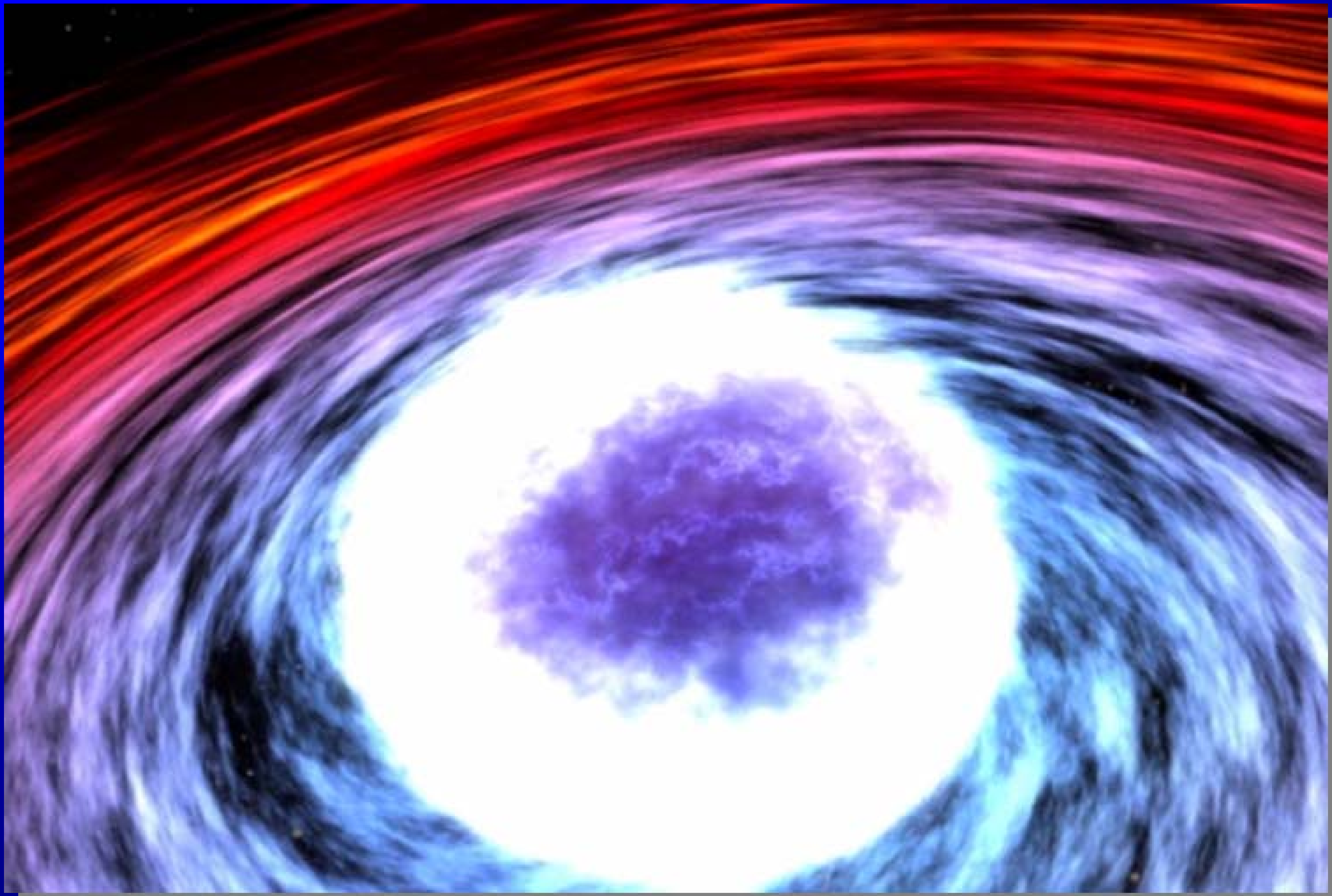
Goddard Space Flight Center

Thermonuclear Bursts: Current Challenges and Opportunities

Tod Strohmayer, NASA's Goddard Space Flight Center



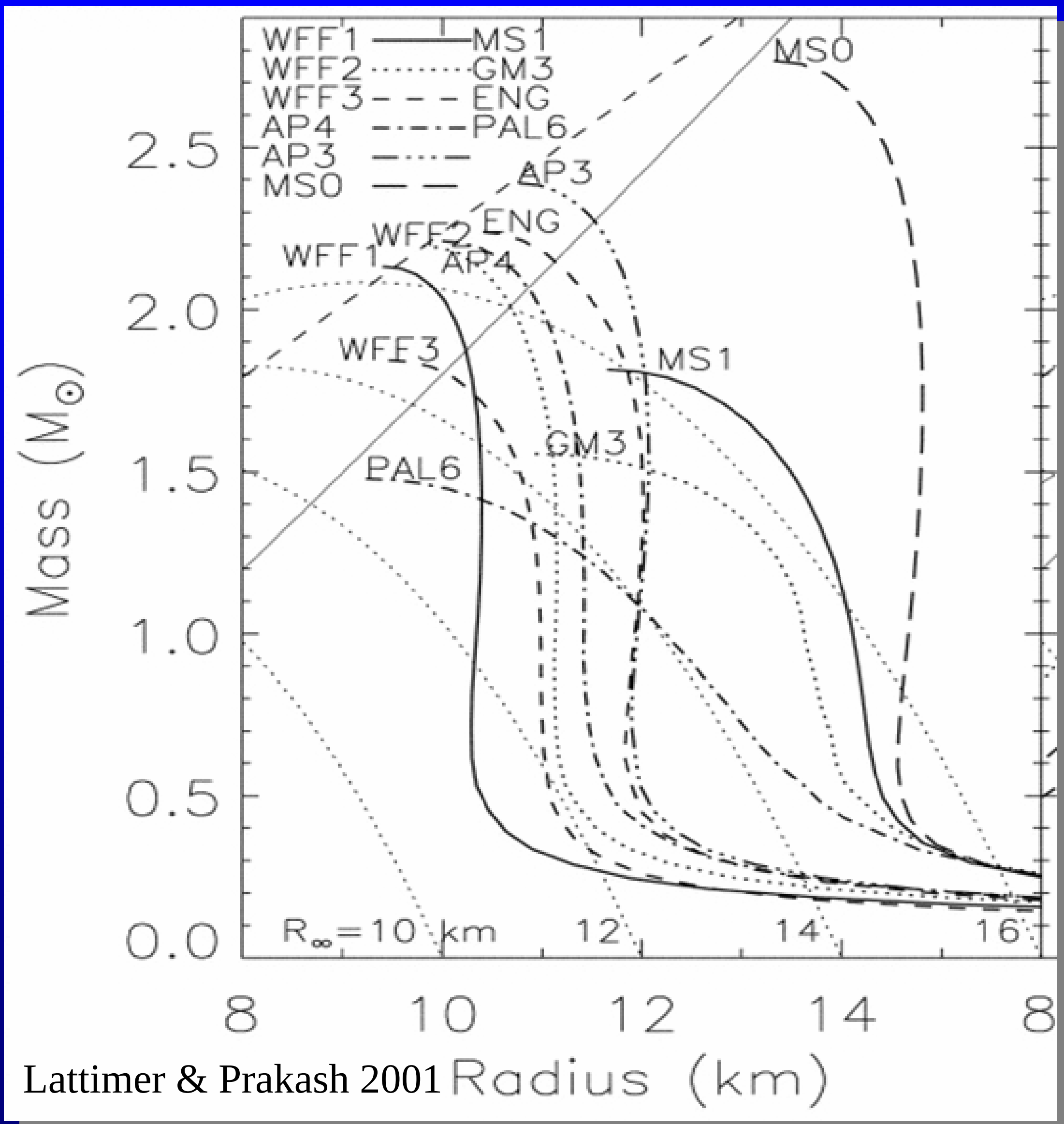
Goddard Space Flight Center

Some Motivation

- Why might a nuclear physicist be interested in accreting neutron stars (in particular, X-ray bursts)? (and vice versa!).
- Accreting neutron stars reveal observable manifestations of nuclear physics (X-ray bursts, superbursts, and related phenomena). These, in principle, can tell us both about fundamental physics (including nuclear physics) and neutron stars, though extracting all the information will be a challenge.
