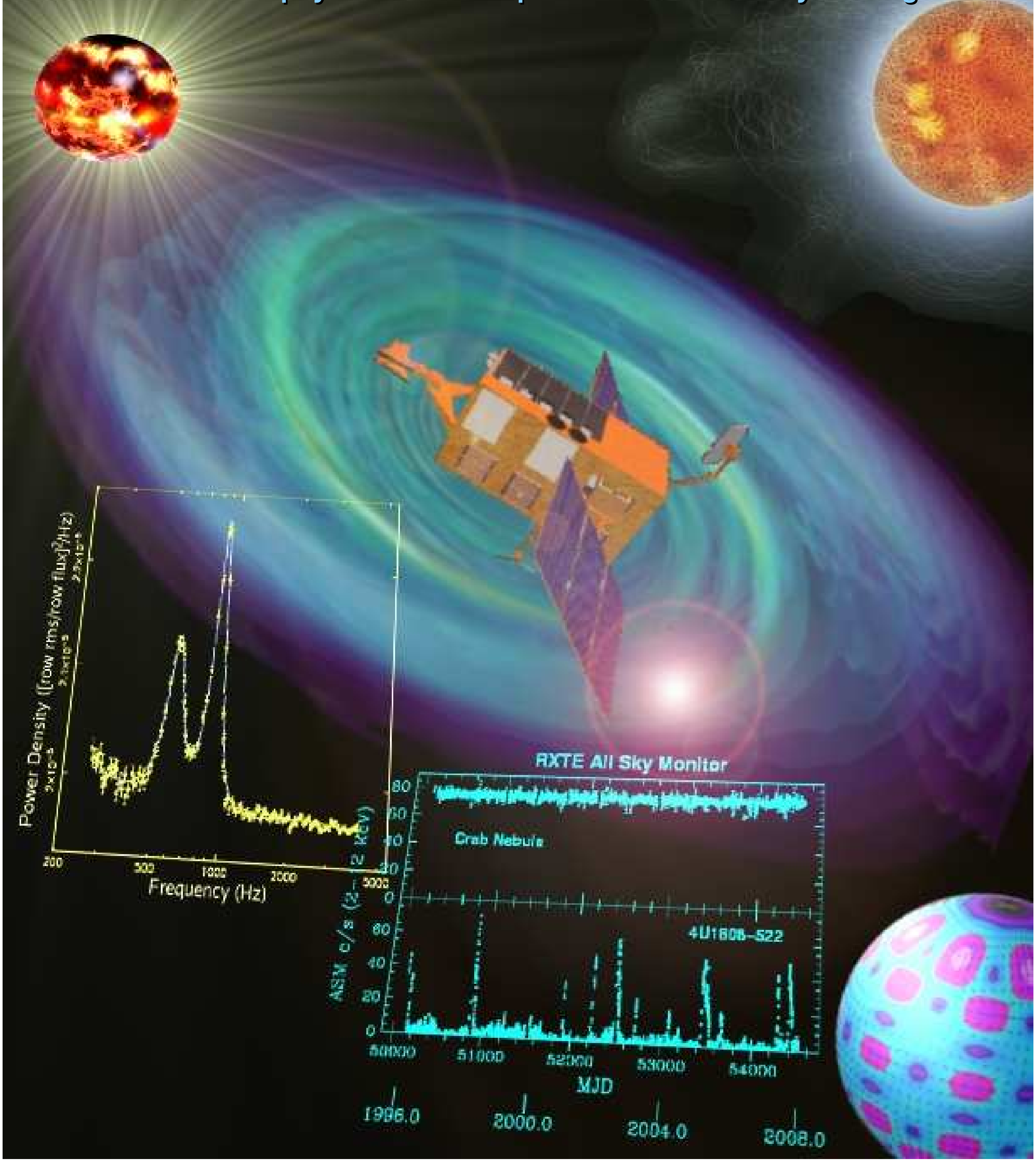
The Rossi X–ray Timing Explorer

A proposal submitted to the 2008 Senior Review of

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 and densely monitor time-critical targets of opportunity. This combination has led to breakthroughs in our physical understanding of the strong gravity, high density, and intense magnetic field environments found in accreting neutron stars, 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 space- and ground-based observatories. *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* and *XMM-Newton*, and especially the soon to be launched *GLAST*, are compelling reasons to continue the *RXTE* mission.

1. Science Proposal

1.1. *RXTE*: to be or not to be?

The most extreme physical environments presently accessible to the human imagination are those associated with the compact stars–black holes, neutron stars, and white dwarfs–produced in the forge of gravitational collapse. Nowhere else in the universe is the gravity stronger, the density higher, the pressure more crushing, the magnetic fields more powerful, than in the vicinity of these objects. The National Academies report, "Connecting Quarks with the Cosmos," argued strongly for astrophysics missions that can address fundamental physics questions such as: did Einstein have the last word on gravity? are there new states of matter at exceedingly high density and temperature? is a new theory of matter and light needed at the highest energies? These questions are also key components of NASA's strategic plan for astrophysics. Indeed, two of the key priorities identified in that plan are: to explore the edges of space-time with black holes, and to explore the extreme physics associated with compact stellar remnants (neutron stars and black holes). *RXTE* remains uniquely capable of exploring such questions and continues to advance our physical understanding of these environments.

RXTE's scientific program remains and highly productive, and continues to be pursued with enthusiasm by a broad base of users that includes a large community of multi-wavelength observers requesting coordinated observing with *RXTE*. A sense of the impact of *RXTE* results on the field of X-ray astrophysics can be gained by thumbing through the recently published volume, *Compact Stellar X-ray Sources* (ed. W. H. G. Lewin & M. van der Klis, Cambridge University Press). It is no exaggeration to say that this new broad review of the field is simply brimming with *RXTE* results obtained over the past decade. *RXTE* observations have truly been instrumental in rewriting the textbooks.

This proposal describes the wide range of exciting new scientific opportunities that will result with two additional years of operations beyond the current observing Cycle 12, the steps that are being taken to keep costs to a minimum, and the changes we propose to the observing program to increase its productivity and usefulness to the astrophysics community. The compelling reasons for continuation of the mission are summarized in Box 1. Chief among these is the fact that *RXTE* continues to provide capabilities not present in any other operating observatory, and that these unique abilities are still enabling a highly productive science program. Indeed, it is clear to us that NASA's overall astrophysics science posture is much stronger with *RXTE* than without it.

The continuing high rate of refereed publications is an important indicator of *RXTE*'s productivity. In the two year period 2006–2007, refereed publications were steady at about 160 per year (similar to the rate for the previous 6 years). Another indicator of *RXTE*'s impact is the large number of Ph.D. theses that have made significant use of *RXTE* data. In many cases whole dissertations were based on particularly rich *RXTE* data sets. At present we know of 80 completed Ph.D. theses, as well as many others still in preparation. There is no indication that the use of *RXTE* data has slackened in the past year or two.

RXTE has carried out more simultaneous and/or coordinated observing programs with ground- and space-based telescopes than any other current orbiting observatory. This results from *RXTE*'s nearly unconstrained viewing and rapid planning capability. *RXTE* has and will continue to devote a substantial fraction of its science program to coordinated observations. Arrangements are in place with *Swift* and *INTEGRAL* to confirm indications of new sources and to coordinate plans for follow-up observations. This has already led to important new

Box 1: Key Reasons to Continue *RXTE* Operations

- *RXTE*'s science program remains broad and unique: 2–200 keV energy band, high throughput sub-millisecond timing, and observing "agility" remain unduplicated.
- *RXTE* continues to be highly productive: the refereed publication rate remains high at ≈ 160/year.
- Provide crucial scientific support for multi-wavelength and multi-mission coordinated observing programs: Necessary for *GLAST* and ground-based TeV (HESS, VERITAS, MAGIC) science programs (blazars, pulsars, black hole transients); unique contributions to many ground and space-based observing campaigns (*Chandra*, *XMM-Newton*, *INTEGRAL*, *Swift*, *Suzaku*, LIGO; see §1.2.3; §1.2.6).
- New science opportunities: new neutron star mass estimates using simultaneous fast timing (*RXTE*) and high spectral resolution (*XMM-Newton* and *Suzaku*) observations (see §1.2.3); new black hole spin measurements (see §1.3.3).
- Cost effective: *RXTE* delivers high impact science on a modest budget.
- Improved community service and TOO alerts, more public data: new "core science" programs ($\approx$50% of *RXTE* data) will be made public immediately (see Box 3 and §1.5.1).

discoveries, the new accreting millisecond pulsar (AMP) SWIFT J1756.9-2508 (§1.2.1); and several new high mass X-ray binary (HMXB) pulsars, for example. We expect more such discoveries. *RXTE* will continue to support coordinated observations with *Chandra*, *XMM-Newton*, *Swift*, *INTEGRAL*, *Suzaku* and LIGO.

An important new opportunity will be the ability to overlap and coordinate observations with *GLAST*, which will explore the 100 MeV to 300 GeV range with unprecedented sensitivity after its planned May 2008 launch. The last few years have seen enormous progress at TeV energies as new observatories, such as HESS, came on line. This energy range will open up even further with high sensitivity provided by the HESS, VERITAS, and MAGIC observatories. *GLAST* and the new TeV instruments will be monitoring numerous blazars (§1.4.1) to understand the physics of these highly variable, jet-dominated, supermassive black holes (BHs). With its flexible scheduling, nearly all-sky coverage, and complementary energy band, *RXTE* will provide critical support for these and other *GLAST* programs.

To date, most *RXTE* observing time has been competitively awarded through the annual peer-reviewed guest observer (GO) program although 20 - 25% has recently gone to responses to unanticipated targets of opportunity (TOOs), for which the data is immediately made public. While this model has served the mission well we propose a modification to it that we believe will increase the impact and productivity of future *RXTE* observations. A careful review of the approved observing programs over the last several cycles reveals that a group of "core" *RXTE* science observations continue to be awarded every year. These programs represent about half of *RXTE*'s observing time (hereafter, we refer to these observations as the "core program.") This is not surprising, as it simply reflects a set of important science goals that are uniquely well suited to *RXTE*. In future observing cycles (beginning with Cycle 13) we propose that the core program will no longer be competed in the AO process. These observations will still be done, but the data will now become public immediately. Specific components of the core program are discussed in more detail in §1.5, but it includes much of *RXTE*'s TOO science and monitoring programs. Some PIs of these programs had voluntarily made data public in the past, but now all data in the core program will be made public immediately. This change in the observing program would have important benefits, as upwards of 50% of *RXTE* data would become available immediately to a much broader community of users. The remaining time would still be awarded competitively through a scaled-down peer review process.

Recent *RXTE* discoveries show that the X-ray sky remains as active as ever. The appearance of transient sources–either new objects or recurrences of known ones–continues to provide new diagnostic and revealing phenomena. Recent examples include the first transient Z source (XTE J1701−462; see §1.2.3), and the new intermittent AMP SAX J1748.9−2021 (§1.2.1). Transients have played a major role in many *RXTE* discoveries (Box 2) and will continue to do so. A key component of the core program is to make dense observations of any new AMP or black hole transient. To further facilitate and maximize transient science the region of the Galactic bulge and ridge monitored with the Proportional Counter Array (PCA) will be increased by half. These scans reach a limiting sensitivity of ≈ 2 mCrab; are much more sensitive to transients than the All Sky Monitor (ASM); are processed in near-real time; and will now be immediately made public (see the Galactic Scan website [1] for an indication of the capability).

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 operations beyond our current Cycle 12, until Feb. 28, 2011, with completion of data distribution, calibration, and documentation in FY 2011. This would provide ≈ 3 years overlap with *GLAST* and allow reevaluation of the situation in the Senior Review of 2010.

