under strong-field gravity? Here we briefly describe how *RXTE* discoveries of high frequency QPOs (HFQPOs) in black hole binaries have provided a new probe of these questions.

HFQPOs in the range from ∼40–450 Hz have now been discovered with *RXTE* in 7 black hole binaries (McClintock & Remillard 2003). Since the last Senior Review two new sources with HFQPO detections have been found (XTE J1746−3213 at 156 Hz and 234 Hz, and XTE J1650−500 at 250 Hz). In general these QPOs are transient and low amplitude (typical rms $\sim 1\%$), though there is a strong dependence of amplitude on energy. These are the highest frequency oscillations seen from black hole systems. Their frequencies are roughly consistent with the orbital frequencies expected near their event horizons, thus they provide a rare probe of strongly curved spacetime. The highest frequency so far seen, the 450 Hz QPO in GRO J1655−40, has a frequency higher than the Kepler frequency at its innermost stable circular orbit. This has been used to argue for a non-zero spin in this black hole (Strohmayer 2001; Remillard *et al.* 2002; Wagoner *et al.* 2001). Figure 6 summarizes the present HFQPO detections.

HFQPOs and General Relativity. The presence of HFQPO appears to be strongly correlated with black hole spectral state. Most detections occur at high luminosity, when a steep power-law dominates the spectrum (the so-called SPL state). Moreover, HFQPO amplitudes are strongest in the 6–30 keV energy band, which is higher than that of a thermal/disk component when it is present.

Four of the seven sources exhibit HFQPOs with frequencies in a 3:2 ratio (Remillard *et al.* 2004). For the most part these frequencies appear to be stable for a given black hole, despite large changes in luminosity (eg. a factor of 10 in XTE J1550−564). HFQPOs are then quite different from both black hole low frequency QPOs and the neutron-star kHz QPOs, which exhibit substantial variations in frequency. The presence of commensurate frequencies can be seen as a signature of an oscillation driven by some type of resonance condition. Abramowicz & Kluzniak (2001) proposed that HFQPOs represent emission from a radius where there is a resonance in the general relativistic coordinate frequencies. Commensurate values for two of the coordinate frequencies (i.e. azimuthal, radial, or vertical) can then be matched to the HFQPOs either directly or via beat frequencies. If resonance is indeed at work, then the correct association can accurately yield the value of the dimensionless spin parameter (a_*) for systems with optically measured masses. In fact, reasonable values ($0.25 < a_* < 0.95$) can be derived from the observed HFQPOs for either 2:1 or 3:1 ratios in either orbital:radial or vertical:radial frequencies (Remillard *et al.* 2002).

An important prediction of General Relativistic models for the HFQPOs, including resonance and "diskoseismic" models, is an inverse scaling of frequency with black hole mass. Figure 7 shows a plot of HFQPO frequency versus mass for the three systems with dynamical mass measurements. The dashed line shows the best fit to a simple M^{-1} relationship (McClintock & Remillard 2003), and supports such a scaling. Interestingly, the apparent agreement with a simple M^{-1} scaling would require similar values of a_* for these systems.

Spectra from Black Hole Binaries. Although the energy spectra of accreting black holes in outburst are complex they are dominated by two emission components: a soft thermal component and a hard power-law or cutoff power-law component extending up to hundreds of keV. The soft component is very likely thermal emission from an accretion disk, but the origin of the hard component is an active area of *RXTE* research. Canonical spectral states are defined as "high-soft" and "low-hard" depending on whether the soft or hard components dominate; or "very high" when both are strong. McClintock & Remillard (2003) approach state definitions from a more physical motivation. The very high state is better characterized as the SPL and the high-soft as "thermally dominant" of TD. Transitions between states can occur rapidly on time scales of days or less; Target of Opportunity capabilities of *RXTE* are therefore critical for studying these transitions (Kalemci *et al.* 2004). HEXTE and PCA together are needed to address the question of a cutoff temperature in the 30–150 keV range.

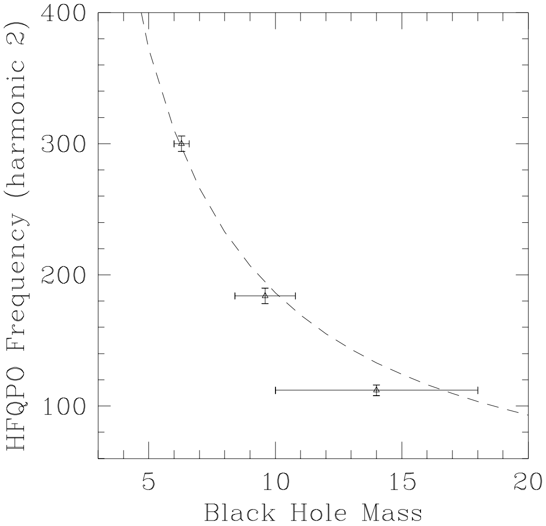

Fig. 7.— Relationship between HFQPO frequency and BH mass for the three BHBs that exhibit a pair of HFQPOs with a 3:2 frequency ratio. The frequencies are plotted for the stronger QPO seen at $2 \times \nu_0$, and the dashed line shows the best fit for a M^{-1} relation: $\nu_0 = 931M^{-1}$.

The presence of a jet is especially interesting in light of the strong correlation between X-ray and radio flux that is observed in the Low-Hard state (Corbel *et al.* 2000; Markoff *et al.* 2003; Gallo *et al.* 2003). Currently, significant theoretical and observational effort is going into understanding whether this correlation occurs because both the X-ray and radio emission are produced in the jet (Markoff *et al.* 2001; Georganopoulos *et al.* 2002; Markoff & Nowak 2004), or because the X-ray flux and the power dissipated in the jet both scale with mass accretion rate (Heinz & Sunyaev 2003).

Modern terrestrial and orbiting telescopes with new detectors that can perform improved photometry and spectroscopy, now allow correlated broadband temporal and spectral studies. In the X-ray band, broad Fe K lines from XTE J1550−564 (and others, e.g., Miller *et al.* 2004) were studied simultaneously, with high resolution (by *XMM-Newton* or *Chandra* gratings) to detect the line, and broad band spectroscopy to constrain the continuum

(*RXTE*). Line broadening is due to both general relativistic effects and Comptonization, both of which are strong effects near the event horizon. When the launch of the high resolution spectroscopy mission ASTRO-E2 (2005), the need for correlative broad band continuum observations by *RXTE* will increase. At long wavelengths, Hynes *et al.* (2003) have suggested that the optical spectra, and specifically its rapid variability correlated with *RXTE* observed variability, implies that a substantial fraction of both the optical and X-ray spectra are due to synchrotron radiation. If a substantial part of X-ray radiation is due to a jet, then the expected spectral break between radio and X-ray should be in the infrared. Upcoming *Spitzer* observations will likely be important to discern such a break; however, *Spitzer* observations are extremely constrained, and only *RXTE* can reasonably be expected to perform coordinated observing.

