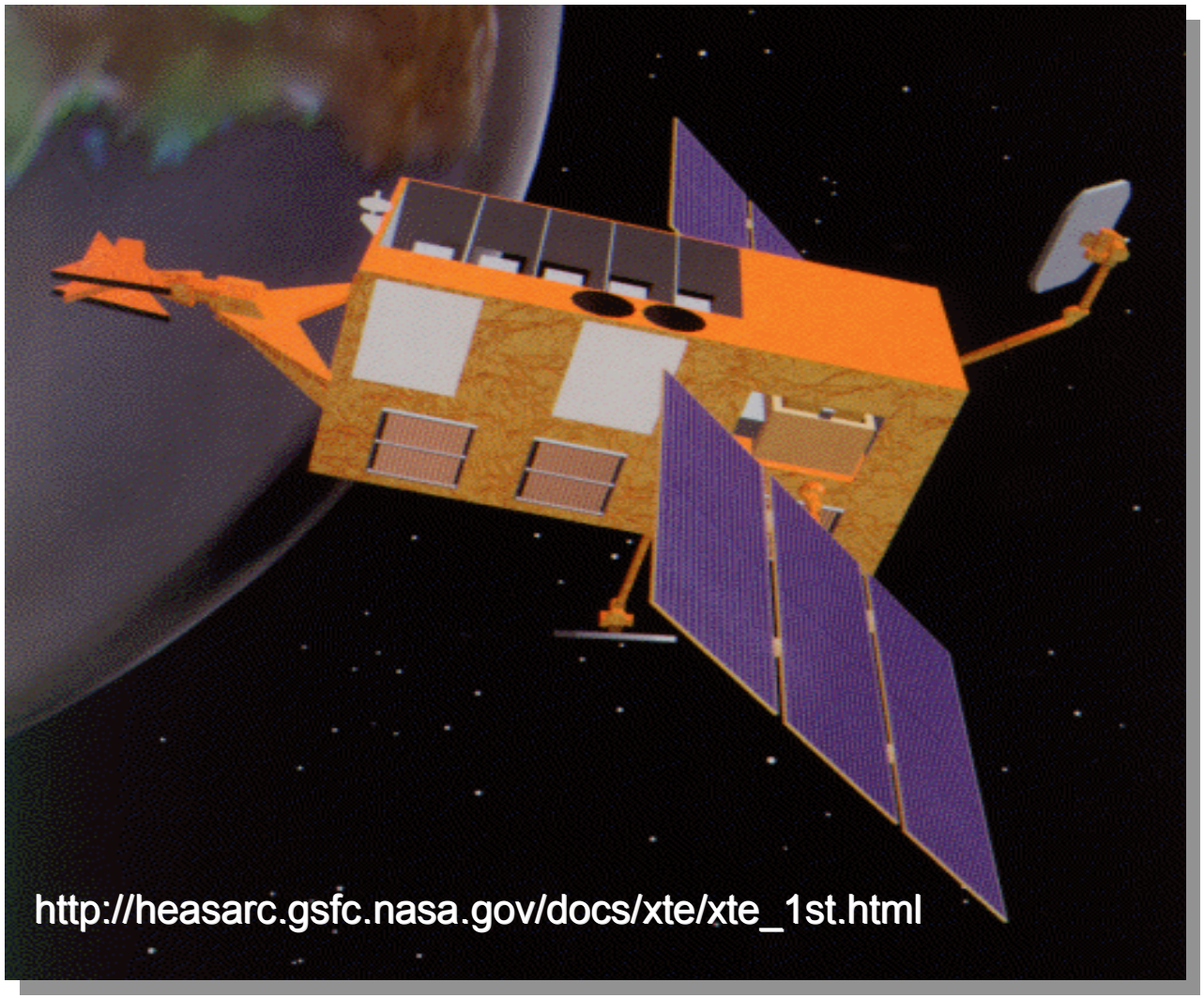
Rossi X-ray Timing Explorer (RXTE)



Fred Lamb

Chair, RXTE Users Group

RXTE Results Cover a Broad Range of Astrophysics

- Discovery of millisecond X-ray Pulsars
  - 2.5 ms accretion powered X-ray pulsar (SAX J1808-369)
  - Six 'nuclear powered' X-ray pulsars (burst oscillations)
  - Fastest rotation-powered X-ray pulsar (16 ms), XTE J0537-6910
- Discovery of sub-millisecond X-ray brightness oscillations (kHz QPOs)
  - High coherence (Q ~ 100)
  - Two frequencies in each source, frequency separation close to NS spin frequency
  - Frequencies vary with mass accretion rate
- Important new constraints on the Mass, Radius, and Equation of State of neutron stars
  - From kHz oscillations
  - From oscillations during thermonuclear X-ray bursts
  - From accreting ms pulsar (SAX J1808-369)
- First evidence for predictions of General Relativity in the strong-field regime
  - Evidence for innermost stable circular orbits around neutron stars.
  - Evidence of Lense-Thirring precession around neutron stars and black holes
- Extensive multi-wavelength coordinated observing campaigns (eg. TeV Blazars)

RXTE Results Cover a Broad Range of Astrophysics (continued)

- Discovery of 'Magnetars': neutron stars with 10^{15} G magnetic fields
  - Soft Gamma-ray Repeater (SGR) burst sources are X-ray pulsars
  - Rapid spin down of SGR pulsars
  - First discovery of a spin up glitch from an Anomalous X-ray pulsar (AXP)
  - First evidence for line emission from an SGR

