Presentation to the 2002 Senior Review of Mission Operations and Data Analysis

Frederick Lamb
University of Illinois
Chairman, RXTE Users Group

The Rossi X-Ray Timing Explorer
RXTE addresses many fundamental questions, including –

- Gravitational physics in the strong-field regime
- Physics of ultradense matter and ultrastrong magnetic fields
- Mass inflows and outflows in accretion-powered systems

RXTE has capabilities unmatched by any other current or planned mission –

- Large collecting area and low background
- Broad (2-200 keV) energy coverage; will provide the only coverage above 10 keV
- Provides timing from 1 µs to 10 Ms
- Continuous monitoring of the X-ray sky
- Rapid response (15 min) when necessary for new sources and changes in known sources
- Highly flexible (even “last-minute”) scheduling, excellent coverage of the night sky
- Uniquely high telemetry rates
- Sophisticated onboard data processing
• RXTE has many unique capabilities

• These capabilities are continuing to yield major discoveries that address fundamental questions

• Follow-up observations are critical to capitalize on these discoveries and to resolve outstanding questions

• Coordinated observations with Chandra, XMM-Newton, INTEGRAL, and the new TeV observatories will increase greatly the scientific yields of all these efforts
Some Major Scientific Discoveries and Accomplishments Since June 2000

- Sidebands on kilohertz QPOs in neutron stars
- Pairs of stable high-frequency QPOs in black holes
- Firmer evidence for black holes with significant spin
- Evidence for 3:2 frequency relation of black hole QPOs
- Superbursts from neutron stars
- Two more millisecond accretion-powered pulsars (making 3 total)
- Strong correlation of X-ray and TeV flaring in blazars
- Evidence for SGR-like bursts from an anomalous X-ray pulsar
- Large glitches in the spin of the fastest rotation-powered pulsar
- Discovery of additional pulsars with cyclotron resonance lines
Some Major Scientific Discoveries and Accomplishments Since June 2000

Events Last Month (May 2002)

• Discovery of a third millisecond accretion-powered pulsar (XTE J0929–314, $\nu_{\text{spin}} = 185$ Hz)

• Discovery of a new black hole candidate (XTE J1908+094)

• Simultaneous very strong X-ray and TeV flare in 1ES 1959+650

• Strong X-ray flare in Eta Carinae

• X-ray and radio observations of unusually strong optical flaring of the black hole SAX J1819.3–2525 = V4641 Sgr

• Largest outburst of black hole candidate GX 339–4 since 1988, revealing microquasar behavior (Belloni et al. 2002)

(10 RXTE IAU Circulars in May)
RXTE Publications

- The yearly rate of RXTE-related refereed publications has increased by a factor \( \sim 10 \) from 1996 to 2001
- More than 730 refereed papers and 430 IAU Circulars have now been published
- More than 2,000 RXTE-related papers have been published to date (\( \sim 1,000 \) since the 2000 Senior Review)

Requested Budget for Guest Observations

- The 1998 Senior Review recommended that $1,000 k be transferred from the RXTE budget to the ADP budget to support RXTE and other observations via this program
- For AO-8 we are requesting an average of $10 k for successful RXTE observing proposals, which amounts to $700k per year
Productivity and Guest Observing Budget

Differences in AO-7 Operation Mode

• Less reluctance to interrupt non-TOO's (60% more TOO observing time during the first 3 months of AO-7 than in AO-6)

• Greater confidence in the value of short observations and skill at planning are making possible more extensive monitoring programs

• Chandra and XMM-Newton coordinated observations are more common (~20% of the total)

• Chandra cycle 5 TACs will be able to allocate 500 ksec of RXTE time

Justification of the Requested Budget

• The requested yearly budget is only ~ 40% of the average budget over the first 5 years of the mission

• The requested budget has (very modest) support for GOs

• Support for a postdoc to maintain the ASM calibration

• 50% of a programmer to revise the software to protect the unique scheduling capability of RXTE
Physics of Nuclear Burning and Neutron Star Dynamics from X-ray Burst Oscillations

Ignition begins at a single point, creating a bright spot.

As the bright spot rotates with the star, we see X-ray oscillations.

The oscillation frequency varies systematically during a burst.

(Strohmayer et al. 1996, 1998)

Implications for physics of neutron stars and nuclear burning –

- The oscillations imply spin rates ~ 250–350 Hz, as expected from magnetic equilibrium.
- The oscillations in burst tails require confinement, possibly by the magnetic field.
- Oscillation amplitudes and waveforms constrain neutron star compactness (M/R).
Discovery of “Superbursts” With Nearly Stable Periodic Oscillations

- Duration and total X-ray energy is ~ 1,000 times that of Type I X-ray bursts
- So far seen in five neutron stars. ASM saw 2 superbursts from 4U1636–53.
- Nuclear energy release occurs at much greater depths than in Type I bursts
Kilohertz Quasi-Periodic X-ray Brightness Oscillations in Accreting Neutron Stars

Key kilohertz QPO properties –

- Observed in > 20 neutron stars
- High coherence \( (\nu/\delta\nu \sim 30–200) \)
- Two principal oscillations
- Their frequency separation \( \Delta\nu \) remains fairly constant, about equal to the neutron star spin frequency
- The frequencies of the kHz QPOs can vary by several hundred Hz within ~ 100–1,000 seconds

X-ray flux power density spectrum observed by Wijnands et al. (1998)
Constraints on Properties of Dense Matter
Evidence for General Relativistic Effects

Left: Comparison of upper kilohertz QPO frequency with NS EOS
Evidence for the Predicted ISCO Signature Observed in 4U1820–30

Left: QPO frequencies vs. countrate during 1996–97 (Zang et al. 1998)
Right: QPO frequencies vs. countrate during 1998 (Kaaret et al. 1999)
Discovery of Three Accretion-Powered Millisecond Pulsars in Ultracompact Systems

\[ \nu_{\text{spin}} = 401 \, \text{Hz}, \quad f(\text{M}) = 3.9 \times 10^{-5} \, \text{M}_\odot \]

\[ \nu_{\text{spin}} = 435 \, \text{Hz}, \quad f(\text{M}) = 1.3 \times 10^{-6} \, \text{M}_\odot \]

\[ \nu_{\text{spin}} = 185 \, \text{Hz}, \quad f(\text{M}) = 2.7 \times 10^{-7} \, \text{M}_\odot \]
Discovery of Pairs of High-Frequency QPOs in Galactic Black-Hole Candidates

Stable frequencies, with evidence for 3:2 frequency ratios

QPOs are strongest at photon energies greater than 10 keV

Amplitude ratios change systematically with X-ray spectral state
Coordinated RXTE & Chandra Observations of Fe Lines in Galactic Black-Hole Candidates

- RXTE/PCA and Chandra/HETGS line spectra agree well
- The Fe line is broad with a very narrow central component
- The reflection continuum is very clear in the RXTE spectrum

Miller et al. (2002)
Discovery of Strong Positive Correlation Between X-ray and TeV Flaring

Mk 501 (Krawczynski et al. 2002)

Further coordinated observations with TeV observatories are a major focus of the observing program in the current AO-7 observing cycle.
Health of the Proportional Counter Array

PCU performance has been stable over the past 18 months

On average, 3 PCUs are in use at any one time

All 5 PCUs are used when needed