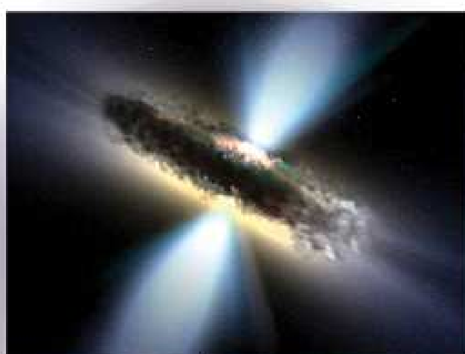
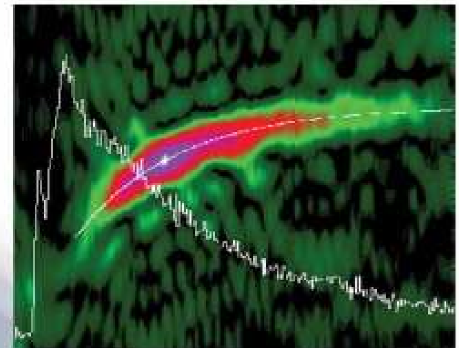
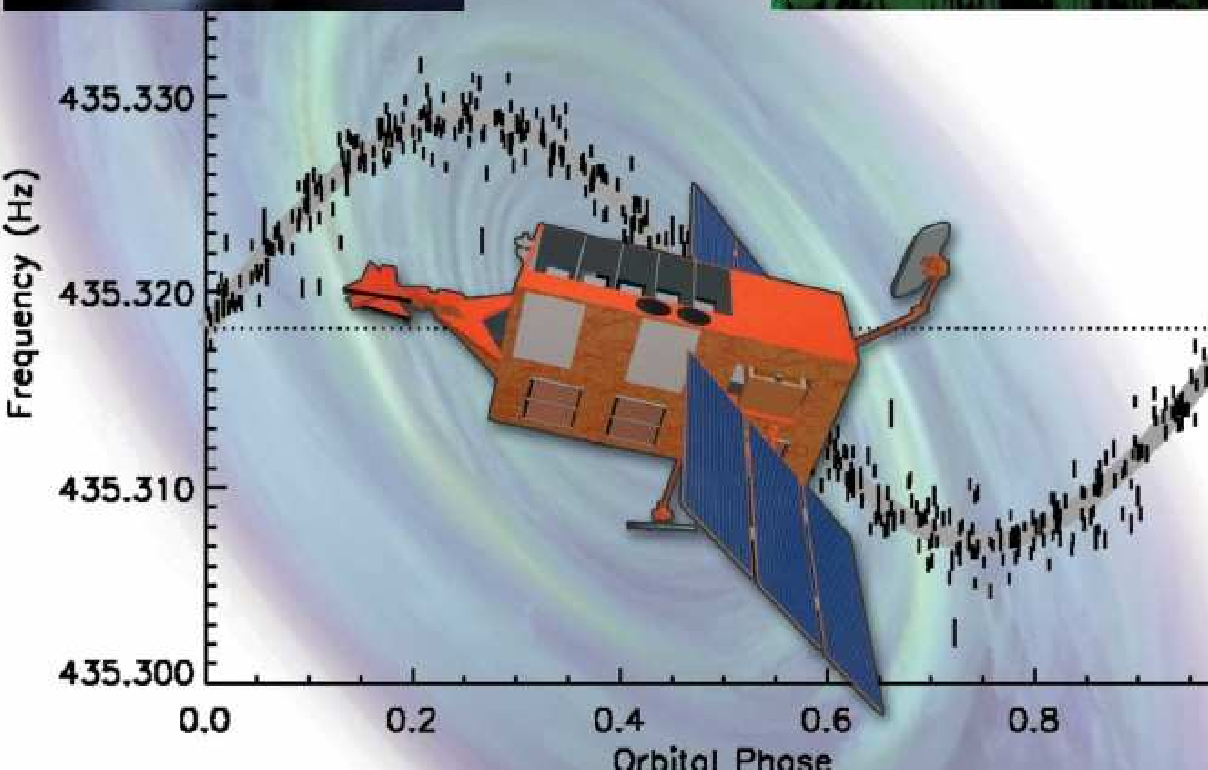
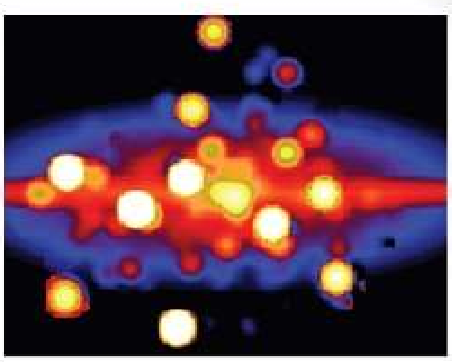
The Rossi X-ray Timing Explorer

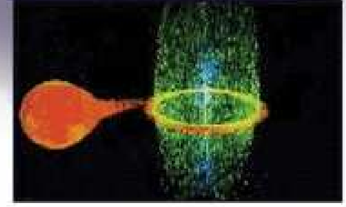






A proposal submitted to the 2006 Senior Review of Astrophysics Mission Operations & Data Analysis Programs





Rossi X-ray Timing Explorer

Proposal to the 2006 Senior Review of
Astrophysics Mission Operations & Data Analysis Programs

TABLE of CONTENTS

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Astrophysics Mission Operations & Data Analysis Programs

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Summary

The *Rossi X-ray Timing Explorer (RXTE)* is an X-ray observatory with a powerful and unique combination of large collecting area, broad-band spectral coverage, high time resolution, flexible scheduling, and ability to respond quickly to time-critical targets of opportunity. This combination has led to breakthroughs in our understanding of the basic physics of the strong gravity, high densities, and intense magnetic fields found in neutron stars, accreting white dwarfs, and galactic and extragalactic black holes. Understanding the physics that occurs in these extreme environments is a key objective of NASA's Strategic Plan. *RXTE*'s ability to discover and study phenomena that occur on the natural timescales of neutron star surfaces and black hole event horizons is unique among all past and present astrophysics missions. During the two years since the last Senior Review, *RXTE* has continued to achieve dramatic new scientific milestones, both on its own and in combination with other NASA satellites. *RXTE*'s unique capabilities, its high productivity at modest cost, and its crucial support for the observing programs of ground-based instruments, such as the new generation of TeV gamma-ray telescopes, and other space-based observatories, such as *Chandra*, *XMM-Newton*, *INTEGRAL*, and *GLAST*, are compelling reasons to continue the *RXTE* mission.

1. Science Proposal

1.1. Introduction and Overview

A major thrust of humanity's exploration of the universe is understanding extreme environments and the wondrous phenomena found there. *RXTE* is uniquely capable of exploring the most extreme environments known, which include neutron stars and black holes, accretion flows onto them, and the systems in which they are found; the later stages of the evolution of massive stars; and regions of strong gravity, high densities, and ultrastrong magnetic fields. *RXTE* has been and continues to be highly successful in advancing our understanding of these environments and the physical processes that occur there.

Box 1 summarizes some of the major accomplishments of the *RXTE* mission. Highlights of the many discoveries made since the 2004 Senior Review are listed in Box 2. *RXTE*'s original scientific program remains highly productive and is being pursued with enthusiasm by *RXTE*'s broad base of users, who compete for observing time through the annual peer-reviewed guest observer program. This proposal describes the wide range of important and exciting new results anticipated with two years of operations beyond the current observing cycle and the steps that are being taken to keep costs to a minimum.

Three relatively recent developments in the observing program are noteworthy. First, two years ago the scans of the Galactic plane with the Proportional Counter Array (PCA) were expanded in terms of time and scope. These scans are much more sensitive to transients than those of the All Sky Monitor (ASM). Second, there has been a gradual shift to greater total exposures on important targets. For example, 300 ks was obtained on the millisecond pulsar SAX J1808.4–3658 while it was in outburst in June 2005, and more than 2 Ms were obtained on the black-hole binary GRO J1655–40 in outburst. Third, we have improved our ability to coordinate observations and rapidly release results with other space observatories. We have an agreement with *Swift* to confirm each other's preliminary indications of new sources and to coordinate plans for follow-up observations. We have a close working relationship with *INTEGRAL* for following up its discoveries of new sources and for simultaneous coverage for observations. We have supported, through proposals, cross calibrations with *Suzaku*. We award up to 500 ks of *RXTE* time for *Chandra* proposals that request time from both observatories. In many additional cases we coordinate separately proposed observations with *Chandra* and *XMM-Newton*.

The continuing high rate of publications is an important indication of *RXTE*'s productivity. In the two year period 2004–2005, refereed publications increased to 328 (compared to 316 for 2002–2003). In the same periods, rapid communications (IAUCs, ATels, and GCNs) increased to 165 from 144. There were 703 total abstracts for 2004–2005, compared to 710 posted for 2002–2003 by 2004.

RXTE has also addressed many secondary objectives including X-ray bright white dwarf systems (e.g. TV Col, RS Oph), active-star coronae, colliding winds (η Car), supernova remnants, γ-ray bursts, and the Galactic ridge. Monitoring the brightest ULX in M82 led to discovery of a possible 62 d binary period (Kaaret et al. 2006).

Box 1: Major Accomplishments of *RXTE*

- 3 *RXTE*-related Rossi prizes; > 320 Guest Observer PIs; > 1300 refereed papers; > 47 Ph.D. theses.
- Measured millisecond neutron star spins using pulsations and oscillations during thermonuclear bursts.
- Discovered evidence for limits to the spin-up of neutron stars in low-mass systems.
- Demonstrated that the frequencies of the twin kilohertz oscillations in neutron stars and the 10–100 Hz oscillations in black hole candidates are related to the mass of the compact object and its spin.
- Obtained valuable accretion-disk and compact-object diagnostics from 2–200 keV spectroscopy.
- Discovered close similarities between Soft Gamma-ray Repeaters and Anomalous X-ray Pulsars (pulsations, frequency changes, and bursts).
- Measured multiple cyclotron lines in high-mass binary pulsars.
- Established connections between radio jet formation and accretion disk instabilities.
- Showed that the X-ray, GeV, and TeV emissions of blazars are co-located.
- Showed that the variability of stellar and supermassive black holes is similar, with frequencies that scale inversely with the mass.

Box 2: Highlights of 2004–2005 Discoveries

- High publication rate: steady 160 refereed per year.
- Neutron star spins: two new millisecond X-ray pulsars, possible torsional crust oscillations in SGRs (Fig. 3), rotation rate glitches in AXPs and isolated pulsars.
- Accretion disks: signatures of the disk inner edge predicted by GR (Fig. 2), kHz oscillations from Cir X-1.
- Thermonuclear burning: explanation of narrow resonance scattering lines in thermonuclear bursts; burst oscillations from two additional sources.
- New transients: a second bursting pulsar, SWIFT J1626.6–5156, and the first transient Z-source.
- Strong magnetic fields: cyclotron harmonic structure in V0332+53 (Fig. 4); the fundamental cyclotron line in A0535+26; systematic cyclotron line shifts in Her X-1; SGR-like bursts from a transient candidate magnetar.
- BH accretion: recurring high-frequency X-ray oscillations in repeating BH transients, a new comprehensive framework for understanding the evolution of the spectral states of stellar-mass BHs (Fig. 5), identification of two distinct accretion flows (Fig. 6).
- Jet formation: superluminal radio jet ejection coincident with an X-ray flare of H1743–322, correlated X-ray and radio emission in BH low states.
- Active Galactic Nuclei: scaling of AGN variability with accretion rate, observation of correlated X-ray and TeV flares from Mrk 421 (Fig. 7).