Relativistic Jets from Microquasars. Galactic black hole systems that exhibit relativistic jets are collectively referred to as "microquasars," since they appear to contain scaled-down versions of the jets in AGN. Microquasars provide the opportunity to observe the formation and evolution of mass ejections on timescales of seconds to days, while such processes take years to millennia in quasars. Since GRS 1915+105 was first discovered to have bipolar jets with velocities up to $0.96c$ (Mirabel & Rodriguez 1994), five more systems have been discovered, some by *RXTE*. X-ray jets have also been detected. In 2000, Tomsick *et al.* (2003) detected relativistic motion of the X-ray jet components of XTE J1550−564, two years after its *RXTE*-detected outburst.

Current theories favor magnetic fields as the mechanism to collimate and accelerate the ejected material, while the ejection power may be drawn from the black hole spin and/or accretion disk energy (see Blandford 2000). *RXTE* will continue its efforts to investigate the disk/jet connection by detecting X-ray spectral changes that preceed jet formation observed in the radio band (e.g. Dhawan *et al.* 2004). Coordinated radio/X-ray campaigns will take a leap forward between 2006–2008 when the 30,000 antenna Low-Frequency Array (LOFAR; US/Holland/Australia/Germany) radio system gradually becomes operational. The array will monitor a large fraction of the sky daily for known and new radio transients, including microquasars. *RXTE*'s ability to probe the inner black hole accretion disk complements radio observations of the jet plasma emission.

Blazars. Blazars are radio-loud AGN that show rapid variability, high polarization and high luminosity. These indicate that, unlike the more isotropically-emitting Seyfert 1s, the radiation from blazars is produced in relativistic jets oriented close to the line-of-sight. For BL Lac type (blue) blazars (Fossati *et al.* 2004), the X-rays are synchrotron and the Compton scattered component is TeV and for radio bright (red) blazars (e.g. 3C279, Wehrle *et al.* 1998; 3C273, Marscher *et al.* 2002) the X-rays are Compton scattered and the radio/IR is the synchrotron.

The key test is the measurement of the lags between the synchrotron and Compton scattered components, and the measurement of the relative amplitudes of variation. *RXTE* has achieved pioneering measurements of correlated variability in the X-ray and TeV bands (e.g., Mkn 421; Fossati *et al.* 2004; 1ES 1959+650, Krawczynski *et al.* 2004). The Mkn 421 data show a tight correlation between X-ray and TeV light curves, with no measurable lag, and — most intriguing — that the X-ray and γ-ray flux brightness variations closely follow a quadratic relationship. The *RXTE*/γ-ray monitoring of 1ES 1959+650 found an "orphan" γ-ray flare, that was not accompanied by an X-ray flare or by significant optical variability. While these findings confirm the overall synchrotron/Compton picture, they also offer a serious challenge to the theory, forcing the modeling toward regions of the parameter space previously considered too extreme (e.g. very high Doppler factor, strong non-equipartition between particles and magnetic field).

The next few years offer the possibility of dramatic gains in resolving this controversy. The next generation of TeV telescopes will begin operations (VERITAS, Weekes *et al.* 2002; MAGIC, Lorenz 2003; HESS, Hinton, 2003; CANGAROO III, Enomoto *et al.* 2002), the two latter giving access to the southern sky for the first time. These will achieve a factor of $\gtrsim$10 improvement in sensitivity. This means that 1) it will become routinely possible to obtain TeV light curves with coverage and quality (energy and time resolution) comparable to those achieved in the X–ray bands, and 2) the better sensitivity and the access to the southern sky will expand significantly the sample of TeV blazars, or candidates. After 2006, GLAST will open up the 100 MeV–300 GeV view.

Seyfert PSDs. *RXTE* has made important contributions to our understanding of the phenomenon of rapid X-ray variability in Seyfert galaxies and other AGN. It has, for the first time, allowed us to construct high dynamic-range PSDs spanning four decades or more in frequency for over a dozen Seyferts, with characteristic PSD turnovers or 'breaks' being detected in ten objects so far (Edelson & Nandra 1999, Uttley, M^{c}Hardy & Papadakis 2002, Markowitz *et al.* 2003, M^{c}Hardy *et al.* 2004, Marshall *et al.* 2003). Comparison of Seyfert PSD break time-scales with black hole mass estimates from optical reverberation mapping suggests a linear scaling with mass — the first direct link seen between the optically-estimated masses and the X-ray variability properties (Markowitz *et al.* 2003).

Although breaks seem to be a common feature of Seyfert PSDs, There is now strong evidence that different AGN show different PSD shapes (Figure 8). The Narrow Line Seyfert 1 (NLSy1) NGC 4051 shows continuing

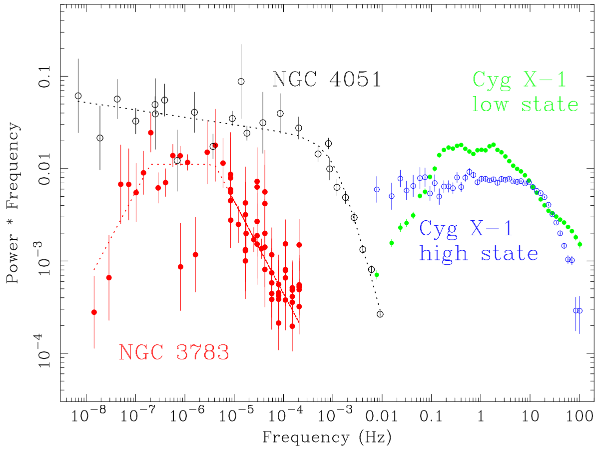

Fig. 8.— Comparison of PSD of NGC 4051 and NGC 3783 with typical high and low state PSDs observed in Cyg X-1.NGC 3783 shows a low frequency cutoff similar to that seen in Cyg X-1 in the low state, while NGC 4051 resembles the high state.

power down to very low frequencies (10^{-8} Hz), whereas the broad line Seyfert (BLSy1) NGC 3783 shows evidence for a cut-off in the variability power below 10^{-7} Hz. These results suggest a direct analogy with the high-soft state and low-hard state PSDs of black hole X-ray binary (BHXRB) systems such as Cyg X-1, which shows a similar dichotomy of shapes, and are consistent with the idea that NLSy1 occupy a different accretion state to BLSy1, a picture that is also supported by the different break time-scales in these systems (M^{c}Hardy *et al.* 2004). Since the state of a BHXRB is linked to properties such as the presence of radio jets (Fender 2003) and outflows, determining the existence of these different states in Seyferts is crucial to understanding the AGN phenomenon.