- Neutron stars probe physical regimes beyond that obtainable in a laboratory. Nuclear symmetry energy, equation of state, existence of new states of matter, gravitational physics.
- I will summarize some recent efforts to do this, using X-ray timing observations of accreting neutron stars.

Goddard Space Flight Center

Fundamental Physics: The Neutron Star Equation of State (EOS)



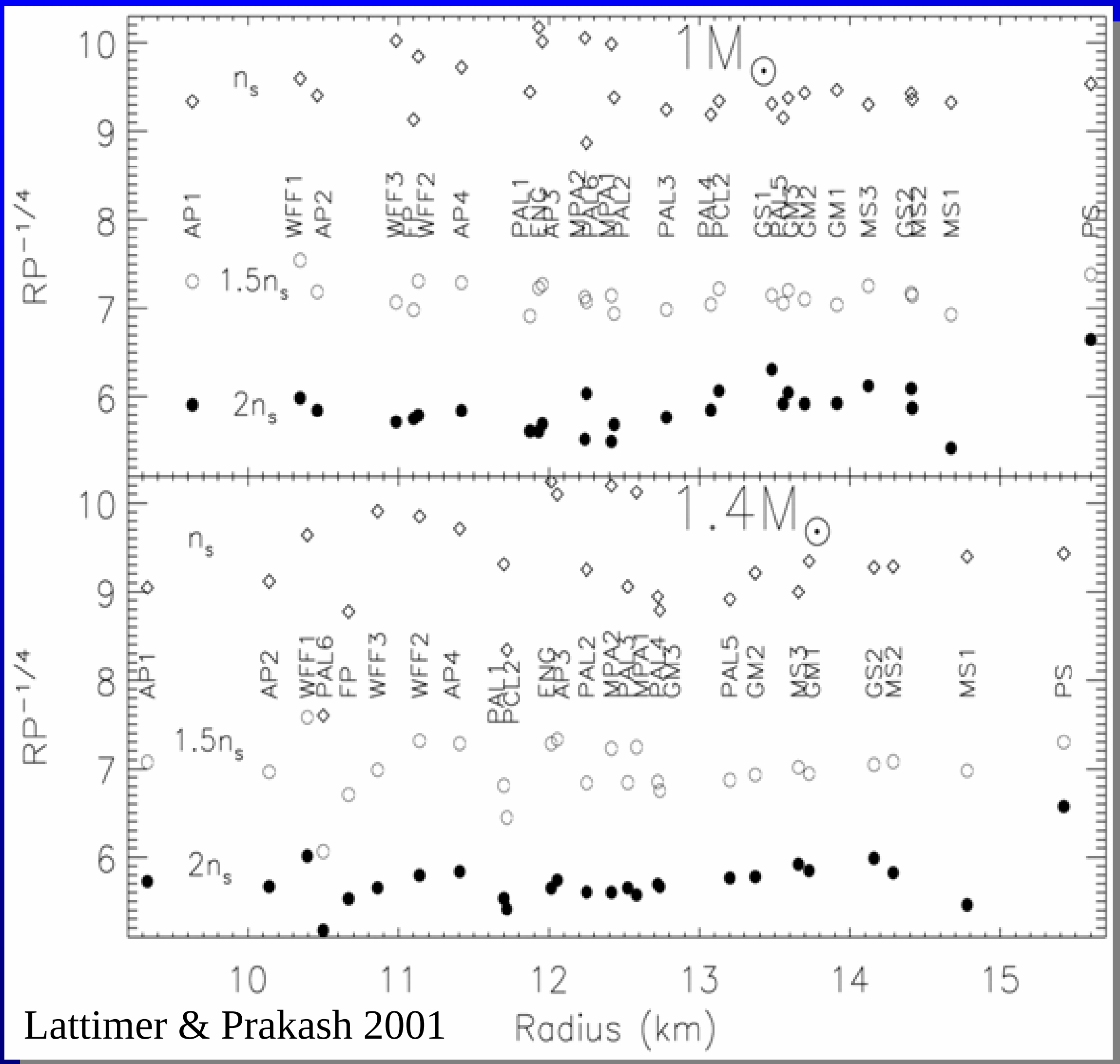
Lattimer & Prakash 2001

$$dP/dr = -\rho\, G\, M(r) / r^2$$

- Mass measurements, limits softening of EOS from hyperons, quarks, other “exotica”.
- Mass measurements limit highest possible density achievable in neutron stars (thus, in nature.

Goddard Space Flight Center

Fundamental Physics: The Neutron Star Equation of State (EOS)