Proposed Focus for 2007–2009 Observations

In the coming years, the *RXTE* mission will pursue its goals by addressing new opportunities and new questions raised by earlier results.

We do not yet have a full understanding of the processes that generate the kilohertz quasi-periodic oscillations (kHz QPO) in neutron star low-mass X-ray binaries (LMXBs); achieving this will provide a powerful new tool. We expect to discover additional examples of millisecond accreting pulsars with kHz QPOs. All known accretion-powered millisecond pulsations and kHz oscillations have been discovered with *RXTE* (§1.2).

Now that it is known that black hole binaries (BHB) can exhibit high-frequency QPOs (HFQPO) and that more than half of those cases exhibit a HFQPO pair with the frequencies in a 3:2 ratio, it is important to know if they always occur as one of a pair of frequencies with a 3:2 ratio. Since the high frequency QPOs have all been found only by sifting through many observations of black-hole transients, we plan to obtain dense observations of new outbursts of BHBs (§1.3).

RXTE's recent discoveries show that the sky has by no means exhausted its supply of new, rare, diagnostic, and revealing phenomena that can be found via observations of transient sources. Transients played a major role in many *RXTE* discoveries (Boxes 1 and 2) and will continue to do so. The *RXTE* results build on the results of previous X-ray missions, and show that the outbursts in these sources recur on a wide range of time scales from less than 1 year to more than 30 years. Continuation of the *RXTE* mission will yield both new phenomena and new information on recurrent sources.

We will continue to support coordinated observations with *Chandra*, *XMM-Newton*, *Swift*, *INTEGRAL*, and *Suzaku* and expect that our arrangements for timely notification of new sources with *Swift* and *INTEGRAL* will lead to additional new discoveries.

The coming years will see great progress at GeV and TeV energies as new observatories and instruments come on line. The 100 MeV to 300 GeV range will be explored by *GLAST* after its planned August 2007 launch. The TeV energy range will be explored at high sensitivity by the HESS, VERITAS, and MAGIC projects after they reach full operation by 2007. The core program of *GLAST* and the new TeV instruments will be monitoring numerous blazars (§1.4.1) to understand the physics of these highly variable, jet-dominated, super-massive BHs. With its flexible scheduling, nearly all-sky coverage, and complementary energy band, *RXTE* can provide critical support for these new programs.

Detecting gravitational waves (GW) is a major quest in astrophysics and an enormous world-wide effort is underway to improve sensitivities including the upgrade of LIGO. It is quite reasonable to expect that corroborating electromagnetic observations could prove critical for confirming the initial indications of GWs. Detection of GWs from accreting pulsars in the applicable frequency range of > 30 Hz is one possibility, and here *RXTE* is well-positioned to provide the frequencies to guide the search for GWs as well as to corroborate early results.

RXTE's overarching objectives and the specific goals of continued observations address the NASA Strategic Plan sub-goals 3D.1 and 3D.2. Neutron stars and black holes are where to study strong gravity and its consequences of high density, strong magnetic fields and even jets. They are the end points of stellar evolution. Supermassive BHs are instrumental in the formation and the evolution of galaxies and the universe.

The current cost of *RXTE* is a fraction of that during its prime mission, and we continue to aggressively pursue cost reductions. As described in §3, we plan to use our extensive experience in operating the observatory to increase efficiency, to use more automation, and to accept some increased risk while maintaining our key capabilities. We will reduce staff throughout the program and significantly reduce our usage of TDRSS. A peer-reviewed science program with the ability to respond to TOOs and to coordinate with other observatories is the most effective way to utilize this marvelous observatory.

In summary, continuation of the *RXTE* mission is an efficient use of resources that will significantly contribute to the goals of NASA's Strategic Plan. We propose two additional cycles of operation beyond our current cycle 11, until Feb. 28, 2009, with completion of data distribution, calibration, and documentation in FY2009. This would provide overlap with *GLAST* and allow reevaluation of the situation in the Senior Review of 2008.

1.2. Neutron Stars

Neutron stars represent extremes in gravity, density, and magnetic fields, hence study of them yields insight into fundamental physics at the limits of current understanding. High frequency brightness variations can be driven by accretion, stored rotational energy, thermonuclear burning on the neutron star surface, or by powerful inherent magnetic fields. The emission region can be the neutron star surface or the inner portions of the accretion disk. *RXTE* has discovered that accreting neutron stars with relatively low magnetic moments can exhibit kilohertz quasi-periodic oscillations, which reach frequencies of $\sim$ 1,300 Hz, close to the maximum allowed by general relativity for stable orbits. Also, when neutron star magnetic fields exceed $B_c = 4.4 \times 10^{13}$ G, exotic quantum electrodynamic processes become important. *RXTE* has been at the forefront of the study of these "magnetars." Thus, *RXTE* probes the structure and environment of neutron stars.

1.2.1. Spins

Since the last Senior Review *RXTE* has identified two new accreting millisecond pulsars; IGR J00291+5934 (Markwardt et al. 2004a,b; Galloway et al. 2005), and HETE J1900.1-2455 (Morgan, Kaaret & Vanderspek 2005), with spin rates of 599 and 377 Hz, and orbital periods of 2.46 and 1.39 hr, respectively. In addition, oscillations during thermonulcear X-ray bursts have been discovered in two objects; EXO 0748-676 (Villarreal & Strohmayer 2004), and A1744-361 (Bhattacharyya et al. 2006), with frequencies of 45 and 530 Hz, respectively.

These discoveries are providing unique insight into the evolution of millisecond pulsar binaries and the physics that controls spin evolution of accreting neutron stars. Because the X-ray detection of such systems is not limited by selection effects at high spin rates, unlike radio pulsar searches, *RXTE* has provided strong evidence that few if any accreting neutron stars in low-mass systems have spin rates above about 750 Hz (Chakrabarty et al. 2003). Further observations can determine whether this is due to magnetic braking, gravitational radiation, or the limited amount of angular momentum that can be accreted in such systems. **Further *RXTE* observations will be crucial in providing the unbiased spin frequency distribution required to understand neutron star spin evolution.**

RXTE observations of X-ray bursts from the eclipsing neutron star LMXB EXO 0748–676 have revealed the spin frequency to be 45 Hz (Villarreal & Strohmayer 2004). While this is the smallest known spin frequency for a burster, the spin is consistent with the narrow absorption line features detected by Cottam, Paerels & Mendez (2002) with the *XMM-Newton* grating instruments (i.e. little Doppler broadening). If more precise measurements of line profiles can be made, then fits of the line profiles to detailed models will provide a measurement of the neutron star radius (Özel & Psaltis 2003; Bildsten, Chang, & Paerels 2003; Chang, Bildsten, & Wasserman 2005; Chang et al. 2006; Bhattacharyya et al. 2006). A radius measurement at the 5 - 8 % level would constrain the nuclear symmetry energy (Lattimer & Prakash 2001). ***RXTE* observations are crucial to measure spin periods to enable such radius measurements.**

Possible future events with major impact. The accreting millisecond pulsar SAX J1808.4–3658 has had multiple outbursts in the *RXTE* era. For a well sampled outburst, it is possible to construct a coherent pulse timing solution, and derive a mean spin frequency precise to better than $\sim$few$\times 10^{-7}$ Hz. Measurements of this precision are sensitive enough to distinguish between the spin-down torques due to gravitational radiation and magnetic braking.

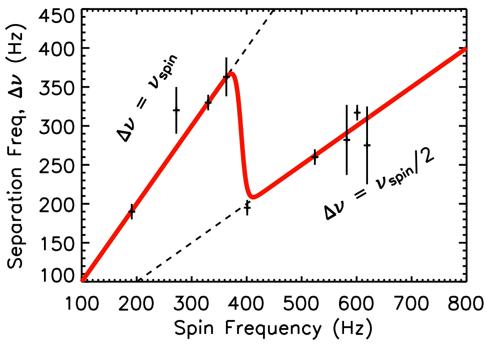

Fig. 1.— kHz QPO separation frequency, $\Delta\nu = \nu_2 - \nu_1$, versus spin frequency $\nu_{\rm spin}$, demonstrating the close harmonic relationship between the spin and separation frequencies. The red line shows the transition from the $\Delta\nu = \nu_{\rm spin}$ branch to the $\Delta\nu = \nu_{\rm spin}/2$ branch around $\nu_{\rm spin} = 400$ Hz.

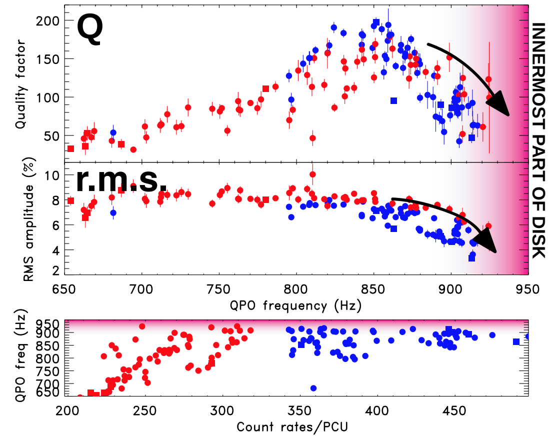

Fig. 2.— Oscillator quality factor, Q, and r.m.s. amplitude as a function of frequency of the lower kHz QPO peak in 4U 1636–536. The frequency appears to have an upper limit of $\sim$ 930 Hz (represented by the pink region), indicative of the inner edge of the accretion disk. The oscillation strength and coherence decrease as the frequency approaches the limit as well. Colored points indicate that the trend is independent of count rate. Original figure from Barret et al. (2005b).

Another development with major impact would be the detection of thermonuclear burst oscillations from additional accreting millisecond pulsars. Currently only SAX J1808.4–3658 and XTE J1814–338 show both accretion-powered millisecond pulsations and burst oscillations. The burst oscillations in these sources show behavior qualitatively similar to that seen in nonpulsing burst oscillation sources, however, questions have been raised (e.g., Piro & Bildsten 2005) about whether there are important quantitative differences, such as the rate at which the burst oscillation frequency locks to the stellar spin frequency, or how closely the asymptotic burst oscillation frequency matches the spin frequency. With only two burst oscillators for which the spin frequency is known to high precision it is difficult to resolve these questions. More examples would be invaluable.

1.2.2. Strong Gravity and Accretion Flows

Kilohertz QPO. Quasi-periodic brightness oscillations in the $\sim$ 100 − 1300 Hz range (kilohertz QPOs) have now been observed with *RXTE* from more than 25 neutron star LMXBs. Typically, two distinct peaks are detected in the power spectrum, at lower and upper frequencies ν_1 and ν_2 respectively.

The QPO frequency separation, $\Delta\nu = \nu_2 - \nu_1$, is approximately equal to either the spin frequency or half the spin frequency (Fig. 1). This behavior suggests a resonant interaction between the stellar spin and the accretion disk (Muno et al. 2001; Wijnands et al. 2003; van der Klis 2000). Current ideas suggest that the upper frequency, ν_2, is close to an orbital frequency near the inner edge of the disk.

