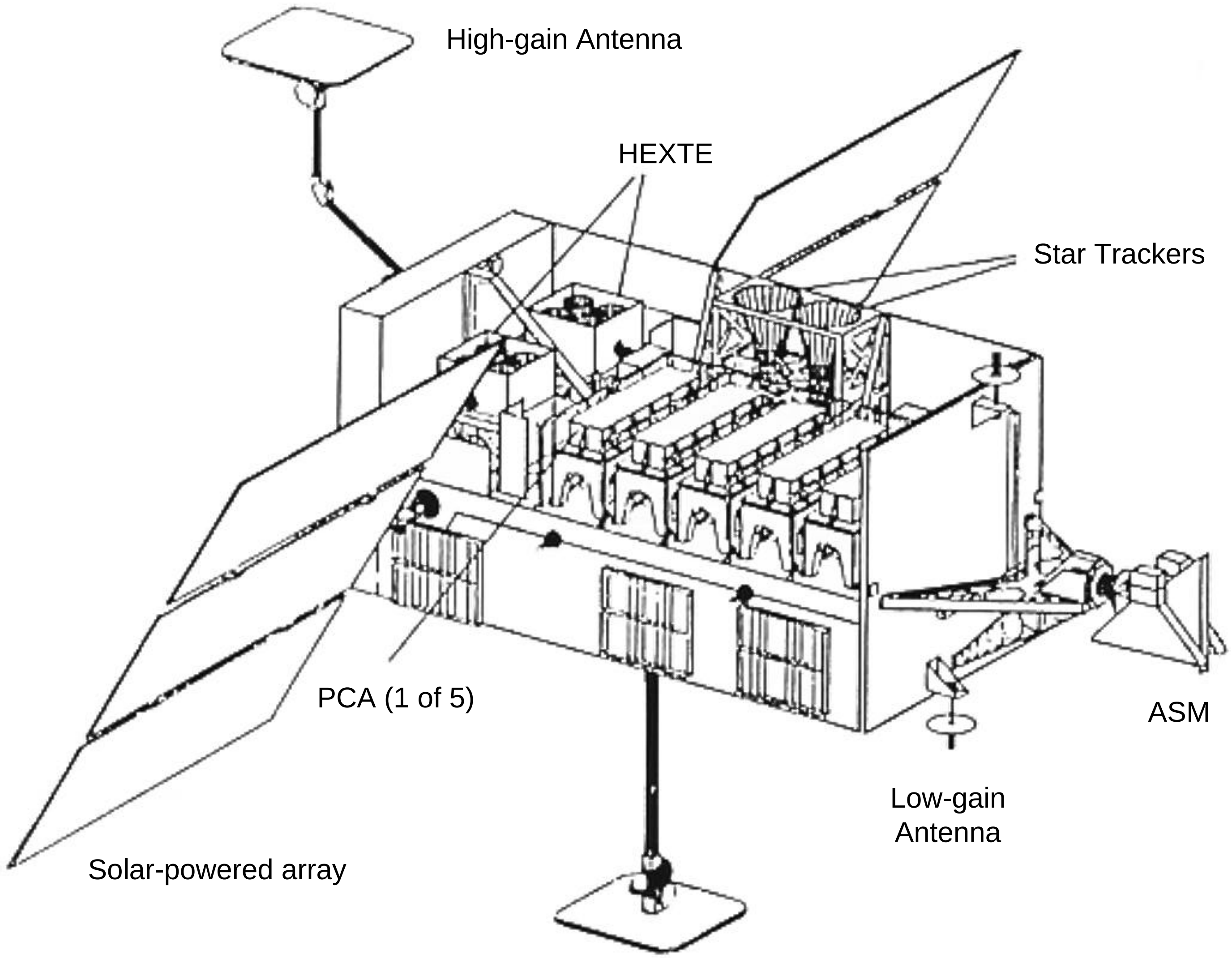
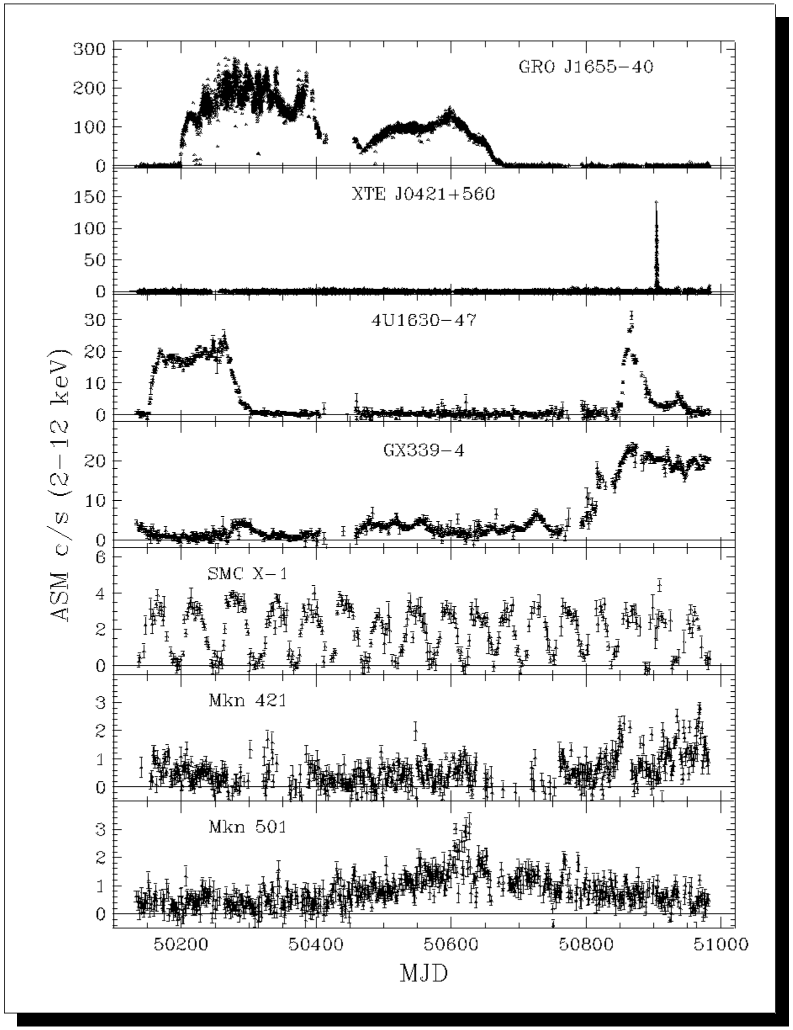
The Rossi X-ray Timing Explorer



RXTE Satellite and Instrumentation



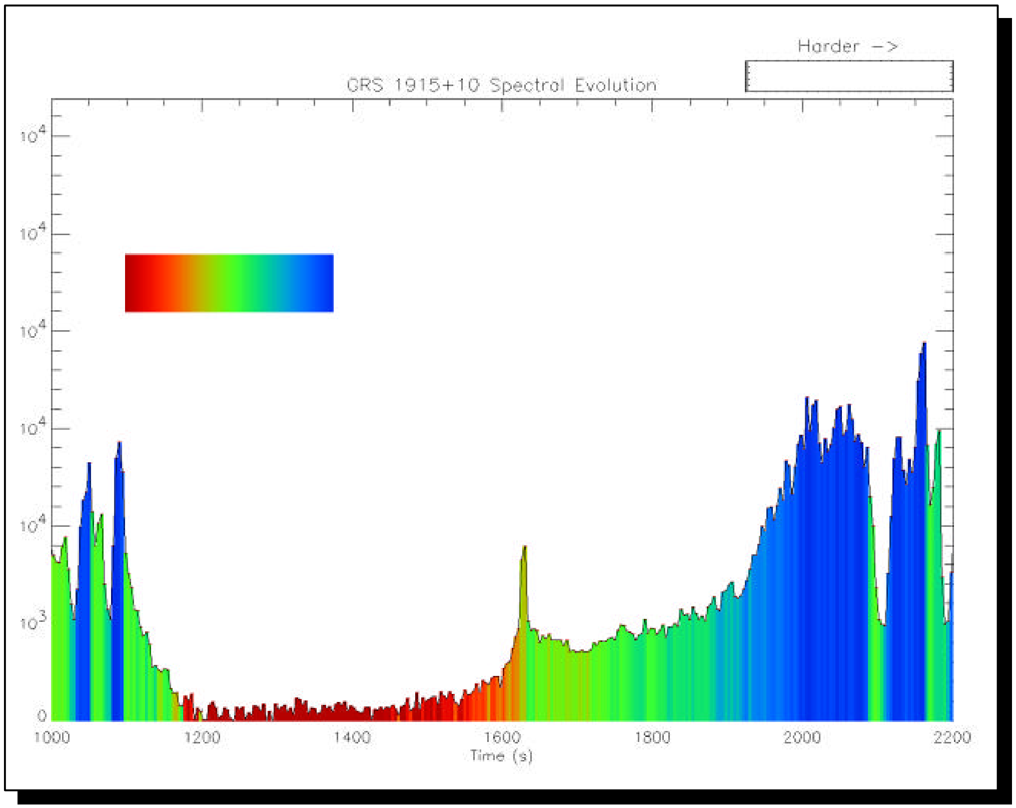
I. All Sky Monitor (ASM)

- Three rotating, scanning shadow cameras
- 30 cm^2 per camera, Xenon position sensitive proportional counters
- Monitor 80% of sky to 10 mCrab in one day, 30 mCrab in one hour
- 2 - 10 keV band
- Current catalog contains 280 sources
- Rapid alert capability for new transients, known transients, and detailed source states

RXTE Satellite and Instrumentation

II. Co-aligned, Narrow Field Instruments

Proportional Counter Array (PCA)