Box 2 summarizes *RXTE*'s major science themes and highlights some of the recent discoveries. We briefly de-

[1] `http://lheawww.gsfc.nasa.gov/users/craigm/galscan/main.html`

Box 2: Recent *RXTE* Science Highlights

- High science impact continues: 3 *RXTE*-related AAS High Energy Astrophysics Rossi prizes (8 winners); > 400 Guest Observers; have reached ∼ 1700 refereed papers, 868 rapid notices (ATels, IAUCs, GCNs), 80 Ph.D. theses.
- High magnetic fields: discovery of magnetar behavior in a rotation-powered X-ray pulsar (Fig. 5; §1.2.4).
- Neutron star spins: two new accreting millisecond pulsars (AMP, 10 total) and discovery of intermittent X-ray pulsations (Fig. 1; §1.2.1); measurement of long-term spin down in an AMP, and first evidence for a sub-millisecond neutron star spin rate (§1.2.1).
- Accretion physics: signatures of the disk inner edge predicted by general relativity (Fig. 3; §1.2.3); first transient Z source (XTE J1701-462) reveals evolution in inner disk radius with mass accretion rate (Fig. 4; §1.2.3).
- Thermonuclear burning on neutron stars: confirmation of mHz quasiperiodic oscillations (QPOs) as marginally stable nuclear burning, mHz QPO frequency predicts occurrence of X-ray bursts (Fig. 2; §1.2.2).
- Black hole accretion: BH spin measurements from X-ray spectroscopy (§1.3.3); estimates of BH mass using X-ray QPO – spectral correlation (§1.3.1).
- Jet formation: strongly correlated X-ray and radio emission in neutron stars, formation of jets in low - hard spectral states (Migliari et al. 2007a).
- Intermediate Mass Black Holes: confirmation of earlier *RXTE* evidence of the 62 day orbital period of the ultra-luminous X-ray source M82 X-1, supporting an intermediate mass black hole interpretation (§1.3.1).
- Supermassive black hole jets: correlated X-ray and radio emission in blazars, with optical polarization, identifying the jet acceleration region (§1.4.1).

scribe some of the most important new discoveries, and discuss specific goals for future observations below.

1.2. Neutron Stars

Neutron stars (NS) represent extremes of density, gravity and magnetic fields that enable unique insights into the limits of physical theories. *RXTE* has discovered kilohertz (kHz) quasiperiodic oscillations (QPOs) from more than two dozen, low magnetic field accreting NSs. The highest frequencies measured approach the limit for stable circular orbits in General Relativity ($\approx 1,300$ Hz). Spin frequencies have now been directly seen in ten AMPs, as well as during thermonuclear X-ray bursts (burst oscillations) in a total of sixteen systems (including two of the AMPs). Observations of X-ray bursts provide a means to directly access the surfaces of NSs. *RXTE* observations have also been instrumental in establishing the existence of highly magnetized ($B > 10^{14}$ G) NSs,

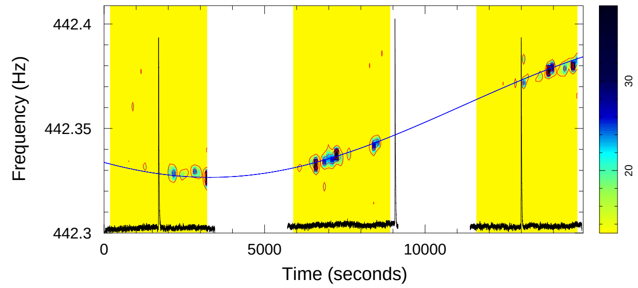

Fig. 1.— Dynamic power spectrum (image) and X-ray lightcurve from *RXTE* observations of SAX J1748.9−2021 reveal 442.35 Hz pulsations preferentially following X-ray bursts, **which indicate the neutron star emission regions are modified after nuclear burning**. Orbital Doppler frequency variations are indicated by the solid curve. (A burst was likely missed in the gap around 5000 s; Altamirano 2008a).

"magnetars."

1.2.1. New Spin Measurements; Intermittent Pulsations

RXTE remains the only X-ray observatory with the capability to routinely measure the millisecond spin rates of low mass X-ray binary (LMXB) NSs. While several observatories, including *INTEGRAL*, *Swift*, and *RXTE* can find new transients, *RXTE* is the only one with the sensitivity and fast timing capability to determine if these objects are millisecond pulsars.

Since the last Senior Review, *RXTE* has identified two new AMPs: SWIFT J1756.9−2508 (Krimm et al. 2007), and SAX J1748.9−2021 in the globular cluster NGC 6440 (Fig. 1; Altamirano et al. 2008a). These NSs have spin rates of 182 and 442 Hz, and orbital periods of 55 minutes and 8.7 hours, respectively. The latter is the longest orbital period yet measured for an AMP. In addition, burst oscillations were recently discovered at 294 Hz in the transient IGR J17191−2821 (Markwardt et al. 2008).

A new phenomenon associated with these discoveries is the occurrence of intermittent pulsations in several sources. The pulsed signal can appear and then disappear on timescales of hundreds of seconds. In two cases, pulsations appear preferentially after thermonuclear bursts: NGC 6440 showed 442 Hz pulsations with an 8.7 hour orbital modulation during an outburst (Fig. 1; Gavriil et al. 2007; Altamirano et al. 2008a); and pulsations in the outburst decay of the AMP HETE J1900.1−2455 (Galloway et al. 2007; Kaaret et al. 2006), although the timescale for change was much longer than in the first case. Casella et al. (2008) also found highly significant 550.3 Hz pulsations from Aql X-1 in a single 150 second interval (out of ≈ 1.5 Ms of data), which is within 0.5 Hz of the known spin frequency.

These new findings do away with the notion that pulsations — or the lack of pulsations — are a fixed property of these systems. Galloway et al. (2007) hypothesized that accretion changes can alter the magnetic field and thus the pulsed properties. However, the apparent connection with thermonuclear burning suggests that the mechanism is also related to surface processes that affect the field. Although this phenomenon is not yet fully understood, it is providing important clues to the relationship between surface magnetic field, accretion rate, and nuclear burning. Future *RXTE* observations will be crucial in elucidating the physics of intermittency, as only *RXTE* can make the necessary pulsation measurements.

RXTE observations of the transient XTE J1739−285 have provided evidence for what may be the fastest spinning NS yet discovered. Kaaret et al. (2007) report evidence for burst oscillations at 1,122 Hz in a single X-ray burst from the source. The existence of a NS spinning this fast would rule out several stiff, mean-field nuclear equations of state (EOS; see Lattimer & Prakash 2001; 2007; Bejger, Haensel & Zdunik 2007). Because this frequency is substantially higher than the next highest confirmed NS spin frequency of 716 Hz (Hessels et al. 2006), and it has such important implications for NS structure, it is essential that it be confirmed. This will be an important goal of continued *RXTE* operations.

RXTE observations have enabled the first determination of the long term rotational and orbital torques on accreting pulsars. Hartman et al. (2007) determined that the transient pulsar SAX J1808.4−3568 spun down at a mean rate of $5.6 \pm 2 \times 10^{-16}$ Hz s^{-1} over six years, and that the bulk of this spin-down occurred during X-ray quiescence. This measurement places limits on the pulsar's surface dipole magnetic field of $< 1.5 \times 10^8$ G, and also constrains the existence of a mass quadrupole that, if present, would lead to the emission of gravitational radiation. An upper limit on the fractional mass quadrupole of $Q/I < 5 \times 10^{-9}$ (I is the moment of inertia of the NS), is obtained assuming all the observed spin down is due to gravitational radiation. They also found the orbital period is growing at a rate of $3.5 \pm 0.2 \times 10^{-12}$ s s^{-1}, much faster than expected from gravitational radiation losses, but similar to the quasi-cyclic period variations measured for several so-called "black widow" pulsars, which appear to be ablating their companions (Arzoumanian et al. 1994; Doroshenko 2001). Measuring the orbital and spin torques in more systems is highly desirable, and can only be done by *RXTE*.

1.2.2. Seeing the Surface

RXTE observations have recently confirmed a new manifestation of thermonuclear burning on NSs, marginally stable burning. This occurs near the critical accretion rate at which burning becomes stable. The nuclear heating rate is then almost exactly equal to the cooling rate due to radiation from the fuel layer ($\propto T^4$), and the burning becomes oscillatory with a period of $\sim$2 min, approximately the geometric mean of the accretion and thermal timescales for the burning layer (Heger et al.

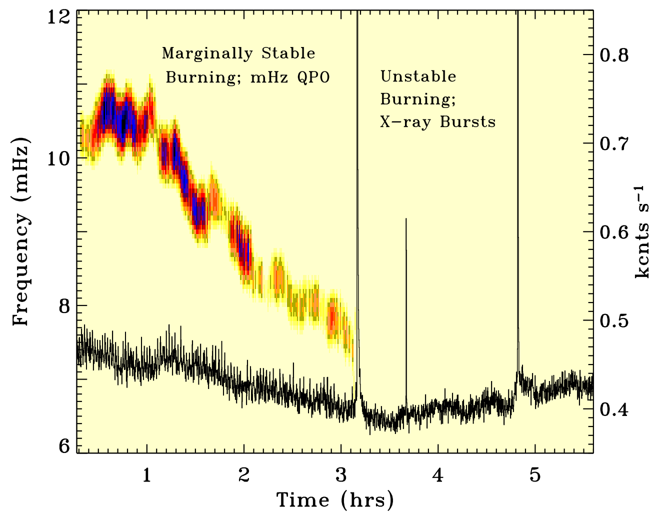

Fig. 2.— Dynamic power spectrum (image) and X-ray light curve from *RXTE* observations of 4U 1636−53, showing the evolution of mHz QPOs (after Altamirano et al. 2008b). The QPOs drift down in frequency and disappear after the onset of X-ray bursts. **The QPO frequency is sensitive to the surface gravity, $\propto M/R^2$, and represents a new probe of NS structure.**

2007; Cumming 2006). Revnivtsev (2001) first reported the observation with RXTE of 7–9 mHz QPOs from two accreting NS binaries (4U 1608−522 and 4U 1636−536). Because the QPO energy spectrum was unusually soft, and they only appeared in a narrow range of mass accretion rates, Revnivtsev et al. (2001) suggested the QPOs might be associated with nuclear burning. This speculation was confirmed with detailed theoretical calculations by Heger, Cumming & Woosley (2007), who showed that the frequency is sensitive to the hydrogen abundance in the accreted fuel and the surface gravity. Recently, Altamirano et al. (2008b) reported the apparent separatrix between marginally stable and unstable burning, when the behavior changed from $\sim$8 mHz oscillations to bursts (Fig. 2). Because they occur in a limited mass accretion rate range, it requires long exposures and/or close monitoring to observe these QPOs. Since the predicted QPO frequency depends on the surface gravity ($\propto M/R^2$) and the composition, they can provide a new probe of NS structure (Heger et al 2007). Future *RXTE* goals will be to observe such QPOs from more objects, particularly ultra-compact systems (e.g. 4U 1820−30), for which the composition is constrained.

1.2.3. Accretion Physics and General Relativity

The kilohertz QPOs are the highest frequency periodic phenomena known in astronomy, and they likely result from the dynamics of matter at the inner edge of the accretion disk, barely kilometers above the NS surface (van der Klis 2006). They are commonly observed in a pair with a lower frequency $\nu_{\rm low}$ and an upper frequency at $\nu_{\rm up} = \nu_{\rm low} + \Delta\nu$, where $\Delta\nu$ is approximately constant

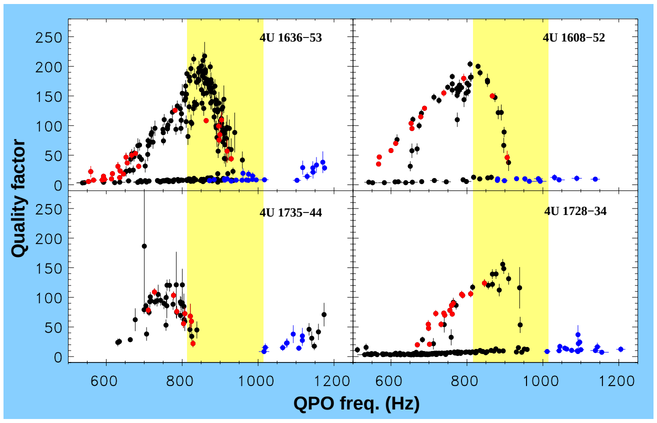

Fig. 3.— Coherence, or Quality factor, $Q \equiv \nu/FWHM$, as a function of QPO frequency for the kHz QPOs observed with *RXTE* from four LMXBs (after Barret et al. 2007). Lower QPOs are red, upper QPOs blue, and single QPOs black. Four sources clearly show the same trend in coherence for the lower QPO, an increase to a peak in the range 750–900, followed by a sharp decline, **behavior consistent with a fundamental prediction of GR. The yellow regions show the approximate range of $\nu_{\rm ISCO} - \Delta\nu$ for $1.8 < M_\odot < 2.1$.**

in a given source. $\nu_{\rm up}$ can approach 1,300 Hz, and likely represents an orbital frequency at a special radius in the inner disk. Barret, Olive & Miller (2007) have systematically studied the frequency, amplitude and coherence of kHz QPOs in several systems, and find a tendency for the *coherence* of the lower QPO to fall sharply after reaching a maximum of $\approx$ 200 at 800–900 Hz (Fig. 3). Barret et al. (2007) suggest that this occurs when ν_{low} approaches $\nu_{\rm ISCO} - \Delta\nu$, where $\nu_{\rm ISCO}$ is the orbital frequency at the innermost stable circular orbit (ISCO; a key prediction of General Relativity). This effect was first seen in 4U 1636–53, but since 2006, it has been confirmed in three additional sources: 4U 1608–52, 4U 1735–44, and 4U 1728–34. The projected frequency at which Q goes to zero varies in the range from about 850 – 950 Hz, consistent with expected variations in the mass of the NSs from $\approx 1.8 - 2.1 M_\odot$. Although others have suggested that the observed drop in coherence is related to spectral changes (Mendez 2007), Barret et al. (2007) showed with additional data from 4U 1636–53 that the coherence behavior is independent of the spectrum.