€First detailed studies of galactic micro-quasars

  - Discovery of seven new jet systems (eg. CI Cam, V4641 Sgr)
  - Discovery of jet-disk connections

- New probes of the geometry and physics of AGN (especially at > 10 keV)
  - New evidence for the Unified Model of Sy I and Sy II galaxies
  - Discovery of the characteristic variability timescale in AGN (NGC 3516)
  - New constraints on Compton reflection (MCG-5-23-16, MCG-2-58-22, Cen A)
- New evidence for cosmic-ray acceleration in supernova remnants
- New understanding of X-ray variability
  - Discovery of 34 new transients, discovery of 'rapid' transients (CI Cam)
  - In-depth study of 60 outbursts, monitoring of 40 different periodic systems

RXTE addresses dynamics in the strong-gravity regime

- Minimum stable orbit of motion around black holes or compact neutron stars
- General relativity effects in saturation frequency for kilohertz QPOs
- General relativity effects in disk oscillation modes for black hole hectohertz QPOs
- Framedragging effects, if not measured already, can be addressed
- Spin of galactic black holes is constrained by both timing and spectral signals
- Jets are evidently formed in these regions
- Complements spectroscopy of AGN Fe edges and emission lines from inner disk
- Will complement optical (e.g. HST) and x-ray spectral evidence of accretion onto black holes in quiescence and formation of an advection dominated accretion flow (ADAF)

RXTE addresses the highest densities and magnetic fields

- Aim is agreement of multiple approaches to measuring masses and radii of burster neutron stars, the only ones for which both parameters are so far possible

- Magnetic fields as strong as 10^{15} G are possible, which could decay, and now examples are in hand to study these possibilities

- Neutron stars are possible sources of gravitational waves if they have quadrapole moments, depending on the equation of state (EOS)

- Glitches are being seen in young neutron stars which are not radio sources, glitches bigger than those of the radio pulsars

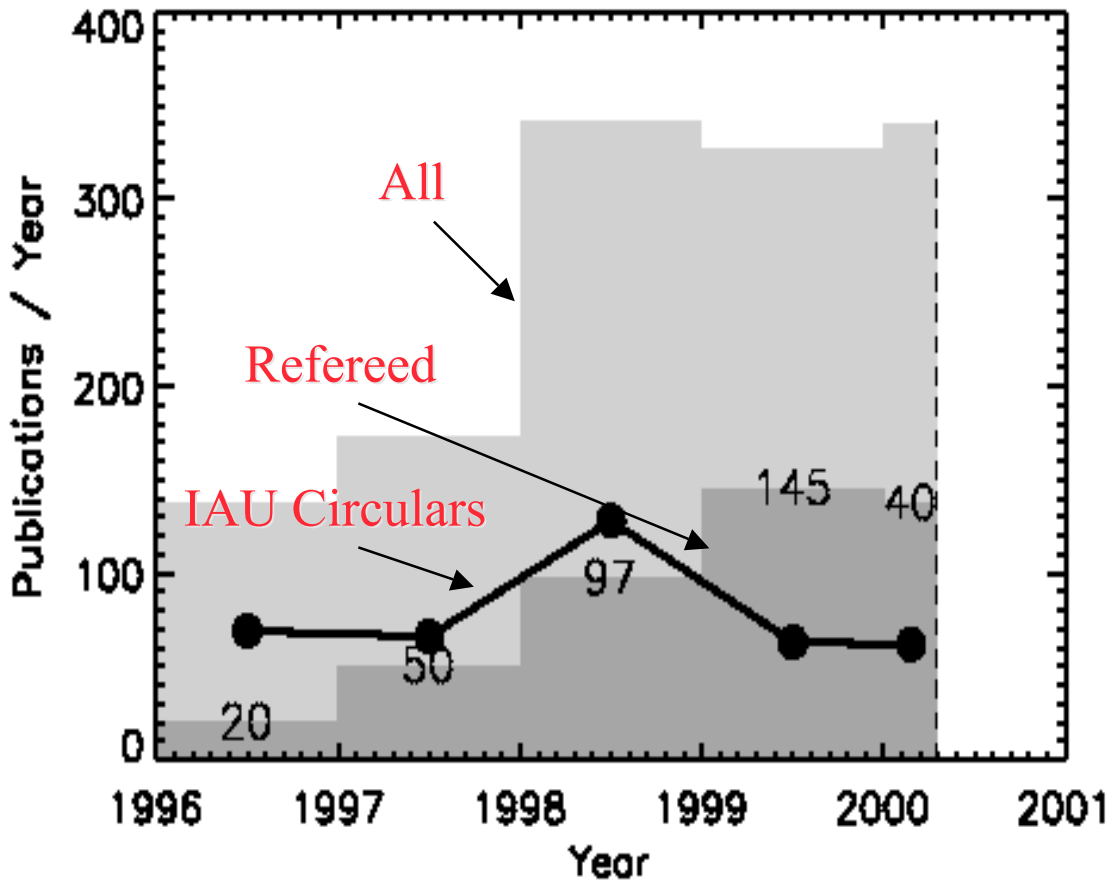
- Nearly half of radio pulsars and old neutron stars may have come by way of a binary companion and this population probably has masses and possibly has magnetic field histories different from those born single