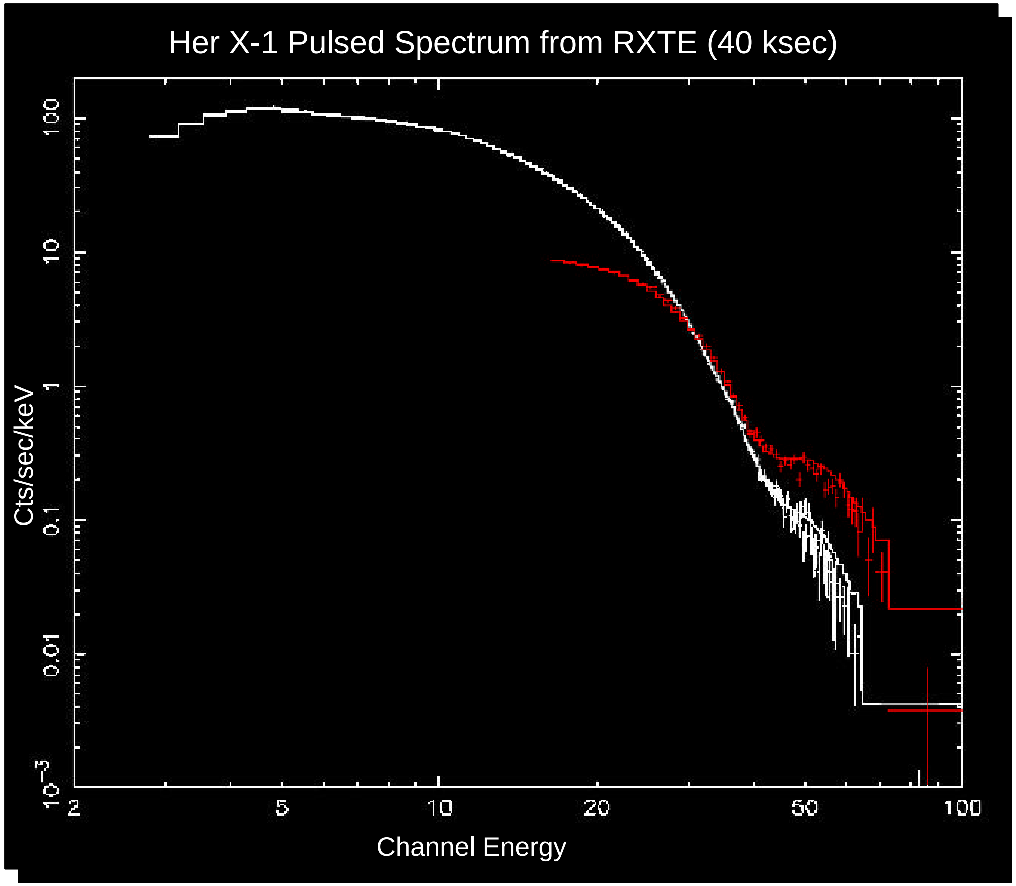


- 7000 cm^2 Xenon-filled proportional counters
  - 5 identical units
- 2 -60 keV energy range
- 1^o field of view (FWHM)
- High throughput, microsecond time resolution
- 18% energy resolution at 6 keV
- Efficient background rejection

RXTE Satellite and Instrumentation

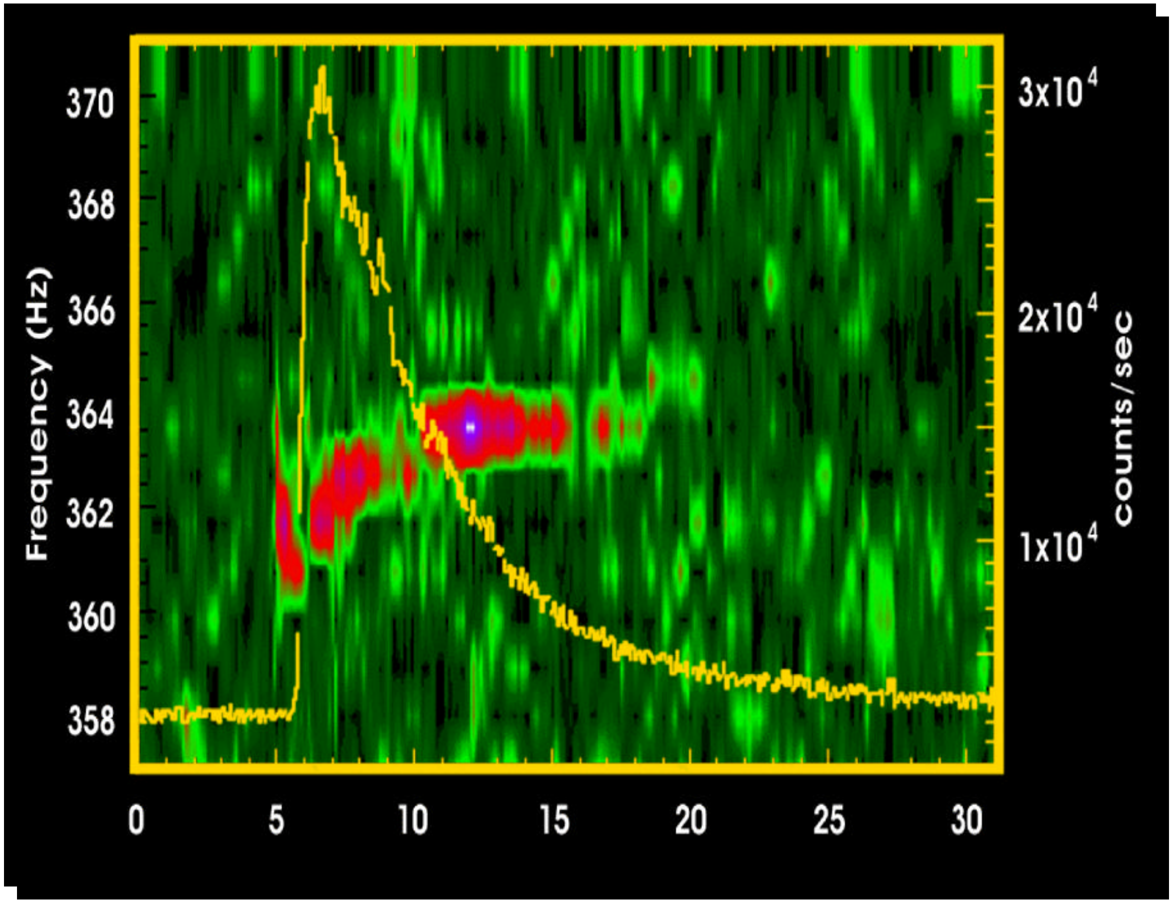
II. Co-aligned, Narrow Field Instruments

High Energy Timing Experiment (HEXTE)



- 1600 cm^2 phoswhich scintillators
  - 2 clusters of 4 detectors
- 15 - 250 keV energy range
- 1^o field of view (FWHM)
- On-/Off-source rocking for background monitoring
- 18% energy resolution at 60 keV

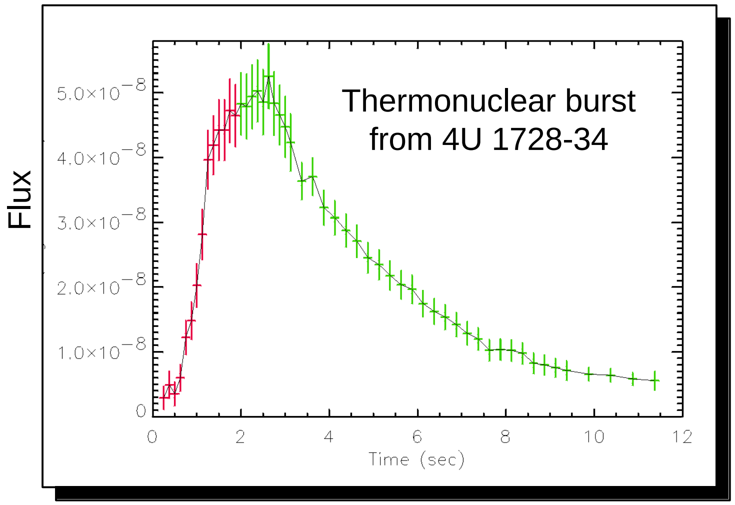
Nuclear Powered X-ray Pulsars
Probing the Surface Layers of a Neutron Star

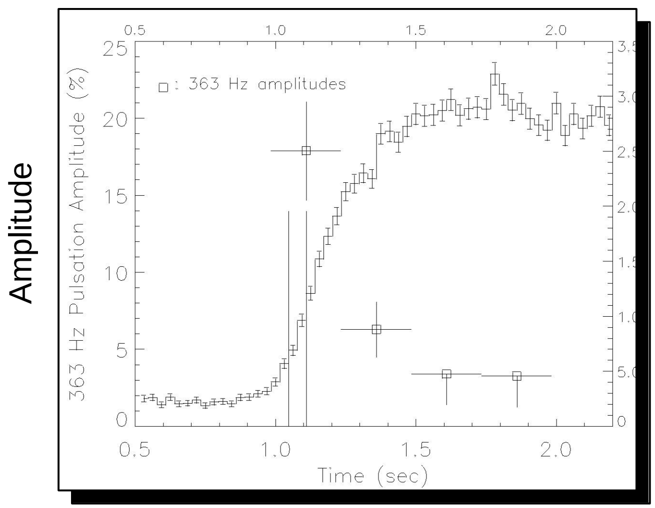


Thermonuclear flash expands neutron star surface layers by ~ 30 meters

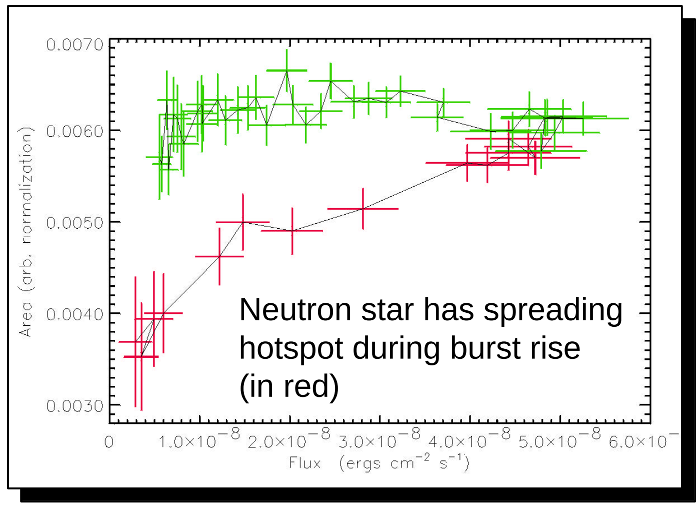
- Expanding surface layers have higher moment of inertia and spin slower due to conservation of angular momentum
- Surface layers spin up again as surface cools and settles