Continued operation of *RXTE* is essential to investigate if Seyferts occupy different accretion states and explore how these states correlate with the AGN type. Continued monitoring will extend the Seyfert PSD measurements to lower frequencies and, crucially, improve signal-to-noise across the entire PSD, allowing a survey of Seyfert PSD shapes which can test whether low-frequency cut-offs are exclusively associated with Broad Line objects. Furthermore, Several new campaigns underway to monitor quasars and determine whether their PSD breaks occur at the relatively high frequencies expected from a “high-state” interpretation. Only a third of the 40 or so bright AGN accessible to *RXTE* (Revnivtsev *et al.* 2004) have been adequately monitored so far. Amongst the remaining targets are many Seyfert 2s and a number of radio galaxies, which are significantly under-sampled in the current surveys of AGN PSDs, but whose variability could be explored with continued operation of *RXTE*.

Seyfert Inter-band Correlations. Long-term Seyfert 1 monitoring with *RXTE* has given insight into X-ray and optical/UV inter-band variability, though the picture revealed has been both intriguing and confusing. X-ray and optical/UV variations are uncorrelated in some targets such as NGC 3516 (Maoz *et al.* 2002) and NGC 7469 (Nandra *et al.* 1998), though Nandra *et al.* (2000) saw NGC 7469’s X-ray spectral index correlate with its UV flux. In NGC 4051, the optical band varied far less than the X-rays (Peterson *et al.* 2000). In contrast, strongly correlated inter-band variability has been seen in the relatively higher-mass sources NGC 5548 (Uttley *et al.* 2003a; Figure 9) and Akn 120 (Marshall *et al.* 2003). The X-ray and optical emitting regions may be more co-spatial in higher mass sources due to lower inner disk temperatures. Curiously, NGC 5548’s optical emission varied more than was seen in the X-rays, ruling out thermal reprocessing as the sole source of optical variability. Automated observatories such as the Liverpool Telescope and SALT are coming on line; continued simultaneous *RXTE* monitoring for sources spanning a wide range in black hole mass is the only way to make further progress in this area. *RXTE* PCA monitoring has been used to trigger *Chandra* observations of particular states (Uttley *et al.*, 2003b), while *RXTE* ASM monitoring was successful in triggering PCA observations of short-lived windows in the high column density of NGC4388 (Elvis *et al.* 2004).

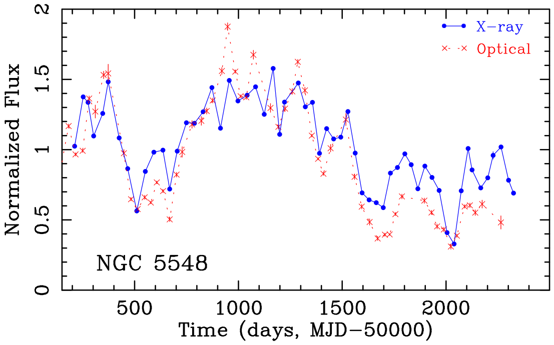

Fig. 9.— Comparison of X-ray and optical monitoring light curves for NGC 5548 (top), showing strongly correlated inter-band variability, and NGC 4051 (bottom), in which the optical band varies much less than the X-ray band.

1.4. Opportunities in the X-ray Sky

Many *RXTE* targets with the greatest scientific impact show transient behavior with a broad distribution of outburst and recurrence timescales. Of these sources, several groups are crucial to *RXTE* science, including the accreting millisecond pulsars (Section 1.2.1) and 15 of 18 dynamical black hole binaries (Section 1.3). *RXTE*’s all-sky monitoring, flexible and rapid response, and fast timing capabilities make it uniquely suited to extracting important science from these sources.

RXTE relies on the ASM for monitoring of known sources and discovery of new ones. Figure 10 highlights some of the transient activity seen by the ASM since

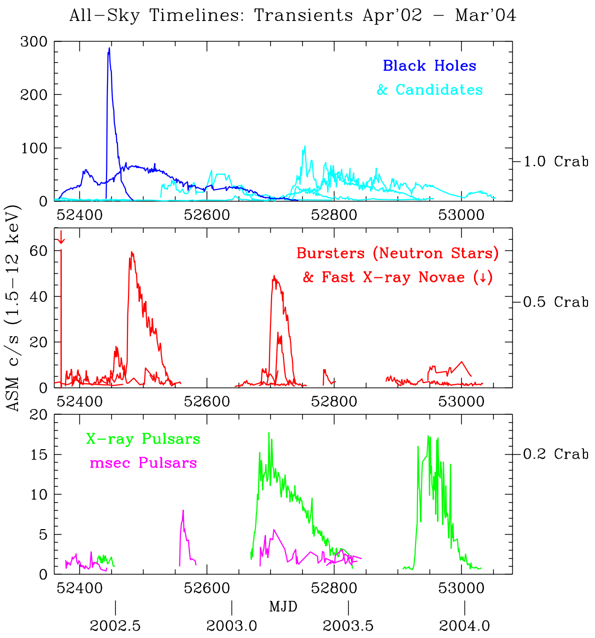

Fig. 10.— The time-line for X-ray transients over the two-year interval since 2002. Black hole binaries (top; dark blue) and candidates (light blue); Seven neutron star transients, identified by X-ray bursts (middle), and "fast X-ray novae" (arrows); accretion powered X-ray pulsars (bottom; green) and millisecond pulsars (magenta).

April, 2002, for different classes of compact objects. Some of the new science results described in this proposal were obtained from the transient sources shown here. In addition to the ASM, monitoring of the galactic bulge region with the PCA began in 1999. PCA monitoring is significantly more sensitive than the ASM in crowded fields, such as the Galactic center region, and the rewards have been extensive. Three new millisecond pulsars have been discovered, and the original millisecond pulsar (SAX J1808.4−3658) has had two more outbursts. As these outbursts are relatively short-lived (i.e. weeks), *RXTE*'s rapid follow-up capability is essential.

Both *INTEGRAL* and *Swift* (scheduled for launch in September 2004) are gamma-ray missions which have the capability to discover X-ray transients above 15 keV and in some cases notify observers automatically. The sensitivity of *Swift*'s BAT instrument should reach ∼10 mCrab in a 40-minute observation. Sky coverage for both *INTEGRAL* and *Swift* will not be complete because of observing constraints. *Swift* also does not plan to follow up galactic transients with its X-ray Telescope (XRT) during its prime mission because its key science goals involve gamma-ray bursts. In addition, the narrow field instruments have smaller areas and more limited timing capabilities than *RXTE*, especially in the 2–10 keV band. Thus *RXTE* follow-up of *Swift*-discovered transients will provide new opportunities, and several such programs were approved in *RXTE* cycle 9. *RXTE* will also continue to investigate hard spectrum sources discovered by *INTEGRAL* in its galactic plane survey, which may be heavily obscured black holes (Swank & Markwardt 2003).