RXTE addresses the instabilities of mass flow in accretion-powered X-ray sources

- Multiple transients demonstrate classes of parameters like duration and luminosity
- Most black-hole transients at outburst emit relativistic radio jets
- Black-hole transients in their low states power radio emitting outflows
- Spectral variations during transient events manifest further instability of the disk and coronal flows as they exchange the radiation responsibility
- Precessing tilted accretion disks, of which Her X-1 is the model, exhibit other cycles, including change of the tilt (and ensuing off states)
- New limit cycles are identified, from high/low state cycles of the black hole LMX-3 to the traversals in color/color diagrams of Z and atoll LMXB
- Bright AGN also have variations on the scales of 100 days whose origins are not at all understood

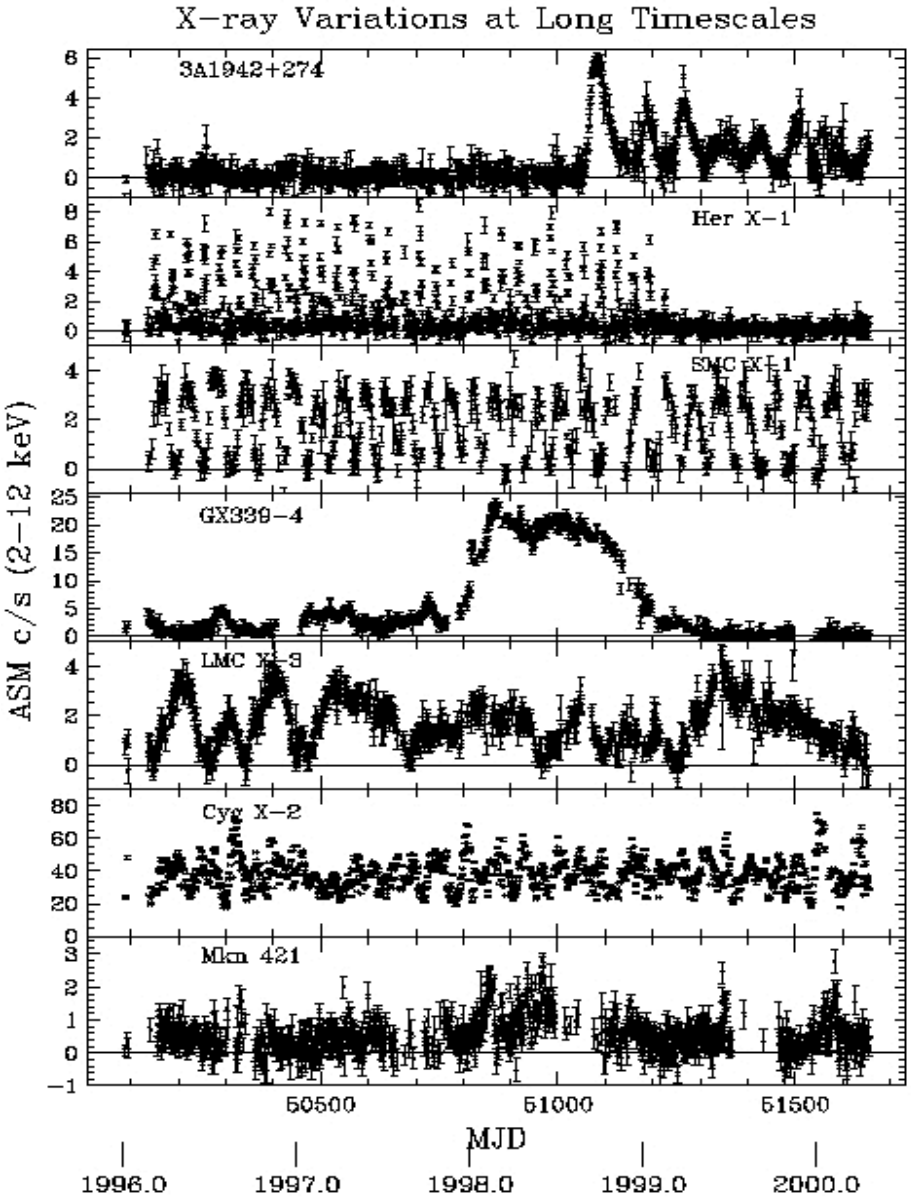
RXTE Publications and User Community Interest

- Currently 352 papers in refereed journals, 321 IAU Circulars (~ 65 per year)
- Total publications (including conference proceedings) now exceeds 1,100 for the mission



- User community interest in RXTE remains strong
  - 195 AO-4 proposals and 206 AO-5 proposals (factor of 4 oversubscribed).
  - AO-5 had greatest number of proposals of any AO, and with no GO funding since AO-3.
  - 'Rossi2000' meeting (3/24/2000) at GSFC attracts 160 researchers, 150 abstracts, 4 press releases

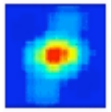
RXTE is a Valuable Asset to the Astronomical Community