Nuclear Powered X-ray Pulsars
Origin of Oscillations at the Spin Frequency

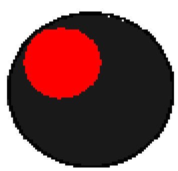




- X-ray spectroscopy indicates that at onset of bursts only a portion of the neutron star surface, a hot-spot, is emitting X-rays
- The hot-spot flashes into and out of view as the neutron star rotates, causing the X-ray brightness to oscillate at the spin frequency

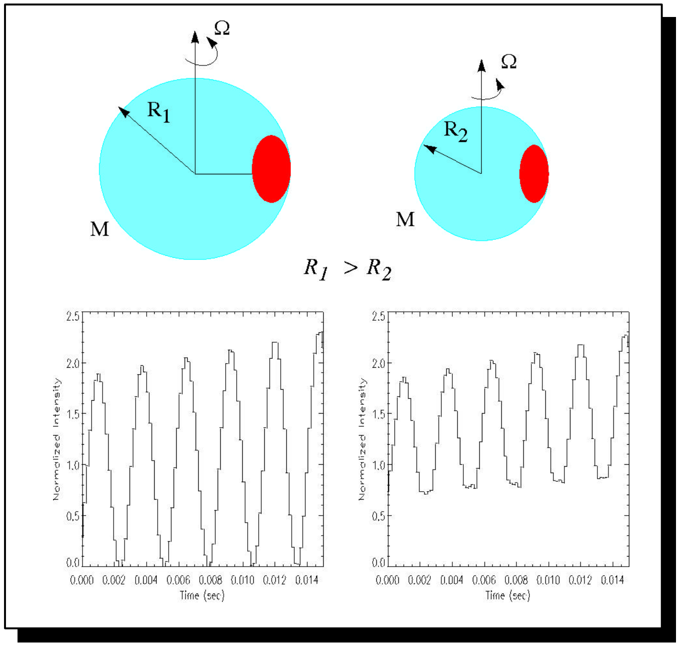


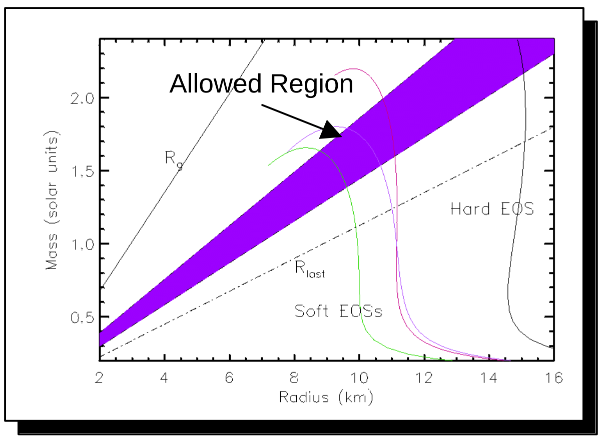
- The X-ray oscillation amplitude near burst onset can exceed 50%, which provides powerful constraints



Neutron star with
hotspot (red)

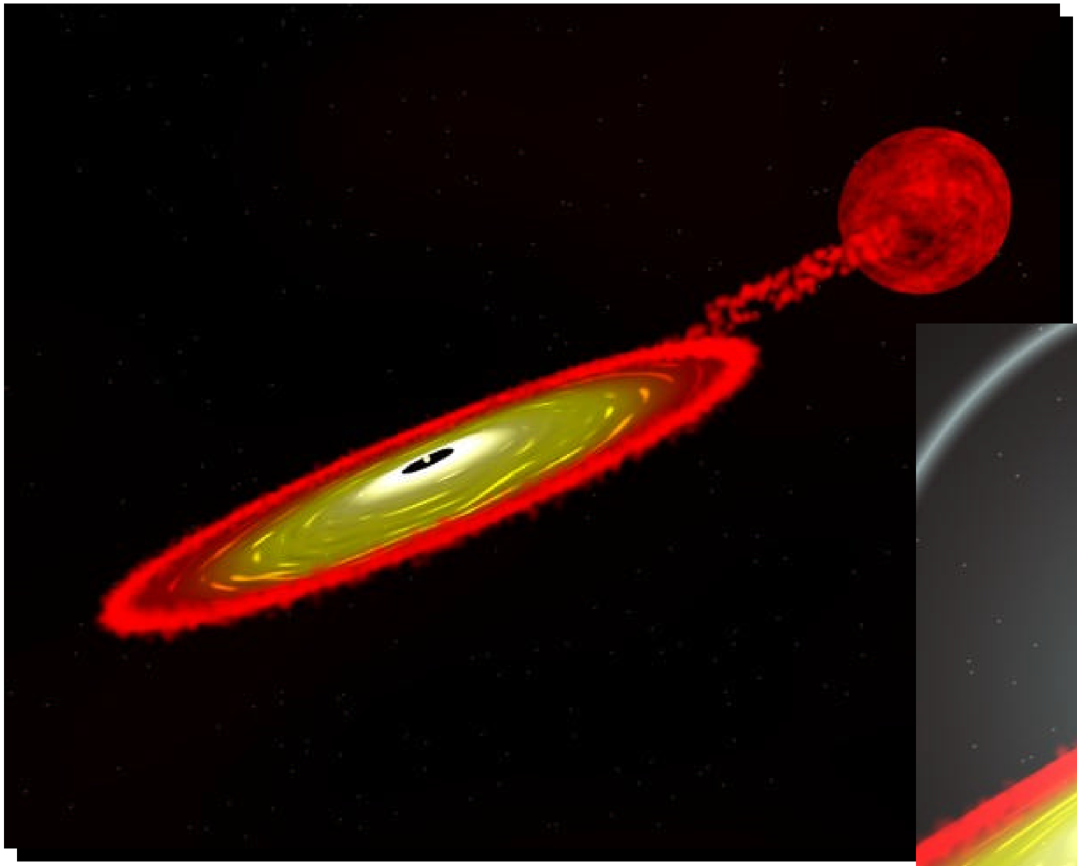
Nuclear Powered X-ray Pulsars
Constraining the Neutron Star Equation of State

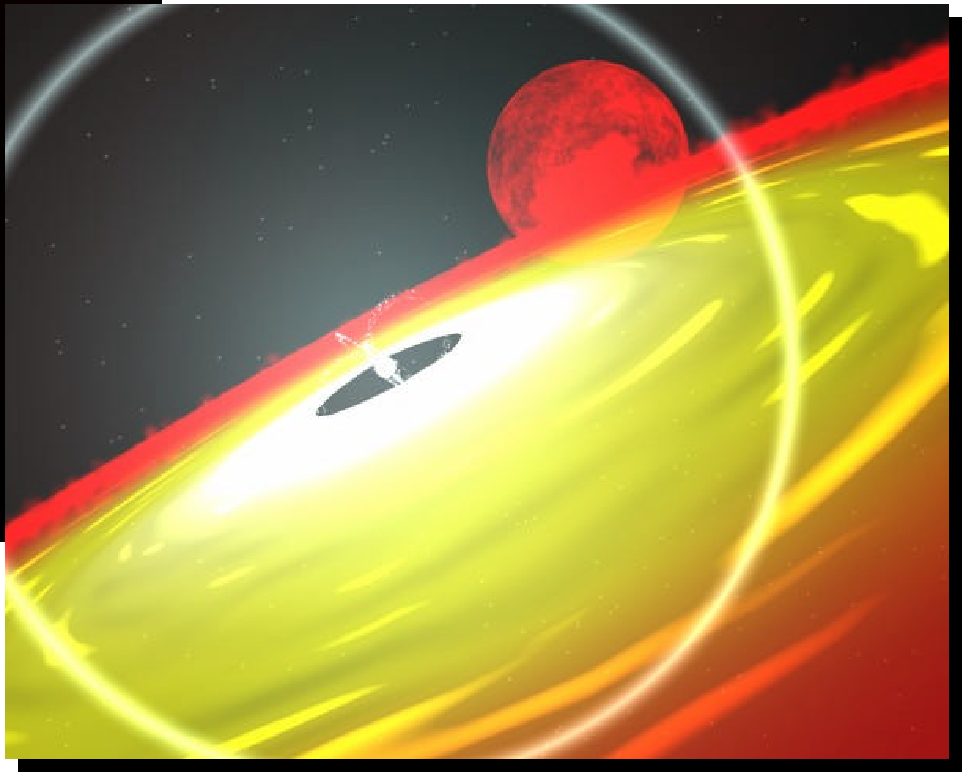




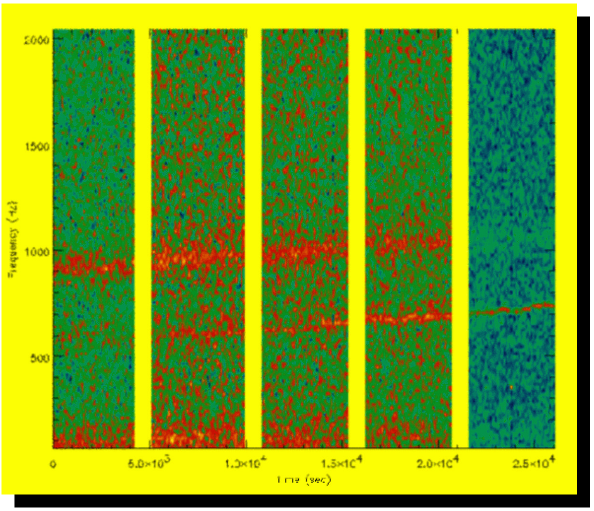
- General Relativity predicts deflection of light by stars. The magnitude of deflection depends on the ratio of stellar mass to radius, GM/c^2R (the "compactness")
  - Neutron star compactness is ~ 0.25
  - The Sun's compactness is ~ 2×10^{-11}
- More compact stars cause greater deflection, weaker brightness oscillations from hot spots
  - Neutron star deflection > 30 degrees
  - Solar deflection = 5×10^{-4}
- Observed oscillation amplitudes place an upper limit on GM/c^2R ~ 0.27. (The neutron star cannot be so compact as to be unable to produce the observed amplitude.)
- Large stars produce overtones that are not seen