Recent high spectral resolution studies of several accreting NSs with *XMM-Newton* (Bhattacharyya & Strohmayer 2007) and *Suzaku* (Cackett et al. 2008) have revealed evidence for relativistically broadened Fe Kα fluorescence lines from their accretion disks. Spectral fits to the line profiles provide upper limits on the radius of the NSs (in units of GM/c^2), since the accretion disk cannot approach closer than the stellar surface. Current limits for Serpens X-1, 4U 1820−30, and GX 349+2 span the range from 14 – 16.5 km (for a $1.4M_\odot$ NS). Kilohertz QPOs have also been observed with *RXTE* from two of these sources (4U 1820−30, and GX 349+2). The orbital radius estimated from the upper QPO frequency for these two objects is then nicely consistent with the radii inferred from the Fe line profiles (Cackett et al. 2008). This supports the notion that the upper kHz QPO frequencies represent orbital frequencies near the inner edge of the disk. Indeed, if the orbital velocity (obtainable from the spectral line fits) and the orbital frequency (from the QPOs) are measured at the same radius, then this gives a measure of the NS mass. Hence, simultaneous *RXTE* observations with either *XMM-Newton* or *Suzaku* can provide a new method to measure NS masses, and for a population of stars for which accurate mass measurements have been extremely difficult. *Suzaku* observations to support this program have recently been approved. *RXTE* is essential to these studies, as only it can make the QPO measurements. These simultaneous observations will be a primary goal for extended *RXTE* operations.

The discovery of XTE J1701–462 in early 2006 has recently led to a major advance in our understanding of accreting LMXB NSs. This source is the first NS transient to have reached super-Eddington luminosities and the first to evolve, from outburst peak to quiescence, through all spectral sub-classes of NS LMXBs (e.g. "Z" and "atoll" types). Using ∼850 *RXTE* observations (∼2.6 Msec), Lin et al. (2008) were able to address long-standing questions regarding the role of the mass accretion rate ($\dot{M}$) in mediating changes between these different sub-classes. Only *RXTE* could obtain such dense sampling on a single transient outburst.

Lin et al. show that the sub-classes only differ in $\dot{M}$ and that differences in B-field, spin, or viewing angle are not necessary. As $\dot{M}$ increases, Lin et al. observe a growing inner disk radius, possibly the result of Eddington-limited radiation pressure, while the impact zone on the NS maintained a constant size (Fig. 4). This "recessed" disk configuration appears to be subject to instabilities, that define two of the spectral branches for Z sources. At moderately high $\dot{M}$ a "flaring" instability occurs in which the disk reverts back to its original radius, while at higher $\dot{M}$ the launch of radio jets occurs. XTE J1701–462 is the only source in which these phenomena have been studied from super-Eddington $\dot{M}$ into quiescence, making it the de facto reference point to which accretion in other NS LMXBs will be compared.

1.2.4. Magnetars

Two source classes have been identified as magnetars: the Soft Gamma-ray Repeaters (SGRs) and the Anomalous X-ray Pulsars (AXPs). SGRs occasionally emit bright (∼10^{41} ergs s^{-1}), short (∼0.1 s) X-ray bursts. Three SGRs have also emitted giant flares that are much more energetic, with energy releases upwards of 10^{45} ergs (see Hurley et al. 2005). The AXPs are characterized by bright X-ray pulsations which cannot be accounted for by rotational power alone. AXPs have rotation pe-

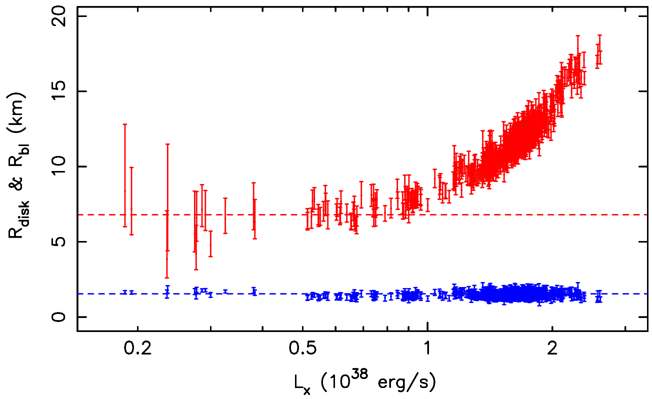

Fig. 4.— The global luminosity evolution of disk (red) and boundary layer (blue) radii of XTE J1701–462. Instabilities start when the disk radius begins to increase (around $L_x \sim 8 \times 10^{37}$ erg/s), and may indicate **Eddington-limited radiation effects in the inner disk.**

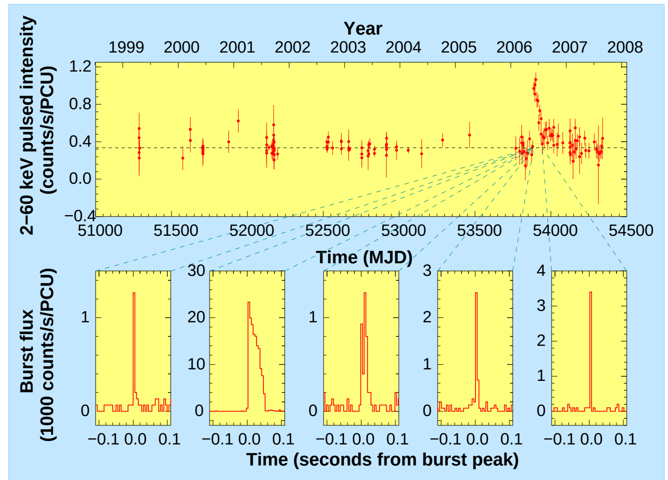

Fig. 5.— Pulsed flux history (top) of PSR J1846−0258 showing the outburst of June 2006 as recorded by *RXTE*. The horizontal dotted line shows the persistent flux level. The 2–60 keV *RXTE* X-ray lightcurves, in 5 ms bins, of five bursts (bottom) detected from PSR J1846−0258 (Gavriil et al. 2008b). **These data represent the first observation of magnetar behavior in a rotation-powered pulsar.**

riods in the range 2–12 s, and are all rapidly spinning down. There are now several observational links between SGRs and AXPs: *RXTE* discovered SGRs are also pulsars with similar spin periods and spin-down rates (Kouveliotou et al., 1998; Kouveliotou et al., 1999; Klan et al., 2003); and that AXPs are also bursters (Gavriil et al., 2002). Since then, a total of five AXPs have been observed to burst, and all but one of these bursts were discovered by *RXTE* (Kaspi et al., 2003; Woods et al., 2005; Krimm et al., 2006; Gavriil et al., 2008a). Recently Gavriil et al. (2008a) discovered highly significant spectral emission lines in a burst from AXP 4U 0142+61 with *RXTE*. The most prominent feature was at ∼14 keV, and similar features have been observed in bursts from AXPs 1E 1048.1−5937 and XTE J1810−197 (Gavriil et al., 2002; Woods et al., 2005). If these features are interpreted as proton cyclotron lines, then they imply magnetic fields of $\sim 2 \times 10^{15}$ G.

A significant puzzle concerning magnetars has been whether there exists a magnetic field threshold for onset of magnetar behavior (bursts and long-term flares). That is, can "regular" high-field rotation-powered pulsars also show magnetar-like behaviors? Recently Gavriil et al. (2008b) discovered magnetar-like X-ray bursts from the young rotation powered pulsar PSR J1846−0258 for the first time using *RXTE*. [2] The bursts were accompanied by a pulsed flux enhancement, and a dramatic change in timing noise, all uncharacteristic of rotation-powered pulsars but consistent with the properties of magnetars (Fig. 5). This indicates that rotation-powered pulsars can indeed sometimes appear as magnetars! Recent theoretical work suggests that magnetar fields may form in the stellar core and then migrate outwards, perhaps tied to quark matter phase transitions in the core (Bhattacharya & Soni 2007). While such ideas are still speculative, they could be addressed with deep observations of a larger sample of high-field pulsars, in order to further probe the pulsar – magnetar connection.

[2] Although transient radio emission has been observed from two AXPs (Camilo et al., 2006, 2007), magnetar-like emission had never been observed from a rotation-powered pulsar until now.

1.2.5. Pulsar – TeV Associations

In the last few years observations with HESS have dramatically improved our knowledge of the TeV sky. HESS has now found that some extended TeV sources appear to be coincident with pulsar wind nebulae (PWN; Aharonian et al. 2006; Forot et al. 2007). A number of HESS sources are suspected PWN, but not yet confirmed pulsars. Recently, Gotthelf et al. (2008) used *RXTE* to detect 70.5 ms pulsations from the TeV source HESS J1837−069 (=AX J1838.0−0655; Fig. 6), which was suspected to be a PWN based on *Chandra* imaging. Subsequent observations found a spin-down rate of 4.9×10^{-14} s s^{-1}, consistent with a young, energetic pulsar (Kuiper et al. 2008). Both HESS and VERITAS should find a sizable samples of putative PWN – TeV associations. It will be an *RXTE* goal to observe these objects, in order to confirm new pulsar associations, and establish the energetics of the PWN.

1.2.6. Hard X-ray Studies: Piercing the Fog

The hard X-ray capabilities of *RXTE* are complementary to those of *INTEGRAL*. With its large field of view imaging capability, *INTEGRAL* has detected over 500 hard X-ray sources consisting of approximately 200 X-ray binaries, including previously known as well as new "IGR" sources. However, in most cases, *INTEGRAL* lacks the sensitivity to determine the natures of these sources, making follow-up observations with

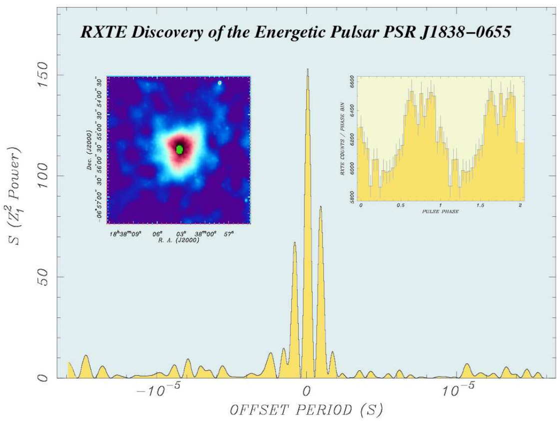

Fig. 6.— *RXTE* discovery of the energetic pulsar associated with HESS J1837−069. *RXTE* power spectrum (main panel), *Chandra* image of AX J1838.0−0655 (left), and pulse profile from *RXTE* data (right; after Gotthelf et al. 2008). **These data confirm that pulsar wind nebulae can be strong TeV sources.**

RXTE and other missions essential (e.g., Galloway et al., 2005). An interesting class of "IGR" sources are the obscured HMXBs, which exhibit column densities as high as 10^{23-24} cm^{-2} due to a strong stellar wind that enshrouds the compact object. Eleven of the "IGR" HMXBs are known to harbor NSs as evidenced by the detection of X-ray pulsations (Bodaghee et al., 2007).