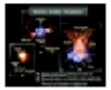


- RXTE performs and enables extensive coordinated multi-wavelength campaigns, "RXTE schedules last"
  - 25% of non-TOO time coordinated with either space or ground based observatories
  - Space missions; HST, CGRO, ASCA, SAX, ROSAT, Chandra, XMM, IUE, FUSE, ISO, EUVE, etc.
  - Groundbased; Arecibo, Greenbank, VLA (radio); Keck, Palomar, ESO, CTIO (optical); Hegra, Whipple (TeV)
  - Total coordinated time 18 Msec (210 days), 12 from space, 6 with ground
- RXTE ASM is only instrument routinely monitoring X-ray sky
  - ASM results quickly and widely distributed on the internet.
  - Increased importance with loss of BATSE
- No near-term replacement for RXTE

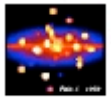
Education and Outreach: The RXTE Learning Center

RXTE Discovery Archive


Meet our Neighbor, a Most Curious Black Hole
(February 2000)

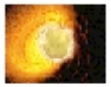

Invasion of the Giant X-ray Bubbles
(January 2000)


The Universe Lights Up on Beethoven's Birthday:
RXTE Pinpoints Location of Gamma Ray Burst
(December 1999)


RXTE Captures the Ongoing Light Show at the Galactic Center
(June 1999)

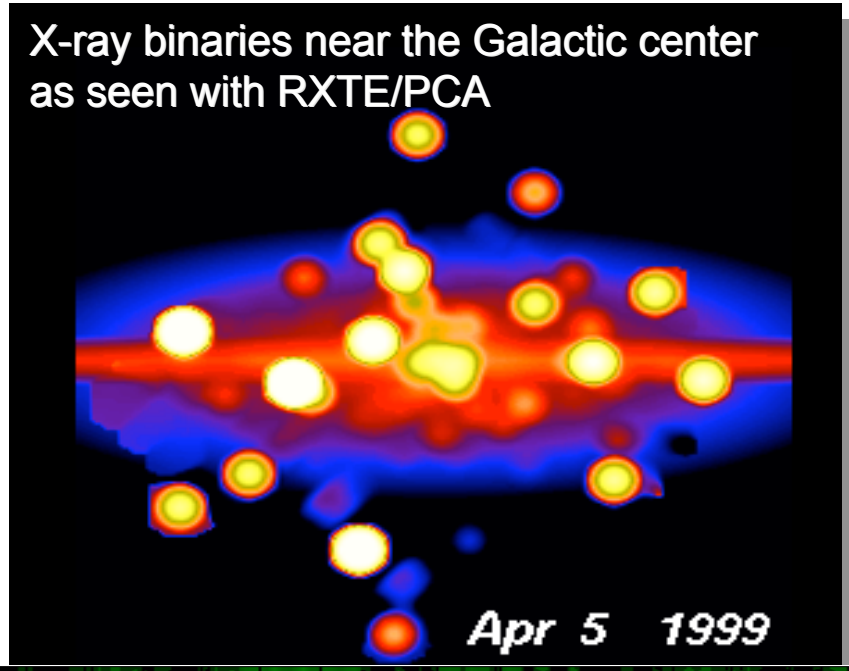

RXTE Observation Helps Astronomers Link Galactic and Supermassive Black Holes!
(February 1999)

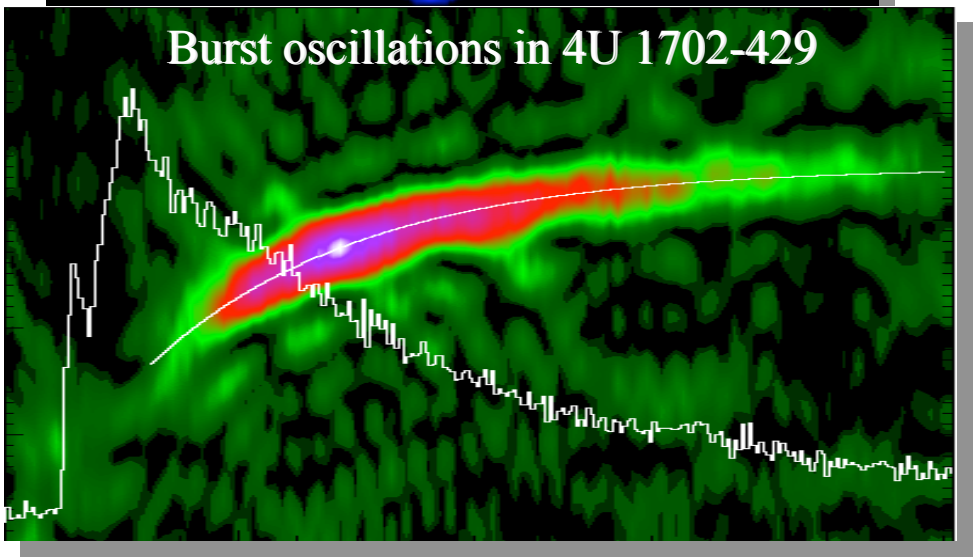

RXTE Gathers More Clues About the Nature of Pulsars!
(January 1999)


RXTE Watches Tremendous Gamma-ray Flare Blast Earth!
(October 1998)

- RXTE Learning Center: Web-based resource for teachers and students.
  - Started by summer teacher intern, (Eleanor Roosevelt H.S)
- Uses RXTE science as a basis for education and lesson plan materials.
  - Currently getting ~ 45,000 hits/month
- Continually add new discoveries
- RXTE Information and Activity Booklet featuring an introduction to X-ray Astronomy, RXTE spacecraft and science.
  - about 17,000 distributed on paper and CD