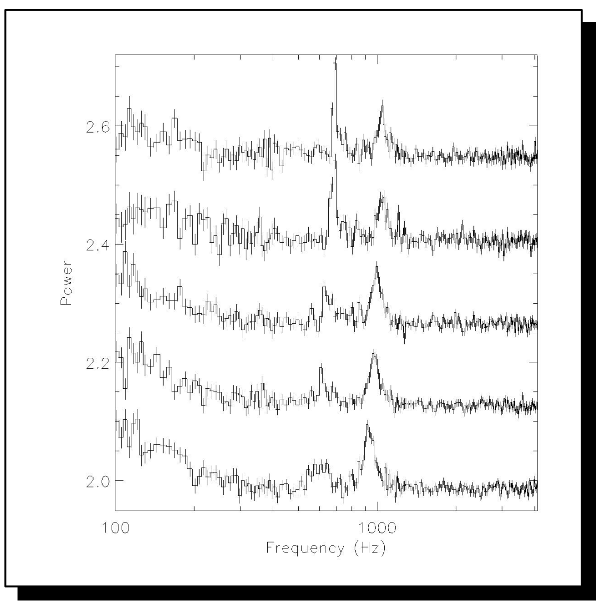
A Millisecond X-ray Pulsar





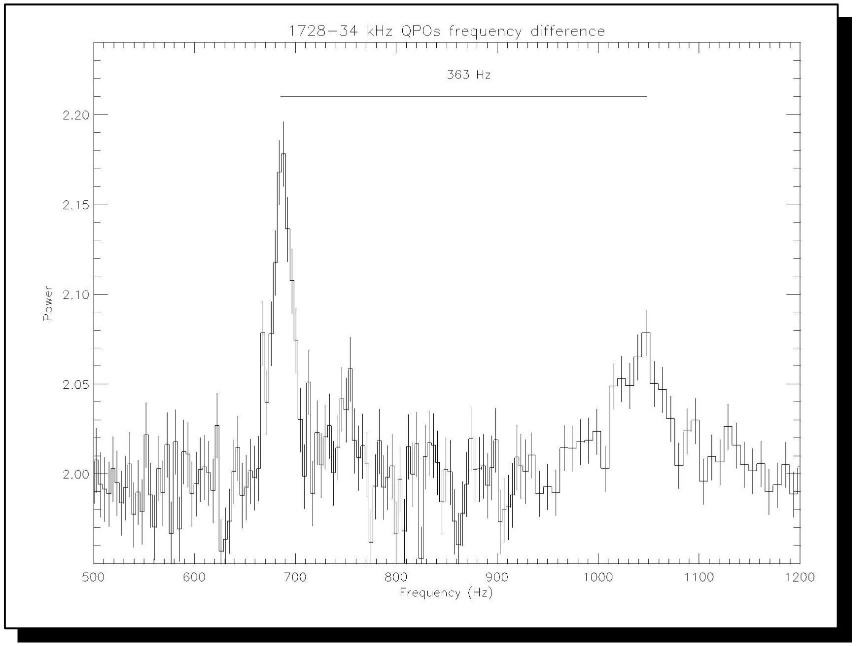
Millisecond Oscillations from Accreting Neutron Stars: Kilohertz QPOs



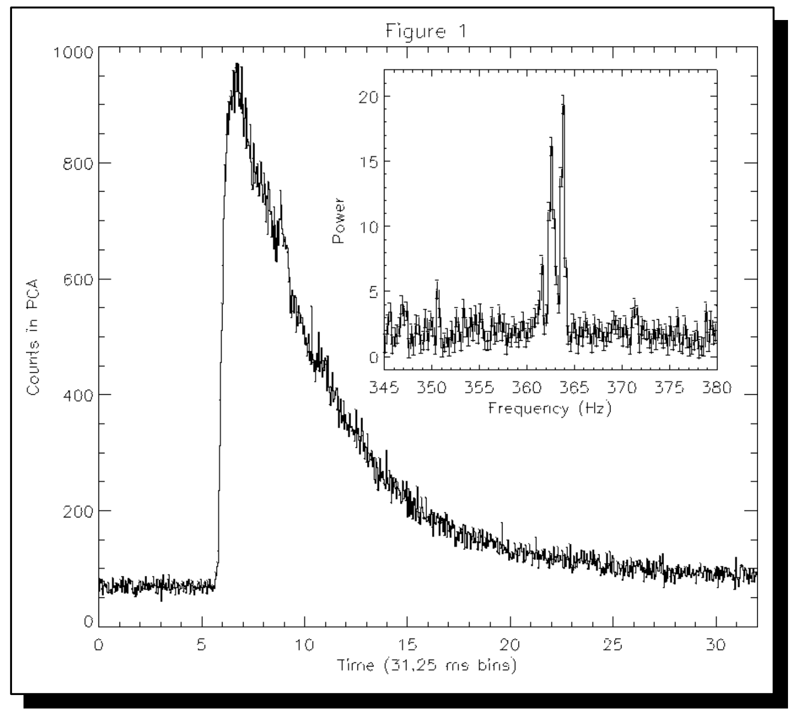


- Discovered by Strohmayer et al. (1996) and van der Klis et al. (1996) in the NS-LMXBs 4U 1728-34 and Sco X-1
- Seen in a total of 16 LMXB systems to date
- Oscillation frequencies from 500–1200 Hz
- Oscillation amplitudes (2–20 keV) range from < 1% to 10%, amplitudes increasing with photon energy
- Oscillations are quasi-periodic (QPO), with coherence or 'Q' values as high as 200
- The oscillation frequency increases systematically with accretion rate

Millisecond Oscillations from Accreting Neutron Stars: Kilohertz QPO

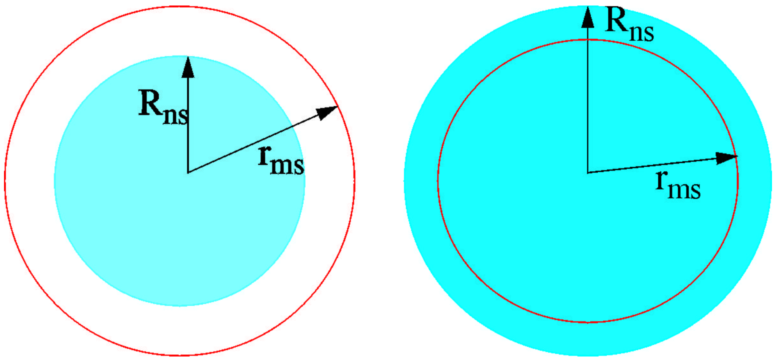


- Pairs of QPO peaks with nearly constant frequency separation are seen in many sources.
- Frequency separation linked to spin frequency observed during thermonuclear X-ray burster

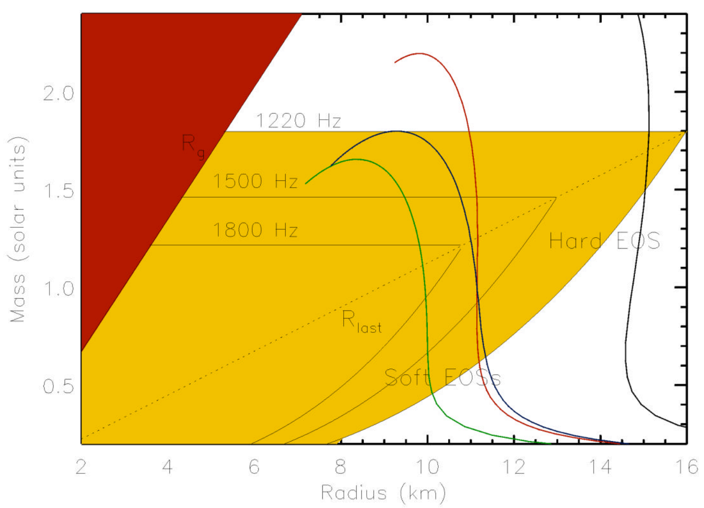


- Millisecond oscillations probe physics within a few kilometers of the neutron star surface, and gravity in the strong-field limit
- RXTE is the only current or planned satellite that can make such measurements

Millisecond Oscillations from Accreting Neutron Stars: Constraining the Neutron Star EOS

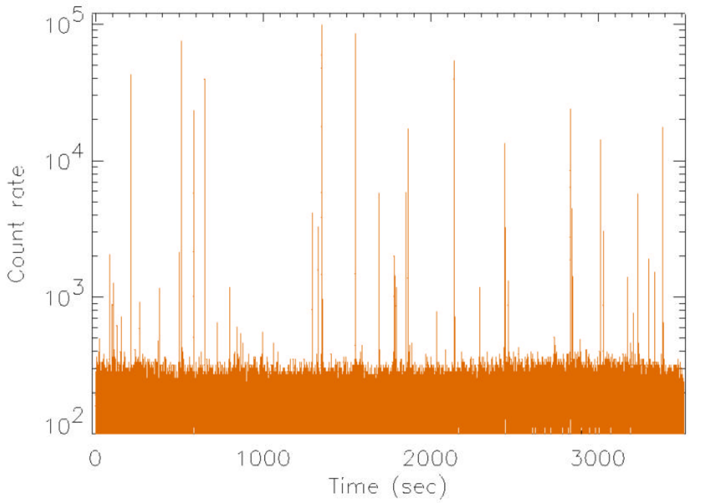


NS M - R constraints from kHz QPO

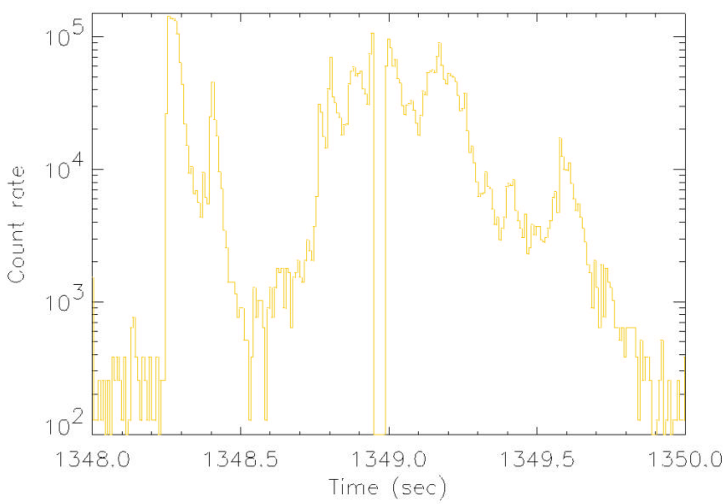


- General Relativity predicts that there are no stable circular orbits with radii less than the marginally stable radius, R_{ms}
- If QPO frequencies are orbital, they should reach an upper limit at R_{ms} or else at the stellar surface
- R_{ms} depends only on neutron star mass & spin
- Uncertainty in neutron star EOS is such that star could be larger or smaller than R_{ms}
- Upper limit to frequency at either R_{ms} or the stellar radius => yields constraint region in the M - R plane
- The highest observed QPO frequency to date is 1,220 Hz