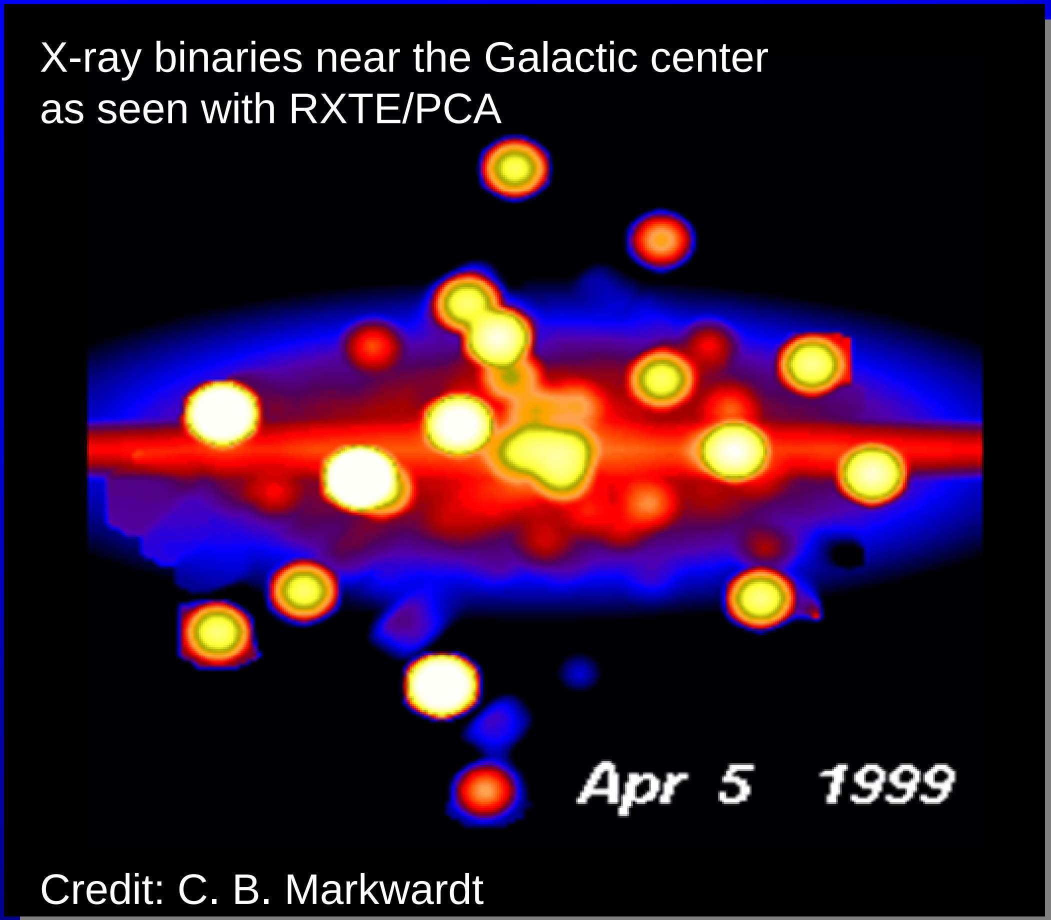


Lattimer & Prakash 2001

- R weakly dependent on M for many EOSs.
- Precise radii measurements alone would strongly constrain the EOS.
- Radius is prop. to $P^{1/4}$ at nuclear saturation density. Directly related to symmetry energy of nuclear interaction (isospin dependence).

Sources of Thermonuclear Bursts: LMXBs Containing Neutron Stars

Goddard Space Flight Center



Fun fact: a typical burst is equivalent to 100, 15 M-ton 'bombs' over each cm^2 !!

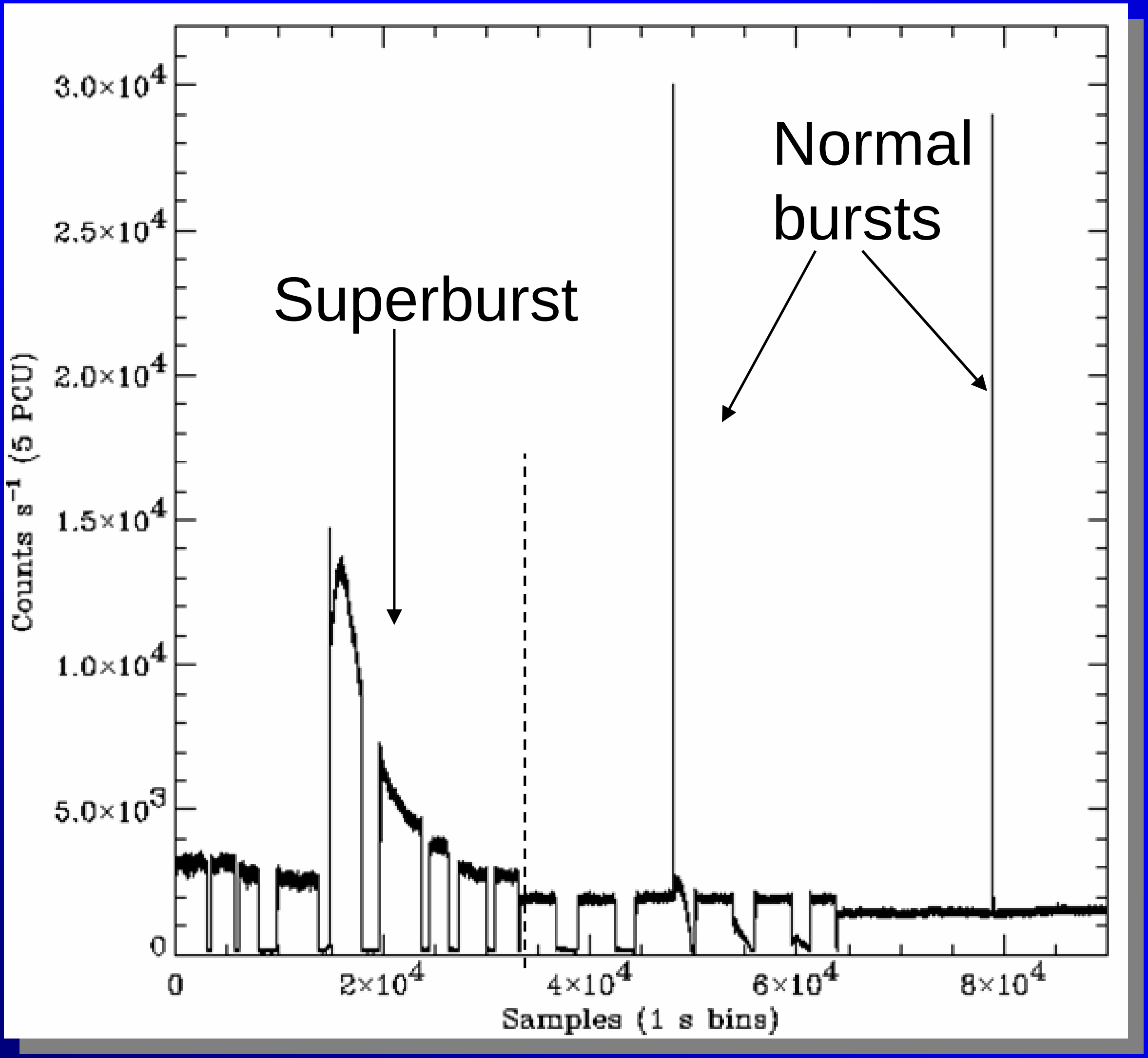
- Accreting neutron stars in low mass X-ray binaries (LMXBs).
- Approximately 70 burst sources are known.
- Concentrated in the Galactic bulge.
- Bursts triggered by thermally unstable He burning at column of few x 10^8 gm cm^{-2}
- Liberates ~ 10^{39} – 10^{43} ergs.
- Recurrence times of hours to a few days (or years).

Goddard Space Flight Center

Why Study Bursting Neutron Stars?

- X-ray bursts: seeing surface emission from neutron stars.
- “Low” magnetic fields, perhaps dynamically unimportant < 10^9 G (from presence of bursts, accreting ms pulsars).
- Accretion supplies metals to atmosphere, spectral lines may be more abundant than in non-accreting objects.
- Models suggest several tenths M_{sun} accreted over lifetime, may allow probe of different neutron star mass range, mass – radius relation, neutron star mass limit.
- However, presence of accretion may also complicate interpretation of certain phenomena.