RXTE Science: Nuclear-powered Pulsars

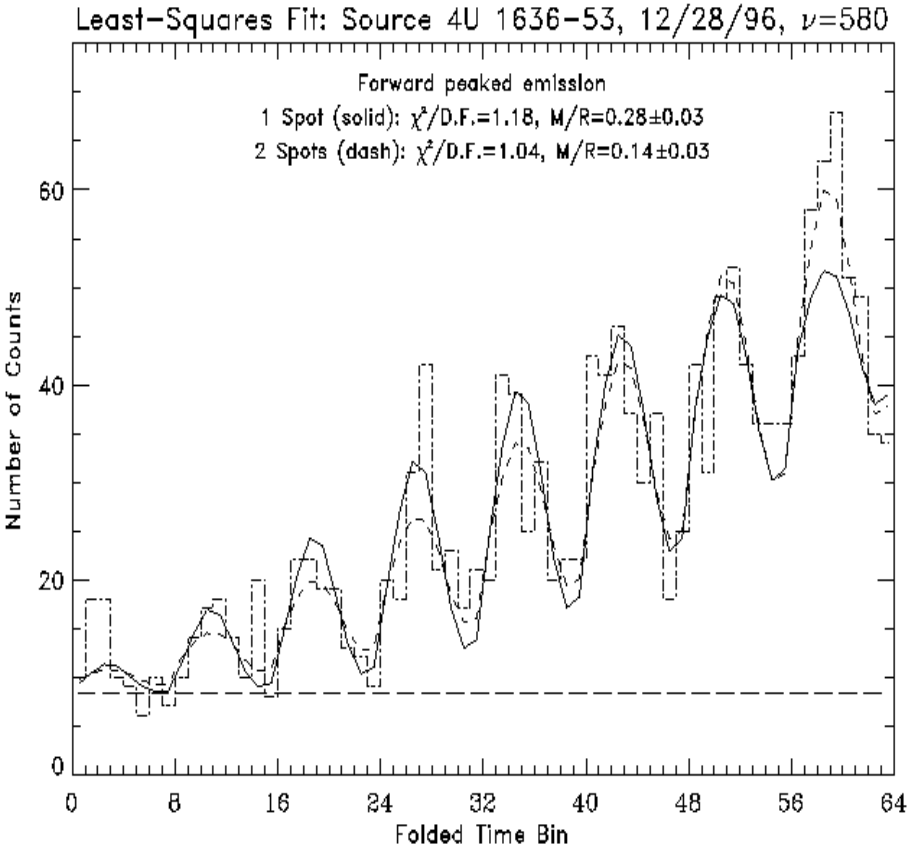


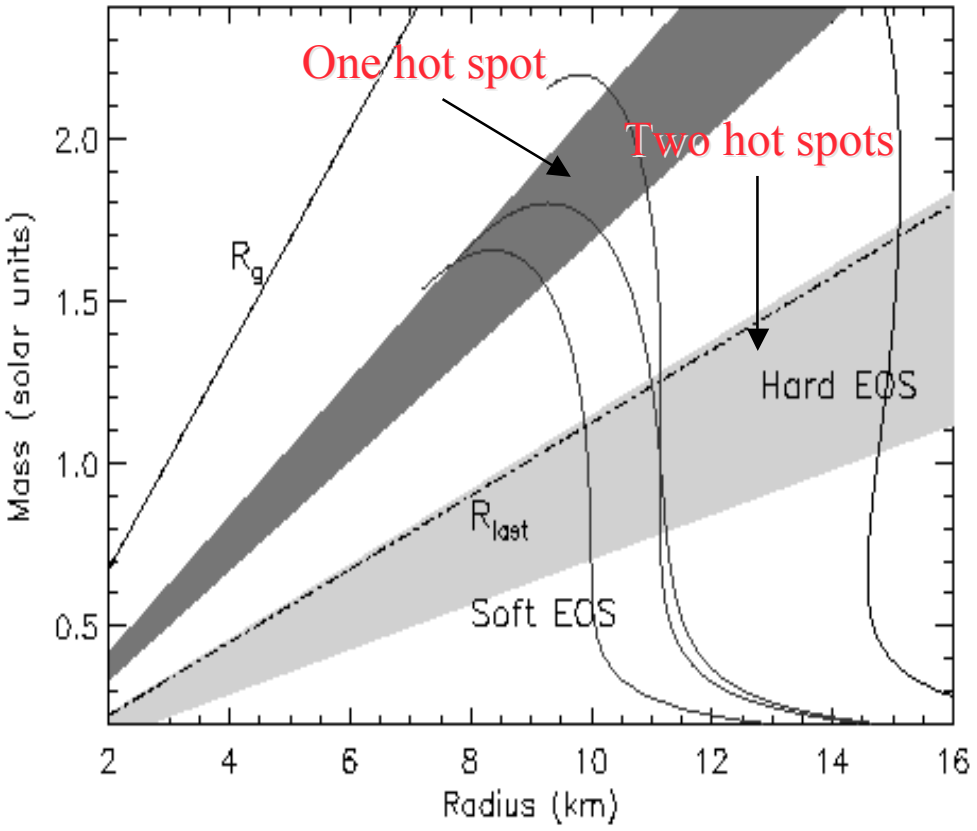


- Millisecond oscillations observed during X-ray bursts from accreting neutron stars, 'burst oscillations',
- Oscillations caused by nuclear hot spot on spinning neutron star (300 - 600 Hz). Seen in 6 LMXB sources to date.
- First confirmation of spin-up hypothesis for ms radio pulsars (recycled pulsars).
- New Mass - Radius constraints for neutron stars.
- Implications for dense matter Equation of State (EOS), and fundamental physics