The Soft Gamma Repeater SGR 1806-20: An Outburst Observed with RXTE



Bursts from SGR 1806-20

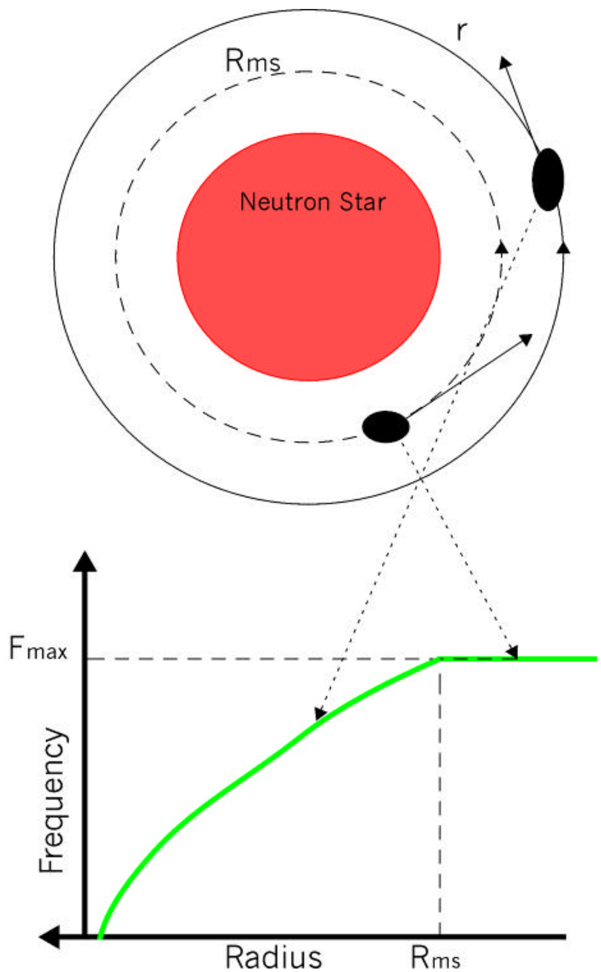


8 ms resolution of a burst from SGR 1806-20

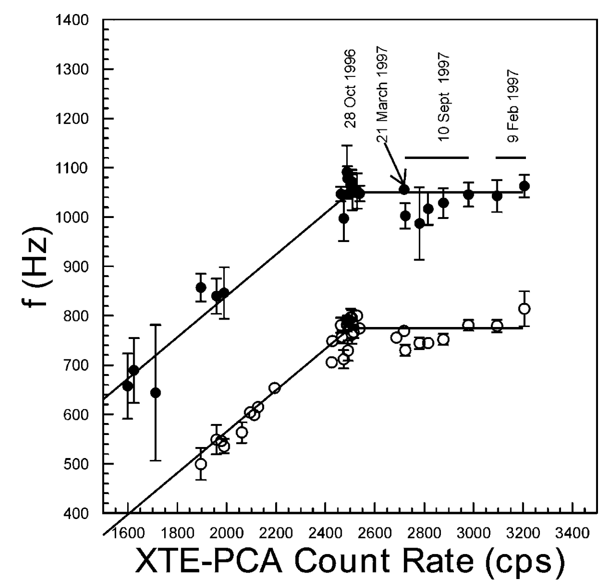
- First bursts detected with BATSE, SGR 1806-20, becomes burst active in November of 1996
- PCA detects hundreds of weak bursts, many of which previous instruments could not detect
- Some bursts arrive in a never-seen-before "rapid-fire" bunching mode
- PCA spectra provide first evidence for spectral evolution within bursts and from burst to burst
- HEXTE detects bursts above 100 keV
- Spectra show cut-off below 6 keV, which indicates a super-critical magnetic field

Tests of Strong-field General Relativity: Evidence for a Last Stable Circular Orbit

General Relativity predicts unstable circular orbits within the marginally stable radius, $R_{ms} = 6GM/c^2$

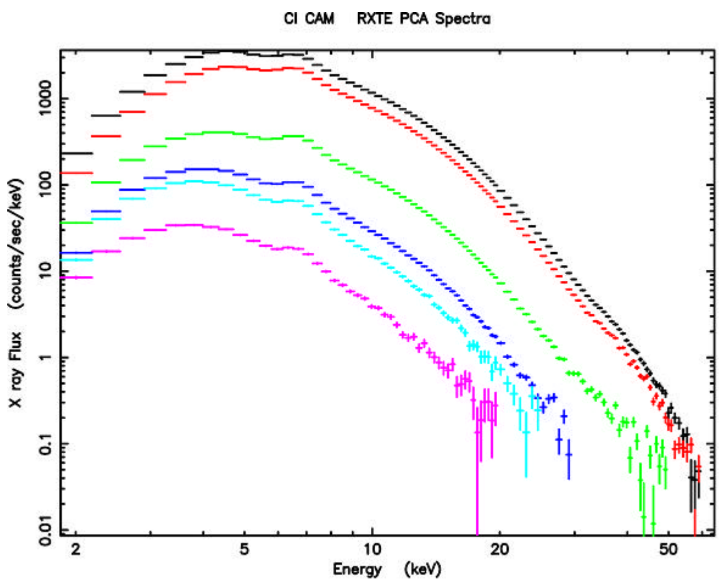


- Highest kilohertz QPO frequency may represent the Kepler orbital frequency near the neutron star surface (Miller, Lamb, & Psaltis 1998)
- Highest observed QPO frequencies in many sources appear to have an upper limit ~ 1,200 Hz (Zhang, Strohmayer, & Swank 1997)
- kHz QPO frequencies in 4U 1820-30 reach a plateau, similar to what would be expected upon reaching the marginally stable orbit.
- If correct, suggests M ~ 2.2 M⊙ for 4U 1820-30, requires stiff EOS to achieve this mass



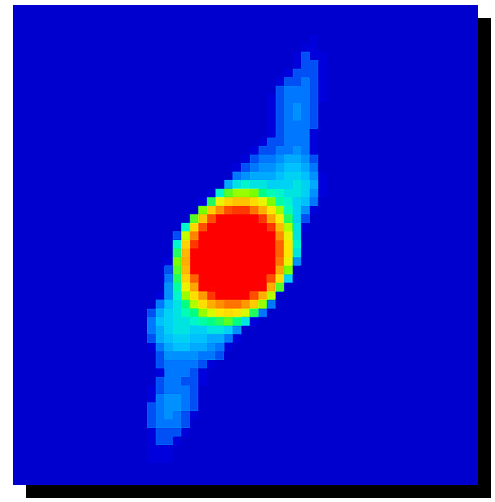
RXTE

RXTE Discovery of Mysterious Galactic Jet Source: CI Cam

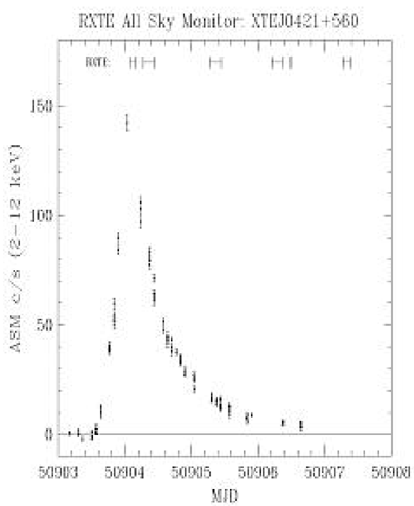


- RXTE/ASM detects fast rising transient on March 31, 1998 (Smith et al. 1998). Sources reaches 2 Crabs in about 9 hours.

- RXTE/PCA determines source position within 1 arc min from scanning data (Marshall et al. 1998). Source location coincident with known symbiotic star, CI Camelopardalis (CI Cam).



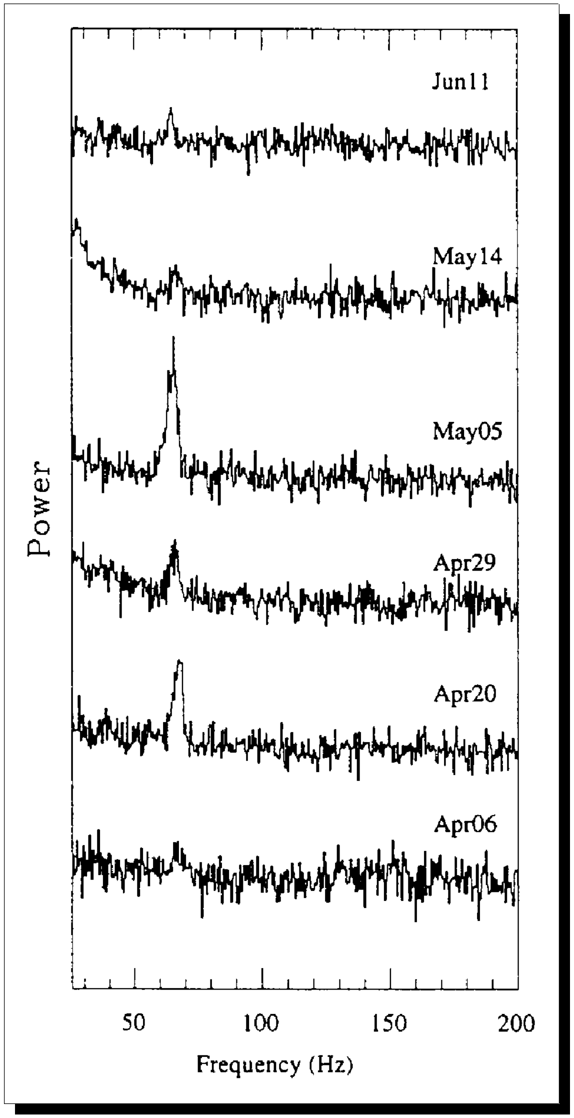
Very Fast-Falling X-ray Transient



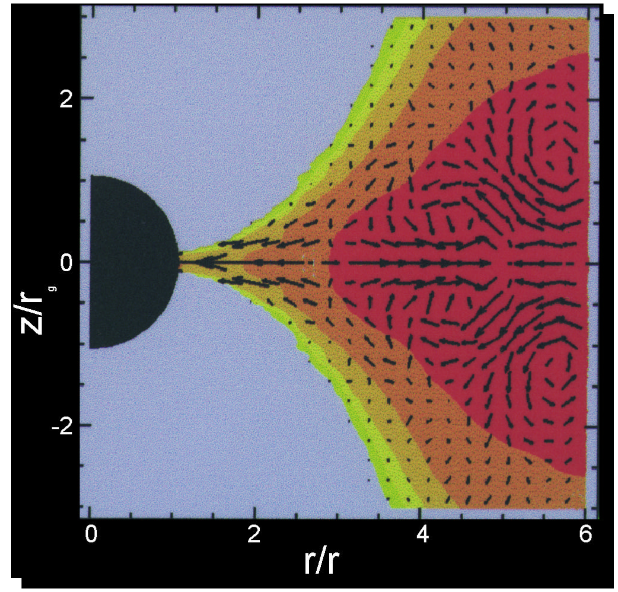
- Radio observations of PCA error box reveal variable radio source showing corkscrewing jets emanating from a compact radio source (Hjellming & Mioduszewski 1998).