To maximize the science return from transient sources in the time remaining to *RXTE* we plan to implement several modifications to the observing program. (1) The potential to discover faint transients will be increased by enlarging the area of sky coverage of PCA Galactic bulge scans, and extending the analysis to higher energies. (2) We will reduce the priorities of monitoring programs for targets that are already well represented in the *RXTE* archive. (3) We will increase the priorities for programs of high-impact science suffering from small-number statistics. Examples of the latter would include observations of accreting millisecond pulsars and also black holes in the QPO-rich states. Since the burst detection rates of pulsars do scale with exposure time, and since the QPO detections are primarily limited by statistics, we expect to improve our productivity for these examples by undertaking such measures.

Observations coordinated with other observatories, either space or ground based are currently a large fraction of the *RXTE* program. We anticipate that coordinated time will continue to be sought after to provide complementary broad band spectroscopy and X-ray timing information. As noted above, there are new facilities coming on line which enable new types of correlative studies.

While we have emphasized the role of transients and long observations of persistent sources of kilohertz oscillations, we have also reported important results from monitoring various types of sources, for which the ASM does not provide sufficient information. These include especially AGN, SGR and AXP magnetars, rotation powered pulsars, accreting high field pulsars, black hole candidates, persistent LMXBs, and at least one star (η Car). *RXTE*'s support of these programs would be reduced by increased focus on millisecond pulsars and BH transients, but a balanced program can be woven.

Continued Support for *RXTE*
RXTE is operating as an extended mission at a drastically reduced cost. With innovation it has maintained unprecedented capabilities. During the next four years, the ASM remains the only monitor of the entire X-ray sky (2–10 keV), the PCA remains the most sensitive tool for discovery of galactic center transients, the PCA remains the only instrument which can study kHz timing, and the PCA and HEXTE together provide the best tools for simultaneous spectral/temporal variations of black hole transients. The data have remained highly sought after by observers. Achieving the best science from a unique mission which will not be duplicated soon warrants an increase in support to these scientists.

1.5. Bibliography

Please see `http://heasarc.gsfc.nasa.gov/docs/-xte/whatsnew/papers.html`.

2. Technical Description and Budget

2.1. *RXTE* Operations Overview

Continuing Success. *RXTE* has an efficient operations center which provides a highly flexible scheduling system, automatically monitors the X-ray sky for science opportunities, rapidly and frequently responds to TOOs, tailors instrument configurations to each observation, autonomously monitors the health and safety of the instruments, captures essentially all of the telemetry, rapidly delivers the data to observers in standard, well-documented formats, provides documented analysis tools based on standard analysis packages, and provides expert advice to the community. Through innovation these services are being provided with resources substantially smaller than those required in the prime mission. Significant improvements since the last Review include (1) expansion of ability to schedule TOOs and coordinated observations with no increase in staff; 2) improved standard products summarizing the observations; 3) faster and more reliable SOF computer capabilities with fewer computers to maintain.

The community continues to take data from the *RXTE* archive at an impressive rate – last year the amount of downloaded data was more than twice the amount of data in the archive.

Proposed Changes. Mutually contradictory goals compete for *RXTE*'s time. Long uninterrupted observations compete with TOO interruptions, some monitoring campaigns, and time constrained observations. We attempt to balance the requests in response to demonstrations of science need while maintaining an efficient program. Reviewing now the trends of the program, the User Group's consensus is that we need to assure that *RXTE* will make the observations that will most advance its science contributions. Actual data show that observations of LMXB and AGN have both used about 24% each of the observing time. It is felt that the important questions discussed in this proposal, in particular concerning LMXB and BH transients, should benefit by a greater concentration of time spent.

We will propose extension of the program of PCU scans of the galactic center region to facilitate capturing a larger selection of transient millisecond pulsars. Time allocations in the review process can favor more large proposals in the categories of LMXB and XRB BHs. The project scientist's decisions determine the allocation of TOO observation time, the coherence of the observing time that a TOO actually obtains, and protection of the non-TOO observations. We have improved our tools for examining the pattern of observations of sources throughout the mission as well as for an on-going observation. These will be useful for the project scientist, proposers and reviewers in deciding how to best use *RXTE*'s future time. The performance of the different subsystems are described in more detail below.

2.2. System Status

2.2.1. Flight Segment

Flight operations have gone smoothly since the last Senior Review. The spacecraft and instruments continue to function well, and should do so well past the end of fiscal year 2008 (FY08). No consumables limit the duration of the mission. *RXTE* is currently predicted to re-enter the Earth's atmosphere in 2010.

As was the situation two years ago, two of the 5 PCA detectors remain on for all observations, and the other detectors are on during observations for which they are most useful. This practice of "resting" three detectors and having the spacecraft *automatically* turn them off when evidence of high voltage breakdown is seen has stabilized their performance.

The ASM continues to operate reliably. A careful examination reveals a gradual degradation of the detectors, but this has not significantly changed its capabilities since the last Senior Review. All 8 anodes in SSC 1 continue to function properly. A gradual increase in gain is not expected to impact the performance for many years. Two of 7 operating anodes in SSC 2 have substandard calibration and may be turned off in a few years. Two of the 8 anodes in SSC 3 are functioning well, and are expected to last for years. The ASM Drive Assembly continues to operate with no problems.

HEXTE continues to operate reliably with essentially no change in the last two years.

2.2.2. Ground Segment

RXTE has a responsive ground system appropriate for its mission of responding to targets of opportunity. The spacecraft is controlled by the Flight Operations Team (FOT) in the Mission Operations Center (MOC) while science planning, science monitoring, and instrument monitoring are done in the co-located Science Operations Facility (SOF), which is part of the Science Operations Center (SOC). The SOF provides a daily list of instrument commands and spacecraft pointing directions to the FOT, which loads them into the spacecraft's stored command processor. Additional commands to adjust instrument configurations or pointing directions can be sent during command contacts, which occur approximately once per 90 minute satellite orbit. An entirely new plan can be produced and loaded when needed for a TOO. Production science data processing is now done in the SOF, and the FITS files are delivered to the HEASARC for archiving and access by users. Final production data sets are typically available to users in one to two weeks instead of the several months typical in the early part of the mission.