The NSs in the IGR HMXBs are also unusual because of very slow spin periods, in the 1000–6000 s range. Using *INTEGRAL*, Patel et al. (2007) measured a change in the spin period of 94 s, of the $\sim$6000 s pulsar IGR J16358−4726. Such a rapid spin-up via accretion would require the NS to have a very strong magnetic field (10^{13-15} G), which could make this source the first known binary magnetar. While *RXTE* observations of some of the IGR HMXBs have already occurred (e.g., Thompson et al., 2006), the binary magnetar possibility considerably strengthens the case for continuing such programs for IGR J16358−4726 as well as for other IGR HMXB with *RXTE* in the future.

1.3. Stellar Black Holes

1.3.1. The Stellar Black Hole Population

The population of black holes (BH) in the galaxy, estimated at $\sim 10^8$, reflects the evolution of stars that created them (van den Heuvel 1992; Agol et al. 2002). X-ray observations have identified 20 objects with dynamical mass measurements, confirming that the compact object is a BH, and 20 more candidate BHs were identified by their X-ray spectral and temporal properties (Remillard & McClintock 2006). Mass, distance, and spin measurements are required to understand the physical properties of BHs and to use them as markers of stellar evolution.

The scaling properties of timing features may make it possible to determine BH masses from *RXTE* data alone. The scaling of the high frequency part of power spectra has recently been shown to be a BH mass estimator (Gierlinski et al. 2008). Shaposhnikov & Titarchuk (2007a, 2007b) also developed a QPO – spectral index scaling method to estimate BH mass. They verified the method using the masses of GRO J1655–40 and GRS 1915+105, known from optical and IR observations, obtaining a mass of $(15.6\pm1.5)M_\odot$ for GRS 1915+105. For Cyg X-1, where the low mass-function is an obstacle for a dynamical mass measurement, the scaling method gives a BH mass of $(8.7 \pm 0.8)M_\odot$ — the most tightly constrained limit on the mass for this source. Applied to XTE J1650–500, the method gives $(3.8 \pm 0.5)M_\odot$, within the mass range of 2.3–7.3 $M_\odot$ from optical data.

Beyond the range of ordinary stellar BHs are the putative intermediate mass BHs with masses 100–1000 $M_\odot$ (IMBHs). *RXTE*'s flexible scheduling has enabled frequent monitoring of the ultra-luminous X-ray source (ULX) M82 X-1, and has identified a 62 d period, likely the orbital period of a Roche lobe overflow binary containing the ULX (Kaaret & Feng 2007). Only a giant or supergiant companion would fill its Roche lobe in such a system, and calculations show that it could supply sufficient mass to power the ULX (Li 2004; Portegies Zwart et al. 2004), supporting the hypothesis that M82 X-1 is an IMBH. In addition, the QPO – spectral index scaling method yields 250–1000 $M_\odot$ for this object, further supporting the IMBH hypothesis (Dewangan et al. 2006).

Many galactic black hole candidates are discovered as transient outbursts. Moderately bright ($\sim$0.1–1 Crab) BH transients occur at a rate of only 1-2 yr^{-1}; however, they provide a wealth of information. The emission from bright transients is initially very hard. Although *INTEGRAL* or *Swift*/BAT may detect them, the *RXTE*/ASM and PCA scans of the galactic ridge are also powerful black hole finders. The beginning of the outburst may be accompanied by radio emission (Shaposhnikov et al. 2007, Corbel et al. 2004, Fender et al. 1999). *RXTE*-detected transients can trigger radio follow-up, yielding accurate positions, which can facilitate optical identification, as occurred for H1743-322 (ATel 146), SLX 1746-331 (ATels 1235,1237, & 1252), and XTE J1720-318 (ATel 117; IAUC 8056); and also radio-based parallax distance measurements, such as GRS 1915+105 (McClintock 2008). *RXTE* would continue observations of these important objects in the future.

1.3.2. Inflows and Outflows

The relationship between the matter that falls toward a BH in the accretion disk and the jets and winds that stream away from it remains a major open question. Insight can come from understanding the nature of the corona, a region of hot ($\sim$100 keV) electrons where Comptonized hard X-ray (>10 keV) emission is produced. The geometry and energetics of the corona are unknown, and

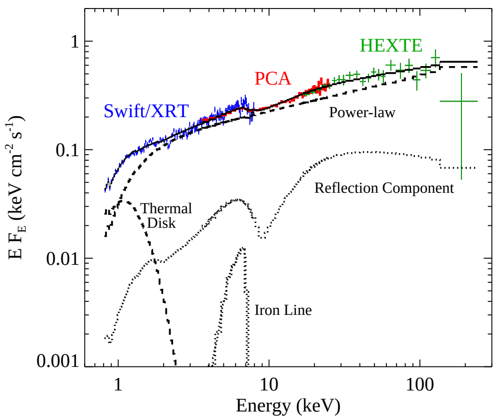

Fig. 7.— Broad-band X-ray spectrum of GX 339–4 in the hard state (*RXTE* PCA, HEXTE and *Swift*/XRT). The model includes an accretion disk and a red-shifted broad Fe line — **indicating a disk extending to the innermost stable orbits of GR** — as well as a power-law with a relativistically broadened reflection component (Tomsick et al. 2008).

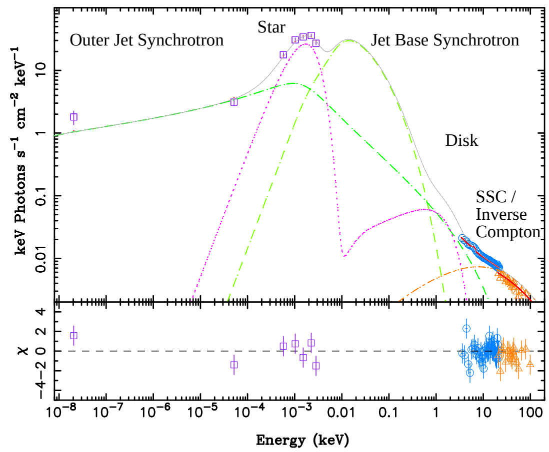

Fig. 8.— GRO J1655–40 hard state spectral energy distribution, **supporting the presence of a "compact jet" originating near the black hole** (Migliari et al. 2007b; Markoff et al. 2005). From left-to-right, the SED includes measurements with VLA, *Spitzer*, ground-based optical/IR, PCA, and HEXTE.

it is even debated whether it is part of the inflow or the outflow. Combining *RXTE* and multi-wavelength data with theoretical modeling has recently led to interesting new insights.

Generally, it has been known that BH transients display a number of spectral and temporal states, one in which an optically thick thermal disk spectrum is dominant with a temperature near 1 keV (the "soft" state) and one in which a hard power-law is dominant (the "hard" state). While the basic observational properties of the soft state can be well-explained by an optically thick accretion disk around a BH, the physics of the hard state, which is the only state where a steady jet is present, remains elusive. The standard picture for the hard state has been that a large increase in the inner radius of the optically thick accretion disk occurs when the source enters this state, and that the inner part of the disk is replaced by a quasi-spherical corona. The advection-dominated accretion flow (ADAF) model (Narayan 1996) attempts to describe such a system, and has had considerable success in explaining some BH observations (Esin et al. 1997; Garcia et al. 2001). In addition, there is considerable evidence that the inner radius increases at the very lowest accretion rates (McClintock et al. 2003), and there is some evidence that a large inner radius is a hard state property (e.g., Zdziarski et al. 2003).

However, recent careful analysis of observations of several transients (GX 339–4, Swift J1753.5–0127, and XTE J1817–330) seen simultaneously with *RXTE*, *XMM-Newton* and *Swift*/XRT (Miller et al. 2006; Miller, Homan, & Miniutti 2006; Rykoff et al. 2007; Tomsick et al. 2008) suggest that the disk exists down to what is plausibly the ISCO, well into what is accepted as the hard state (see Fig. 7). In these cases, the spectra were all dominated by a hard power-law, but a soft disk component was also seen with $kT \sim$0.2–0.4 keV. Although the precise value of the inner radius cannot be determined from the detection of this component, for GX 339–4, a broad iron line and a Compton reflection component were also detected. Fits to the spectra with a model that attributes the line broadening to relativistic effects[3] give an inner radius $\approx 4GM/c^2$ (i.e., very close to the ISCO; Miller et al. 2006; Tomsick et al. 2008). While the *RXTE*/PCA energy resolution near the iron line is not as high as *XMM-Newton* and *Swift*, the PCA provides spectra with much higher statistical quality. Also, both PCA and HEXTE are important for determining the continuum, allowing for better constraints on both the broad iron line and the soft component.

There is great promise in obtaining measurements of the inner disk radius for BH transients in the hard state simultaneously with multi-wavelength measurements of the "compact jet" with VLA, ATCA, Ryle, etc. In some cases compact jet radio emission is strongly correlated with X-ray flux, motivating models where the X-rays arise in the base of the jet via synchrotron and synchrotron self-Compton emission (Markoff et al. 2005) rather than in a static corona. If the optically thick disk extends to the ISCO it may imply that the disk provides the nozzle of the jet near the BH. The compact jet model of Markoff et al. (2005) accurately described the spectral energy distribution of GRO J1655−40 extracted from *RXTE*, *Spitzer*, VLA, as well as ground-based optical and IR observations (Fig. 8). The fits yielded physical parameters, such as a jet nozzle radius close to the ISCO (Migliari et al. 2007b).

[3]Note that other models have also been advanced to explain broadening, e.g., Done & Gierlinski 2006; Laurent & Titarchuk 2007.

1.3.3. Angular Momentum

The famous "no hair" theorem states that BHs are deceptively simple, requiring only two numbers to describe their structure; mass (M) and spin ($a/M = cJ/GM^2$, where -1$\leq a/M \leq$1). While some 20 masses have so far been estimated (see §1.3.1), the effects of spin are confined to the immediate environs of the BH and are much more difficult to discern. At a fixed BH mass the spin sets the location of the ISCO, and therefore the distance of closest approach of the disk. The spin can be determined with X-ray spectroscopy by determining the temperature and emitting area of the thermal disk. This is done by fitting the thermal (soft state) continuum to relativistic accretion disk models (Li et al. 2005; Davis et al. 2005), but accurate mass and distance measurements are also needed. *RXTE* provides the most sensitive X-ray continuum observations to enable spin measurements, and several groups have been persuing this approach. Shaffee et al. (2006) report values of a/M =0.65−0.75 and 0.75−0.85 for GRO J1655−40, and 4U 1543−47, respectively. McClintock et al. (2006) find a/M =0.98−1 for GRS 1915+105, and Davis et al. (2006) place a limit a/M <0.26 for LMC X-3. Spin estimates are presently being aggressively pursued for the transients XTE J1550−564, XTE J1859+226, XTE J1650−500 and XTE J1817−330, as well as for the persistent sources LMC X-1 and LMC X-3 (J. McClintock, private communication). Spin measurements of future transients will be an important goal for continued *RXTE* operations.

The dynamical frequency of a 10 $M_\odot$ BH is ≈1000 Hz at the ISCO, while the highest frequency BH oscillations yet observed are 450 Hz (Remillard & McClintock 2006). Even small amplitude kHz oscillations are easily detectable for bright transients (e.g. Sco X-1, 0.7% r.m.s.). The oscillation frequencies in the disk depend on the angular momentum of the BH. Models which predict a 2:3 relation between QPO frequencies, seen in several BH transients, also predict higher harmonics (Schnittman & Bertschinger 2004). Only *RXTE* could detect these harmonics, and the sensitivity is improved if a very bright outburst is observed. The rate of >1 Crab BH transients is about 0.5 yr^{-1}. BH transients brighter than 10 Crab are even rarer: only five have ever been observed. However, rare events *have* been captured by *RXTE* (e.g. magnetar giant flares and LMXB superbursts). Detecting any bright BH transient with *RXTE* will potentially lead to important measurements of BH mass and spin, both from nearby "ordinary" BHs and exceptionally luminous distant BHs.