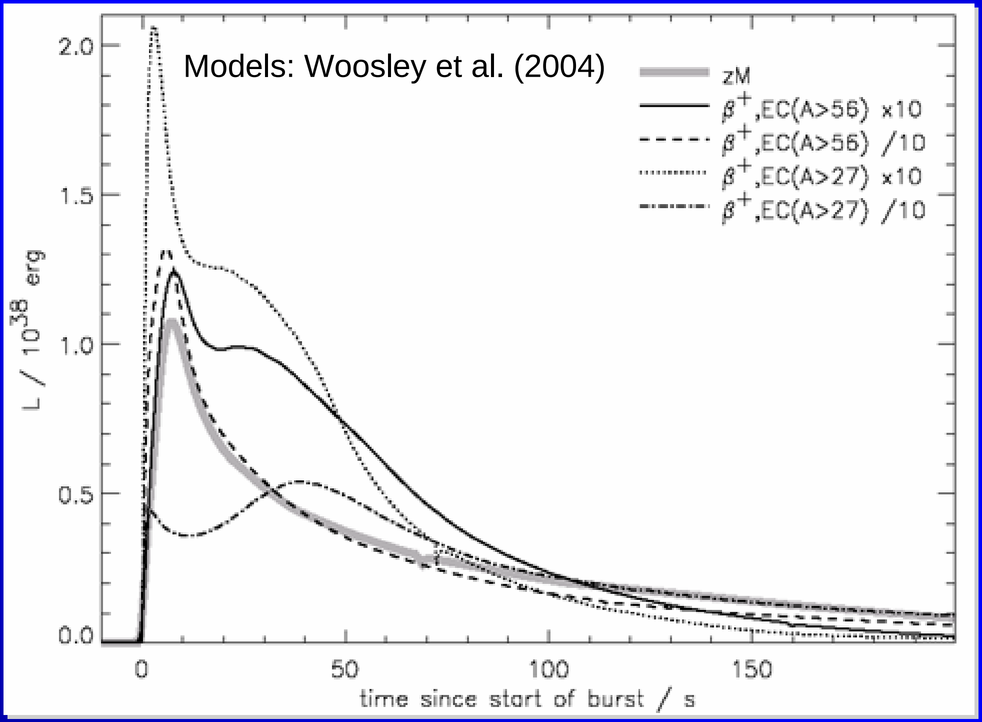
Accreting Neutron Star binaries: What do we see?

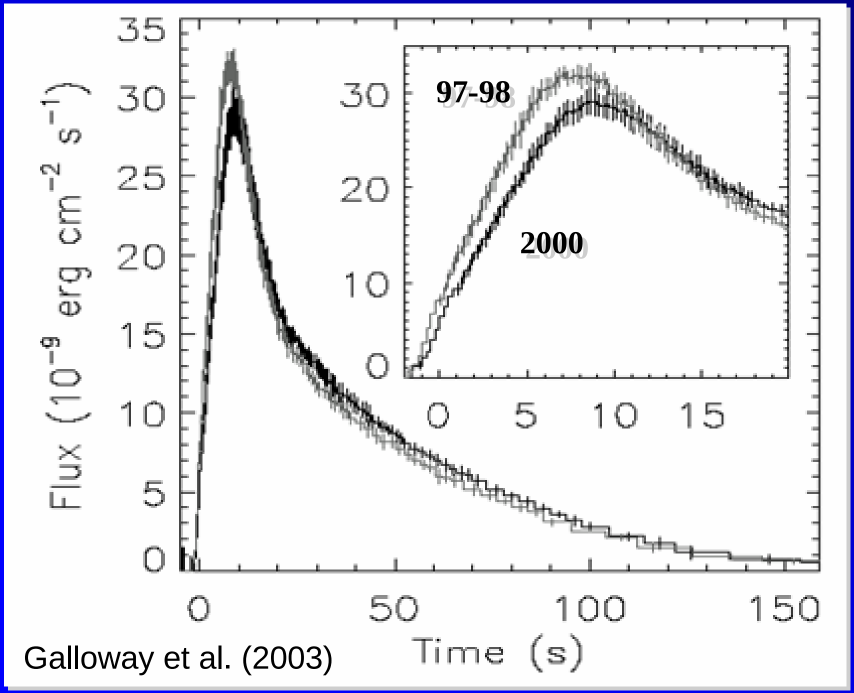


- Accretion of matter converts gravitational potential energy to radiation (X-rays, persistent flux)
- At various accretion rates, thermonuclear instabilities occur in the accreted material. X-ray bursts.
- Can produce normal bursts (hours to days) and superbursts (years).

Goddard Space Flight Center

X-ray Bursts: Nuclear Reactions on Neutron Stars





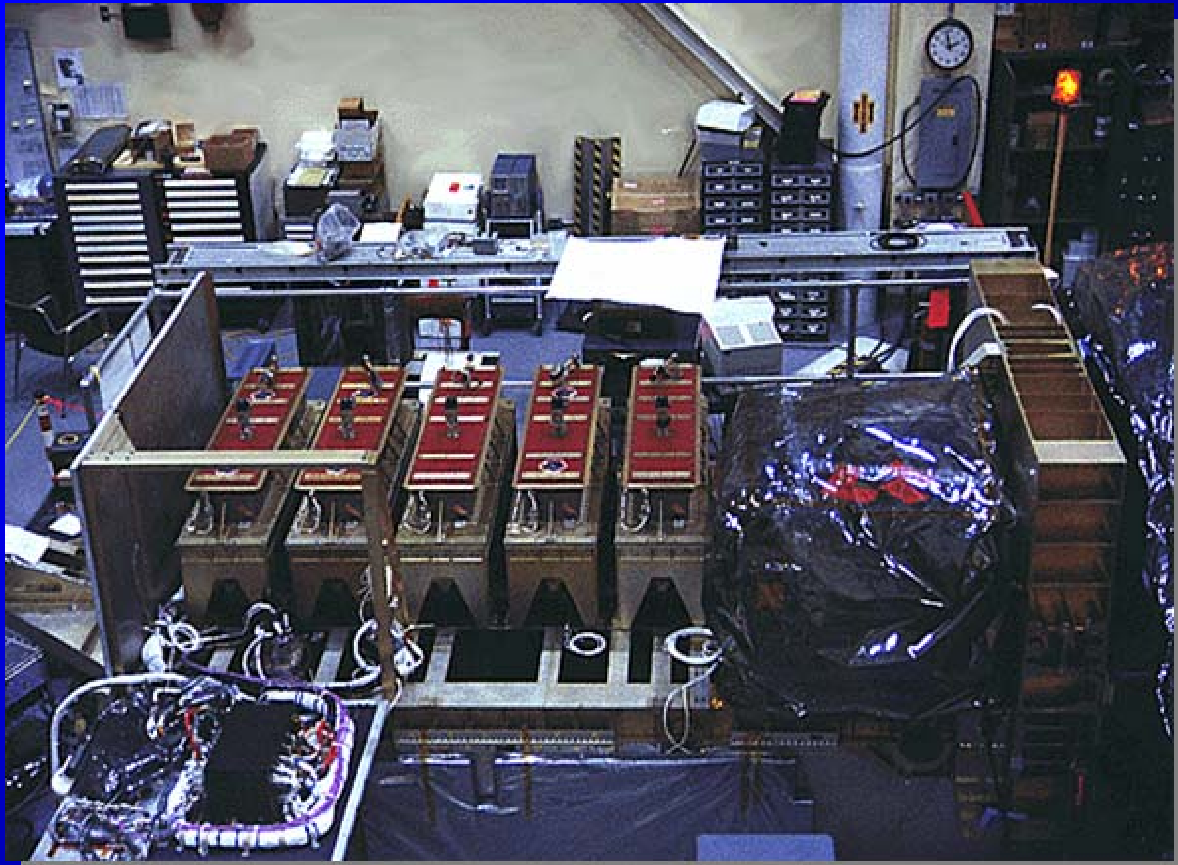
- Accreted light elements undergo extensive nuclear processing, rp-process important when significant hydrogen present.
- Unstable burning produces X-ray bursts; superbursts and normal bursts.
- Ignition, propagation and energy production with time depend on detailed nuclear processes, rp process burning produces bursts with ~100 s durations.
- Bursts with pure helium are shorter, 10 - 20 s.