The interpretation of the upper peak frequency as close to an orbital frequency would allow important and exciting inferences to be drawn from the current *RXTE* data set. As discussed initially by Miller, Lamb, & Psaltis (1998), the persistence of an oscillation for many cycles is impossible inside the innermost stable circular orbit (ISCO), where gas spirals rapidly to the star and cannot survive long enough to produce even moderately coherent oscillations. Thus, the existence of an ISCO sets an upper limit on the kHz QPO frequency if they are produced by orbital motion. For a non-spinning star, the highest observed upper QPO frequency $\nu_{2,\rm max}$ then limits its mass to $M < 2.2\,M_\odot(1000~{\rm Hz}/\nu_{2,\rm max})$ and its radius to $R < 19.5~{\rm km}(1000~{\rm Hz}/\nu_{2,\rm max})$, and poses the strongest current limits on how stiff the equation of state (EOS) of matter beyond nuclear saturation density can be (Lattimer & Prakash 2001; Klähn et al. 2006).

Evidence for the existence of an ISCO would provide support for this key prediction of strong-field general relativity. Recently, Barret, Olive, & Miller (2005a,b) have found new evidence for an ISCO, in 4U 1636–536. Consistent with theoretical expectations (e.g., Miller, Lamb, & Psaltis 1998; Lamb & Miller 2001, 2003), they find a reproducible upper limit on the QPO frequency and a sharp drop in the coherence of the QPO near this limit (Fig. 2). The frequency limit is the same in different observations and is independent of measures of the mass accretion rate such as the count rate, hard color, and soft color. This argues against plasma effects and in favor of the ISCO interpretation.

Measurement of the frequency of the ISCO near a neutron star gives a fairly precise estimate of its mass. The ISCO frequency inferred by Barret et al. (2005a,b) in 4U 1636–536 gives $1.8 - 2.1\,M_\odot$, which is consistent with current realistic high-density equations of state, but near the maximum masses they predict (Lattimer & Prakash 2001).

Currently, there are a few sources other than 4U 1636–

536 that show similar trends of quality factor with frequency, but for most we do not yet have enough data to make a strong case. **Additional focused *RXTE* observations are essential to pursue this effect because of its fundamental physics implications.**

Possible future events with major impact. The only two sources that have both persistent pulsations and kHz QPOs (SAX J1808.4–3658 and XTE J1807–294) lie on two different branches of Fig. 1. However, analysis of the comparatively weak outburst of SAX J1808.4–3658 in June 2005 shows possible evidence for a pair of kHz QPOs whose separation lies on the opposite branch from the previous detection for the same source (M. Klein-Wolt, personal communication). This intriguing possibility suggests that spin is not the only factor that regulates the QPO spacing. The next outburst of SAX J1808.4–3658 is due in late 2008. Further observations of this system and others are needed to solidify the dependence of kilohertz oscillations on spin.

In addition, any single source with a QPO at 1600 Hz would immediately pose extremely strong constraints on the EOS of dense matter, and would in fact rule out most mean field models, because the implied radius would be smaller than these models predict (Lattimer & Prakash 2001).

1.2.3. High Density Physics

RXTE has recently found fast QPOs during the hyperflares produced by SGRs. These may be the first detections of global seismic vibrations of neutron star crusts (although see Levin 2006). If so, they could provide probes of neutron star structure analogous to helioseismic probes of the Sun. SGR hyperflares are the brightest cosmic events in terms of flux received at Earth, and although many satellites have detected them, *RXTE* is one of the few in orbit with the timing capabilities and large detector area needed to study their fast timing properties.

Israel et al. (2005) found that the X-ray flux in the pulsating tail of the December 2004 flare from SGR 1806-20 was oscillating at several discrete frequencies; ≈ 18, 30, and 92 Hz, and suggested some of these could be identified with specific torsional vibration modes of the crust. The periods of such modes (denoted ${}_lt_n$, where l is the spherical harmonic index for the mode, and n gives the number of nodes in the radial displacement eigenfunction) depend on the shear wave speed in the crust and its size (Strohmayer et al. 1991; Duncan 1998). A summary of current observational results on the SGR QPOs and their interpretation is given in Fig. 3. The properties of the fast oscillations seen so far in two sources appear to be similar, strongly supporting the conclusion that they share a common origin. Most recently, evidence for additional, higher frequency oscillations at 148 and 625 Hz has been found in the SGR 1806–20 hyperflare (Watts & Strohmayer 2006; Strohmayer & Watts 2006). Indeed,

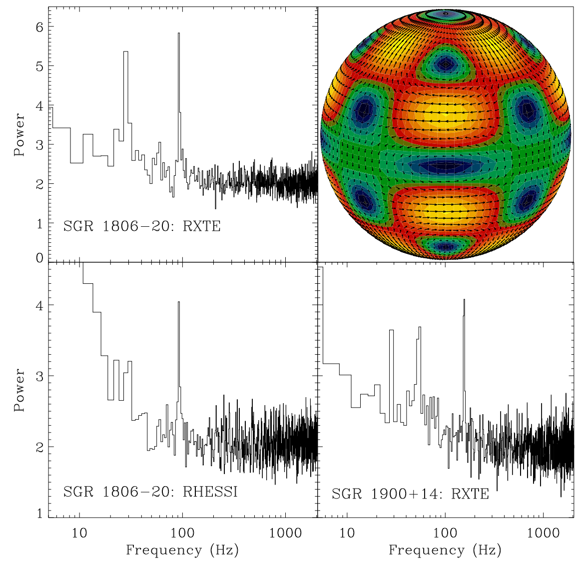

Fig. 3.— Power spectra showing fast X-ray oscillations discovered with RXTE during SGR hyperflares. Oscillations at 29 and 92 Hz from SGR 1806-20 were first discovered with RXTE (top, Israel et al. 2005), and were subsequently confirmed in RHESSI data (bottom). A sequence of three frequencies (28, 53, and 155 Hz) are shown from the SGR 1900+14 flare. These and other oscillations have been linked with low order torsional vibration modes (${}_lt_n$) of the neutron star crust (Piro 2005). The frequencies in SGR 1900+14 fit a mode sequence with $l = 2, 4, 7, 13$ ($l = 7$ not shown), while the pair of oscillations in SGR 1806-20 are identified with $l = 2$ & 7 modes. The pattern of surface motions for an $l = 4, m = 2$ mode is shown in the top right panel.

the 625 Hz oscillation fits nicely within the torsional mode picture as a low l, $n = 1$ mode. The periods of crustal shear modes depend on the global structure of the star and thus the EOS of matter in the deep interior. Thus secure mode identifications could lead to new constraints on the EOS of dense nuclear matter.

Possible future events with major impact. Two SGR hyperflares have occurred in the *RXTE* era. At this point the frequencies are strongly suggestive of torsional vibrations, but their implications remain uncertain because their number is limited. Are different modes excited in each flare? Are the strong QPOs seen in both sources, in the 84–92 Hz range, a clue as to the primary oscillation mode of the crust? QPOs from another giant flare observed with *RXTE* would go a long way towards answering questions about the origin of the phenomenon, and based on previous rates of hyperflares the probability of such an event within the next two years may be as high as tens of percent.

1.2.4. High Magnetic Fields

SGRs and AXPs are believed to be magnetars. The proposal by Thompson & Duncan (1995, 1996) that magnetars have magnetic fields two orders of magnitude greater than even the strongest-field normal pulsars was confirmed decisively with the *RXTE* discovery of pulsations and period change in the persistent emission of SGR 1806–20 and SGR 1900+14 (Kouveliotou et al. 1998, 1999). Similar discoveries were made later for AXPs (e.g., Kaspi, Chakrabarty, & Steinberger 1999; Pivovaroff, Kaspi, & Camilo 2000; Guseinov et al. 2003; Ibrahim et al. 2004). The confirmation of these strong fields means that magnetars are unique laboratories for the most extreme predictions of quantum electrodynamics, because no terrestrial experiment can simulate these conditions. For example, several reports of emission and absorption lines in magnetar bursts (Woods et al. 2005; Ibrahim et al. 2002, 2003; Strohmayer & Ibrahim 2000) suggest processes like proton cyclotron resonance may be observable under certain conditions; this would have great theoretical interest (e.g., Bulik & Miller 1997; Zane et al. 2001, Ho & Lai 2001, 2003, 2004; Lai & Ho 2002, 2003a,b; Özel 2003; Ho et al. 2003, 2004).

Long-term phase-coherent pulse timing with RXTE has led to the discovery of three rotational glitches from two AXPs during the last 7 years. As sudden spin frequency changes followed by gradual recovery, glitches provide a unique window into the structure and angular momentum distribution in the neutron star interior. Two glitches from the AXP 1RXS J170849.0−400910 have shown two different kinds of glitch recovery behaviors (no recovery vs. rapid recovery), suggesting that a range of crust-interior interactions is possible (Kaspi et al. 1999; Kaspi & Gavriil 2003; Dall'Osso et al. 2003). Another glitch from 1E 2259+586 also coincided with a series of bright bursts and extreme changes in the persistent emission properties, suggesting a radical reconfiguration of the neutron star magnetosphere (Kaspi et al. 2003; Woods et al. 2004). Given the diversity of behavior seen in just three glitches, **additional glitch measurements, obtainable only through RXTE monitoring, are needed to better understand these events**. In addition to glitches, which are infrequent, monitoring the magnetars has shown that they are subject to large changes in torque and pulsed flux (e.g. Kaspi et al. 2001). Thompson, Lyutikov & Kulkarni (2002) refined their original models because of such observations, and **future pulse timing monitoring will test their model**.

1.2.5. Accreting Pulsars

Recently two historically important transients have produced long-awaited major outbursts: V0332+53 and A0535+26. Both of these objects are Be/X-ray binary systems, which have rare outbursts (type II) that can last months and often reach the Eddington luminosity. The outbursts have allowed for detailed study of cyclotron absorption features in pulsar energy spectra, and of the coupling between the accretion disk and neutron star magnetosphere.

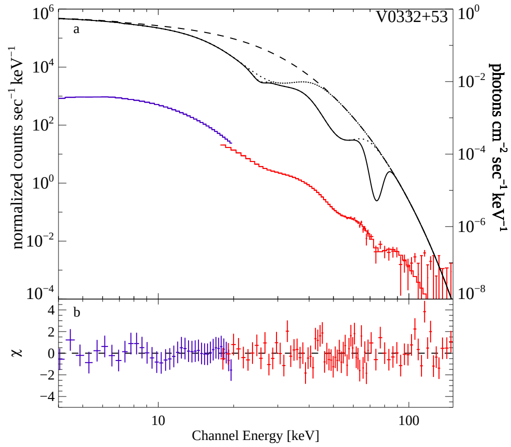

Fig. 4.— The RXTE spectrum of V0332+53 showing three cyclotron lines, including the two newly discovered harmonics at 51 and 74 keV. The non-uniform spacing of the line energies is consistent with the quantum electrodynamic cross-section for resonant Compton scattering, if (as expected) the radiation is emerging from the walls of the accretion column. This is a direct proof for the interpretation of the absorption features as cyclotron lines (Pottschmidt et al. 2005).

Near the peak of the December 2004 outburst of V0332+53, *RXTE* observations showed the previously known cyclotron fundamental at 27 keV ($B = 2.3 \times 10^{12}(1+z)$ G) plus newly discovered harmonics at 51 and 74 keV (Fig. 4). During the outburst tail the fundamental line energy increased monotonically by more than 4 keV. This may have occurred because of a decrease in the height of the accretion shock as the accretion rate declined (Tsygankov et al. 2005).