1.4. Supermassive Black Holes

1.4.1. Multiwavelength Observations of Blazars

Supermassive BHs in Active Galactic Nuclei (AGN) are efficient accretors, converting ≈ 10% of the gravitational energy of the accreted material into radiation. In

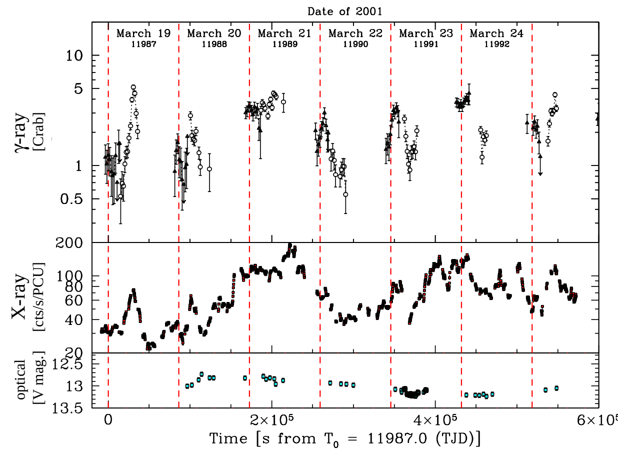

Fig. 9.— Simultaneous light curves for Mkn 421 between HEGRA, Whipple, and *RXTE* show clear keV–TeV correlations — **which support the concept that a single population of electrons is responsible for both via Synchrotron emission and inverse Compton scattering** — but there is also complexity that requires further investigation (Fossati et al. 2008).

some AGN, a similar fraction of energy powers bipolar jets. The energetics alone show that jets play an important role in the accretion process, and likely transport not only energy but also angular momentum from the inner parts of the accretion disk. In blazars, a subset of AGNs that includes high-powered quasars and lower-power BL Lac objects, the jet is aligned with the line of sight. The highly relativistic motion of the jet medium leads to an amplification of the apparent luminosity by several orders of magnitude. Blazars provide the rare opportunity to observe the jet very close to the BH, thereby revealing the inner workings of AGN jets.

Important recent blazar discoveries include the detection, using ground based Čerenkov telescopes, of fast variability (∼2−5 min timescales) in the γ-ray flux from the BL Lac objects Mrk 501 (Albert et al. 2007) and PKS 2155−304 (Aharonian et al. 2007). The variability implies a linear dimension of the emission region that is much smaller than the BH's Schwarzschild radius, suggesting that the standard AGN jet structure paradigm needs to be revised (Begelman, Fabian & Rees 2008; Krawczynski 2007). By tracking a blob injected into the base of the jet of the BL Lac in 2005, Marscher et al. (2008) identified the location of the acceleration and collimation zone containing a toroidal magnetic field. *RXTE* observations as part of a multi-wavelength campaign were crucial in tracking the outburst.

Observations of BL Lac objects with *RXTE* and TeV observatories lend support to synchrotron (X-ray) and Inverse Compton (γ-ray) models. However, individual flares show (see Fig. 9) rather complex correlations (Błażejowski et al. 2006; Aharonian et al. 2008; Fossati et al. 2008). Upcoming *RXTE* and Čerenkov telescope (HESS and MAGIC, both in the process of being signif-

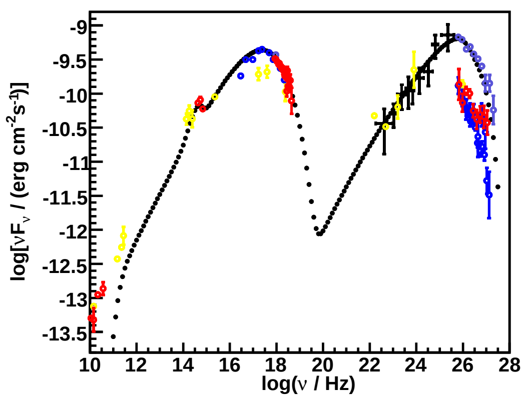

Fig. 10.— Spectra of Mkn 421 from previous measurements with simulations of expected *GLAST* contributions (crosses), **showing the synergy of *RXTE* and *GLAST* joint observations**. The data shown in various energy bands were not simultaneous. Interpreting the variability will require time histories in the different bands (D. Horan et al. 2008, in prep.)

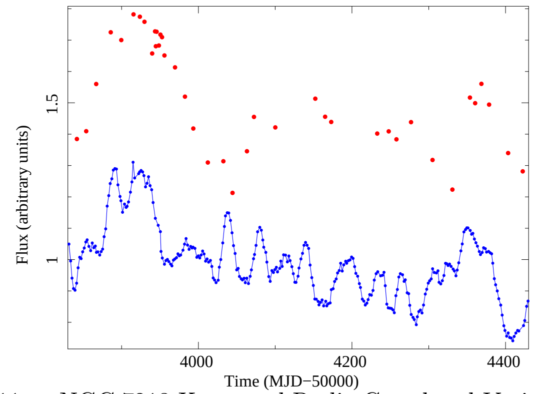

Fig. 11.— NGC 7213 X-ray and Radio Correlated Variability. The 2–10 keV *RXTE* PCA fluxes (blue line) and 3 cm VLA fluxes (red dots) are correlated with <20 day lag, **suggesting they are responding to the same accretion rate modulations**. (Uttley et al., in prep).

icantly upgraded, and VERITAS which was completed in April 2007) observations will aim at scrutinizing these correlations. These observations, together with radio and optical coverage, will help discriminate between leptonic and hadronic emission models, thus identifying the emitting particles.

RXTE will provide crucial scientific support for the *GLAST* mission, which is expected to detect several hundred blazars over a wide range of redshifts. With its wide field of view, *GLAST* will track γ-ray variability on month to year long timescales for hundreds of sources, and on day to week long timescales for dozens of sources. *RXTE* will monitor the X-ray emission of these sources, which is key to understanding the particle acceleration processes in the highly relativistic jet plasmas. During the rising phases of flares, we expect to "see" low-energy particles passing through the *RXTE* band before they emit in the *GLAST* regime. In the decaying phases of flares, we expect to see the imprints of the radiative cooling of the particles in the broad band energy spectra measured with *RXTE*, *GLAST* and (for some objects) Čerenkov telescopes. Fig. 10 shows how X-ray (*RXTE*), γ-ray (*GLAST*), and TeV observatories are required to define the broadband spectrum.

The tentative association of the arrival directions of the highest energy cosmic rays detected by Auger with the positions of nearby AGN (Auger et al. 2007) has increased the interest in hadronic models in which blazars accelerate particles to $> 10^{19}$ eV energies. The combination of *RXTE*, *GLAST*, and ground based Čerenkov telescopes would be ideally suited to evaluate the possibility that the particles are accelerated in the blazar zone rather than in shocks of the kpc-jet or the other large radio structures.

Key for all the blazar science described here is the accumulation of a set of smoking-gun observations such as measurements of X-ray/TeV spectral correlations during blazar flaring epochs, and measurements of short term flux variability with *RXTE* and *GLAST* for a set of quasar-type blazars. Continuing *RXTE* would allow us to catch several blazars in bright flaring states during which *GLAST* and Čerenkov telescopes can measure the higher energy emission with the required accuracy.

1.4.2. Black Hole Unification

RXTE's important contributions to AGN science include establishing connections between accreting stellar-mass and supermassive BHs through their X-ray timing properties and through multi-wavelength correlations which explore disk/jet connections.

Simultaneous X-ray/radio monitoring of radio-loud AGN is yielding invaluable new information about the connection between accretion flows and relativistic jets. Marscher et al. (2002) saw dips in the long-term *RXTE*/PCA light curve immediately preceding ejections of new VLBI radio knots in the jet of Seyfert 3C 120. This was confirmed with extended monitoring by Marscher & Jorstad (2006). These events may be analogous to those observed in microquasar GRS 1915+105, suggesting that the inner accretion flow has temporarily become advective. A similar effect may be taking place in 3C 111 (Marscher 2006), NGC 1052 (Ros & Kadler 2006), PKS 0558–504 (Gliozzi et al. 2007), all of which are monitored by *RXTE* and several radio observatories. Large radio ejection events occur at most a few times a year; thus, several years of monitoring are required to test the disk/jet association and to determine whether the lags between X-ray dips and radio ejections depend on BH mass or accretion rate. Some blazars show correlations between X-ray and radio flux (PKS 1510−089), as expected if both the radio and X-ray emission originate in the jet.

The past two years have seen the first radio/X-ray monitoring of a low-luminosity, "radio-intermediate" Seyfert. Preliminary results from *RXTE*/PCA and ATCA monitoring indicate *correlated* variability (see Fig. 11). Similar results have been tentatively obtained with *RXTE* and VLA monitoring of the radio-quiet Seyfert NGC 4051. If the X-ray flux is accretion disk output, both it and the jet respond to the same accretion rate fluctuations. Continued regular monitoring spanning several years is required to achieve statistically significant correlations and to constrain the lags. Regular, ∼weekly X-ray and radio sampling would be proposed to continue for virtually all of the aforementioned targets during 2009−2011, with monitoring of additional faint radio sources planned, using EVLA and eMerlin.

In Seyfert AGN, which are non-beamed, joint X-ray and optical/UV monitoring aims to relate the variable X-ray corona and optical thermal disk emission. The key variability timescales are weeks to years, as the the optical band shows no variability below day-long timescales. Sampling in the optical finally matches that obtained by *RXTE*, thanks to newly operating 2 m class robotic telescopes, such as the Liverpool Telescope on La Palma and SMARTS in Chile. Now, a systematic look at the relationship between the two bands is possible, and the number of significant correlations has tripled (McHardy et al., in preparation.). The emerging picture is that optical variability is driven on short timescales by X-ray reprocessing, while on long time scales it depends on intrinsic thermal emission. The goal of separating out these two variability components and achieving statistically significant correlations requires longer lightcurves. Such projects depend critically upon the continuation of *RXTE*.

RXTE has characterized the rapid X-ray variability in Seyfert AGN on timescales from hours to years, The resulting broadband power spectra obtained for 18 AGN not only confirm the theoretical expectation that AGN variability scales with BH mass, but also inversely with accretion rate (McHardy et al. 2006). This relation is supported by a good correlation between variability timescale and the width of permitted optical emission lines, and is consistent with the notion that for a given BH mass, some physical property decreases as accretion rate increases (e.g., disk truncation radius, Markowitz & Uttley 2005). Continued *RXTE* monitoring of selected targets will allow for better access to the lowest temporal frequencies, more precise broadband power spectra, and better tests of whether Seyferts have states similar to stellar BHs.

1.5. *RXTE*'s Current and Future Programs

1.5.1. Objectives

RXTE's current Cycle 12 includes operations through Feb 2009. We propose to operate for an additional two years, through Feb 2011. The current program is scientifically broad and remains productive. A summary of the most important objectives is shown in Box 3. The program not only produces results like those described in this proposal, but keeps open the opportunity to apply *RXTE*'s unique capabilities to rare but high impact events like those in Box 4.

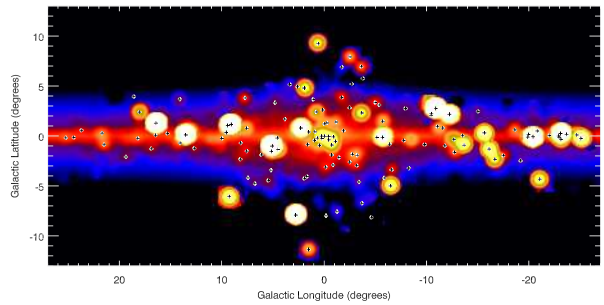

Fig. 12.— *RXTE* map of the Galactic center and ridge, reconstructed from PCA scans over the region. The effective point spread function is 1° (FWHM), but centroids are precise to 5–10 arcmin (except in the central bulge). Dedicated PCA scans can achieve ∼2 arcmin positions. **Expanded PCA scans will discover new and faint transients.**

For the extended observing program we propose several changes. The most significant is the creation of the core program, introduced in §1.1, a set of observations and science objectives that capitalize on the unique capabilities of *RXTE* and its flexible scheduling. The core program observations will be made public immediately, and include: Follow-up observations of new galactic sources; dense observations of new and recurrent AMPs and BH transients; regular scanning observations with the PCA of the Galactic bulge and ridge. The core program represents about half of *RXTE*'s observing time. Objectives comprising the core program are also indicated in Box 3.