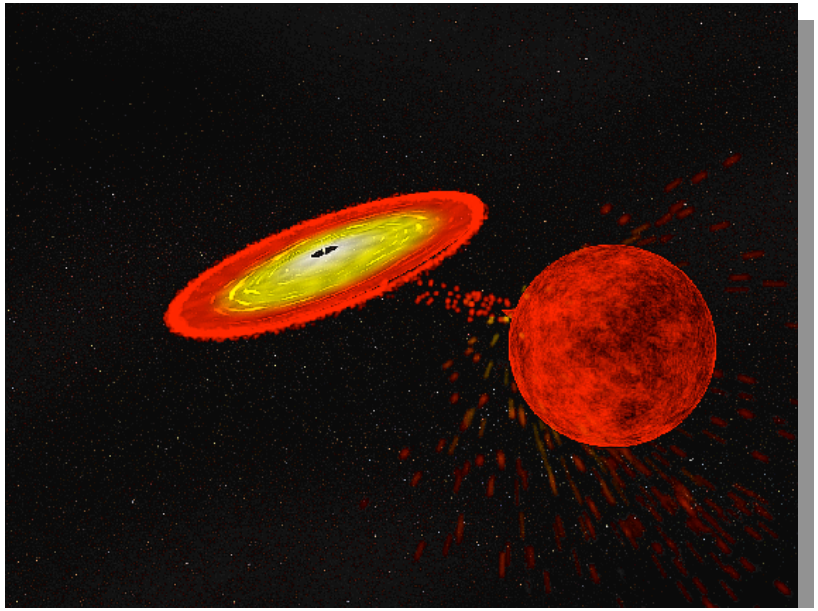
RXTE Science: Burst Oscillations Probe the Structure of Neutron Stars

- Pulse strength and shape depends on M/R or 'compactness' because of light bending (a General Relativistic effect).
- More compact stars have weaker modulations.
- Two spot model for 580 Hz oscillation in 4U 1636-53 supports stiff (hard) EOS

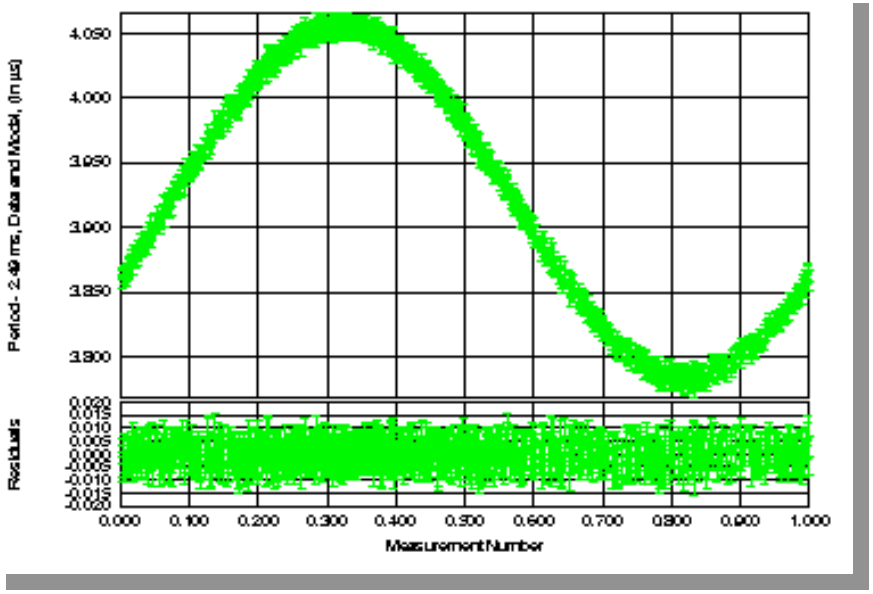




RXTE Science: Discovery of the First Known Accreting Millisecond Pulsar (J1808-369)