RXTE will remain the only mission routinely monitoring the entire X-ray sky. Data from each dwell of the ASM are analyzed automatically in the SOF, and for each source in the ASM catalog the average flux during the last three dwells and during the previous 24 hours are compared with specified trigger levels. These levels have been established to accommodate all relevant accepted TOO proposals. The operations staff is automatically alerted when a new source is found. More sophisticated tests using more complete data sets are run daily at MIT. In addition, data taken during maneuvers between sources are routinely searched for new sources and there is an ongoing program to scan the galactic bulge to look for new sources. Because of this real-time monitoring, in the last two years 11 new X-ray sources (including two millisecond pulsars) have been announced to the community via IAU Circulars or Astronomer's Telegrams and there were 20 announcements of significant changes in the state of previously known sources. These discoveries provide unique opportunities for *RXTE* as well as other missions.

The capacity and speed of *RXTE*'s replanning system far exceed those which have been available for other astrophysics missions. In the past two years, *RXTE* has spent 27% of its observing time looking at targets of opportunity (88 TOOs in AO-7 and 83 TOOs in the first 46 weeks of AO-8). Many of these observations were "public", and the data were immediately available to the community. The number of rapid re-plans has increased from 29 in 2001 to 42 in 2002 to 67 in 2003.

The ambitious scheduling goals of *RXTE* permit observations based on any set of scientifically justified constraints, place no limits on the number of constrained observations, and support whatever coordinated observations observers are able to arrange. Spacecraft physical constraints limit *RXTE* to about 400 minutes of maneuvering per day, which constrains the numbers of short snapshot-type observations that can be performed. The fraction of time for constrained observations has gradually grown. For AO-7 and the first 46 weeks of AO-8, $\sim$ 80% of the non-TOO observations were coordinated with other observatories or had some other scheduling constraint.

The robust scheduling system for *RXTE* is one of its great strengths. The average observing efficiency for *RXTE* is approximately as predicted pre-launch. Good observing time during both AO-7 and AO-8 averaged 59% of the elapsed time.

RXTE continues to operate 24 hours per day, but automation has greatly reduced the required staff. The Automated Mission Operations System (AMOS) runs continuously in the MOC. It manages the spacecraft data recorder, conducts TDRSS contacts, and monitors the health and safety of the spacecraft and the instruments. In January, 2004, the MOC decreased the amount of staffed time from 16 hours to 12 hours per day. We are investigating a further decrease to 8 hours per day. This follows a change to the flight software that cants the solar arrays during safe-hold so that quick ($<$ 24 hours) response is no longer needed to prevent damage to them. A similar automatic system in the SOF monitors the health and safety of the instruments, detects deviations from the observing plan, and verifies that computers and data interfaces are operating properly. The SOF is now staffed about about 8 hours per day on weekdays and $\sim$ 2 hours per day on weekends and holidays. The SOF controllers and schedulers (3 in total) all have multiple responsibilities, with scheduling activities accounting for about 1 full time equivalent (FTE).

2.2.3. Guest Observer Support

Except for unanticipated TOOs, all scientific observations with *RXTE* are chosen in an open competition from proposals submitted by the scientific community in response to periodic NASA Research Announcements (NRAs). This competitive process makes the unique capabilities of *RXTE* available for the most compelling scientific questions. The response to the recent NRAs shows that the community considers *RXTE* to be a valuable asset. The number of proposals received in response to AO-6, AO-7, AO-8, and AO-9 were 158, 168, 188, and 167 respectively. The fraction of proposals for TOOs has increased, more extensive monitoring campaigns are being carried out, and *RXTE* is now doing many coordinated observations with *Chandra*, *XMM-Newton*, and *INTEGRAL*.

The Guest Observer Facility (GOF) provides tools, documentation, and expert advice to GOs for both proposal preparation and the analysis of *RXTE* data. Support is available via the GOF Web site or e-mail to the *RXTE* help desk, which answered an average of 20 queries per month in the past year. GOF on-line documentation includes a list of frequently asked questions, the "*RXTE* Getting Started Guide", extensive information about *RXTE* data files and instrument characteristics in "The ABC of XTE", and detailed instructions for a growing list of analysis tasks in "The *RXTE* Cook Book". The GOF has also developed specialized data analysis tools specific to *RXTE.* These tools allow the user, for example, to clean the data according to standard criteria, to choose selected intervals for analysis, and to gather data for detailed spectral or temporal analysis by running a single, easy-to-use script.

The GOF also provides technical support for the reviews by NASA HQ of *RXTE* observing proposals. The support includes updates of the research announcement, obtaining the review panel, distributing copies of the proposals, assistance during the review itself, informing proposers of the results, and delivering a data base to the SOF describing in detail the desired observations. The GOF then provides technical support for the subsequent budget review.

The recent HEAsoft 5.3 release in November, 2003, provides improved detector response matrices and better fine clock corrections. The new response matrix generator updates the time-dependent model components and produces better agreement with the spectrum of the Crab Nebula for the individual detectors. Improvements to the clock fitting procedure reduced the overall errors from ~ 8 microseconds to less than ~ 3 microseconds. The background fitting process has been improved so that the correct background model files are now automatically linked.

Delivery of data to the community is a key responsibility. GOs can watch real-time displays of their X-ray observations at their home institutions, download quicklook FITS files of the science data within hours, and download preliminary production FITS files the next day. Processing time for the daily quicklook FITS files has been reduced from ~ 4 hours to ~ 1 hour, and FITS keywords have been added to the files so that they can be analyzed in the same fashion as the production data. The *RXTE* production data processing pipeline, which was completely redesigned in 2001 to run faster with less staff, continues to operate smoothly. Running the pipeline now requires only 0.7 FTE compared with 1.0 FTE in 2002 and 6 FTE early in the mission.

Significant improvements have been made to *RXTE*'s Standard Products in the last two years. The new Standard Products provide a compact summary of each observation. A new merged light curve provides a quick overview of the source behavior. The other products provide background subtracted light curves and spectra for various time bins for the PCA and the HEXTE. Standard Products are now available for all observations through AO-6. We expect to complete standard products for AO-7 and AO-8 by June, 2004. We have also started to produce standard products during the production processing of new observations.

At the end of 2003 the *RXTE* archive at the HEASARC had 1143 GB of data, and served 2446 GB of data to the astronomical community during the year. *RXTE*'s data volume and its "attractiveness" (the ratio of the transfer rate to the size of the archive) are significantly larger than the values for any other mission in the HEASARC (including *XMM-Newton*, *ROSAT*, *ASCA*, *CGRO*, and *BeppoSAX*). In addition, the attractiveness significantly increased from 2002 to 2003. Clearly the *RXTE* archive is a valuable resource for the community.