This change in the observing program is not expected to substantially change what is observed, but to streamline the discovery process. These programs typically support *many* investigations and immediate public access to the data would speed up the discoveries that could affect other observations. Programs which require detailed input by the proposing scientists would remain solicited and reviewed, with a proprietary data period of 1 year.

The core program includes PCA scans of the central regions of the Galaxy, which are used to reconstruct source "images" of the ridge (Fig. 12). This approach has reliably detected transients when they appear at the level of a few mCrab, with position accuracies of arc minutes. In follow up observations triggered by these scans or by detections by other missions, pulsations have been found for 8 millisecond pulsars. One quarter of known stellar black holes are in the region currently scanned.

The extraordinary events of Box 4 depend on transient occurrences of rare events. The recurrence time scales of bright black hole transients, low mass X-ray binary superbursts, and magnetar giant flares are all several years,

Box 3: Major *RXTE* Objectives

- Search for new NS and BH X-ray transients and recurrences of known objects: increase area of PCA scans of Galactic Bulge by 50% (core program); continue ASM monitoring and light curves.
- Discover new AMPs among new transients: comprehensive follow-up observations to search for orbital modulation, kHz QPOs, X-ray bursts, burst oscillations, spin rate changes, pulse intermittency (§1.2.1) and orbital period changes, coordinate with radio, optical, gamma-ray and other X-ray observatories (core program).
- Discover new BH binaries: comprehensive follow-up observations to search for QPOs, continuum spectroscopy for spin estimates and X-ray state transitions (§1.3.3), coordinate with radio, optical, gamma-ray, and other X-ray observations (core program).
- Discover new HMXB pulsars and search for cyclotron lines and measure their characteristics (core program).
- Accretion and jet physics, NS structure: observations (including multi-wavelength and coordinated observing) of selected NS and BH binaries (§1.2.2; proposed program).
- Physics of strong magnetic fields (magnetars): observations of SGRs, AXPs, and high-field rotation-powered pulsars, monitor spin rate changes, search for glitches and bursting activity (§1.2.4; proposed program).
- Physics of AGN accretion and jets: long-term X-ray timing, coordinated *RXTE*, optical and radio observations to study accretion disk - jet connections (§1.4.2; proposed program).
- Provide broad-band spectral and fast timing support of observations by other X-ray missions; *Chandra*, *XMM-Newton*, *INTEGRAL* (§1.2.5), *Swift*, *Suzaku* (§1.2.3; proposed program).
- Physics of blazar jets: coordinated timing and spectroscopy observations with *RXTE*, *GLAST*, and ground-based TeV observatories (§1.4.1; proposed program).
- Support *GLAST* γ-ray pulsar science: provide pulse ephemerides for γ-ray pulsar searches, support identification of new *GLAST* sources (§1.2.5).

so extension by 2 years of a 13 year mission significantly increases the number of events that would be studied by *RXTE*.

1.5.2. Coordinated Observations

PCA/HEXTE with Radio through TeV. *RXTE* made coordinated observations of more than 120 out of 338 targets in the two year span of 2006–2007. *RXTE* partners with all other X-ray observatories: *Chandra*, *XMM-Newton*, *INTEGRAL*, *Swift*, and *Suzaku*. *RXTE* does a smaller number of special observations coordinated with *HST* and *Spitzer*. *RXTE* also coordinates with optical and infrared ground-based observatories. Radio observations have figured in results for all major categories of targets, as has been discussed. Seven accepted Cycle 12 proposals will be triggered by *AGILE* and *GLAST* GeV results. VERITAS, HESS and MAGIC have already triggered some cycle 12 observations.

Monitoring with the ASM and the PCA The *RXTE* ASM offers long term light curves, freely available, that have been used in many papers about transients, to provide context on a day–year time scale. The three channels covering 2-12 keV provide flux and hardness ratios sensitive to black hole state changes. The PCA Galactic bulge scans (see Fig. 12) have also been used, for fainter galactic transients where the ASM sensitivity is reduced by source confusion.

GLAST. The launch of *GLAST*, a major new observatory, will be a breakthrough in γ-ray sensitivity. *RXTE* will assist *GLAST* in the understanding of several types of targets. Prominent among these are the blazars discussed in §1.4.1. For many transient γ-ray sources, *RXTE* will be best able to look for an X-ray counterpart at the time of the transient and to track its X-ray behavior. While the PCA is limited by fluctuations of the contributions to the X-ray background to sources brighter than about 0.5 mCrab, the brightest of blazars has flares of 50 mCrab. Six proposals for coordinated observations of blazars were accepted in *RXTE*'s Cycle 12. Three *GLAST* programs have been accepted in the *GLAST* Cycle 1 for very sensitive measurements of γ-ray counterparts to Galactic sources observed with *RXTE*. Only *RXTE* can provide simultaneous monitoring with high time resolution. For a half dozen X-ray pulsars which are radio-quiet, *RXTE* will provide the pulse period history which will allow the *GLAST* flux to be searched for pulsations.

LIGO. LIGO is scheduled to start another science data run with enhanced sensitivity in early 2009 that will run for about 18 months and for which noise will be reduced by about a factor of two from the run completed in 2007. X-ray pulsars are important candidates for GW searches, and many of them rely on X-ray timing from *RXTE*. (Abbott et al. 2007a, 2007b).

1.5.3. Mission Complementarity

Current X-ray Missions. There is no current substitute for the 2–200 keV bandpass, dense sampling, and the μs time resolution at high throughput that *RXTE* provides. *RXTE* can easily insert short, frequent observations into its schedule. Its more flexible solar constraint of 30°–180° means that, for example, the Galactic center can be followed for 10 months of the year, while *INTEGRAL* can observe for 3 months, *Swift* for about 9 months, and *Suzaku* for 3 months. *Swift* has demands on its observing schedule from its core science program of GRBs. While *INTEGRAL* and *Swift* are imagers, the 2–10 keV effective area of even one of the PCA detectors

Box 4: Possible Events of High Impact

- Detect additional high frequency components of a transient accreting black hole brighter than 10 Crab.
- Measure the radius at the inner edge of a BH accretion disk by simultaneously observing a HFQPO and relativistically broadened Fe line.
- Determination that an absorbed transient detected by *Swift* or *INTEGRAL* is a high inclination black hole in which *RXTE* can detect oscillations.
- Observe additional magnetar hyperflare oscillations and test the crustal vibration mode hypothesis.
- Confirm binary magnetars with the observation of bursts in binary INTEGRAL transients that appear to have spin downs associated with strong magnetic fields.
- Find a correlated X-ray and LIGO GW signal.

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.

Future X-Ray Missions. India's *Astrosat* is designed to be much more advanced than its previous X-ray mission, Indian X-Ray Astronomy Experiment (IXAE), and includes instruments with the capabilities of *RXTE* and the *Swift* instruments, XRT and UVOT.[4] A recent press report[5] suggests that much work remains before *Astrosat*'s official launch date of April 2009. Overlap with *RXTE* would allow comparison of fluxes, spectra, and timing. *Astrosat* has no public plans to provide the coordinated observations necessary for *GLAST* and ground based observations.

1.6. Bibliography

References for this proposal,[6] and a time ordered list of *RXTE*-related publications[7] are on the RXTE website.

2. Technical Description and Budget

2.1. *RXTE* Operations Overview

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. Innovations continue to produce improved products while reducing costs.

The community continues to demonstrate its interest in *RXTE* data by downloading it at an impressive rate. Users downloaded 6.8 TB of *RXTE* data in 2007, four times the amount in the archive – a rate second only to that of *Swift* and 3 times more than that for any other mission in the HEASARC.

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 seven years. No consumables limit the duration of the mission, and *RXTE* is predicted to re-enter no earlier than 2013.

The instruments should operate for many more years, although there is a slow degradation in their performance. PCU 2 (numbering 0 to 4) is now on for all observations, and the other detectors are on during observations for which they are most useful. "Resting" these 4 detectors and having the spacecraft automatically turn them off when evidence of high voltage breakdown is seen has stabilized their performance. On Dec. 25, 2006, the gas from the anti-coincidence layer on the top of PCU 1 was lost. This was the second PCU that lost its anti-coincidence layer probably due to a micro-meteorite. The ability to detect X-rays is not affected, but the background increased from ∼2 mCrab to ∼4 mCrab.

The ASM continues to monitor the X-ray sky with its 3 cameras. Repeated observations of the Crab demonstrate that the ASM is working well, and it has an accurate calibration. The average exposure time per week has changed little in the last 2 years, and 17 of the original 24 wires remain operational. All 8 anodes of the proportional counter in SSC 1 are fully operational, but the detector gain is increasing at $\sim 10\%\ \mathrm{yr}^{-1}$ because of a slow leak. The increased gain has caused an increase in the frequency of latch-ups (automatic shut-offs of the high voltage in response to high count rates), but changes in ASM operations have been quite effective in minimizing the impact. We cannot confidently forecast its lifetime, but SSC 1 may operate for another two years. Barring an unexpected event, SSC 2 and SSC 3 should continue to function for several more years. The Drive Assembly continues to operate reliably. 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 with

[4] http://meghnad.iucaa.ernet.in/~astrosat/

[5] http://tinyurl.com/3acqco

[6] http://xte.gsfc.nasa.gov/docs/xte/references2008.html

[7] http://xte.gsfc.nasa.gov/docs/xte/whatsnew/papers.html

little change since the last Senior Review. Since an anomaly in Dec. 2005, Cluster A always stares at the source instead of rocking between the source and a background direction. The FTOOL *hextebackest* is now available so that users can estimate its background using the data from Cluster B, which continues to rock[1] (Pottschmidt et al. 2006).

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 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.

Three types of data products are produced for the PCA and HEXTE. "Realtime" data is usually complete within 3 hours, but may have some gaps. It is used for the PCA Galactic bulge scan analysis to look for new sources. "Pseudo-production" data files are archived automatically once per day from the complete data set, but using some predictive rather than as-flown information about the time-line. These data can be retrieved from the SOF by guest observers. Production processing is done within 8 days, with all as-flown information. Processing is done automatically in the SOF, with the FITS files delivered to the HEASARC for access by users. Only 0.7 FTE are now required to monitor the process and resolve the problems that occasionally occur. 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. The staff is automatically alerted when a new source is found. More sophisticated tests are run daily at MIT.

Because of the near real-time monitoring, since the 2006 Senior Review, 83 Astronomer's Telegrams have been released announcing new sources, changes in states of sources, and other results. These discoveries provide unique opportunities for *RXTE* and other missions.

RXTE continues to operate 24 hours per day, but automation has greatly reduced the required staff. The MOC's Automated Mission Operations System manages the spacecraft data recorder, conducts TDRSS contacts, and monitors the health and safety of the spacecraft and instruments. 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 uses a system for remote status reporting as well. The SOF does planning updates on weekends on an on-call basis.

2.2.3. Guest Observer Support

Except for unanticipated TOOs, all *RXTE* observations have been chosen in an open competition from proposals submitted by the community in response to NASA Research Announcements (NRAs). This competitive process has made *RXTE*'s unique capabilities available for the most compelling scientific questions. The community clearly continues to consider *RXTE* a valuable asset. The number of proposals received for Cycles 10, 11, and 12 were 150, 128, and 153 respectively. (Cycles 10 and 11 were for 12 months, and Cycle 12 was for 18 months.) The corresponding over-subscription factors for observing time were 4.64, 5.61, and 6.00. The fraction of TOO proposals has increased, there are more large proposals, and more extensive monitoring campaigns are being carried out. As discussed in §1.5.2, *RXTE* is doing coordinated observations with many observatories. The number of unanticipated TOOs has increased in response to the difficulty of synchronization of proposal cycles between *RXTE* and other observatories.