- PCA observations reveal strong Fe K alpha line emission, but virtually no significant X-ray variability so typical of accreting neutron stars and black holes.

67 Hz Quasi-Periodic Oscillations from Superluminal Source GRS 1915+105

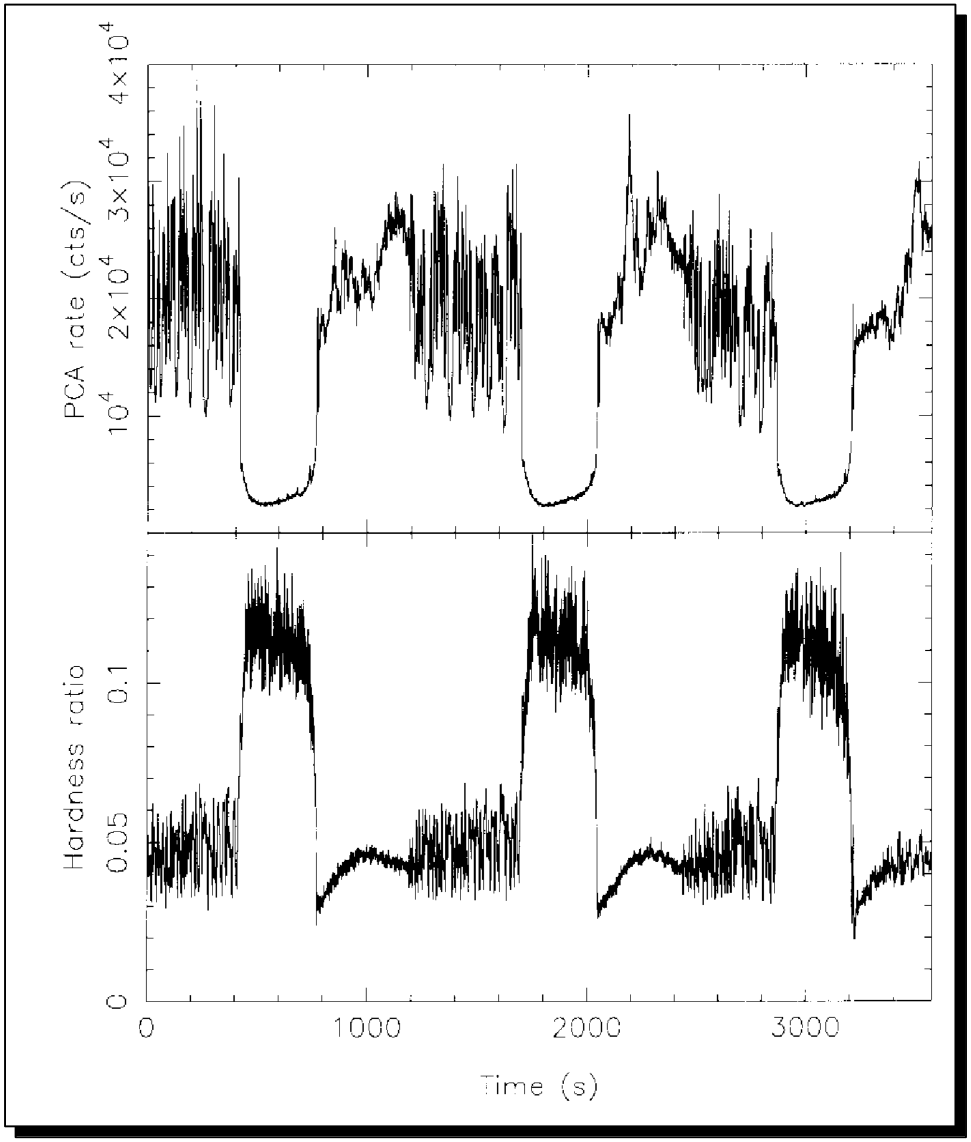


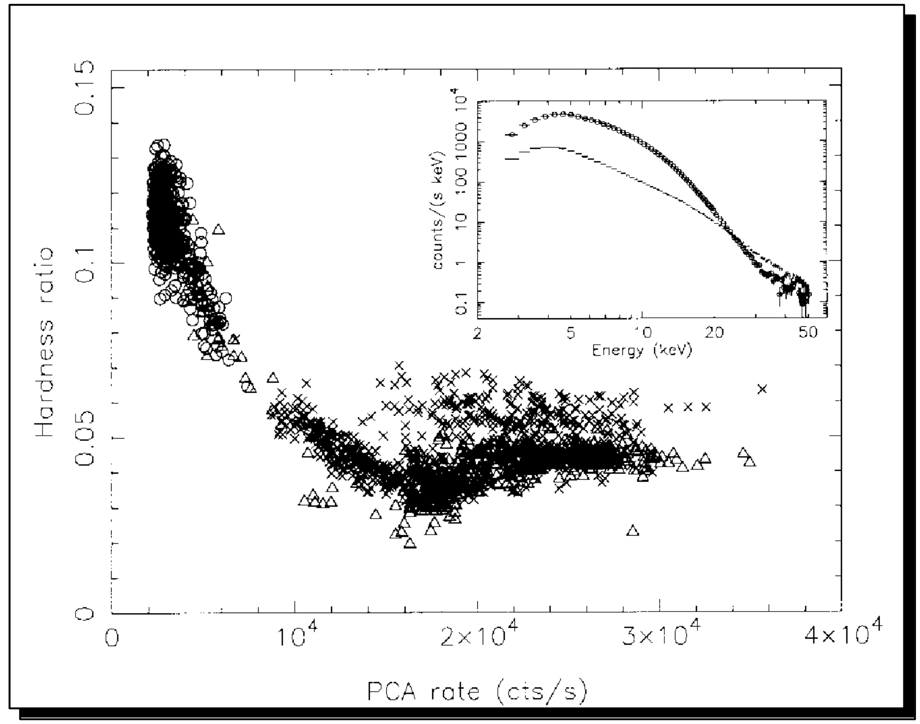
Morgan, Remillard, and Greiner (1996)



- Morgan et al. (1997) discover 67 Hz QPO in 31 RXTE observations —
  - Strong energy dependence
  - Amplitude increases from 1% to 6% from 5-20 keV
- QPO is thought to be produced in the inner accretion disk, close to the black hole —
  - Orbital frequency of ISCO => 33 $M_\odot$ non-rotating black hole
  - Vertical disk oscillation (Nowak et al., 1996) => 10 $M_\odot$ non-rotating black hole
  - Lense-Thirring precession (Cui et al., 1998)

Highly Complex but Structured Variability from GRS 1915+105



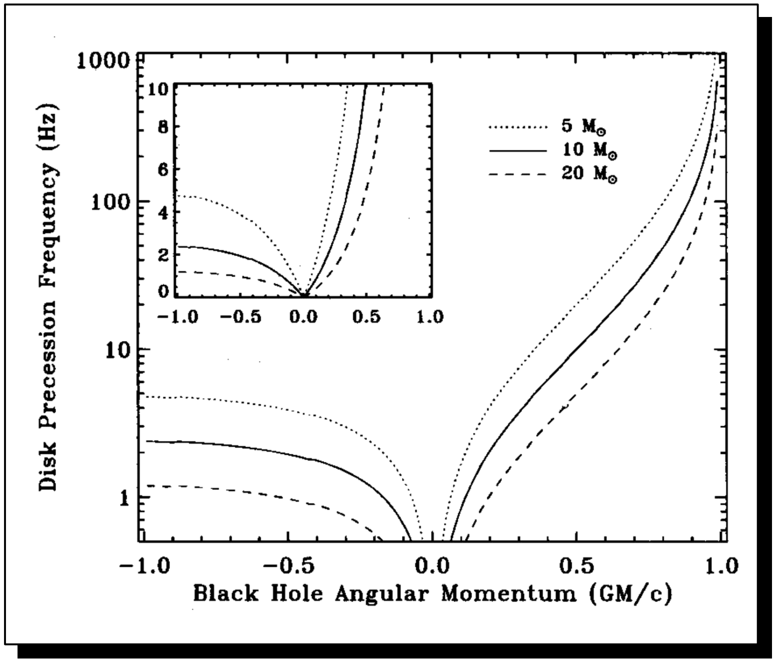


Belloni et al. (1997)

Spectrum shows dramatic changes, with soft "disk component" disappearing during low states

Frame Dragging Around Spinning Black Holes

Cui, Zhang, and Chen (1998); Stella and Vietri (1998)



Inferred Black Hole Spin

Source	Mass ($M_\odot$)	QPO Frequency (Hz)	a	References
GRO J1655-40	7	300	+0.95 (+0.93)	1, 2
GRS 1915+105	30	67	+0.95 (~+1)	3, 4
GS 1124-68	6.3	8	+0.35 (-0.04)	5, 6
Cyg X-1	10	9	+0.48 (+0.75)	7, 8

Cui, Zhang, and Chen (1998)