NASA's Rossi X-ray Timing Explorer (RXTE)

Goddard Space Flight Center

Launched in December, 1995, 10th anniversary approaching, party at Goddard (week of AAS meeting in DC)!

http://heasarc.gsfc.nasa.gov/docs/xte/xte_1st.html

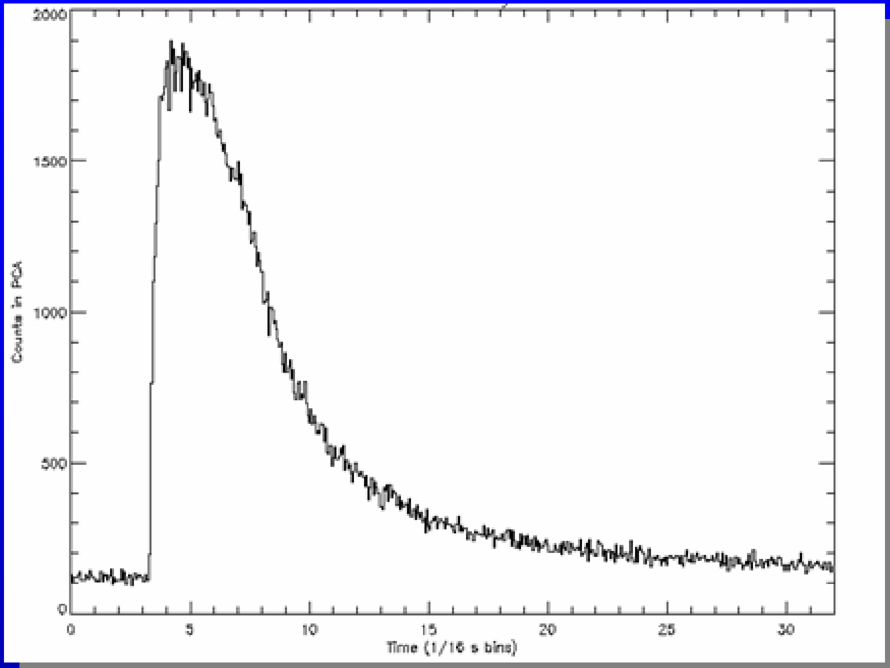


RXTE's Unique Strengths

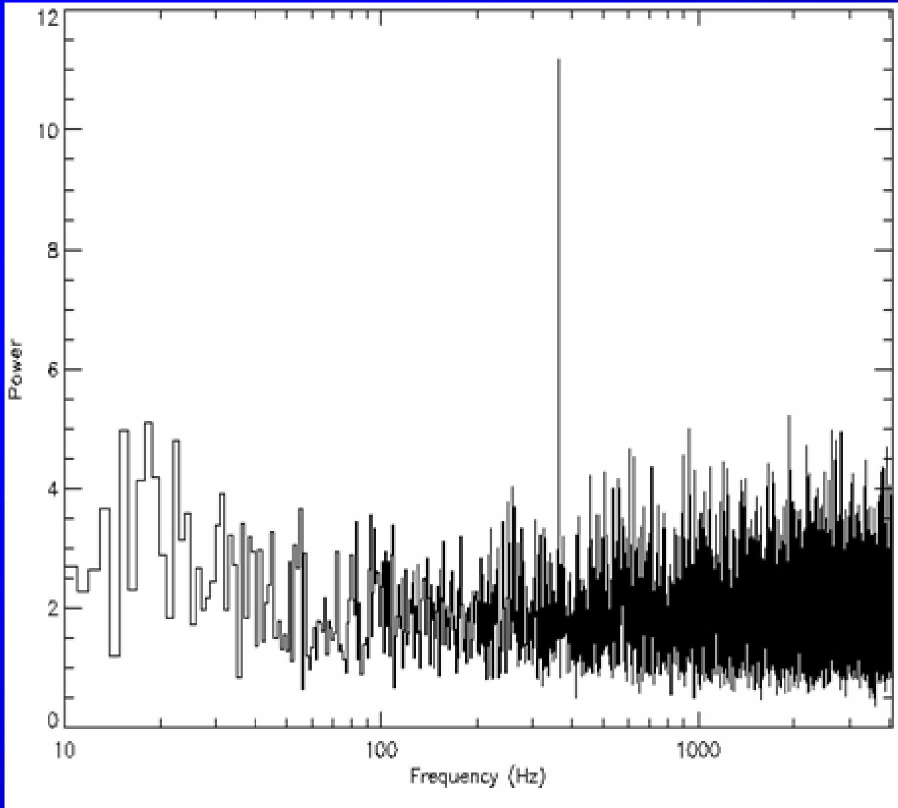
- Large collecting area
- High time resolution
- High telemetry capacity
- Flexible observing

Discovery of 363 Hz Burst Oscillations from 4U 1728-34

Goddard Space Flight Center



- Discovered in Feb. 1996, shortly after RXTE's launch (Strohmayer et al, 1996)
- First indication of ms spins in accreting LMXBs.



- 4U 1728-34, well known, reliable burster.
- Power spectra of burst time series show significant peak at 363 Hz.