2.2.4. Instrument Teams Support

The instrument teams (ITs) are responsible for monitoring the long-term health and safety of their instruments, responding to any problems, and maintaining an accurate calibration. MIT created and maintains both the ASM and the Experiment Data System (EDS), which processes and packages all PCA and ASM data for telemetry on board. The EDS is a low-maintenance system for which new configurations are sometimes needed. In contrast, operating the ASM requires a large and continuing effort: 1) MIT maintains the rotation-planner software which controls the viewing angles of the ASM so that it avoids the earth, Sun, and radiation belts. 2) MIT maintains both the energy calibration of the detectors and the anode position calibration 3) MIT runs (and maintains) the quick-look and production processing of the ASM data to discover new sources and produce light curves of known sources. The results are posted on the ASM and GOF web sites. Data are re-processed to produce pre-discovery light curves of new sources. In the past two years the ASM team has substantially improved the spatial resolution of the position calibration analysis, finished the tool to make light curves from the event data now available in dwells, reduced the systematic noise in the analysis of the Galactic Center region to 1.3 mCrab, and improved the sensitivity of "deep sky maps." The ASM team has plans for further improvements in the spatial resolution of the position calibration, and for improved tools to display and manipulate the ASM light curves.

The UCSD team provides similar services for the HEXTE experiment. The team updates the calibration of HEXTE with yearly measurements and analysis of the detectors' automatic gain control system, the collimator response, and the performance of the CsI anti-coincidence detectors. More frequent monitoring of the dead-time calibration is performed. The team also provides expert advice to GOs for analyzing HEXTE data. The team reviews the data configurations for HEXTE observations, and suggests improvements.

The PCA team maintains the calibration of the PCA as it evolves. They also maintain and upgrade the detector background model (the background is decreasing as the orbit decays). Regular observations are made of selected background "targets" to monitor its evolution. The PCA team is responsible for determining the times for "resting" PCU 1, 3 and 4 and for monitoring the behavior of the detectors. The PCA team also provides the Mission Scientist.

2.3. Budget Description

Both the "in-guideline/minimal" and "requested-/optimal" budgets are provided in Appendix A. The former conforms to *RXTE*'s current budget guidelines in FY05 and FY06 and contains a bare-bones budget for operating *RXTE* in FY07 and FY08. The budgets provide the required New Obligation Authority (NOA), and do not always reflect the expenditures during a FY. The transition by NASA to "full-cost" accounting complicates comparisons with previous years because various overheads are now included in the *RXTE* budget. For the last two years, and the 4 years covered in this proposal, the overall *RXTE* staff is stable at a level greatly reduced from the prime mission.

The various organizational elements of the *RXTE* ground system are mapped into the requested Four-Way Breakdown as follows. There is no "Development" activity. "Data Services" (2a) are the costs of providing the telemetry and commanding services of NASA's Space Network for *RXTE*. These services are provided by NASA in-kind as shown in Table III. "Mission Services" (2b) represents the budget for flight operations, flight dynamics, sustaining engineering, hardware maintenance, facilities, project management, and user planning system support. The small budget for "Other Mission Services"(2c) has been included in Mission Services (2b). "Science Center Functions" (3) are carried out by the SOC in collaboration with the three instrument teams. "Science Data Analysis" (4) is carried out by a combination of the ITs and GOs. Instrument calibration is the responsibility of the ITs; the results are compiled and made available to the community by the GOF. MIT is responsible for definitive analysis of the ASM data; these results and the data themselves are in the public domain. In general, scientific analysis is the responsibility of GOs. The E/PO budget is included in (4) and described in Chapter 3.

2.3.1. In-Guideline/Minimal Budget

RXTE has seen enormous changes since the prime mission phase as efficiency has increased and innovations have been implemented. These changes enable a continuation of the exciting science described in Section 1 at a greatly reduced cost. *RXTE* is already in its extended mission, and the budgets are all consistent with the "bare-bones" paradigm. There is limited support for GOs. It is assumed there will be no significant new problems.

The Mission Operations Center (MOC) operates the spacecraft by monitoring its health and status, managing the spacecraft telemetry system, and integrating command loads. The MOC operations staff, which was 16 FTE during the prime mission, is now only 7.0 FTE. FDF support and management require 3 FTEs. Although the budget increases by $\sim$ \$935k from FY04 to FY05, the resources needed for operating *RXTE* will not change. The FY04 budget is reduced by a \$300k carry-over from FY03 and a \$635k in-kind NASA attribution of the full-cost overhead (Table III).

The SOF operations staff has been reduced from 12 during the prime mission to 4, and the programmer support has been gradually reduced to the current 0.9 FTE. The GOF staffing is now 2.4 FTE compared to the total GOF and XSDC staffing of 16 FTE during the prime mission.

The ITs peaked at a total of 33 FTE in 1996, including programming staff, administration, scientists, graduate and undergraduate students. The current minimal budget covers 10.5 FTE. For PCA, EDS/ASM and HEXTE instrument support, the 1996/2004 values were 9.25/3, 13/4.5, and 10.1/3, respectively. This is barely enough to maintain the expertise and discharge their responsibilities.

There is modest funding of the GO program at \$700k per year so that the *RXTE* data can be effectively used by the community. A winning proposal from a US institution typically receives $\sim \$16,000$.

2.3.2. Requested Budget

The "In-Guidelines/Minimal" budgets are very lean. In many areas, loss of a key person would severely impact the ability to carry out the mission. The mission has benefitted from continued availability of participants involved in the design and build phases, even when they are no long directly supported by the project. Accumulated experience allows the teams to make differential improvements within a minimal budget. We do not propose new operations projects which would require additional manpower.

The major goal of the "Requested" budget is to double the funding for the GO program so that the *RXTE* data can be effectively used by the community. The average support for successful *RXTE* proposals is substantially less than the typical support of $\sim$ \$50k for winning *Chandra*, *XMM-Newton*, or *INTEGRAL* proposals. This affects the effort that U.S. scientists can afford to devote to *RXTE* science.

2.3.3. Other Budget Tables

Table III provides the NASA in-kind attributions by FY. The budgets are identical for both the minimal and optimal scenarios. Line 2a covers services by the Space Network for tracking, commanding, and receiving telemetry. Line 2b covers *RXTE* allocations for the GSFC multi-mission support project for services including sustaining engineering and facilities. The FY04 values are anomalously large because of a one-time payment for some of *RXTE*'s full-cost overhead. Table IV describes the budgets for the ITs.