For Cycles 13 and 14 we propose the core program of observations (§1.5.1 and Box 3) that have been highly ranked for the last 5 cycles *and* for which data made public immediately would allow faster dissemination of results that lead to follow-on observations by other observatories. For some of these the proprietary rights have been waived in recent cycles. At least half the observing time would still be competed for by proposal.

The Guest Observer Facility (GOF) provides tools, documentation, and expert advice to GOs for proposal preparation and data analysis. Support is available via the GOF Web site [2], the *RXTE* help desk, which answers ~ 10 queries per month. GOF on-line documentation includes FAQs, 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 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 reduction in number of proposals reviewed would allow a small reduction (0.2 FTE) in the GOF personnel.

Significant improvements have been made to *RXTE*'s Standard Products. Mission-long Standard Products now

[1] http://rxte.gsfc.nasa.gov/docs/xte/whatsnew/hextebackest_poster.pdf

[2] `http://rxte.gsfc.nasa.gov/docs/xte/xte_1st.html`

provide a compact, decade-long summary for the 204 sources for which there have been at least 30 observations.

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. The staff has been reduced as the tasks have been streamlined and none of the scientists are working entirely on *RXTE*. With the reduced GOF staff, the ITs are also responding to an increased fraction of the questions to the *RXTE* help desk.

MIT maintains both the ASM and the Experiment Data System (EDS), which processes and packages all PCA and ASM data for telemetry. The EDS is a low-maintenance system for which new configurations are sometimes needed. New modes were uploaded in 2007 that may make possible identification of occultations of Sco X–1 by Trans-Neptunian Objects (Jones et al. 2007). 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 MIT ASM[3] and the GOF[4] Web sites. Data are re-processed to produce pre-discovery light curves of new sources.

The UCSD 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. Essentially all of the marginal cost of operating HEXTE is the support for the HEXTE team. UCSD's expertise is necessary to resolve operational anomalies and for occasional advice on data modes.

The PCA team maintains the calibration of the PCA as it evolves. They also maintain and update the detector background model as the orbit decays using regular observations of selected background "targets". Corrections to both the background determination and to energy responses were made in 2007 and additional improvements are forthcoming. The PCA team monitors the detector behavior, determines the times for "resting" PCU 0, 1, 3 and 4, and provides the Mission Scientist.

2.3. Budget Description

The "in-guideline/minimal" budget is provided as an Appendix. With the minimum budget *RXTE* can operate through Feb. 2011 and complete the archiving in the remainder of FY11. No "augmented" budget is proposed. There is no funding for Guest Observers in either the current or proposed budget. The budgets provide the required New Obligation Authority (NOA) rather than the FY expenditures. Since contracts are often funded beyond the current fiscal year, the NOA for a given year can be very different than the money actually used to operate for that year.

RXTE's budget is consistent with the "bare-bones" paradigm. We propose to reduce costs by moving the MOC to an existing multi-mission operations center at GSFC in which some functions and personnel would be shared with other missions. The move will reduce the MOC staff by 2 FTE for the final 2 years of operation and also reduce maintenance costs. The resources needed for the move are given in the Development Budget (II.1) for FY08.

Mission Services (II.2.b) is dominated by the contracted FOT, but also includes computer system administration, hardware and software maintenance, and sustaining a part of the flight dynamics facility and flight software maintenance capability, which are moved in FY09, as directed, from the in-Kind contribution (IV.2.b) to direct mission costs (II.2.b). The values in FY10 and FY11 reflect actual costs, while the FY08 and FY09 values are affected by the phasing of the NOA. Other Mission Services (II.2.c) comprises the (part-time) GSFC Mission Operations Manager.

The in-Kind costs are dominated by Space Communications Services (IV.2.a), which provide the telemetry, tracking, and commanding services of NASA's Space Network. *RXTE* relies exclusively on TDRSS for these services. The costs are based on per minute rates for the various services and the expected utilization. The rest of the Mission Operations budget in the in-Kind category (IV.2.c) pays for project and contract management and facilities.

"Science Center Functions" (I.3) are carried out by the SOF and GOF in collaboration with the ITs. The SOF operations staff has been reduced from 12 during the prime mission to 2.3, and the programmer support has gradually declined to the current 0.3 FTE. The GOF staffing is now 1.6 FTE compared to 16 FTE during the prime mission. The peak staffing for the ITs was 33 FTE in 1996. In FY08 the ITs have a staff of 6.5 FTE (not including 2 relatively inexpensive graduate students). No NOA is required for MIT or UCSD in III.2 and III.3 in FY08 and FY09 because their contracts were funded in a prior fiscal year. The NOA requested for them in FY10 and FY11 is needed to support their costs. As in previous proposals, the budget for ITs is split equally between "Science Center Functions" and "Science Data Analysis".

The EPO budget for FY09 through FY11 is 1.1% of the total *RXTE* budget. §3 has details of our E/PO program.

[3] http://xte.mit.edu/

[4] http://heasarc.gsfc.nasa.gov/docs/xte/asm_products.html

3. Education and Public Outreach

3.1. Goals

In this section we describe our Education and Public Outreach (E/PO) program, in the context of the new NASA Education Strategic Framework. Our program is responsive to NASA's E/PO goals to 1) strengthen NASA and the nation's future workforce, 2) attract and retain students in STEM disciplines, and 3) engage Americans in NASA's missions. We expect to achieve NASA's desired E/PO outcome #2, namely to "attract and retain students in STEM disciplines through a progression of educational opportunities for students, teachers and faculties." Our proposed program also results in outcome #3 "build strategic partnerships and linkages between STEM formal and informal education providers that promote STEM literacy and awareness of NASA's missions."

RXTE scientists have been directly engaged in contributing to the public understanding of science through the mission's vibrant E/PO program. We have developed strong collaborations between scientists, educators and students, and have an impressive track record of innovation. Highlights include the *RXTE* Learning Center, one of the first on-line 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.

The *RXTE* team remains dedicated to sharing the excitement and discovery of high-energy astrophysics with students, educators and families, as demonstrated in our E/PO plans for this proposal period. We have formed a new partnership with the H. B. Owens Science Center and Challenger Learning Center, part of Prince Georges County Public Schools. We capitalize on this collaboration to contribute focused, standards-based *RXTE*-related science content to existing successful student enrichment programs starting in the 2008/2009 academic year. In addition, we will also leverage off the existing, and highly successful E/PO programs of the Astrophysics Science Division (ASD) at NASA's Goddard Space Flight Center.

The goals of the *RXTE* E/PO program are to use the fascinating topics of black holes, pulsars, and active galaxies to engage students in National Science Education Standards-based activities that teach or reinforce the concepts of

- the electromagnetic spectrum,
- the scientific method,
- forces, specifically gravity.

We achieve these goals by developing activities that span the curriculum by including reading, art and music, so that a broad array of teachers can fit the activities into their plans, and so that the subject matter is viewed as engaging and accessible to the widest possible segment of the population, including under-represented populations.

We briefly review our recent E/PO accomplishments and describe our goals for the next two years below. Table 1 maps our E/PO goals and expected outcomes to the new NASA E/PO evaluation factors (SMD EPO Guide v2 2006 December).

3.2. Recent Accomplishments

In our previous E/PO plan, we proposed a collaboration with the H. B. Owens Science Center. This partnership is now in place. The H. B. Owens Science Center (HBOSC) is a 27,500 square foot facility owned and operated by the Prince George's County Maryland Public Schools, and is located about two miles from NASA's Goddard Space Flight Center. 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 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 HBOSC is home to the largest planetarium in the state of Maryland, and one of the most sophisticated. Its size and features enables presentation of planetarium shows that equal those seen at planetariums in major cities. Some 8,000 stars are projected onto the 55 foot diameter dome, where they can be comfortably viewed from 174 reclining, upholstered seats. Nearly 100 slide projectors and special effects devices, as well as video and computer capabilities, ensure that planetarium audiences feel totally involved in the astronomical and space experience.

The HBOSC houses one of the original Challenger Learning Centers (CLCs). These hands-on space science learning centers offer realistic mock-ups of Mission Control and an orbiting space station. The Challenger Learning Center's[1] simulations correlate directly with the Voluntary State Curriculum for the state of Maryland and emphasize processes of science, concepts of science, habits of mind, and applications of science.

Between 2006 and 2008, the HBOSC distributed several hundred copies of "The Universe in a Different Light"

[1] `http://www.challenger.org/clc/scenarios.cfm`

Table 1: E/PO Education Criteria vs. *RXTE* Goals

NASA Evaluation Criteria	*RXTE* E/PO Element
1. Quality, scope, realism appropriateness, including linkage to parent science program	Planetarium show, Challenger Center module and Cosmic Quilt tied to *RXTE* capabilities and discoveries.
2. Continuity: Projects and activities draw from audiences that have demonstrated interest in NASA and connect participants to the next level of engagement.	Teachers visiting Owens choose the program of interest to their students; ASD informal science audiences self-select based on interest; engaging and inspiring activities motivate students to learn more about space science, and potentially choose STEM careers.
3. Partnership/Sustainability: commitment and involvement of team, including science personnel and partners.	Scientists and experienced educators involved. Clear management structure, responsibilities, time-line. Partners have relevant and appropriate experience for proposed effort.
4. Appropriateness of plans for evaluating effectiveness and impact.	Use of existing ASD and Owens Challenger Center, Public Schools evaluation structure.
5. Customer Needs Focus	All activities directly respond to NASA Education Strategy goals. Inclusion in Owens programs, ASD responds to needs and interests of program participants.
6. Content	Program based on *RXTE*'s science and technical activities. All E/PO activities tied to National Science Education Standards.
7. Resource Utilization	Program is realistic in scope. Other planetaria and CLCs can use/distribute.
8. Pipeline	The program/product addresses diverse populations of students.
9. Diversity: contribution to training, involvement and understanding of under-served and/or under-utilized groups in science.	Prince George's County middle school and high school audience directly targeted in activities.

to visiting students and teachers. Currently, *RXTE* scientists are working with the planetarium director to incorporate *RXTE* results directly into a 9th grade planetarium program.

The Astrophysics Science Division (ASD) at NASA's GSFC has an active E/PO program that includes formal and informal education components. Two of these, Family Science Nights at the GSFC Visitor Center, and The Afterschool Universe, are informal, hands-on programs aimed at middle school students and their families with the goals of exciting participants about astronomy and science, and having a positive effect on the participants' attitude towards science. The *RXTE* activity "the Cosmic Quilt" will be incorporated into both of these programs over the next two years.

For "the Cosmic Quilt," students team to research an *RXTE* science topic, then produce a "quilt square" (made from construction paper, yarn and available crafts materials) with a description and illustration of their topic. All teams finally combine their quilt squares into a single quilt demonstrating concepts in high energy astrophysics. An educator workshop based on this activity 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?" Participants choose from a limited set of literary devices in crafting their science descriptions (such as limerick, haiku, acrostic, personification, etc.) thus reinforcing the goals of reading and writing across the curriculum. An agenda and supporting materials for the workshop are available from the RXTE Cosmic Quilt Web page.[2]

The Afterschool Universe is based upon 12 astronomy activities aimed at middle school students to be done on out-of-school time. It was piloted as summer programs in 2006 and 2007, and is now being distributed nationally. As of March 2008, the Cosmic Quilt is included as the summary activity, through which students demonstrate their understanding of topics covered in previous activities in the program.

3.3. Future Plans

Our E/PO goal for the upcoming years is to use *RXTE* results to encourage more young people to pursue careers in science and technology. We will achieve this goal by exposing a broad segment of the local student community to *RXTE* results by incorporating them into existing programs at HBOSC and ASD. We believe our new strategic partnerships with education experts are an excellent use

[2] http://heasarc.gsfc.nasa.gov/docs/xte/outreach/HEG/cq/cosmic_quilt.html

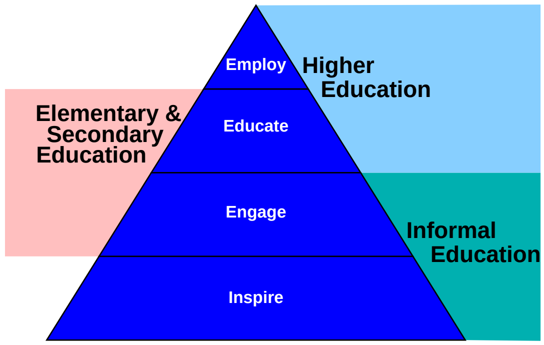

Fig. 1.— NASA's Education Strategic Framework. Our proposed E/PO activities align to the "engage" and "educate" wedges, and will be developed in collaboration with experts in education whose existing programs allow us to maximize the impact of our efforts and the dissemination of our E/PO products.

of existing resources and assure access to our target audience. Our activities correlate directly with the NASA Education Strategic Framework (Fig. 1), specifically the wedges of "engage" and "educate."