Goddard Space Flight Center

Source Summary

Sources	Frequency (Hz)	Separation (Hz)
KS 1731-26	524	260
4U 1728-34	363	363 – 280
Galactic Center	589	Unknown
4U 1636-53	581	276 – 251
Aql X-1	549	Unknown
4U 1702-429	330	330
X1658-298	567	Unknown
4U 1916-053	270	290-348
4U 1608-52	619	312
SAX J1808-365	401*	200
SAX J1750-290	601	Unknown
XTE J1814-338	314*	Unknown

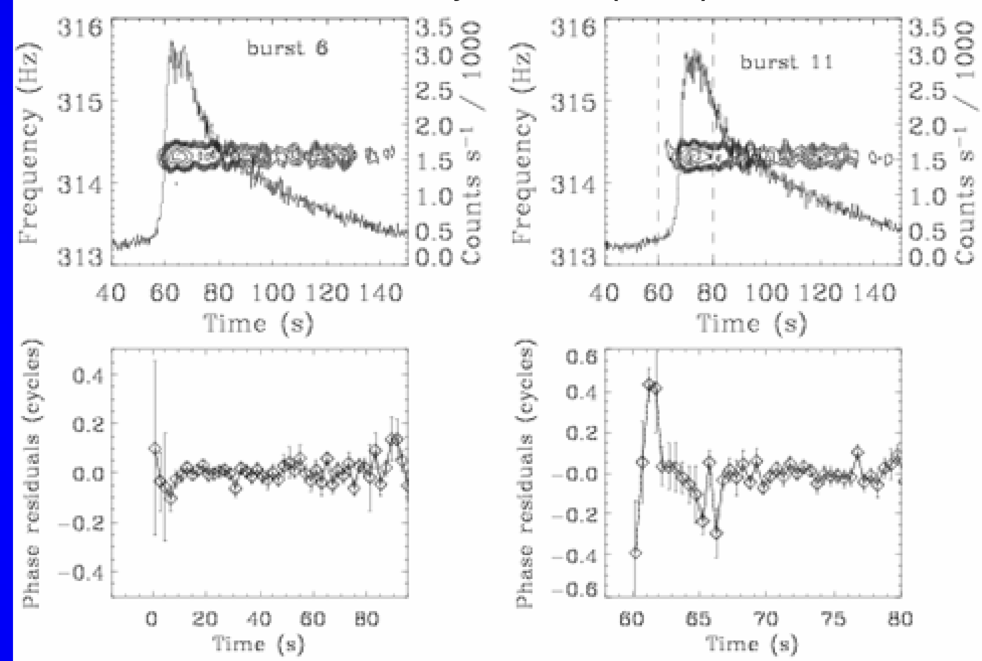
*millisecond pulsar

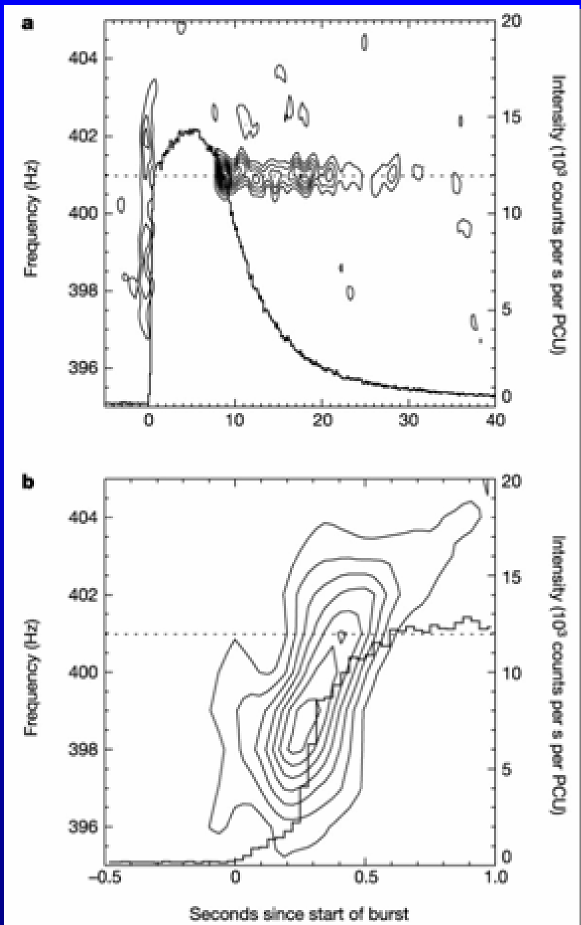
EXO 0748-676 45 Hz

Goddard Space Flight Center

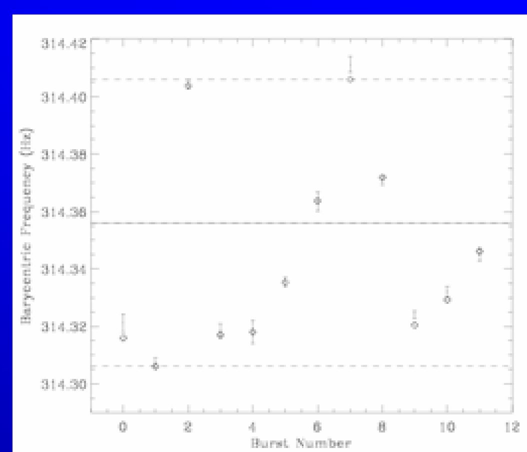
X-ray Bursts from Accreting ms Pulsars: SAX J1808 and XTE J1814

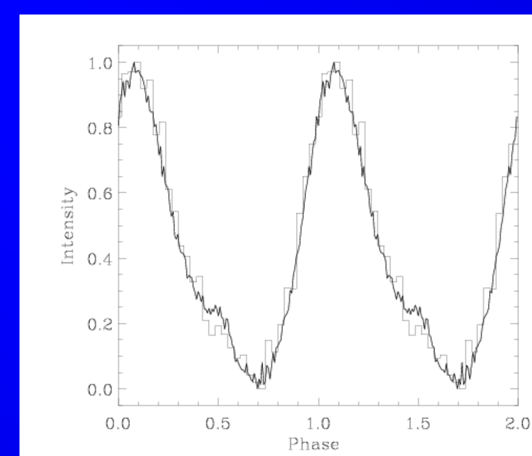
XTE J1814-338: Strohmayer et al. (2003)