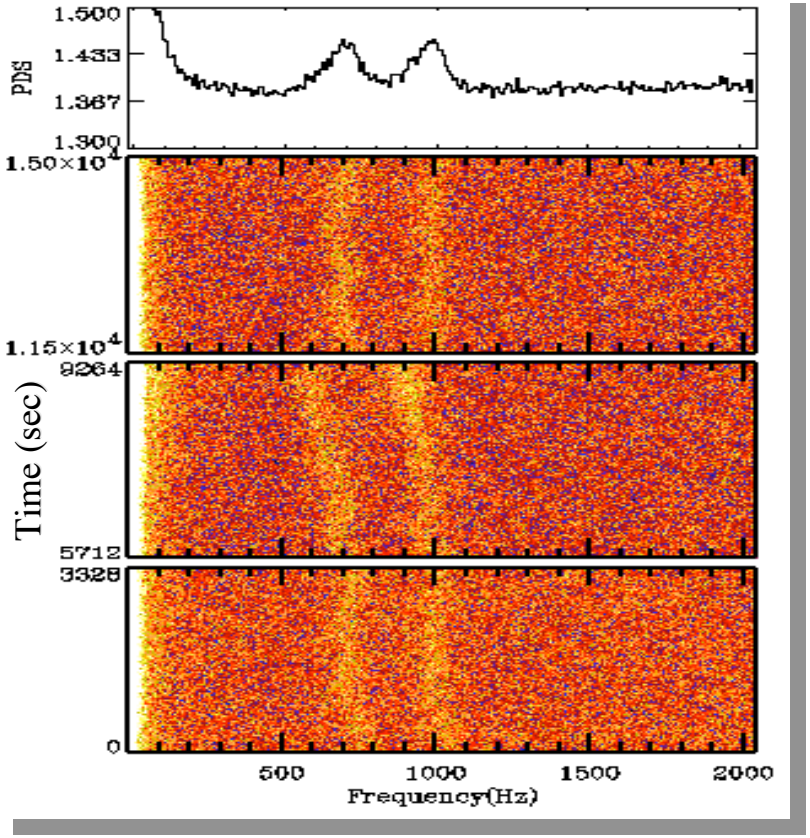
- 2.5 ms coherent pulsations discovered in TOO data from RXTE/PCA observations (4/98, Wijnands & van der Klis)
- Doppler shifts of pulsations show a 2 hr orbital period with a low-mass companion
- First detection of accretion-powered X-ray pulsations *and* thermonuclear bursts in a single source.

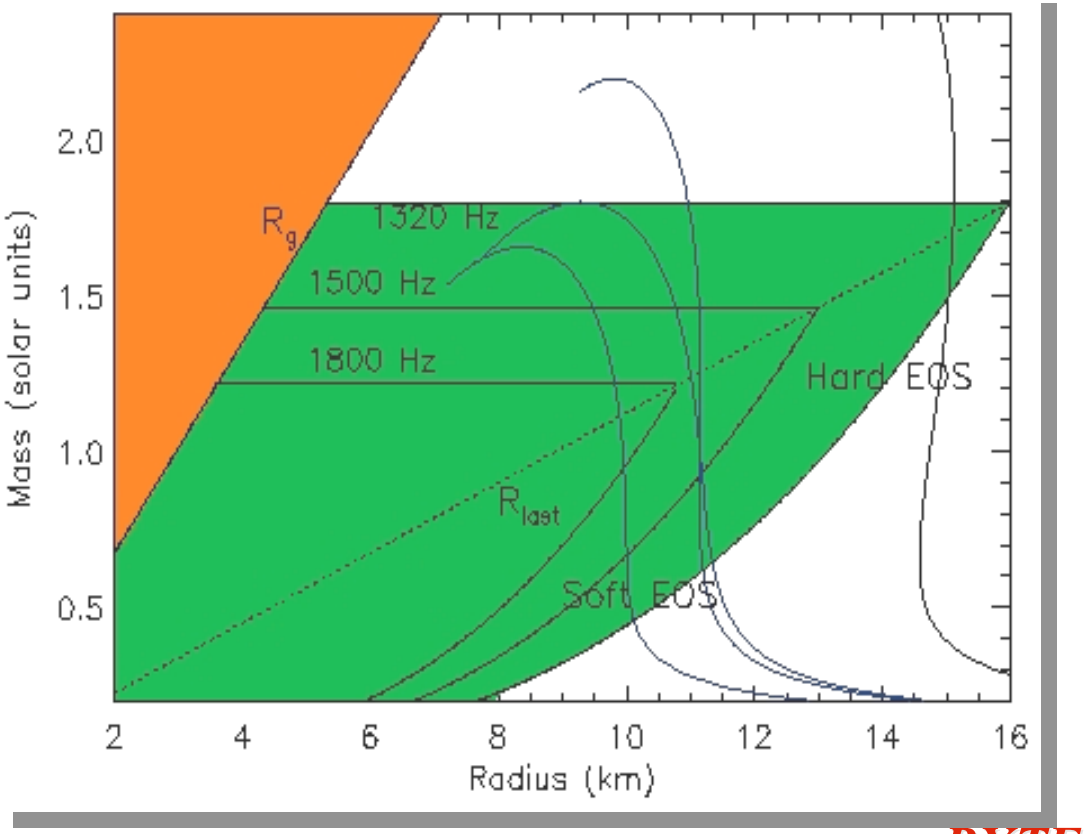


- Validates the theory that millisecond radio pulsars are spun up by accretion
- Magnetic field measurement, 10^9 G, consistent with bursts and radio pulsar estimates.
- Weak outburst in early 2000 revealed new ~ 1 Hz flaring behavior

RXTE Science: Millisecond Oscillations in Accreting Neutron Stars (Kilohertz QPO)