3. Education and Public Outreach

Throughout its mission, *RXTE* has nurtured a healthy Education and Public Outreach (E/PO) program involving strong collaborations between scientists, educators and students. Highlights include the *RXTE* Learning Center, one of the first online astronomy learning centers; the Universe in a Different Light activity booklet containing a "build-your-own" *RXTE* model; and "Live from RXTE!" a collaboration of *RXTE* scientists and Virginia teachers to bring real-time *RXTE* data into the hands and minds of math and science students.

Recent Accomplishments. As promised in the 2002 Senior Review, we combined the ASM animation of the X-ray sky with the AstroCappella song "High Energy Groove" to create the High Energy Groovie Movie, an educational video targeted at middle school science students and the general public. Teacher interns and the GOF created a classroom activity for each verse of the song. The theme of the movie and activities is the inherent excitement of our dynamic high-energy universe. By including graphical explanations of *RXTE*'s most important discoveries, and developing activities that reinforce math and science curriculum concepts, our project achieves the OSS EPO goals of **sharing** the excitement of space science discoveries with the public, **enhancing** the quality of science, mathematics, and technology education, particularly at the pre-college level, and **helping create** our 21st century scientific and technical workforce.

RXTE has a strong link with the HEASARC's E/PO group, which creates an impressive "Bang for the Buck" in realizing our E/PO goals.

In summer 2002, two teacher interns developed eight activities for the Groovie Movie, each linked to the National Science Education Standards. Our E/PO funds covered one teacher intern. The second was shared with the HEASARC E/PO program at no cost to *RXTE*. One activity, "an X-ray Binary Model", lets students hold an accretion disk in their hands (Figure 1). This inexpensive model, simple yet profound, was field tested at two onsite GSFC educator workshops. It proved so popular that the HEASARC E/PO group incorporated it into their national teacher workshops, reaching an additional 250 educators. NASA's GSFC education office has discussed developing a one-page educational lithograph around the activity. One teacher tested all activities in her classrooms for the last two years, and has made improvements based on students' experience and feedback.

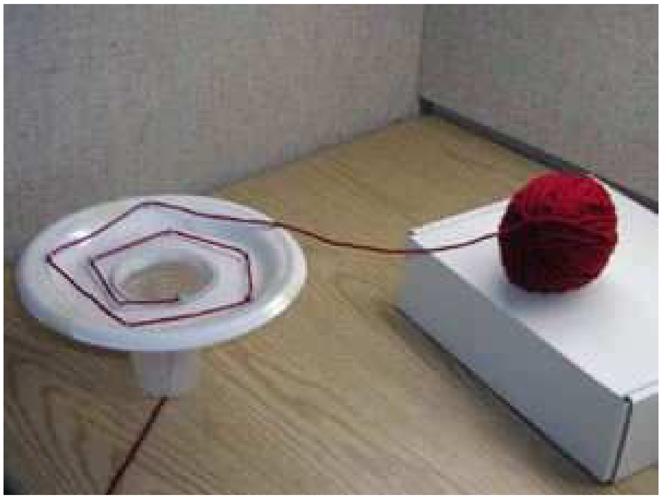

Fig. 1.— Photograph of a completed X-ray binary model. The ball of yarn represents the mass-losing star, the paper plate the accretion disk around a compact object, in this case a black hole. The lip of the cup represents the last stable orbit before the matter disappears past the event horizon.

Work on the movie began in early 2003. It includes many animations of the exotic objects behind *RXTE*'s most exciting results. Since the subject is X-ray astronomy, a few *Chandra* segments were also included. A beta version has been shown to audiences in the High Energy Astrophysics community, and at the AAS Meeting in Atlanta. The movie and activities can be found at: http://rxte.gsfc.nasa.gov/docs/xte/outreach/HEG/-groovie.html. Feedback has been enthusiastic. The movie is now virtually complete pending the addition of some explanatory text, and full credits for the images used (Figure 2).

Future Plans. Our future E/PO plans are two-fold: maximize the effective distribution of the Groovie Movie and activities, and capitalize on opportunities to spread the excitement of *RXTE* discoveries such as the 10th an-

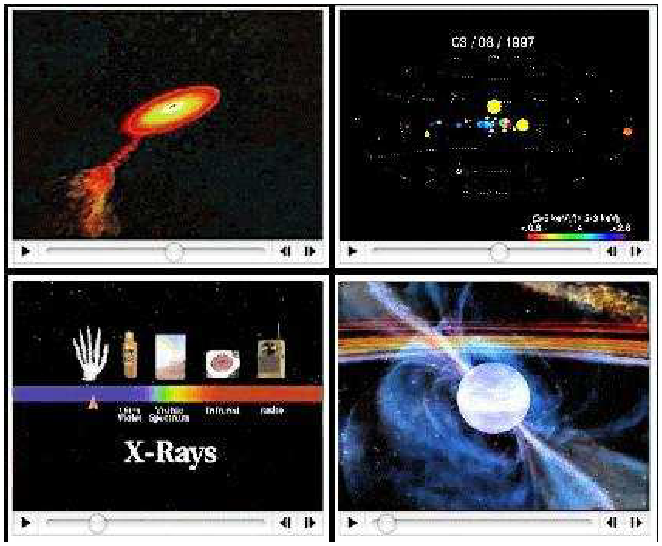

Fig. 2.— Four screenshots from the High Energy Groovie Movie. Top left: a "stellar cannibal" devours its companion; Top right: the X-ray sky as seen by the All-Sky-Monitor on March 8, 1997; Bottom left: the electromagnetic spectrum, showing the location of X-rays and wavelengths more familiar to students; Bottom right: a rapidly rotating pulsar.

niversary of *RXTE* (on 30 Dec 2005) and other physics-related celebrations in 2005.

In 2004 a teacher intern will develop an educators guide for the movie and activities, and develop an educator workshop. We will ask the DePaul Broker/Facilitator teacher network to evaluate the movie, activities and guide. During 2004–2005 we will present the workshop at the Maryland and Virginia Area Science Teachers' Meetings. We will incorporate lessons learned into a workshop for a national educator audience in 2005–2006. At these workshops, and meetings attended by *RXTE* or HEASARC E/PO staff, we will distribute the movie, activities and guide via CD-ROM.

In Sept. 2005 we will invite MD-DC-VA area students to explore the discoveries of *RXTE* during their lifetimes. Students will compose a report "Science in my Life" by researching topics in our *RXTE* Discoveries archive in the Learning Center. This activity will be tied to the National Science Education Content Standard G: The History and Nature of Science. Students will explore Science as a Human Endeavor and the Nature of Science. They will understand science as continually evolving, and explore how scientists use *RXTE* data to test explanations of nature and mathematical models. Teachers will forward the best reports from their class to the *RXTE* and HEASARC E/PO groups, who will choose the most creative 3–6. These students and their teachers will be invited to tour the *RXTE* facilities, and take part in *RXTE*'s 10th Birthday Celebration, an event for which we will seek local and national publicity. With good media coverage, *RXTE*'s 10th birthday will communicate its decade of discovery to a broad segment of the public as well.