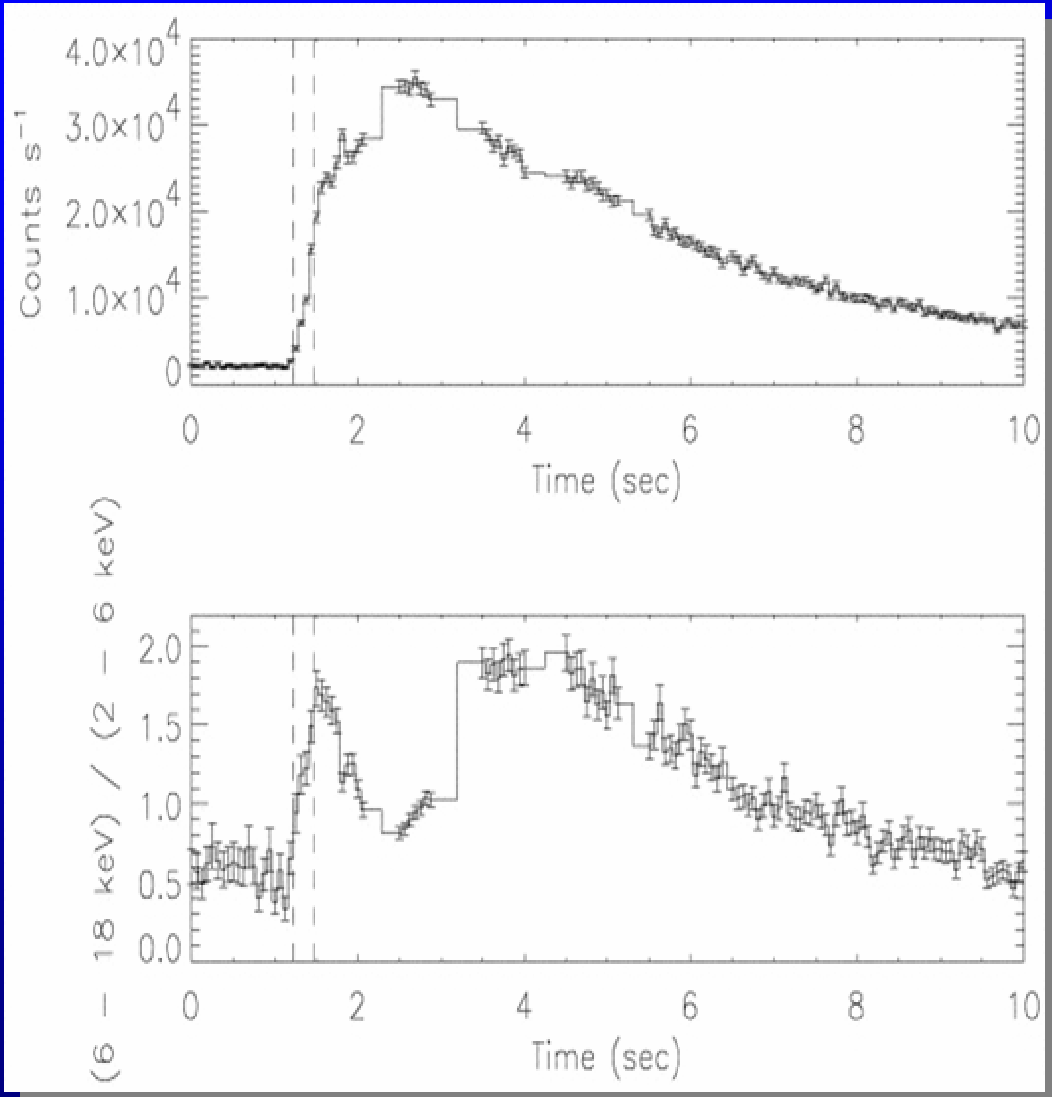
SAX J1808: Chakrabarty et al. (2003)