A0535+26 also underwent an outburst in summer 2005. Observations during the August periastron outburst with *RXTE* (Wilson & Finger 2005) and *INTEGRAL* (Kretschmar et al 2005) revealed a cyclotron line near 45 keV. The line previously detected near 100 keV, (Kendziorra et al. 1994, Grove et al. 1995), is therefore the first harmonic. The lower implied magnetic field of $\approx 4.7 \times 10^{12}$ G, has interesting implications for the interpretation of a QPO frequency versus spin-up correlation in the 1994 giant outburst (Finger et al. 1996, 2006).

For evolutionary studies of HMXB, most of which are accreting pulsars, young systems are important (Portegies Zwart & Verbunt 1996, Podsiadlowski et al. 2002, Grimm et al. 2003). As a result of *RXTE*'s weekly monitoring program, 50 pulsars are now known in the SMC, providing evidence of recent star formation activity (Laycock et al. 2005, Edge et al. 2004) and a sample size suitable for comparative studies.

1.3. Stellar Black Holes

There are now 20 known black hole binaries (BHBs) in the Milky Way and the LMC (McClintock & Remillard 2006). They are typically discovered as outbursts of X-ray transients. Subsequently, optical measurements of the binary motion of the companion star are used to derive a compact object mass. The observed mass range is 4–14 $M_\odot$, which is clearly beyond the 2–3 $M_\odot$ upper limit for neutron stars. An additional ~ 25 sources are considered black-hole candidates (BHCs) because they closely resemble BHBs in X-ray spectral and temporal behavior.

In an astrophysical environment, a black hole (BH) is completely specified in general relativity (GR) by its mass (M) and spin, which is conveniently expressed as a dimensionless parameter, $a_* = cJ/GM^2$, where J is the BH angular momentum. The value of a_* is between 0 (Schwarzschild BH) and 1 (a maximally rotating Kerr hole). Clearly BH spin is related to its GR effects. However, it also constrains the progenitor evolution and black hole formation processes (Heger et al. 2005). There are in fact several predicted measureable effects of BH spin: the continuum spectrum, which is dominated by the inner disk; high frequency quasi-periodic oscillations; and the line profile of Fe K emission from the inner disk. Agreement between them would then be a test of the models, including GR. Estimates for a_* have ranged from 0.2 to 0.998 for different sources (although varying techniques for the same source do not always agree).

Accretion onto black holes occurs in several "states", which must correspond to different flow configurations. A significant amount of material may also be ejected, in the form of jets. Both steady jet outflows and impulsive relativistic ejections ($v/c > 0.9$) appear to be associated with particular BHB states.

Here we highlight the recent progress in studying X-ray states, BH spin, and the properties of jets, and we outline the prospects for further advancements with the continuation of *RXTE*.

1.3.1. Accretion Flows and X-ray States

For almost two decades it has been known that BHBs exhibit at least three states of X-ray spectral and temporal behavior (McClintock & Remillard 2006). Their distinctive character and sharp differences imply that different modes of accretion underly each state. One of the primary objectives of *RXTE* is to enable detailed physical models for the principal components that alternatively govern each state: the accretion disk, a jet, and a compact corona. The impact of these studies extends beyond BHBs; comparative spectral/temporal studies with neutron star LMXBs and AGN suggest that accretion flows in those systems are similar.

An important *RXTE* accomplishment has been to show that X-ray states are not uniquely determined by the mass accretion rate. For 5 BHBs *RXTE* has observed more than one outburst and the differences and similarities have been instructive. Two outbursts of the BHB GX 339–4 are shown in a 'hardness-intensity diagram' in Fig. 5. It is clear that, while below a certain luminosity this source is always in the hard state (right side of the

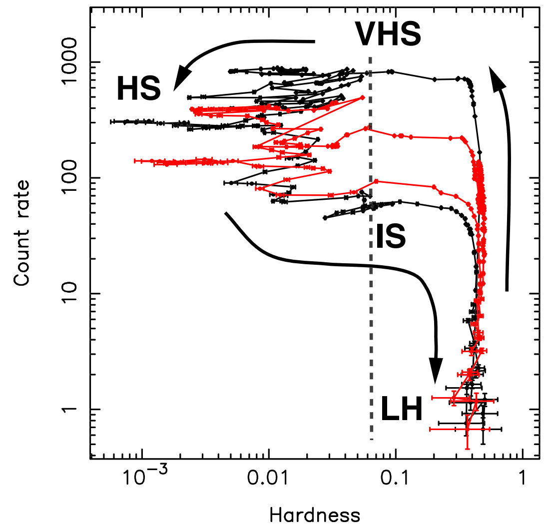

Fig. 5.— Hardness-Intensity diagram of GX339–4 measured by *RXTE* during its 2002/2003 (black) and 2004 outbursts (red) (Homan & Belloni 2005). The horizontal transition (the Very High State) to the left hand vertical track (the High State) can occur at different luminosities in different outbursts. Finally at $\sim 2\%$ of Eddington the source transitions back to the Low Hard state, to complete the 'hysteresis loop' observed in many BHBs. The dashed vertical line shows the "jet-line." Jet ejections tend to occur when the source crosses the line moving leftward; steady outflows exist in the LH state.

diagram), at higher luminosities it can be found in various states, as indicated by the large changes in spectral hardness. Moreover, transitions to the HS occur over a range in luminosities which vary by a factor of ten.

The hardness-intensity diagram provides a useful framework to tie together specific spectral and temporal phenomena (at both X-ray and other wavelengths). Evolution in this diagram can be used to predict behavior and implement state-specific investigations.

The intensively sampled decay light curve of GRO J1655–40, shown in Fig. 6, has revealed the dependence of X-ray luminosity on mass accretion rate. While the decay is exponential on either side of the transition, the low hard state decay time-scale is roughly twice as fast as in the soft state. The simplest interpretation is that the $\dot{M}$ decay rate is constant, but X-ray luminosity L_X changes from a linear dependence on $\dot{M}$ in the soft state to roughly $L_X \propto \dot{M}^2$ in the hard state, as would be expected if the dominant source of X-rays changes from a thin disk to a radiatively inefficient ADAF (Mahadevan 1997) or a jet (Fender et al. 2004).

Further intensively sampled observing campaigns will test this picture for other BHBs in outburst and provide a unique window on the important transition from radiatively efficient to inefficient accretion.

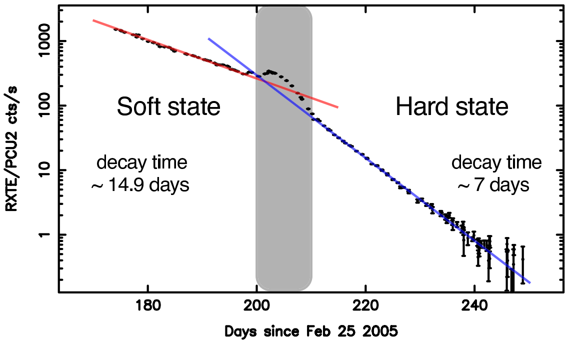

Fig. 6.— The broken exponential decay law observed in the *RXTE* X-ray light curve at the end of the 2005 outburst of GRO J1655–40 (Homan et al., in prep.). The bump corresponds to the state transition, when the spectrum evolves rapidly. The decay time-scale is effectively halved in the LH state, implying a radiatively inefficient flow. LFQPO are prominent in the shaded region.

1.3.2. X-ray Spectroscopy and BH Spin

The thermal radiation from an accretion disk is dominated by the high temperatures at the innermost radii, whose position depends on the BH mass and spin. In principle, one can use the X-ray spectrum to derive a_* if the distance, mass, and disk inclination are known.

GR models of thin accretion disks (Li et al. 2005; Dovčiak et al. 2004) are now being used to constrain a_*, with the help of a new disk atmosphere model to correct for spectral hardening as a function of disk luminosity (Davis et al. 2005). Multiple observations through a range of luminosities are required. Shafee et al. (2006) and Davis, Done, & Blaes (2006) studied two BHBs and found spin values $a_* \sim 0.75$ for each source. The spin results are consistent over variations by a factor ~ 10 in disk luminosity. Consistency checks are crucial for assessing disk and atmosphere models and the technique requires well-calibrated instruments such as *RXTE*'s.

There are only a handful of BHBs for which we have the requisite knowledge (i.e., mass, distance, and inclination) and a wide range of thermal state observations. The most recent bright outburst from a BHC (XTE J1817-330; Jan. 2006 outburst in Fig. 8, middle panel, light blue) is a promising candidate for spin evaluation via X-ray spectroscopy, once Doppler measurements determine the companion mass. Finally, a joint spectral approach, where *RXTE* and *XMM-Newton* are used to measure continuum and Fe line profiles simultaneously, has determined $a_* \sim 0.8$–0.9 for GX 339–4 (Miller et al. 2004).

1.3.3. X-ray Quasi-Periodic Oscillations

High-frequency QPOs (HFQPOs; 100–450 Hz) have been measured for 7 BHBs and BHCs (Remillard & McClintock 2006). HFQPOs have a low amplitude, a hard spectrum, and are associated with steep power law spectra occuring near the jet-line in the VHS (see Fig. 5). In four of the seven HFQPO cases, there is a pair of QPOs with frequencies in a 3:2 ratio. The lower frequency QPO is usually seen at times of higher luminosity, while the upper frequency appears at lower luminosity; sometimes they appear together. Shifts in HFQPO frequencies are limited to 15%, despite changes in luminosity by an order of magnitude. This suggests that the frequencies are related to non-varying quantities such as the BH mass and spin. A model for HFQPOs thus provides a second avenue for derivations of BH spin when the BH mass is known.

Since 2004, HFQPO were confirmed in recurrences of two BH transients. In the BHB GRO J1655–40, we see the same pair of HFQPOs (300 and 450 Hz) that were detected in 1996, while a single HFQPO near 180 Hz is seen with a shift of $8 \pm 4\%$ in the BHC 4U 1630–47. These recurrences are a powerful statement that HFQPOs are the voiceprints of the black holes in BHBs.

Three of the sources that exhibit harmonic (3:2) HFQPOs also have measured BH masses, and in those cases the HFQPO frequencies scale inversely with mass (McClintock & Remillard 2006). This relationship is the one expected for GR phenomena, e.g., coordinate frequencies (Merloni et al. 2001) or diskoseismic modes in the inner disk (Wagoner 1999; Kato 2001), if the values of a_* are similar.

The commensurate frequencies in HFQPO pairs suggest some type of resonance mechanism (Abramowicz & Kluźniak 2001), since linear perturbations in GR disks do not yield such results. Resonances were first posited at specific radii where particle orbits have oscillation frequencies in GR that scale with a 3:1 or 3:2 ratio. However, GR fluid dynamics resonances are considered more physical (Abramowicz et al. 2003; Kluźniak et al. 2004). One recent GR MHD simulation provides evidence for oscillations in the inner disk (Kato 2004).

High frequency QPO detections are rare, but highly diagnostic of the accretion disk and compact object. It will be vital to observe future BHB outbursts and detect these QPOs, in order to both confirm the resonance theories, and to observe material as it passes through the ISCO predicted by GR into the black hole.

LFQPOs (0.01–30 Hz) are more common than HFQPOs and they can be exceedingly strong, e.g., with r.m.s. amplitude $> 20\%$ in some high-luminosity episodes of the hard and intermediate states. Changes in LFQPO frequency are correlated with evolution in X-ray spectral properties, e.g., the slope of the power-law component and the disk fraction (e.g., Vignarca et al. 2003; Remillard & McClintock 2006). The origins of LFQPOs remain uncertain, but the observed frequency changes are commonly interpreted as changes in the size of one or more of the accretion flow components (e.g. inner disk, corona, or the base of the jet). The LFQPOs are especially notable at state boundaries (Fig. 6).