We plan to hold the birthday event locally at the Owens Science Center (MD) or the GSFC Visitors Center, so the public can attend. The winning students will be awarded with astronomy-themed prizes during the party. We will ask Celestron and Meade to donate prizes, and seek donated subscriptions from popular science magazines.

The World Year of Physics in 2005 commemorates the 100th anniversary of Einstein's major works. The APS, AAPT and AIP are leading the US participation, with the theme "Einstein in the 21st Century." This is strongly compatible with *RXTE*'s E/PO efforts, which focus on objects so dense that space-time surrounding them is extremely distorted. We will actively seek out opportunities to connect our E/PO activities to the World Year of Physics.

Our future E/PO plans are bold, and our strong relationship with HEASARC E/PO affords us a high degree of leverage. While the GOF is small, the staff has demonstrated an enduring commitment to E/PO. By distributing the Groovie Movie on CD-ROM at educator workshops, organizing the 10th birthday celebration, and participating in the World Year of Physics, *RXTE* will make significant impacts on educating students and the general public about the unique and exciting science done by high energy astrophysicists.

OSS E/PO Criteria	***RXTE* E/PO**
1. Quality, scope, realism, appropriateness; linkage to parent science program.	Movie, activities directly tied to *RXTE* capabilities, discoveries.
2. Adequacy, appropriateness, realism of budget, including effective use of funds.	Experienced staff reaches broad audience of educators, students, general public.
3. Capabilities, commitment, involvement of team, including science personnel and partners.	Scientist and experienced teacher lead development.
4. Appropriateness of plans for evaluating effectiveness, impact.	Use of DePaul Broker/Facilitator teacher network.
5. Alignment with national education reform efforts.	Activities linked to NSES. Workshop aligned with professional development reform efforts.
6. Training, involvement, understanding of under-served and/or under-utilized groups in science.	DC-area students targeted.
7. Potential for E/PO activity to expand its scope.	Focus on X-ray astronomy; other X-ray E/PO programs can use movie.

Table 1: *RXTE* E/PO Characteristics

E/PO Team, Management and Budget. *RXTE* E/PO is led by GOF scientist Dr. Boyd (0.12 FTE). She has been involved in LHEA E/PO since '95, and has worked with teachers on workshops for local and national audiences. The Project Scientist also spends 0.1 FTE on E/PO. A 0.1 FTE HEASARC graphic designer will contribute to the project, and 0.1 FTE GOF User Support personnel. We will fund one teacher intern each summer. Our budget includes costs for production of a CD-ROM to distribute the movie, activities and guide, and travel costs to meetings. The E/PO budget is between 1.2% and 1.5% of the minimal scenario budget for FY04–08.

4. Budget Forms

NO COST

5. Appendix: Acronyms

AAPT — American Association of Physics Teachers
AAS — American Astronomical Society
AGN — Active Galactic Nuclei
AIP — American Institute of Physics
AMOS — Automated Mission Operations System
AO — Announcement of Opportunity (*RXTE* proposal process)
APS — American Physical Society
ASCA — Advanced Satellite for Cosmology and Astrophysics (X-ray Mission)
ASM — All-Sky Monitor
AXP — Anomalous X-ray Pulsar
BAT — Burst Alert Telescope (*Swift* instrument)
BH — Black Hole
BHB — Black Hole Binary
BHXRB — Black Hole X-ray Binary
Crab — Crab Flux Unit = 2.42×10^{-8} erg s^{-1} cm^{-2} (2–10 keV)
CANGAROO — Collaboration of Australia and Nippon for a GAmma Ray Observatory in the Outback (Gamma-ray observatory)
CGRO — Compton Gamma-Ray Observatory
EDS — Experimental Data System
EOS — Equation of State
EPO — Education and Public Outreach
FDF — Flight Dynamics Facility (at GSFC)
FITS — Flexible Image Transport System
FOT — Flight Operations Team
FTE — Full Time Equivalent
GLAST — Gamma-ray Large Area Space Telescope
GO — Guest Observer
GOF — Guest Observer Facility
GRB — Gamma-Ray Burst
GR — General Relativity
GSFC — Goddard Space Flight Center
HEASARC — High Energy Astrophysics Science Archive Research Center
HEG — High Energy Grating (on *Chandra* Observatory)
HESS — High Energy Stereoscopic System (TeV telescope)
HETE-2 — The High Energy Transient Explorer
HEXTE — High Energy X-ray Timing Experiment (*RXTE* instrument)
HFQPO — High Frequency Quasiperiodic Oscillation
IAU — International Astronomical Union
IAUC — International Astronomical Union Circular
IT — Instrument Team
$\mathbf{L_{Edd}}$ — Eddington Luminosity
LHEA — Laboratory for High Energy Astrophysics
LMXB — Low Mass X-ray Binary
LOFAR — Low Frequency Array
$\dot{\mathbf{M}}$ — Mass accretion rate
mCrab — 10^{-3} Crab Flux Units
MAGIC — Air Cherenkov Telescope (La Palma)
MIT — Massachusetts Institute of Technology
MOC — Mission Operations Center
NOA — New Obligation Authority
NRA — NASA Research Announcements
NS — Neutron Star
NSES — National Science Education Standards
OSS — NASA Office of Space Science
PCA — Proportional Counter Array
PCU — Proportional Counter Unit
PI — Principal Investigator
PSD — Power Spectral Density
PSR — Pulsar
QPO — Quasiperiodic Oscillation
ROSAT — ROentgen SATellite (X-ray observatory)
RXTE — Rossi X-ray Timing Explorer
SALT — Southern African Large Telescope (Gamma-ray)
SAX — BeppoSAX - Satellite per Astronomia X
SGR — Soft Gamma Repeater
SOC — Science Operations Center
SOF — Science Operations Facility
SPL — Steep Power Law State (black hole spectra)
SSC — Scanning Shadow Camera (ASM Detector)
Swift — *Swift* Gamma-ray Burst Observatory
TDRSS — Tracking and Data Relay Satellite System
TOO — Target of Opportunity
UCSD — University of California at San Diego
VERITAS — Very Energetic Radiation Imaging Telescope Array System (Gamma-ray)
XMM — XMM-Newton - X-ray Observatory
XRB — X-ray Binary
XRT — X-ray Telescope (*Swift* instrument)
XSDC — XTE Science Data Center