If the black hole spin and accretion disk plane are tilted, the disk will precess around the same axis

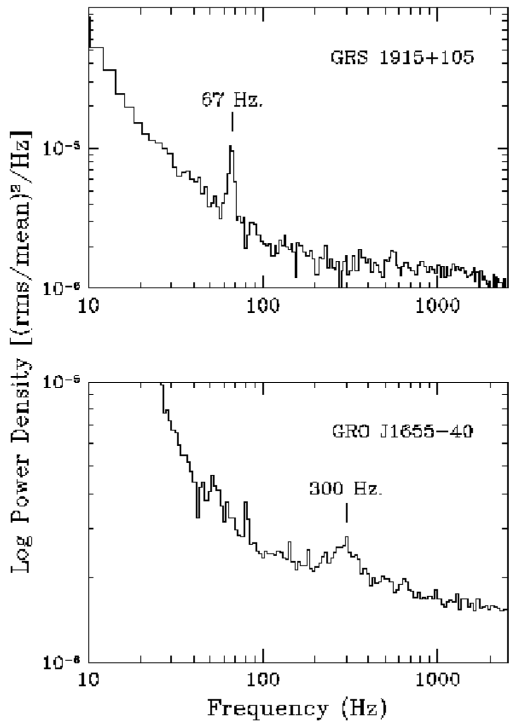
- frame dragging or Lense-Thirring precession

Stable oscillations observed in black hole X-ray binaries by (RXTE) may be evidence for this effect

- disk precession frequency where X-ray emission from accretion disk peaks is in same range
- for jet source, indicates maximally rotating black hole
- for other sources without jets, lower frequency suggests lower black hole spin
- similar effect may be seen in neurton star X-ray binaries (Stella and Vietri 1998)

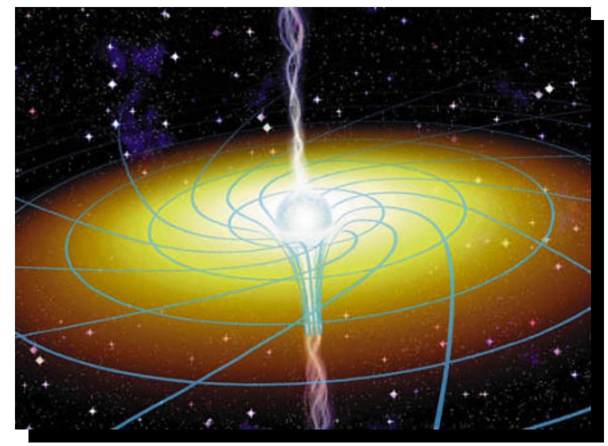
Relativistic Frame Dragging near Spinning Black Holes

RXTE X-ray Spectra and Variability Probe Spacetime near Black Holes



- X-ray Spectroscopy of microquasars GRS 1915+105 and GRO J1655-40 probes the structure of the accretion disk around their central black holes (Cui, Zhang & Chen 1997).

- Model fits to X-ray spectrum of GRO J1655-40 suggest the inner edge of the accretion disk is at ~ 2 GM/c^2, much closer than the last stable radius (6 GM/c^2) of a non-rotating black hole.

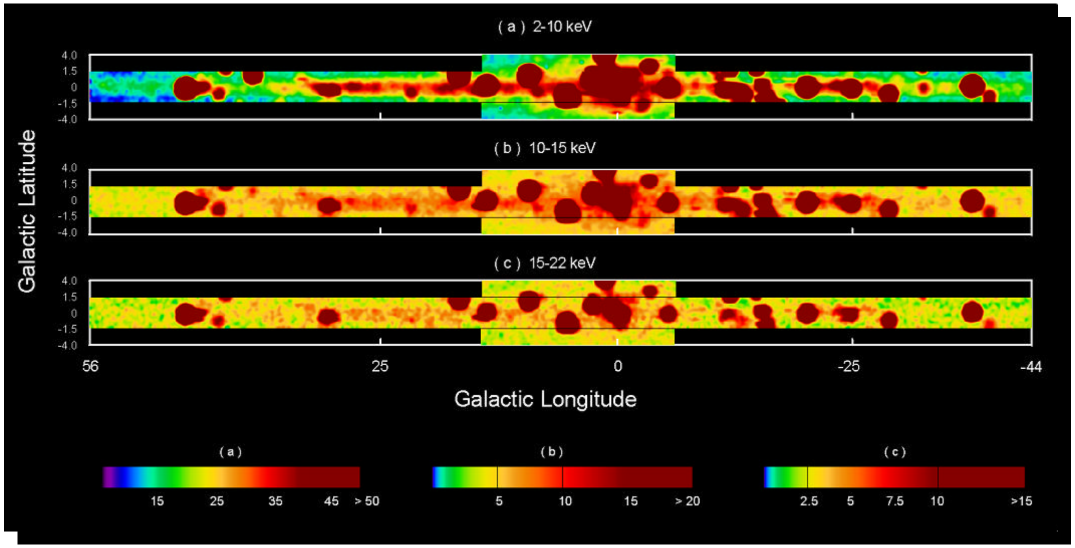


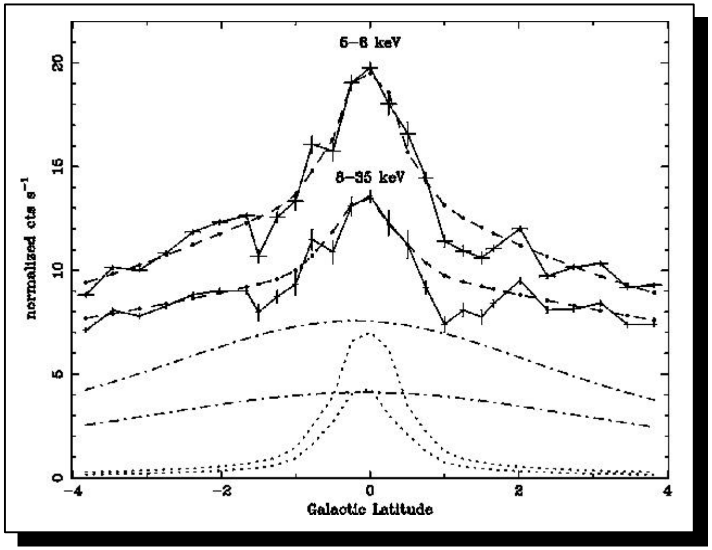
- To bring the last stable orbit to within 2 GM/c^2 requires that the black hole be rotating at ~ 93% of its maximal rotation rate

- Using the known mass of ~ 7 $M_\odot$ for GRO J1655-40 and the estimated rotation rate of ~ 93 % maximal, the precession frequency at the inner edge of the disk should be about 300 Hz.

- 300 Hz QPO are seen in the RXTE/PCA data, supporting this interpretation.

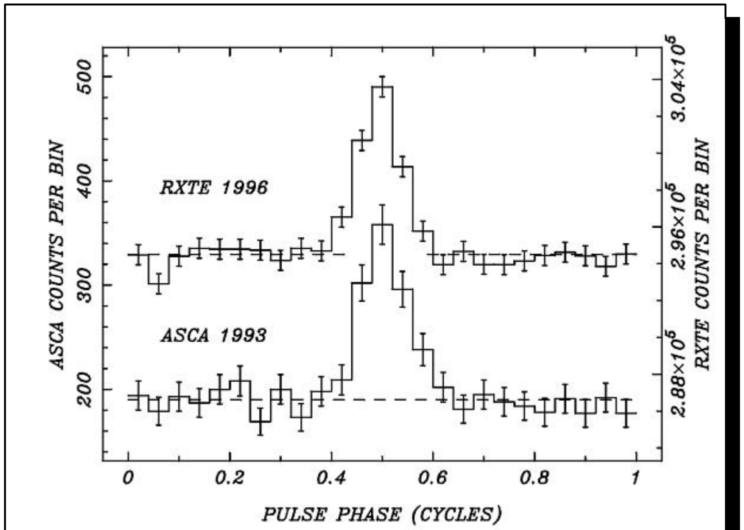
RXTE/PCA Mapping of the Galactic Ridge: Energetics of the Interstellar Medium

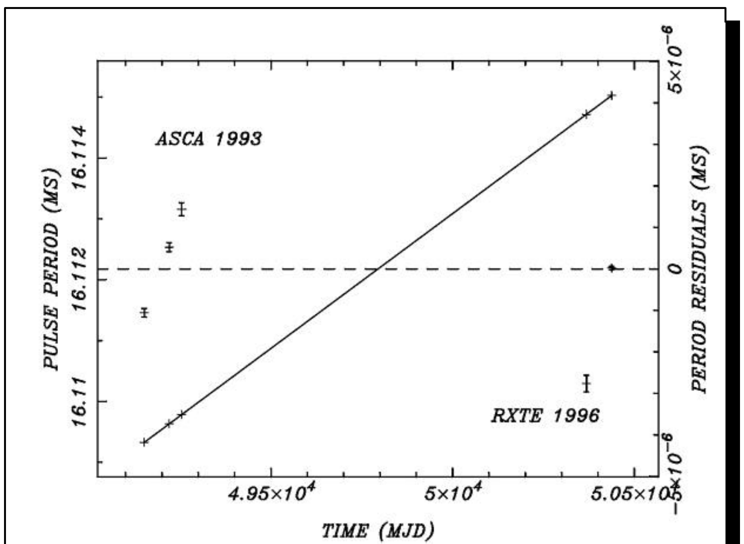




- RXTE/PCA scans show a two component spatial structure to the diffuse emission in the vicinity of the galactic mid-plane.
  - Component 1: Thin disk of full width < 0.5 degrees
  - Component 2: A broad, gaussian component with FWHM of 4 degrees
- Spectrum of diffuse component shows a hard power law tail (index of 1.8) above 10 keV, and an emission line from He-like iron.
- A 2 - 3 keV plasma component suggests that the temperature of the hot phase of the ISM is less than previously suspected.
- A Supernova rate of less than 5 per century can power the thermal emission from the ridge.
- Bremsstrahlung from electrons and protons accelerated in SNR sites may be a major component of the hard power-law tail.