Interpretations of LFQPOs have been complicated by the fact that there are several distinct types (Remillard et al. 2002b; Casella et al. 2005). These types were first defined in terms of measured phase lags (timing hard X-rays vs. soft X-rays), but there are other correlations between types and source characteristics. One type, which has a rather stable frequency (∼5–7 Hz), only occurs near the "jet line" in the hardness-intensity diagram. This type of QPO may then be associated with the launch mechanism for impulsive jets.

1.3.4. Relativistic Jets and Outflows

Relativistic jets and outflows are apparently consequences of accretion (i.e. the "disk-jet connection;" Fender 2006). BHBs that produce radio jets are called "microquasars" because they exhibit scaled-down and rapidly evolving versions of the jets in AGN. Microquasars exhibit several types of jets with different ranges of radio power and ejection timescale. Both BHBs and neutron star binaries produce jets, but the latter have comparatively lower radio power and outflow velocity.

BHBs can emit impulsive jets that appear as bipolar radio knots with velocities as high as $0.98c$ (Mirabel & Rodriguez 1999). They are now believed to be associated with X-ray state transitions; relativistic ejections are produced when the BH crosses the "jet-line" in the X-ray hardness-intensity diagram (e.g. Fender, Belloni, & Gallo 2004; Fig. 5). Ejected plasmoids can travel long distances before interacting with the ISM. For example, a bright X-ray flare of H1743–322 studied by *RXTE* produced a brief superluminal radio ejection, that was imaged one year later by *Chandra* as the ejection impacted the ISM (Corbel et al. 2005; also XTE J1550–564). The X-ray and radio spectra in this phase can be fit with a simple synchrotron model that implies a relativistic plasma with Lorentz factor $\sim 10^7$. Smaller ejections in BHBs are seen as correlated X-ray and radio flares with ∼10 min timescales and a radio-band delay. Recently Wilms et al. (2006) observed Cyg X-1 producing small jets (only the second BHB known after GRS 1915+105). In these cases we have measurements of radio and X-ray spectral evolution during the birth of jets, and these data can be successfully modeled in terms of a synchrotron model for an expanding plasma bubble.

The monitoring programs and flexible scheduling of *RXTE* provide a foundation for research on impulsive jets from microquasars. **X-ray alerts provide guidance for the radio community, including the VLBI observations that define many properties of the jets.** There are only a handful of well-measured ejections, and additional cases can make important contributions.

The more common type of "jet" in microquasars is a quasi-steady outflow associated with the X-ray hard state (§1.3.1). The combined features of a hard X-ray power-law ($\Gamma \sim 1.7$) and optically thick radio emission are often seen at the beginning and end of BHB outbursts. This same state can persist for months in some sources (e.g., Cyg X-1 and GX 339–4). The steady jet is estimated to be mildly relativistic (i.e. $\sim 0.7c$; see Fender 2006), but there is uncertainty about the baryonic content and hence the scale of the mass outflow and the fraction of accretion energy needed to power the jet.

One approach to better understand jets is based on the observation of X-ray transitions to and from the hard state. As noted in §1.3.1, the densely sampled observations of state transitions track the spectral evolution from efficient thermal radiation to inefficient, non-thermal emission. The radio power and the luminosity of the hard X-ray power law often are tightly correlated (e.g. Gallo et al. 2003). Some part of the power-law emission may be due to synchrotron and Compton emission from the base of the jet (Markoff & Nowak 2004; Yuan, Cui, & Narayan 2005; Kalemci et al. 2005).

A current goal of *RXTE* observations is to demonstrate that the state transition of Fig. 6 is generally representative of BHB transitions associated with the formation of a steady jet. There are significant new opportunities on the horizon with the development of new observatories which should make it easier to obtain radio information at the time of the X-ray observations. LOFAR construction is underway in The Netherlands, and the era of wide-angle radio astronomy (10–250 MHz) will begin with its compact core array in 2006, building to phase 1 (15,000 antennas) in the coming years. The Mileura Widefield Array (MWA) will initiate wide-angle radio monitoring (80–16000 MHz) of the southern hemisphere with demonstration instruments in 2007. Both facilities target radio transients as key projects. While the disk/jet connection began as an X-ray/radio connection, the events have infrared, optical and γ-ray signatures as well.

1.4. AGN

1.4.1. Jet-dominated AGN

The emission from blazar AGNs is dominated by a radio-bright, relativistic jet propagating roughly along the line of sight (Urry & Padovani 1995), which outshines emission from the accretion disk. Synchrotron radiation dominates the emission from radio to soft X-ray wavelengths while the hard X-ray to gamma-ray wavelengths are dominated by a component probably formed by inverse Compton scattering on low-energy "seed" photons. Blazars show flares on time scales from hours to weeks. The flares probably arise from sudden acceleration of relativistic electrons and/or ejection of new jet components. Major questions remain, such as how are the electrons accelerated, and what is the origin of the seed photons? Models can be tested only by tracking the evolution of the broadband SED during large flares, when both flux and

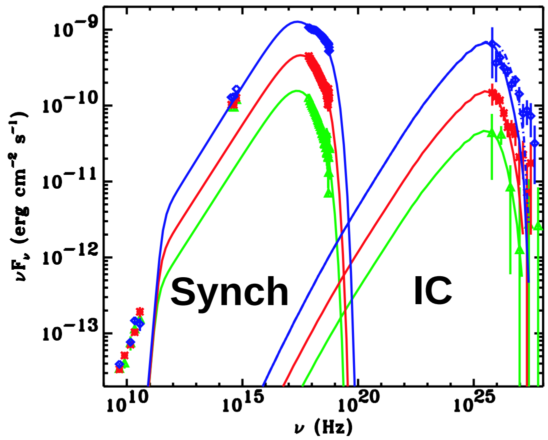

Fig. 7.— An example of how multi-wavelength observations constrain models; from Blazejowski et al. (2005). Data points are from simultaneous Whipple, *RXTE*, optical, and radio observations of Mkn 421. Solid curves are best-fit synchrotron and inverse Compton peaks of the "synchrotron-self-Compton" model SEDs, as a function of luminosity.

level of rapid variability at all wavelengths are highest. Simultaneous multiwavelength monitoring campaigns, emphasizing X-ray and gamma-ray coverage, are required for tracking the SEDs, which may show rapid and complex changes.

RXTE has already contributed significantly to such campaigns, uncovering correlated X-ray/gamma-ray variability in several blazars that suggests X-rays and gamma-rays originate in the same region and from the same electron population (e.g., Wehrle et al. 1998, Aharonian et al. 2003, Krawczynski et al. 2004). However, the origin of the seed photons (e.g., accretion disk, cosmic background, or jet synchrotron photons) is still not fully understood, and may likely differ from one blazar type to the next. Broadband emission models based on current data tend to be forced towards extreme parameters (e.g., very high Doppler factors; Henri & Sauge 2006), and present a challenge to theorists. Figure 7, from Blazejowski et al. (2005), shows example results for Mkn 421. **More-accurate SED modeling based on simultaneous short-term flux and spectral variability in X- and gamma-rays, including identification of time lags, is required to distinguish between the various inverse Compton models.** Previous gamma-ray data were insufficient for strong model constraints (e.g., too-sparse sampling), but the community is poised to make progress in this area – via the combination of *RXTE* and new gamma-ray facilities, as the next few years will see dramatic boosts in our TeV and GeV observing capabilities.

The newest generation of TeV observatories (HESS, VERITAS, MAGIC, all at or approaching full operation by 2007) feature superior sensitivity and higher duty cycles compared to older TeV telescopes like Whipple, CAT, and HEGRA, and will likely increase the number of TeV-detected blazars at redshifts $z > 0.2$. Moreover, they are accessing short timescale flux and spectral variability, enabling us for the first time to trace the full development and evolution of TeV flares. Additionally, *GLAST* will be launched in 2007; its all-sky GeV monitor, the LAT, will scan nearly the entire sky daily with a sensitivity sufficient to uncover thousands of new blazars. For a large subset of new and previously-known blazars (∼50–500 expected), *GLAST* will identify large flares, and, for the brightest sources, track short-term variability during flares with ∼1 day time resolution and additionally provide year-round monitoring.

RXTE has detected all TeV blazars so far, but only ∼12 *CGRO*/EGRET GeV blazars. Since the *GLAST* LAT energy response extends much higher than EGRET's, there will likely be a substantial number of LAT-detected blazars that have synchrotron peaks in the X-ray band, and will be good *RXTE* targets. Both *GLAST* and TeV monitoring will be used to trigger multiwavelength TOO campaigns during bright flares. We expect a sharp increase in the number of such campaigns, and several blazar outbursts may need to be followed at once. It will be necessary to track correlated variability in the X- and gamma-ray bands with comparable time resolutions, in order to determine the SED as a function of time, and hence the relativistic particle distribution.

The high effective area and throughput of the PCA yield excellent sensitivity for bright AGN. Additionally, *RXTE*'s unique combination of rapid slewing, flexible scheduling, and good sun-angle constraints allows rapid response to TOO alerts (<24 hrs), the ability to quickly implement sustained monitoring programs consisting of multiple PCA pointings, and the ability to observe sources most or all of the year. Other X-ray missions (*XMM-Newton*, *Suzaku*, etc.) are characterized by poor sun-angle constraints, poor sensitivity for short exposures, relatively inflexible scheduling, and/or non-optimal TOO response. ***RXTE* is therefore the only X-ray mission capable of supporting TOO multiwavelength monitoring programs and characterizing X-ray variability on time scales spanning $\lesssim$1 day to days/weeks and longer.** Given the anticipated wealth of new gamma-ray data, further progress in AGN jet physics is imminent, **but this depends critically on the continued existence of *RXTE* over the next few years.**

1.4.2. Black Hole Unification Paradigm

RXTE has allowed genuine comparison between accreting stellar-mass and supermassive black holes through their X-ray timing properties and multi-wavelength correlations. Impressive similarities have been found that support a paradigm which explains differences between AGN types, such as radio brightness, in terms of the accretion states observed in BHBs (e.g. Falcke et al. 2004, Uttley 2005).

RXTE has allowed us to characterize rapid X-ray variability in Seyfert (non-beamed) AGN on timescales from hours to years, via intensive and prolonged monitoring campaigns. The resulting broadband PSDs, obtained for over 14 AGN, confirm the theoretical expectation that AGN variability time-scales scale linearly with black hole mass, and scale directly from the equivalent characteristic time-scales in stellar mass black holes (Uttley et al. 2002, Markowitz et al. 2003, McHardy et al. 2004). Also, more recent studies (e.g., Uttley & McHardy 2005) demonstrate that, for a given mass, the variability timescale additionally depends on $\dot{M}$, consistent with models to explain the state transitions in BHBs, in terms of the disk truncation radius decreasing with $\dot{M}$ (Markowitz & Uttley 2005).