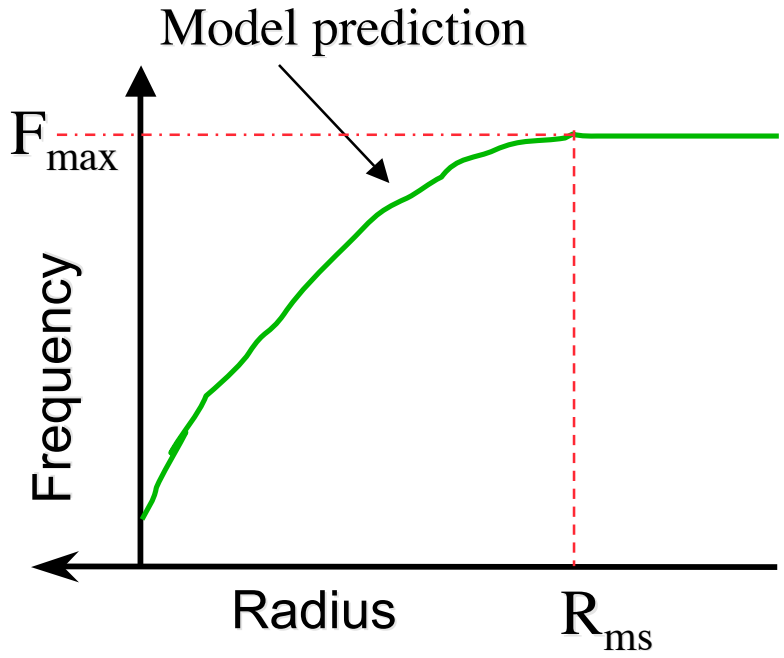
- 500 - 1300 Hz oscillations (QPO), fastest known in astronomy
- Produced within ~ 10 km of the neutron star, high coherence (Q ~ 100).
- Direct probe of General Relativity in a regime not yet tested.
- Constrain M - R relation for neutron stars, EOS of super-dense matter.

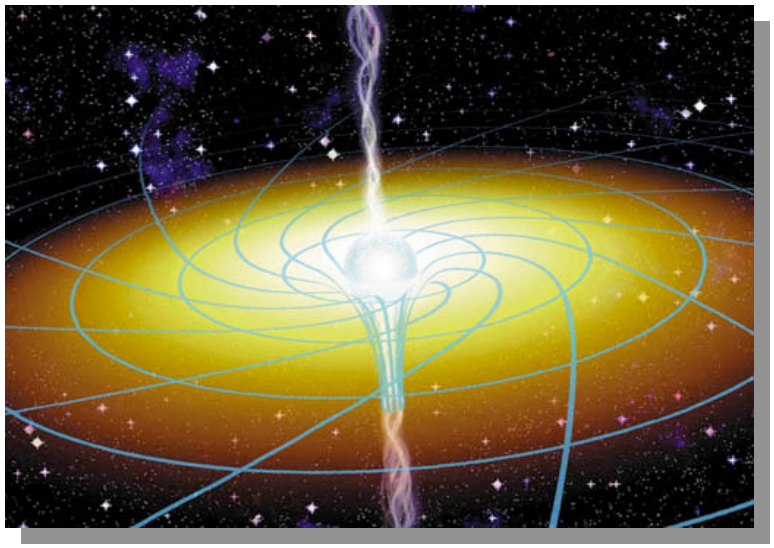


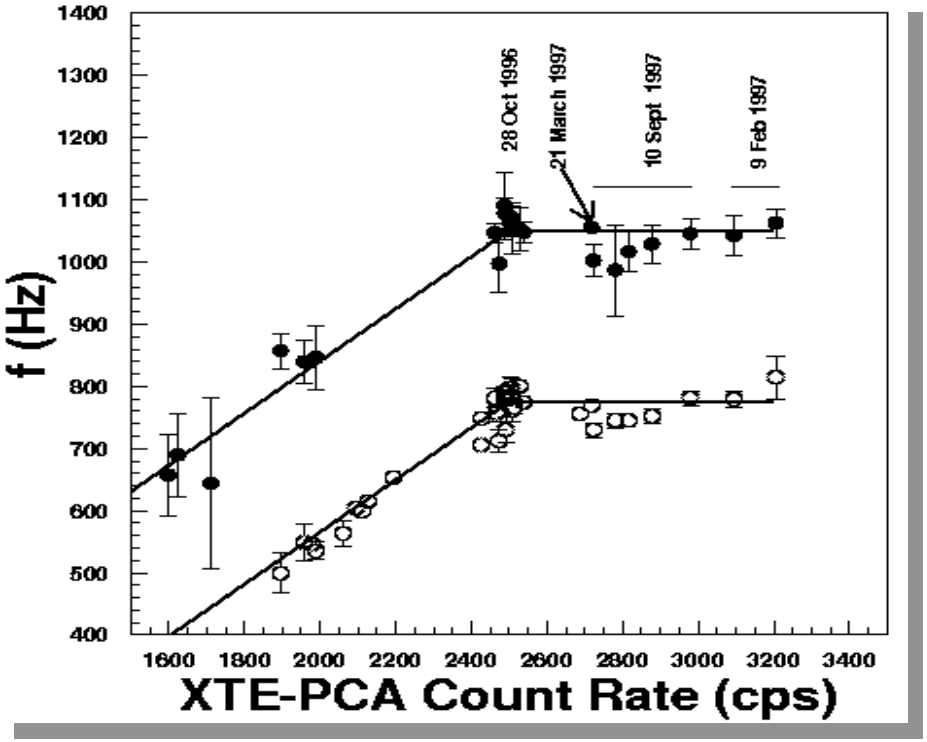


RXTE

RXTE Science: Probes of General Relativity and Evidence for Unstable Circular Orbits







- GR predicts unstable circular orbits inside a special radius (R_{ms}).
- Highest kilohertz QPO related to Keplerian orbital frequency.
- Models predict QPO frequency should reach a limit at radius of last stable orbit, R_{ms}, as observed in 4U 1820-30