RXTE Discovers Fastest Pulsar in a Supernova Remnant: PSR J0537-6910





- RXTE observations by Marshall et al. (1998) to search for a pulsar in SN 1987A reveal a 16 ms pulsed signal
- Analysis of archival ASCA data conclusively associates the pulsations with the SN N157B, not SN 1987A
- The measured period derivative indicates a magnetic field strength of ~ 10^{12} G
- A constant spin down does not fit the combined ASCA and RXTE data well, suggesting that glitches have occurred, as in the Crab and Vela pulsars

Rossi Explorer Flight Operations

- Instrument and spacecraft are healthy —
  - All key spacecraft systems continue to operate successfully
  - The average telemetry rate has exceeded pre-launch expectations
  - Orbit decay and solar array degradation should not be a limiting factor for 10 years
- Flexible scheduling and rapid response is being heavily used —
  - Good observing time is averaging 57% of elapsed time
    (this is essentially all time when the spacecraft is not in SAA or EO)
  - More than 1900 separate observations of 133 targets of opportunity (TOOs)
  - Response times of 3–4 hours are routine, < 30 minutes is possible
  - About 90% of non-TOO observing time is scheduled to accommodate scientific constraints (coordinated observations, binary phase, contiguous viewing, etc.)
  - Currently ~ 30% of observing time is being used for coordinated observations

Prospective Achievements of the Rossi X-Ray Timing Explorer

- Millisecond accretion-powered pulsars and kilohertz QPOs —
  - Establish conditions that produce detonation and deflagration waves, determine whether nuclear fuel is pooled and relation to magnetic fields
  - Establish the physical process that generates the kilohertz QPOs and the relationship between their frequencies and the spin frequency of the star
  - Discover additional accretion-powered millisecond pulsars and observe further outbursts of the 2.5-msec accretion-powered pulsar
  - Use these results to determine the physics of the inner disk, constrain the EOS of dense matter, and explore GR effects in the strong-field regime

- Accreting black holes in the Galaxy —
  - Determine the relationship of X-ray spectra and high- and low-frequency QPOs to fundamental properties (mass, spin) of black holes
  - Develop a detailed understanding of the evolution of the inner disk as jets form
  - Possibility of discovery a bright BH X-ray nova or the first eclipsing BH system

Prospective Achievements of the Rossi X-Ray Timing Explorer

- Supermassive black holes in AGN —
- Origin of gamma-ray bursts —
- Long-term behavior of X-ray binary systems —

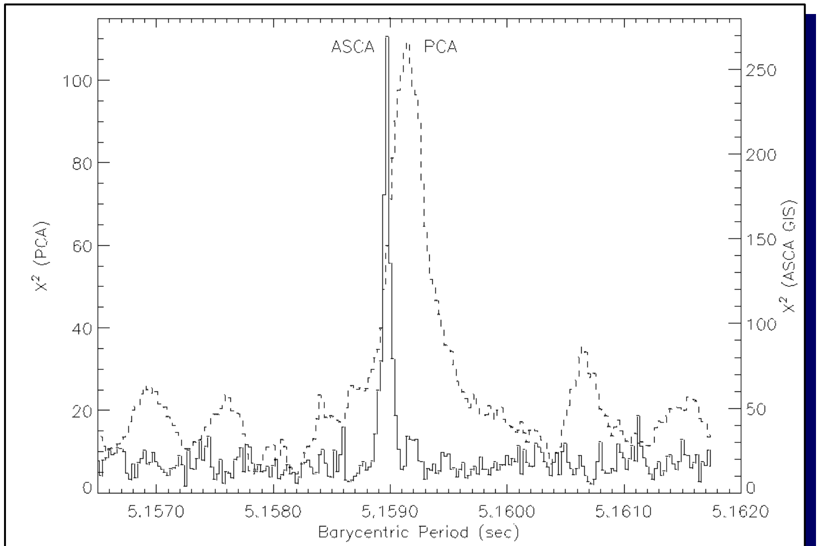
RXTE Operational Successes

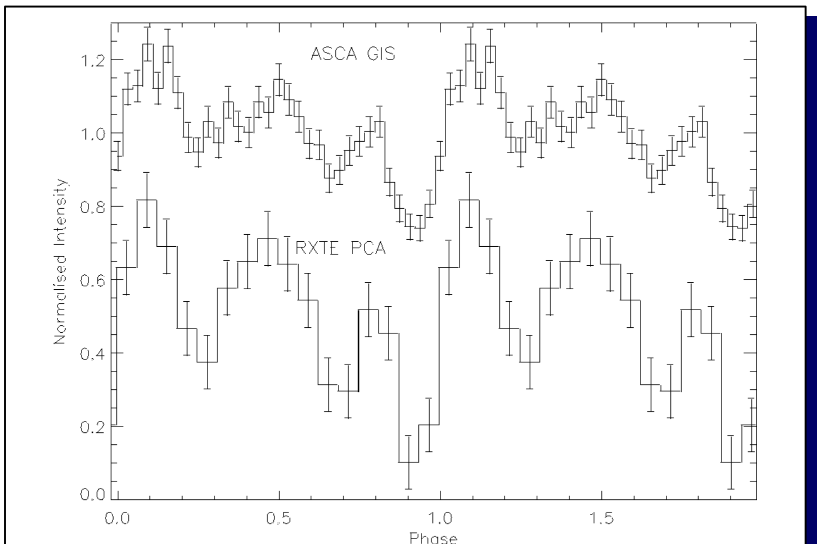
- A Flexible, Responsive, and Efficient Scheduling System
  - No limit on constrained observations—90% of non-TOO time has a constraint
  - 2072 observation of 142 TOO sources as of Jul 23, 1998
  - The most rapid response time is 43 minutes for GRB 971208
  - Observing efficiency is ~ 57%.
- Rapid Access to Data
  - GOs routinely remotely monitor their observations
  - Almost all the real-time data are available for ftp within 24 hours as FITS files
  - ASM light curves are available on the Web
  - Numerous transients have been discovered in the ASM and PCA slew data
- Automation
  - Routine monitoring of instruments is now done automatically
  - A paging system alerts off-site staff to any problems
  - Automatic science monitoring is being added

RXTE Operational Successes

- An extensive, well-documented suite of analysis software is available.
- Data analysis help is readily available
  - Documentation is online
  - ~100 e-mail questions are answered monthly; typical response time is four hours
  - About one team a week visits the GOF for intensive assistance
- Large archive of public RXTE data is online
  - ~13 months of data have become public after their proprietary period
  - ~50% of TOO observations have become public immediately

The X-ray Pulsar in the Soft Gamma Repeater SGR1900+14

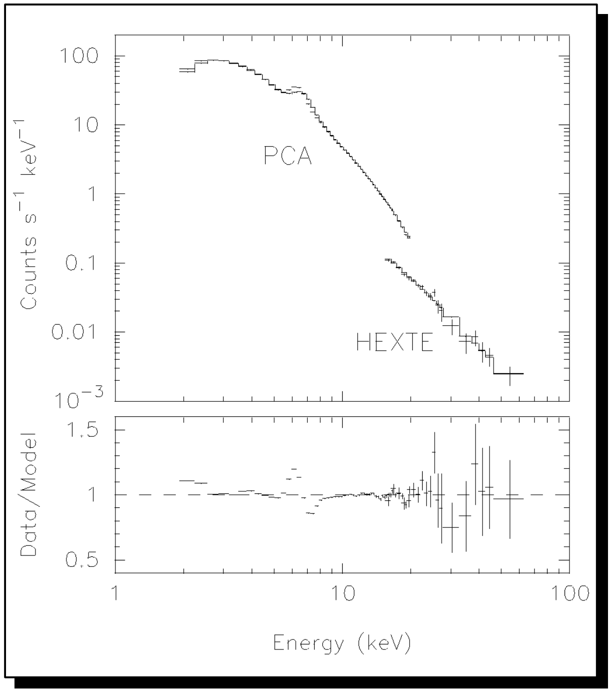




- ASCA data from April 30, 1998, to May 2, 1998, reveal a 5-second pulsar associated with SGR1900+14 (Hurley et al., 1998).
- RXTE observations are performed after BATSE detects an outburst on May 26, 1998.
- Pulsar is detected in PCA data from June 2, 1998. PCA period is significantly longer than ASCA period → P_dot ~ 6.5 x 10^{-11} s/s
- The P_dot value implies a magnetic ***B*** ~ 6 x 10^{14} G, suggesting SGR1900+14 is a magnetar, a neutron star with a superstrong magnetic field

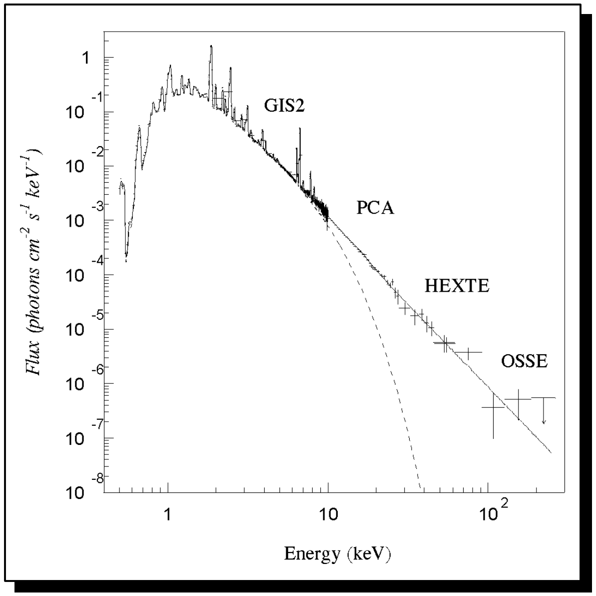
Evidence for Cosmic Ray Acceleration in Supernova Remnants: Cassiopeia A

- Supernova shocks have been hypothesized as the sites of Cosmic-ray acceleration up to energies of about 500 TeV.
- RXTE observations of the supernova remnant Cassiopeia A reveal a non-thermal spectral "tail" that extends to energies at least as high as 60 keV.
- A joint fit to RXTE and ASCA data suggests the non-thermal spectrum is consistent with a model of X-ray synchrotron emission from 10-30 TeV electrons.



The X-ray spectrum of CAS A measured with RXTE

- This result implies that cosmic rays are accelerated to very high energies in the shock of the remnant, which provides very strong support for the idea that Galactic cosmic rays are predominantly accelerated in supernova remnants.



Non-thermal power-law tail from Cas A