Because of the success of the monitoring campaigns recent cycles have extended them to other types of AGN, including low-luminosity AGN, which may be analogues of the LS, and high-luminosity quasars, which might be VHS. Radio galaxies and Seyfert 2s have been undersampled so far, but representives have been found that are bright enough, especially with the well-modelled and currently lower background (Revnivtsev et al. 2004). At least 3-4 years of monitoring are required for reliable PSD measurement. **Continuation of the *RXTE* mission is currently the only way to confirm whether the different states observed in BHBs also apply in AGN.**

Simultaneous X-ray/radio monitoring of AGN is yielding invaluable new evidence about the connection between accretion flows and jets. Marscher et al. (2002) saw "dips" in the long-term *RXTE* light curve (a tracer of disk output) immediately preceding ejections of new radio knots in the jet of the radio-loud Seyfert 3C 120. These events may be analogous to those observed in the microquasar GRS 1915+105. Other sources show correlations between X-ray and radio flux (PKS 1510–089) or X-ray flux and apparent superluminal speed/direction of ejected knots (3C 279). **Continued progress into the nature of this connection requires observation of many more ejection events (requiring seversl years) to test if time-delays between X-ray dips/radio ejections depend on black hole mass or accretion rate.** This year also sees for the first time simultaneous *RXTE*/radio monitoring in a low-luminosity, 'radio-intermediate' Seyfert, NGC 7213, which we expect to be in the LS if the Black Hole Unification picture is correct. Seeing X-ray/radio correlations similar to those in LS BHBs would imply that the accretion flow is radiatively inefficient, a long-standing expectation for low luminosity AGN (e.g. Ho 2005).

Finally, ground-based optical monitoring campaigns of most of the AGN monitored by *RXTE* are underway, using newly operating 2 m class robotic telescopes such as

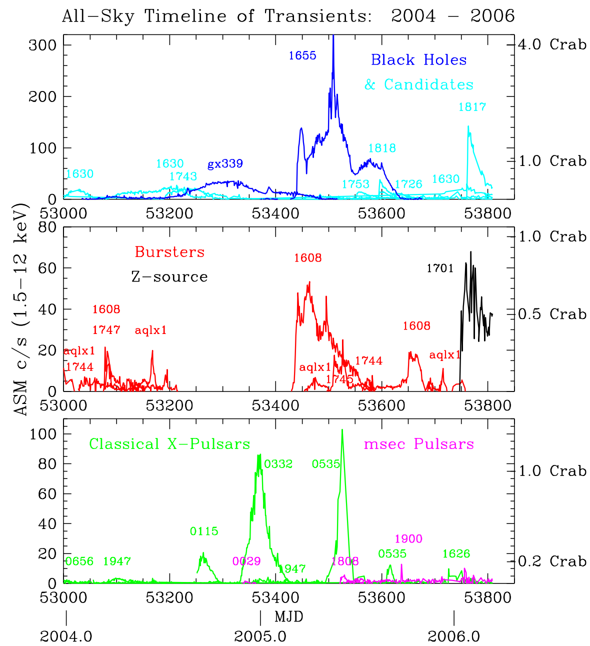

Fig. 8.— All Sky Monitor Timeline of Transients. The 3 panels show different types of transient sources. Note that the scales differ. The millisecond pulsars peak at 0.1 Crab or less and are often (but not always) discovered by more sensitive measurements. This figure shows that often there are multiple transients at the same time.

the Liverpool Telescope on La Palma. **These combined *RXTE*/optical campaigns will provide the first systematic look at the relationship between the optical disk emission and X-ray flux and photon index,** testing whether optical variability in non-beamed AGN is due to variability of the X-ray reprocessing in the disk, or of the mass accretion rate. (e.g. Uttley et al. 2003).

1.5. Opportunities in the X-ray Sky

1.5.1. The Value of Transients

Many key scientific advancements made by *RXTE* resulted from a prompt, comprehensive response to X-ray transients. The ASM views the entire sky, rapidly identifies new outbursts, and closely monitors their evolution. Biweekly PCA scans of the central Galactic plane deepen the sensitivity in that crowded region to a few mCrab. Outbursts of new and known sources trigger frequent pointed observations that support specialized science goals. X-ray transients comprise the majority of sources in several classes that are fundamentally important in high-energy astrophysics, e.g. 90% of the parent population of BH binaries and candidates, 90% of Galactic sources of relativistic jets, and 100% of accreting millisecond pulsars.

In a typical year there are ∼20 outbursts from ∼12 different sources, and ∼4 of these are new. Fig. 8 shows some of this activity over the last two years. Each panel contains examples of rare occurrences. The extremely bright recurrence of the BH binary GRO J1655–40 (top panel, dark blue) was discussed in §1.3. The recent discovery of XTE J1701–462 (middle panel, black) marks the first-ever appearance of a transient with the timing properties of a Z-source (Homan et al. 2006b). The X-ray pulsar V0332+53 (bottom panel, green, maximum near Jan 2005) was only the second source to show multiple cyclotron lines in its X-ray spectrum (Pottschmidt et al. 2005; §1.2). The millisecond pulsar HETE J1900.1–2455 (bottom panel, magenta, maximum near Oct 2005) has exhibited a pulsed amplitude which is a function of the time since its last thermonuclear burst (Galloway, private communication; §1.2).

1.5.2. Overlapping X-ray Missions

RXTE's suite of capabilities brings X-ray transients to the forefront of astrophysics, and there is no current substitute for the dense 2–200 keV sampling and μs time resolution that *RXTE* provides. Both *INTEGRAL* and *Swift* are gamma-ray missions that can find transients above 15 keV. Observations with *INTEGRAL* have the benefit of being relatively long, but *RXTE* can more easily insert short, frequent observations into the schedule. Its more flexible solar constraint of 30°–180° means that sources can be followed for a longer time. *Swift* has demands on its observing schedule from the core science program of GRBs. While *INTEGRAL* and *Swift* are imagers, the 2–10 keV area of even one of the PCA detectors is more than ten times that of either JEM-X on *INTEGRAL* or the XRT on *Swift*. *RXTE* is able to monitor sources brighter than 0.5 mCrab. For bright sources the larger area and high telemetry throughput give *RXTE* the best effective time resolution. The situation may change with the launch of India's *Astrosat* mission, possibly by 2008. However, until that happens, *RXTE* offers truly unique science capabilities.

1.5.3. Coordinated Observations

RXTE supported coordinated observations of more than 120 targets from 2004–2005, and regularly partners with *Chandra*, *XMM-Newton*, *INTEGRAL*, *Spitzer*, and many ground based observatories. As a rough measure of effectiveness, there were more than that number of entries in astro-ph or ADS with both *RXTE* and the name of another mission or the wavelength band in the abstract. In some cases this means observations were triggered by *RXTE* findings, while in others joint observations are described. Such partnering will continue.

1.6. *RXTE*'s Future

RXTE has given us a view of the most exotic objects in the universe that was not possible before. Its unique ability to react quickly to changes in the X-ray sky and bring unmatched observing capabilities to bear has resulted in the discovery of many new astrophysical phenomena. Many of these discoveries have clear interpretations and implications, but all of them are not yet fully understood. Even for these, however, the unique data that *RXTE* has collected suggest answers that will have profound importance for a deeper understanding of physics at the extremes of density, gravity and magnetic

Box 3: Future Program

- Map characteristics of selected neutron star LMXBs, persistent and transient, in order to understand their accretion flows and probe neutron star structure.
- Focus observations on special states of LMXBs (eg. low flux, burst active) to resolve the mystery of why most do not pulse.
- Detect millisecond pulsars among new transients and follow up to search for kHz oscillations, X-ray bursts, and spin rate changes.
- Monitor spin rates of SGRs, AXPs, and rotation-powered pulsars to search for glitches, spin rate changes, and burst activity.
- Monitor the X-ray timing and spectral evolution of transient black holes. Coordinate this with radio, optical and gamma-ray observations.
- Monitor persistent black holes (Galactic and extragalactic) for changes in the accretion flow and the presence of jets.
- Provide broad-band spectral and fast timing information in support of observations by other missions, including *Chandra*, *XMM-Newton*, and *GLAST*.
- Monitor selected AGN to extend our understanding of their variability and test the black hole unification paradigm.
- Monitor Blazars in support of the *GLAST* core science program.

Box 4: Possible Special Events

- Measure the GW spin-down torque of the SAX J1808.4-3658 pulsar between outbursts.
- Find a correlated X-ray and LIGO GW signal.
- Detect orbital period changes in an ultra-compact accreting millisecond pulsar binary.
- Track the evolution of the transient Z-source XTE J1701-330 through an atoll stage, and observe X-ray bursts, during its decay.
- Observe additional magnetar hyperflare oscillations and test the crustal vibration mode hypothesis.
- Measure the radius at the inner edge of an accretion disk by simultaneously observing a HFQPO and relativistically broadened Fe line.

fields. Because of this we have given and will continue to give priority to observations that can specifically address such important science questions.

We expect that with additional years of operations (Cycles 12 and 13 in addition to completion of Cycle 11) we will both make progress on the outstanding questions as well as make new discoveries. Box 3 highlights important components of this continued program. We also list several especially exciting results that could happen with continued operations (Box 4). Rare events of similar importance have happened in previous years. We firmly believe that continued operations will further increase our understanding of the extreme physics of compact stars, as well as how to plan future experiments to settle questions that *RXTE* leaves open.

1.7. Bibliography

References in this proposal are available at: `http://tinyurl.com/hmwuj`

A time ordered list of *RXTE*-related publications is available at: `http://tinyurl.com/zqfhc`

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) improved standard products summarizing the observations for both the PCA and HEXTE, 2) completion of the transition to modern computers in the SOF, 3) continued reduction in staff while maintaining essential services.

The community continues to demonstrate its interest in *RXTE* data by downloading it at an impressive rate – last year the amount of downloaded data was almost four times the amount of data in the archive.

2.2. System Status

2.2.1. Flight Segment

Flight operations have gone smoothly since the last Senior Review. The observatory is healthy and should support continued operations for many years. There have been no safe-hold incidents in over five years. No consumables limit the duration of the mission, and *RXTE* is currently predicted to re-enter the Earth's atmosphere no earlier than 2013.

As was the situation two years ago, 2 of the 5 PCA detectors are on for all observations. The others are on during observations for which they are most useful. "Resting" these 3 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 monitor the X-ray sky although its performance is slowly decreasing. All 8 anodes of the proportional counter in SSC 1 are fully operational, but the detector gain is increasing at $\sim 10\%$ yr^{-1} because of a slow leak. In the past year, latchups (automatic shut-offs of the high voltage (HV) in response to high count rates) became frequent, resulting in a major decrease in operational duty cycle. We modified the ASM commanding software to include HV reset commands immediately prior to every HV on command, improving the duty cycle and reducing the latchup frequency. In the past year, we made extensive efforts to measure the effects of the high gain of the counter and have modified the coded-aperture imaging analysis software to model these effects to first order. We cannot confidently forecast its lifetime, but SSC 1 may operate for another two years. The performance of SSCs 2 and 3 has not changed much in the last two years. The two detectors have 5 and 2 (of 8 original) fully operational anodes. Barring an unexpected event, these detectors should be able to function for several more years. The Drive Assembly continues to operate reliably. While its sensitivity has decreased by $\sim 33\%$ since the beginning of the mission, the ASM will still provide unique sky monitoring in terms of energy range and coverage even if 1 of the 3 SSCs goes out of service.

The HEXTE detectors continue to operate well. There have been recent anomalies in which 1 of the 2 clusters (Cluster A) stops rocking on and off source until it is restarted by ground command. While the investigation of the root cause continues, we have commanded Cluster A to stare at the target instead of rocking. The background from Cluster B, which continues to rock, will be used to compute the background for Cluster A.

2.2.2. Ground Segment

RXTE has a flexible ground system appropriate for its mission of responding to TOOs. 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). 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 orbit. An entirely new plan can be produced and loaded when needed for a TOO. Production science data processing is 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 early in the mission.