Owens Science Center: Planetarium show for ninth graders

The HBOSC is currently redesigning their ninth grade planetarium program for the 2008/09 school year and beyond. It will include concepts relevant to *RXTE* results, such as the electromagnetic spectrum, the Doppler shift, and black holes. The program will align with the Maryland Core Learning Goals 2 (Concepts of Earth/Space Science) and 5 (Concepts of Physics), as well as the Prentice Hall Earth Science text, which covers the electromagnetic spectrum and light exploring the universe. Ideas under consideration include designing the planetarium program around a game-show format. Work is underway to incorporate the animation of the galactic bulge from *RXTE* scans (see the Galactic Bulge Animation page[3]) with the optical projection of the Milky Way by overlaying the *RXTE* animation on the planetarium dome. The captivating graphics and animations from *RXTE* press releases on bursting pulsars and space-time distortions around black holes will also be incorporated. (see Web animation page[4]) for examples). *RXTE* scientists Swank and Boyd are working directly with Planetarium director Patty Seaton to incorporate these *RXTE* results into the planetarium show.

The planetarium show visit involves pre-visit and post-visit activities for students. Existing *RXTE* E/PO activities will be used with the *RXTE* program. Students will complete the Frequency, Wavelength and Energy activity, a puzzle-board matching activity, before arriving at the HBOSC, to become familiar with the concept of the EM spectrum and why astronomers learn more when they compliment visible light with the other parts of the spectrum. After the planetarium show, the post-activity will be a Build Your Own Black Hole Model which uses the common household items of yarn, a paper plate and a cup to describe the somewhat esoteric concepts of accretion disks and mass transfer onto a compact object. Both activities have been classroom tested as part of the *RXTE* E/PO program, and are available on the Web[5]. Incorporating them into the upcoming planetarium program assures that they will reach far more students than they would otherwise, and is an example of how this partnership benefits both sides: RXTE activities will enjoy a larger distribution at no cost to *RXTE*, while HBOSC can incorporate these new activities into their program at no cost to them.

Owens Science Center: Challenger Learning Center Magnetar Anomaly Module

The Challenger Learning Center at HBOSC is a popular field trip destination for students. Each year, several different modules are offered to students at various grade levels. For 2008/09, currently in planning, the Return to the Moon module is expected to be very popular. Both this module, and the Encounter Earth module have been identified as ones in which *RXTE* results can be incorporated. In all CLC scenarios, two student teams (one in mission control and one on an ISS mock-up) work together to solve a mystery such as a malfunctioning satellite in low-Earth orbit.

An educational *RXTE* spacecraft "anomaly" is being developed for the CLC modules. 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 super-strong magnetic field, and a key target for *RXTE*. Radiation from the giant flare came through the side of *RXTE* and saturated the Swift/BAT event counter; it bounced off the moon and lit up the Earth's atmosphere. It ionized the 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.

We will incorporate this event into CLC modules as follows. 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

[3] `http://lheawww.gsfc.nasa.gov/users/craigm/bulge-spr-2003.gif`

[4] http://rxte.gsfc.nasa.gov/docs/xte/learning_center/discover_0696.html

[5] `http://heasarc.gsfc.nasa.gov/docs/xte/outreach/HEG/groovie.html`

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 CLC programs, and can be tied to Core Learning Goals in both Earth science and physics. *RXTE* scientists Swank and Boyd are working directly with the CLC team led by Terry Womack (CLC Lead Flight Director) at HBOSC to incorporate a magnetar giant flare anomaly, based on the actual signals detected during the 2004 giant flare of SGR 1806-20, into the existing learning modules.

Expanding into additional ASD informal E/PO programs

The ASD has a successful program of Family Science Nights that attract capacity crowds to the NASA/GSFC visitor center on a monthly basis. We plan to incorporate the Cosmic Quilt activity into upcoming Family Science Nights. Since the Cosmic Quilt is a self-directed, team oriented research effort that can easily be tied to art and language arts, it is an ideal family activity, and can be incorporated into Family Science Night with minimal modification.

The ASD E/PO group has additional ongoing efforts such as the Blueshift podcast, and a suite of educator workshops and learning experiences. We will work to incorporate existing *RXTE* E/PO activities and new results into these efforts as well, in order to increase our leverage at minimal cost, and take advantage of the full-time E/PO staff co-located with the *RXTE* science staff.

Maximizing Distribution and Impact

We plan to continue to leverage off the existing *RXTE* classroom activities and partnerships with ASD E/PO the HBOSC for our future plans. We have described our recent efforts to incorporate both the planetarium show and the CLC anomaly into the 2008/2009 school year programs offered by HBOSC. During the early part of the period covered by the current proposal, we will finalize these efforts, and evaluate their effectiveness using existing evaluation techniques employed by HBOSC. Depending on the outcome of these evaluations, we will adjust the programs to improve their impact and accessibility. Further, we will explore avenues for wider dissemination, by contacting other planetariums through existing networks such as the Mid Atlantic Planetarium Society (MAPS), and leveraging off the existing national network of CLCs.

By continuing our partnership with the experienced educator staff and facilities that ASD E/PO and HBOSC offer, incorporating *RXTE* science themes into the daily student activities, our project directly aligns with NASA's major E/PO goals, namely

- Target students at all levels, especially in underserved/under-represented communities
- Attract and retain students in STEM careers.
- Through strategic partnerships, increase American's science and technical literacy.

These partnerships are sustainable due to the geographic proximity of GSFC and HBOSC and the high level of motivation of the participants at both institutions.

By incorporating *RXTE* science themes into well-attended Family Science Nights, planetarium shows and CLC modules, *RXTE* will make significant impacts on educating students, educators and families about the unique and exciting science done by astrophysicists. With involvement of several key *RXTE* science team members, a clear management structure, and our ability to leverage off successful and popular existing programs to maximize distribution, program evaluation and impact, we anticipate a high probability of success. Both partnerships ensure that our products will reach our target audiences by incorporating *RXTE* science results and education products into existing programs with a wide audience. We anticipate that these programs will continue to be impacted by our curriculum contributions well beyond the specific funding period covered here. In addition, each partnership will perform the program evaluations at no cost to *RXTE*, resulting in a net savings to our E/PO budget.

E/PO Team, Management and Budget.

RXTE PI Swank and *RXTE* scientist Boyd lead the E/PO efforts. Each has been involved in LHEA E/PO since 1995. Boyd will direct and coordinate the *RXTE*/EPO efforts of all partners under the direct supervision of Swank, including the alignment of *RXTE* E/PO activities to NSES standards. Our partnership with HBOSC, including scope of the planned programs, a general development and implementation time line, evaluation responsibilities and methods has been documented in a Partnership Letter, which is available upon request. The budget includes coverage of the 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 at GSFC each summer. Our budget also includes costs associated with production of the software to support the modification to the CLC module, and some travel costs to local and national educator meetings to present our results. The E/PO budget request is described in the budget appendix.

4. Appendix: Acronyms

AAS — American Astronomical Society

ADAF — Advection Dominated Accretion Flow

ADS — Astrophysics Data System, Harvard, MA

AGILE — Astro-rivelatore Gamma a Immagini L'Eggero

AGN — Active Galactic Nuclei

AMP — Accreting Millisecond Pulsar

AO — Announcement of Opportunity

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

ASD — Astrophysics Science Division (of GSFC)

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

ATCA — Australia Telescope Compact Array

AXP — Anomalous X-ray Pulsar

BAT — Burst Alert Telescope (*Swift* instrument)

BH — Black Hole

BHXRB — Black Hole X-ray Binary

CGRO — Compton Gamma-Ray Observatory

CLC — Challenger Learning Centers

COBE — Cosmic Background Explorer

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

EDS — Experiment Data System

EGRET — Energetic Gamma Ray Experiment Telescope (CGRO instrument)

EM — Electromagnetic

EOS — Equation of State

EPO — Education and Public Outreach

EVLA — Expanded Very Large Array

FAQ — Frequently Asked Questions

FITS — Flexible Image Transport System

FOT — Flight Operations Team

FTE — Full Time Equivalent

FUSE — Far Ultraviolet Spectroscopic Explorer

FWHM — Full Width at Half Maximum

FY — Fiscal Year

GCN — Gamma-ray bursts Coordinates Network

GLAST — Gamma-ray Large Area Space Telescope

GO — Guest Observer

GOF — Guest Observer Facility

GR — General Relativity

GRB — Gamma-Ray Burst

GRO — (Compton) Gamma-Ray Observatory

GRS — *Granat* Source

GSFC — Goddard Space Flight Center, Greenbelt, MD

GW — Gravitational Wave

GX — Galactic X-ray source

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

HEASARC — High Energy Astrophysics Science Archive Research Center

HEGRA — High Energy Gamma Ray Astronomy (experiment on La Palma)

HESS — High Energy Stereoscopic System (TeV telescope)

HETE — The High Energy Transient Explorer

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

HFQPO — High Frequency Quasiperiodic Oscillation

HMXB — High Mass X-ray Binary

HST — Hubble Space Telescope

IAUC — International Astronomical Union Circular

IGR — *INTEGRAL* Gamma-Ray source

IMBH — Intermediate Mass Black Hole

INTEGRAL — INTErnational Gamma-Ray Astrophysics Laboratory

ISCO — Innermost Stable Circular Orbit

ISS — International Space Station

IT — Instrument Team

IXAE — India X-ray Astronomy Experiment

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

L_{Edd} — Eddington Luminosity

LAT — Large Area Telescope (on *GLAST*)

LFQPO — Low Frequency Quasi-periodic Oscillation

LHEA — Laboratory for High Energy Astrophysics (now ASD)

LIGO — Laser Interferometer Gravitational wave Observatory

LMC — Large Magellanic Cloud

LMXB — Low Mass X-ray Binary

$\dot{M}$ — Mass accretion rate

mCrab — 10^{-3} Crab Flux Units

MAGIC — Major Atmospheric Gamma Imaging Cherenkov (telescope on La Palma)

MAPS — Mid-Atlantic Planetarium Society

MCG — Morphological Catalog of Galaxies

MIT — Massachusetts Institute of Technology

MJD — Modified Julian Date

MOC — Mission Operations Center

NASA — National Aeronautics and Space Administration

NOA — New Obligation Authority

NGC — New General Catalog

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 — Pulsating Source of Radio (Pulsar)
PWN — Pulsar Wind Nebula
QPO — Quasiperiodic Oscillation
ROSAT — ROentgen SATellite (X-ray observatory)
RXTE — Rossi X-ray Timing Explorer
SAX — BeppoSAX - Satellite per Astronomia X
SED — Spectral Energy Distribution
SGR — Soft Gamma-ray Repeater
SMARTS — Small and Moderate Aperture Research Telescope System
SOF — Science Operations Facility
SSA — S-band Single Access (TDRSS data mode)
SSC — Scanning Shadow Camera (ASM Detector)
STEM — Science, Technology, Engineering and Mathematics
TB — Terabyte
TDRSS — Tracking and Data Relay Satellite System
TOO — Target of Opportunity
UCSD — University of California at San Diego
ULX — Ultra-luminous X-ray source
UVOT — UltraViolet and Optical Telescope (*Swift* instrument)
VERITAS — Very Energetic Radiation Imaging Telescope Array System (Gamma-ray)
VHS — Very High State (black hole state)
VLA — Very Large Array (radio telescope)
VLBI — Very Long Baseline Interferometry
XMM — XMM-Newton - X-ray Observatory
XRB — X-ray Binary
XRT — X-ray Telescope (*Swift* instrument)
XTE — (Rossi) X-ray Timing Explorer