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 slews are routinely searched for new sources and there is an on-going program to scan the galactic bulge to look for new sources. Because of this near real-time monitoring, in the last two years 7 new X-ray sources and more than 37 significant state changes in previously known sources were announced via IAU Circulars or Astronomer's Telegrams These discoveries provide unique opportunities for *RXTE* and other missions.

RXTE's planning system supports the numerous coordinated observations and TOOs described in §1.5. The experienced planners and incremental improvements in the planning tools make for an effective and efficient system. The good observing time continues to be $\sim 60\%$ of the elapsed time.

RXTE continues to operate 24 hours per day, but automation has greatly reduced the required staff. The MOC's Automated Mission Operations System (AMOS) manages the spacecraft data recorder, conducts TDRSS contacts, and monitors the health and safety of the spacecraft and the instruments. At the beginning of FY07 the MOC will decrease the amount of staffed time from 12 hours every day to 8 hours every weekday. 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 staff no longer needs to monitor status on-site on weekends, and will instead use a newly implemented system for remote status reporting in addition to the automatic monitoring. Planning updates by the SOF will continue on weekends as needed.

2.2.3. Guest Observer Support

Except for unanticipated TOOs, all *RXTE* observations are chosen in an open competition from proposals submitted by the community in response to annual NASA Research Announcements (NRAs). This competitive process makes *RXTE*'s unique capabilities available for the most compelling scientific questions. The community clearly still considers *RXTE* a valuable asset. The number of proposals received for Cycles 8-11 were 188, 167, 150, and 128 respectively. The corresponding oversubscription factors for observing time were 5.16, 5.12, 4.64, and 5.61. The fraction of TOO proposals has increased, there are more large proposals, more extensive monitoring campaigns are being carried out, and *RXTE* is now doing many coordinated observations with *Chandra*, *XMM-Newton*, *INTEGRAL*, and *Swift*.

The Guest Observer Facility (GOF) provides tools, documentation, and expert advice to GOs for both proposal preparation and *RXTE* data analysis. 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 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 for *RXTE*. These 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 provides technical support for the reviews by NASA HQ of *RXTE* observing proposals, including updating the NRA, obtaining reviewers, distributing proposals, assisting during the review itself, informing proposers of results, and delivering a data base to the SOF with details of the accepted observations. The GOF provides technical support for the subsequent budget review.

Rapid data delivery to the community is a key responsibility. GOs can download quicklook FITS files of the science data within hours and download preliminary production FITS files the next day. The *RXTE* production data processing pipeline now requires only 0.7 FTE compared with 6 FTE early in the mission.

Significant improvements have been made to *RXTE*'s Standard Products, which provide a compact summary of each observation including background subtracted light curves and spectra. Standard Products are now available for all observations and are delivered with new observations to Guest Observers along with the lower level data files. We have recently added merged HEXTE light curves so that users can now check source behavior in hard X-rays over extended time periods. We will soon produce mission-long light curves for selected sources.

At the end of 2005 the *RXTE* archive at the HEASARC had 1408 GB of data, and served 5446 GB of data to the astronomical community during the year. *RXTE*'s data transfer 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*, *BeppoSAX*, and *Swift*). 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. With the reduced GOF staff, the ITs are also responding to an increased fraction of the questions to the *RXTE* help desk.

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 significant effort: MIT 1) maintains the rotation-planner software which controls the viewing angles of the ASM so that it avoids the Earth, Sun, and radiation belts, 2) maintains both the energy calibration of the detectors and the anode position calibration, 3) 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.

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. UCSD is now developing a tool for using the background from Cluster B to estimate the background for Cluster A. UCSD also reviews the data modes for proposed 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 is the minimum budget needed to operate *RXTE* through February 2009. The budgets provide the required New Obligation Authority (NOA), and do not always reflect the expenditures during a FY.

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, enabling a continuation of the exciting science described in §1 at a greatly reduced cost. *RXTE* is already in its extended mission, and the budget is consistent with the "bare-bones" paradigm.

"Data Services" (2a) are the in-kind costs of providing the telemetry, tracking, and commanding services of NASA's Space Network for *RXTE*. *RXTE* relies exclusively on TDRSS for these services. The costs are based on per minute rates for the various services. We have recently revised our usage of TDRSS to reduce the number of S-Band Single Access (SSA) contacts while maintaining the throughput needed for *RXTE* science. This change produced a 45% cost reduction.

"Mission Services" (2b) represents the budget operating the MOC. The operations staff, which was 16 FTE during the prime mission, is now only 7.3 FTE, and will become 5.25 FTE at the end of FY06 when the MOC goes to 8x5 staffing. "In-kind" costs represent an allocation to *RXTE* of part of GSFC's multi-mission support costs.

"Science Center Functions" (3) are carried out by the SOF and GOF in collaboration with the three instrument teams (ITs). The SOF operations staff has been reduced from 12 during the prime mission to 2.3, and the programmer support has been gradually reduced to the current 0.3 FTE. The GOF staffing is now 1.6 FTE compared to the total GOF and XSDC staffing of 16 FTE during the prime mission.

The peak staffing for the ITs was 33 FTE in 1996. In FY07 the ITs will have a staff of 6.6 FTE (not including 3 relatively inexpensive graduate students). This is barely enough to maintain the expertise and carry out their responsibilities. All members of the ITs are expert users of *RXTE* data, and part of their research is understanding in great detail the performance of the instruments. Consequently it is difficult to divide precisely their time between "Science Center Functions" and "Science Data Analysis". We estimate that an equal split is a fair description, and this has been used for the budgets.

The EPO budget is $\sim 1.6\%$ of the total "in-guideline-/minimal" budget. §3 has details of our E/PO program.

2.3.2. Requested Budget

The "requested/optimal" budget is the same as the "in-guideline/minimal" budget except that it also includes a modest GO program so that the *RXTE* data can be effectively used by the community. At the proposed funding, a typical winning proposal from a US institution will receive only $\sim \$15,000$.

3. Education and Public Outreach

The RXTE mission has a successful track record in Education and Public Outreach (EPO). Historically, our EPO program involves 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" XTE model; "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; and the "High Energy Groovie Movie" rock video describing X-ray astronomy with RXTE science highlights and classroom activities. Our recent EPO activities have resulted in a successful new partnership with the Owens Science Center and Challenger Learning Center, part of Prince Georges County Public Schools. We will capitalize on this new collaboration to contribute focused, standards-based RXTE-related space science content to existing successful student enrichment programs. Our future EPO plans will inspire the next generation of space explorers. With involvement of several key RXTE science team members, a clear management structure, and our ability to leverage off successful and popular existing programs, we anticipate a very successful program. Since we partner with two successful local education organizations—a NASA Explorer School and a Public School Science Center—our current and future EPO activities are well aligned with the NASA Education Strategy, and will directly impact underserved and underrepresented populations, expanding the pool of human capital to meet future NASA human resources needs.

3.1. Recent Accomplishments

3.1.1. Educator Workshop

In our 2004 EPO plan, we proposed designing, developing and presenting an educator workshop organized around the High Energy Groovie Movie — an educational video produced by the RXTE GOF and the HEASARC, targeted at middle school science students and the general public. This video pairs ASM animations of the dynamic X-ray sky with the AstroCappella song "High Energy Groove," and includes informative "artists' representations" of exciting RXTE discoveries. Previously, teacher interns developed and tested classroom activities for each verse of the song, reinforcing the inherent excitement of our dynamic and changing high-energy universe. Work on the movie was completed in Spring 2005.

Our educator workshop focuses on one of these activities, "the Cosmic Quilt," in which students team to research an RXTE science topic, then produce a "quilt square" with a description and illustration of their topic. The workshop incorporates the history of quilting, and literary tie-ins to astronomy story telling, such as "Follow the Drinking Gourd" and "Why is the Sky Far Away?" Workshop participants are encouraged to instruct their students to choose from a limited set of literary devices in crafting their science descriptions (such as limerick, haiku, acrostic, and personification) thus reinforcing the goals of reading and writing across the curriculum. Topics for quilt squares can be changed to suit specifics of the cirriculum.

Fig. 1.— Master Teacher Valyncia Lindsey with student participants in the Fall 2005 Washington, DC STEM outreach activity.

In summer 2004, Valyncia Lindsey— master teacher at NASA Explorer School Anne Beers Elementary in Washington DC, and winner of the Metropolitan Organization of Black Scientists Outstanding Elementary Science Teacher of the year— interned at GSFC with GOF staff to design and develop the workshop (Figure 1). An agenda and supporting materials for the workshop, which can be tailored to last from 2 hours to a full day, can be found at the Groovie Movie web site.

In the Summer through Fall of 2005, the workshop was presented to two groups of visiting teachers through Goddard's Education office (NASA Explorer Schools Content Workshop and the SUNBEAMS program Professional Development), as well as to a group of student teachers in Shreveport, LA, and the general public as part of the Fall 2005 Science, Technology, Engineering and Mathematics Summit (STEM Summit) through the Washington, DC, STEM Partnership (Figure 2).

3.1.2. Public Outreach Planetarium Program

Beginning in the Fall, 2005, we also partnered with the Howard B. Owens Science Center (HBOSC) in Lanham, MD, to design and present a public program commemorating RXTE's first ten years in orbit. The HBOSC is a 27,500 square foot facility owned and operated by the Prince George's County Maryland Public Schools. Hands-on, data intensive activities provide students with experiences in a broad array of sciences including physics, space science meteorology, optics, computer science, and astronomy. Prince George's County Public Schools' student body is 70% African American, 20% Caucasian, and

Fig. 2.— The Cosmic Quilt, focussing on forces, created by Shreveport, LA student teachers.

10% of other minority groups. The curriculum incorporates a multicultural, interdisciplinary approach with a competency based evaluation component. The HBOSC serves as an extension of the classroom, designing, supporting and augmenting classroom activities as they relate to science instruction. Approximately 90,000 students visit the HBOSC annually as part of the regular school science program. In addition, nearly 5,000 participants are served through their Saturday enrichment programs.

The RXTE planetarium program at HBOSC had a dry run in February 2006 and will be presented as a special event open house in October 2006. The program consists of two alternating planetarium shows per hour (the High Energy Groovie Movie and The Point of No Return: Quasars and Supermassive Black Holes, produced under IDEAS Grant program by the Ralph Mueller Planetarium and University of Nebraska State Museum). Also included are hands-on activities related to the RXTE movie presented by educators and scientists at various stations in the HBOSC, and presentations about the RXTE mission.

3.2. RXTE In The News

In the last two years, we shared unique RXTE results and accomplishments with the public through twelve NASA press releases. Several of these press releases received extensive coverage in print, Internet and/or television media, including neutron star superbursts (Scientists Gain Glimpse of Bizarre Matter in a Neutron Star—Sept 2004), evidence for spacetime distortion in GRS 1915+105 (Black Hole is a Space-bender and Mind-bender —Jan 2005), and the origin of the galactic ridge X-ray background from ten years of slew data (New Map of Milky Way Reveals Millions of Unseen Objects—Feb 2006, Fig. 3). RXTE continues to make thought-provoking discoveries, and will surely do so in the next two years. For especially compelling new results, we will continue to disseminate the excitement through NASA press releases.

3.3. E/PO Future Plans

The HBOSC also houses one of the original Challenger Learning Centers (CLCs). These hands-on space science learning centers offer realistic mock-ups of Mission Con-

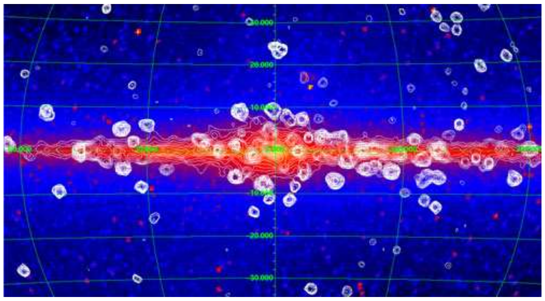

Fig. 3.— Image of the galactic X-ray background superimposed on an image of infrared sources. The X-rays, shown as white contour lines, were detected by NASA's Rossi X-ray Timing Explorer. The infrared background (everything else) was detected by NASA's COBE mission in the 1990s. The white knots reveal very bright X-ray sources, mostly from black hole and neutron star activity. Most of the X-rays in our galaxy, however, come from millions of relatively dim sources. These are the thin, white, wavy lines throughout the galaxy. These appear to be almost entirely unseen white dwarfs and stars with active coronas, a surprise discovery. Credit: NASA/RXTE-COBE/Revnivtsev et al.

trol and an orbiting space station. The Challenger Learning Center's simulations correlate directly with the Voluntary State Curriculum for the state of Maryland and emphasize processes of science, concepts of science, and applications of science.

We propose to leverage off the existing educator workshop and our new partnership with the H. B. Owens Science Center for our future EPO plans. RXTE scientists will work with the planetarium director and the CLC director to incorporate RXTE science themes into daily student activities at the center. We have two approaches: inserting RXTE science into student planetarium shows, and introducing an RXTE "anomaly" into "Encounter Earth"—an existing CLC module.

For the planetarium show, we have already identified several areas of correlation between RXTE science objectives and the Maryland State Voluntary Curriculum/Core Learning Goals for grades 5, 6 and 8, and the science textbook series adopted by Prince George's County Public Schools. Generally, these involved the goal of understanding concepts of physics such as properties of light and motion. The RXTE planetarium show will be based largely on the show developed for the general public described above, but will be modified to incorporate the correlations to the Core Learning Goals.

An educational RXTE spacecraft "anomaly" will be developed for the CLC module. On December 27, 2004, a giant flare from magnetar SGR 1806-20—one hundred times more powerful than previously observed giant flares—was detected by virtually every orbiting spacecraft with high energy detectors. A magnetar is an X-ray pulsar with a superstrong magnetic field, and a key target for RXTE. Radiation from the giant flare came

Fig. 4.— Artist's impression of giant flare from SGR 1806-20 ionizing Earth's atmosphere, December 27, 2004.

through the side of RXTE and saturated many spacecraft detectors. It ionized the Earth's atmosphere down to an altitude of 20 km, just above where airplanes fly. The effect on the atmosphere had a peak that lasted a few seconds. An oscillating tail lasted five minutes, while an ionospheric "afterglow" lasted an hour. The flare changed the ionic density at an altitude of 60 kilometers from 0.1 to 10,000 free electrons per cubic foot — an increase of six orders of magnitude (Figure 4).

These events will be incorporated into the CLC module "Encounter Earth" in which two student teams (one in mission control and one on an ISS mock-up) communicate to solve the mystery of a malfunctioning satellite in low-Earth orbit. In our scenario, an alert from RXTE will be received. The ASM will shut down, and the rates for the PCA and HEXTE will be anomalously high. At the same time, a monitor measuring ionic density will trigger. Students will be guided to help solve this mystery. Are the two events related? Is it from solar activity? What's happening to the ionosphere and to RXTE? They will investigate real data to determine that the events are simultaneous, and rule out a solar origin. They will then be guided to the conclusion that an astronomical event has caused the "anomaly" on the spacecraft and the atmospheric readings. Special-purpose software will be developed by a partnership of RXTE scientists and HBOSC staff to simulate the RXTE spacecraft anomaly and the atmospheric anomaly. This module will reinforce key processes of space and Earth sciences, is easily inserted into the existing "Encounter Earth" program, and can be tied to Core Learning Goals in both Earth science and physics.

By partnering with the experienced educator staff and facilities that the Owens Science Center offers to incorporate RXTE science themes into the daily student activites, our project directly addresses NASA's Education Strategy Education Program's two main goals, to inspire and motivate students to pursue careers in science, technology, engineering, and mathematics (STEM) and to engage the public in shaping and sharing the experience of exploration and discovery.

Table 1: EPO Education Criteria vs. RXTE Goals

NASA Evaluation Criteria	RXTE E/PO
1. Quality, scope, realism & appropriateness, including linkage to parent science program	Planetarium show and Challenger Center module tied to RXTE capabilities and discoveries
2. Customer Focus:	Incorporating results from NASA operating mission dovetails well with HBOSC efforts to bring current space science examples into existing student programs
3. Content:	Our proposed EPO plan makes direct use of RXTE content and people to involve educators and students in NASA STEM
4. Pipeline:	Our focus on RXTE spacecraft anomaly insures our contribution will attract diverse populations to careers in STEM
5. Diversity:	Our partnership with Prince Georges County education resource guarantees we will reach identified targeted groups
6. Evaluation:	Our partnership with HBOSC allows us to use existing evaluation methods and criteria already in place at the site
7. Partnership/Sustainability:	Our proposed EPO plan involves an appropriate regional partner at every stage of design, development and dissemination
8. Resource Utilization	Experienced small staff reaches broad audience of educators, students and the general public.

Our future E/PO plans rely on our ongoing relationship with HBOSC. This partnership is sustainable due to the geographic proximity of GSFC and HBOSC and the high level of motivation, demonstrated commitment and experience of the participants at both institutions. This partnership affords us a high degree of leverage. Our commitment to nurturing this partnership is demonstrated by the fact that we have already begun work on the planetarium show. In addition, we plan to start work on the CLC anomaly activity so it is ready to beta test by the end of 2006. The GOF has demonstrated an enduring commitment to E/PO. By incorporating RXTE science themes into well-attended planetarium shows and CLC modules, RXTE will make significant impacts on educating both students and the general public about the unique and exciting science done by high energy astrophysicists.

3.4. E/PO Team, Management and Budget

RXTE devotes 5% of PI Swank and 10% of GOF scientist Boyd to leading its E/PO efforts. Swank and Boyd have been involved in LHEA E/PO since 1995. The budget also includes coverage of the 2006 summer salaries for CLC director T. Womack and planetarium director P. Seaton from HBOSC to cover development of the RXTE programs. We request salary support for this team, as well as funds to support one teacher intern each summer. Our budget also includes costs associated with production of the software to support the modification to the Challenger Center module, and some travel costs to local and national educator meetings to present our results.

3.5. Web Links

- High Energy Groovie Movie
  `http://tinyurl.com/luhso`
- Washington, DC, STEM Partnership
  `http://www.nassmc.org/states/dc.html`
- Challenger Learning Center
  `http://www.challenger.org/clc/scenarios.cfm`

4. Appendix: Acronyms

ADAF — Advection Dominated Accretion Flow

ADS — Astrophysics Data System, Harvard, MA

AGN — Active Galactic Nuclei

AMOS — Automated Mission Operations System

ASCA — Advanced Satellite for Cosmology and Astrophysics (X-ray Mission)

ASM — All-Sky Monitor (*RXTE* instrument)

AXP — Anomalous X-ray Pulsar

BAT — Burst Alert Telescope (*Swift* instrument)

BH — Black Hole

BHB — Black Hole Binary

BHC — Black Hole Candidate

CAT — Cherenkov Array at Thémis

CGRO — Compton Gamma-Ray Observatory

Crab — Crab Flux Unit = 2.4×10^{-8} erg s^{-1} cm^{-2} (2–10 keV)

CLC — Challenger Learning Centers

COBE — Cosmic Background Explorer

EDS — Experiment Data System

EGRET — Energetic Gamma Ray Experiment Telescope (CGRO instrument)

EOS — Equation of State

EPO — Education and Public Outreach

FITS — Flexible Image Transport System

FOT — Flight Operations Team

FTE — Full Time Equivalent

FY — Fiscal Year

GB — Gigabyte

GCN — Gamma-ray burst Coordinates Network

GLAST — Gamma-ray Large Area Space Telescope

GO — Guest Observer

GOF — Guest Observer Facility

GR — General Relativity

GRB — Gamma-Ray Burst

GSFC — Goddard Space Flight Center, Greenbelt, MD

GW — Gravitational Wave

HBOSC — Howard B. Owens Science Center, Lanham, MD

HEASARC — High Energy Astrophysics Science Archive Research Center

HEGRA — High Energy Gamma Ray Astronomy

HESS — High Energy Stereoscopic System (TeV telescope)

HEXTE — High Energy X-ray Timing Experiment (*RXTE* instrument)

HFQPO — High Frequency Quasiperiodic Oscillation

HMXB — High Mass X-ray Binary

HS — High State (black hole state)

HV — High Voltage

IAU — International Astronomical Union

IAUC — International Astronomical Union Circular

IDEAS — Initiative to Develop Education through Astronomy and Space Science

IS — Intermediate State (black hole state)

ISCO — Inner-most Stable Circular Orbit

ISM — Interstellar Medium

ISS — International Space Station

IT — Instrument Team

JEM-X — Joint European X-ray Monitor (instrument on *INTEGRAL*)

$\mathbf{L_{Edd}}$ — Eddington Luminosity

LAT — Large Area Telescope (on *GLAST*)

LFQPO — Low Frequency Quasi-periodic Oscillation

LH — Low Hard state (black hole state)

LIGO — Laser Interferometr Gravitational wave Observatory

LMXB — Low Mass X-ray Binary

LOFAR — Low Frequency Array

LS — Low State (black hole state)

$\mathbf{\dot{M}}$ — Mass accretion rate

mCrab — 10^{-3} Crab Flux Units

MAGIC — Air Cherenkov Telescope (La Palma)

MHD — Magnetohydrodynamic

MIT — Massachusetts Institute of Technology

MJD — Modified Julian Date

MOC — Mission Operations Center

MWA — Mileura Widefield Array

NASA — National Aeronautics and Space Administration

NOA — New Obligation Authority

NRA — NASA Research Announcement

NS — Neutron Star

NSES — National Science Education Standards

PCA — Proportional Counter Array

PCU — Proportional Counter Unit

PI — Principal Investigator

PSD — Power Spectral Density

PSR — Pulsar

QPO — Quasiperiodic Oscillation

RHESSI — Ramaty High Energy Solar Spectroscopy Imager

RXTE — Rossi X-ray Timing Explorer

SALT — Southern African Large Telescope

SAX — BeppoSAX - Satellite per Astronomia X

SED — Spectral Energy Distribution

SGR — Soft Gamma-ray Repeater

SOF — Science Operations Facility

SSA — S-band Single Access (TDRSS data mode)

SSC — Scanning Shadow Camera (ASM Detector)

STEM — Science, Technology, Engineering and Mathematics

TDRSS — Tracking and Data Relay Satellite System

TOO — Target of Opportunity

UCSD — University of California at San Diego

ULX — Ultra-luminous X-ray source

VERITAS — Very Energetic Radiation Imaging Telescope Array System (Gamma-ray)

VHS — Very High State (black hole state)

VLBI — Very Long Baseline Interferometry

XMM — XMM-Newton - X-ray Observatory

XRB — X-ray Binary

XRT — X-ray Telescope (*Swift* instrument)

XSDC — XTE Science Data Center