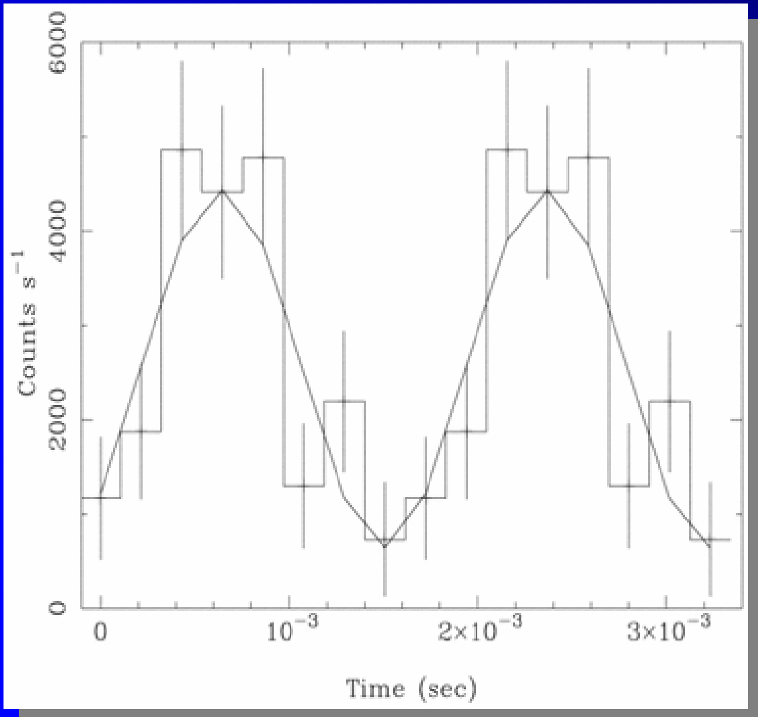




Goddard Space Flight Center

Burst Oscillation Amplitudes at Onset



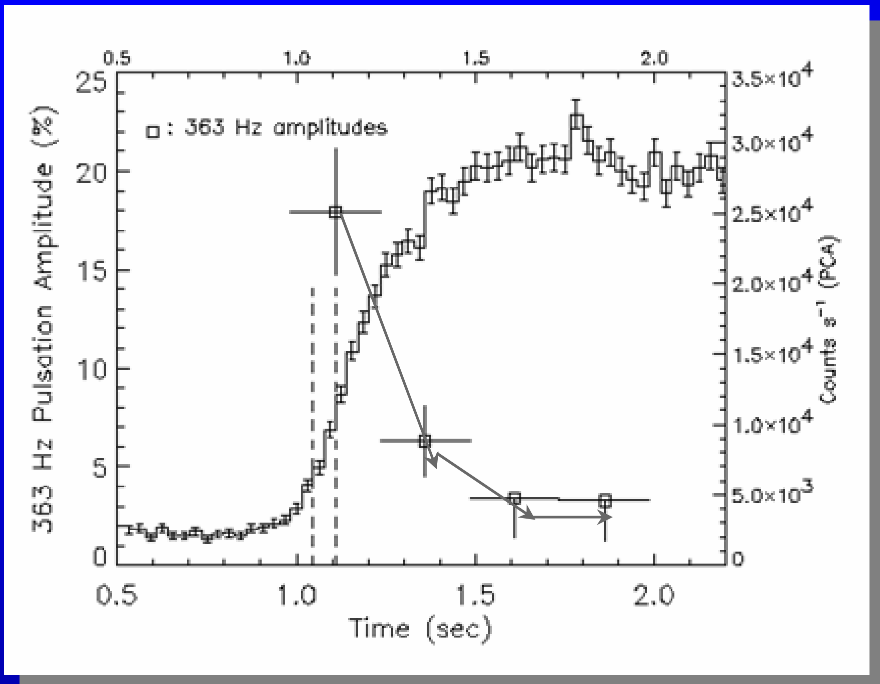


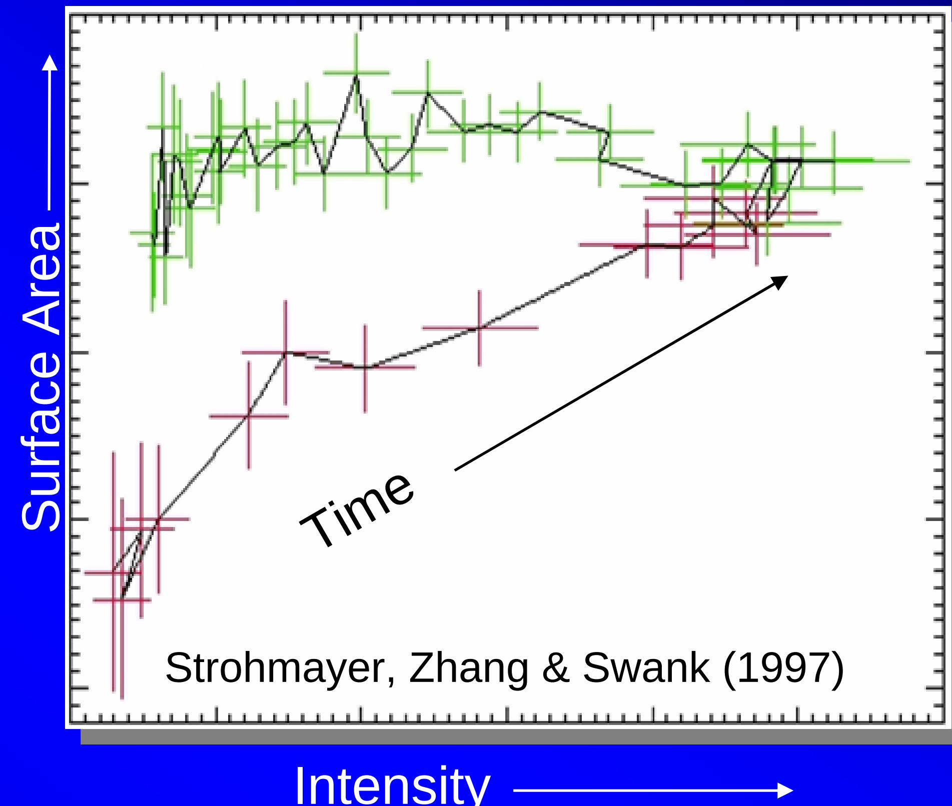
- Oscillations at rising edge approach 100% modulation of the burst flux (persistent flux level subtracted).

4U 1636-53: Strohmayer et al. (1998)

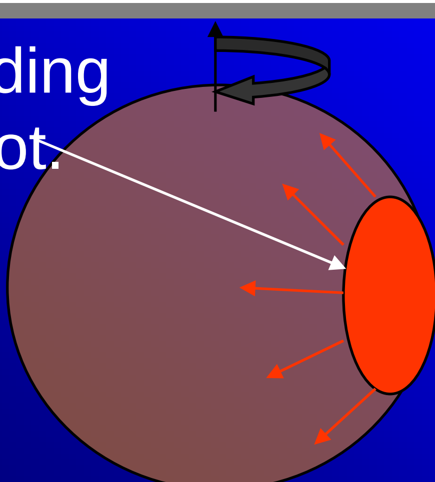
Goddard Space Flight Center

Timing and Spectral Evidence for Rotational Modulation





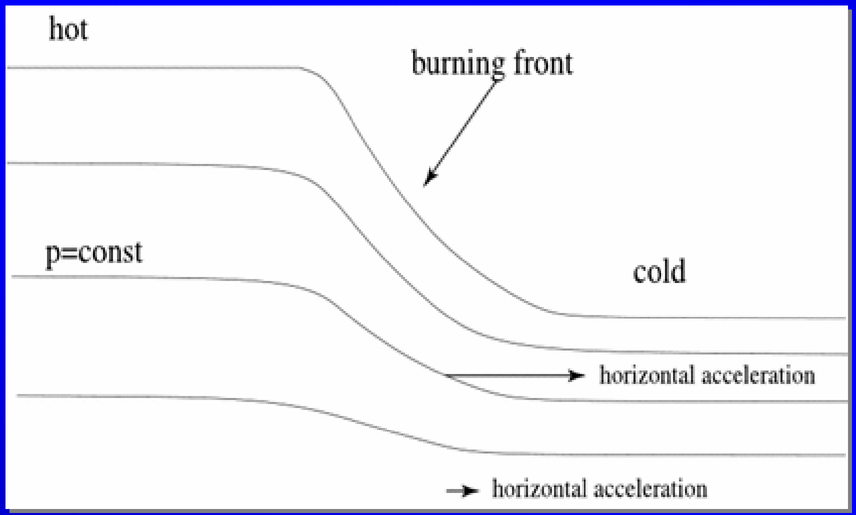
Spreading hot spot.



- Oscillations caused by hot spot on rotating neutron star
- Modulation amplitude drops as spot grows.
- Spectra track increasing size of X-ray emitting area on star.

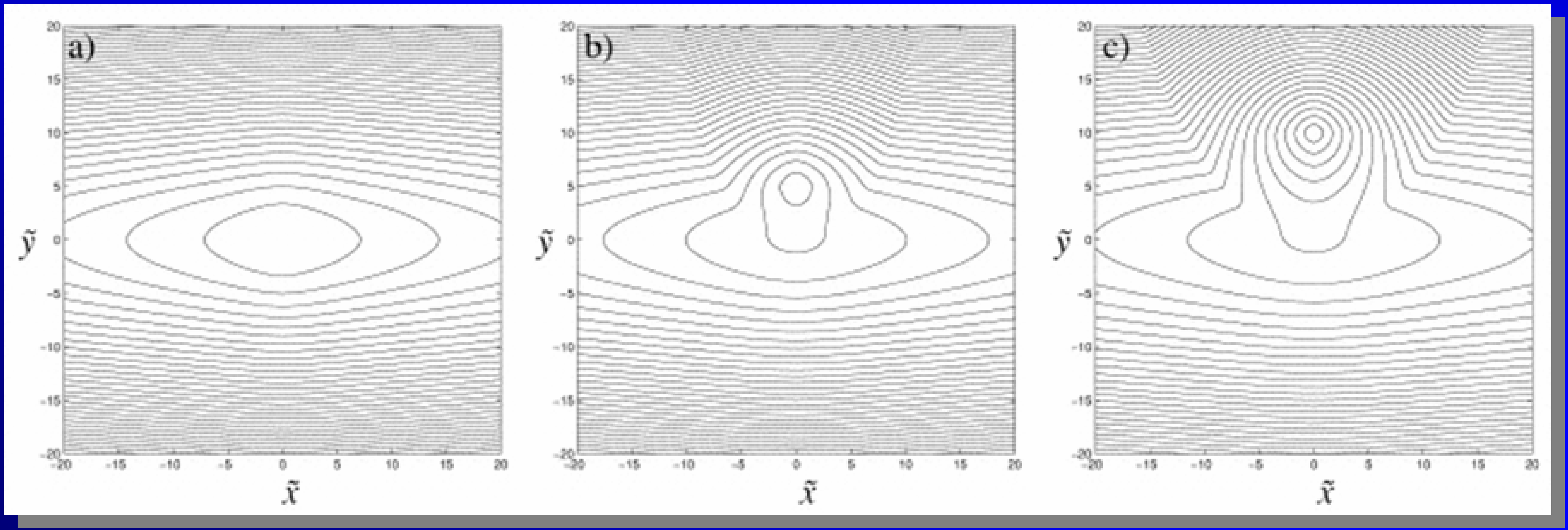
Extreme Weather on Neutron Stars

Goddard Space Flight Center



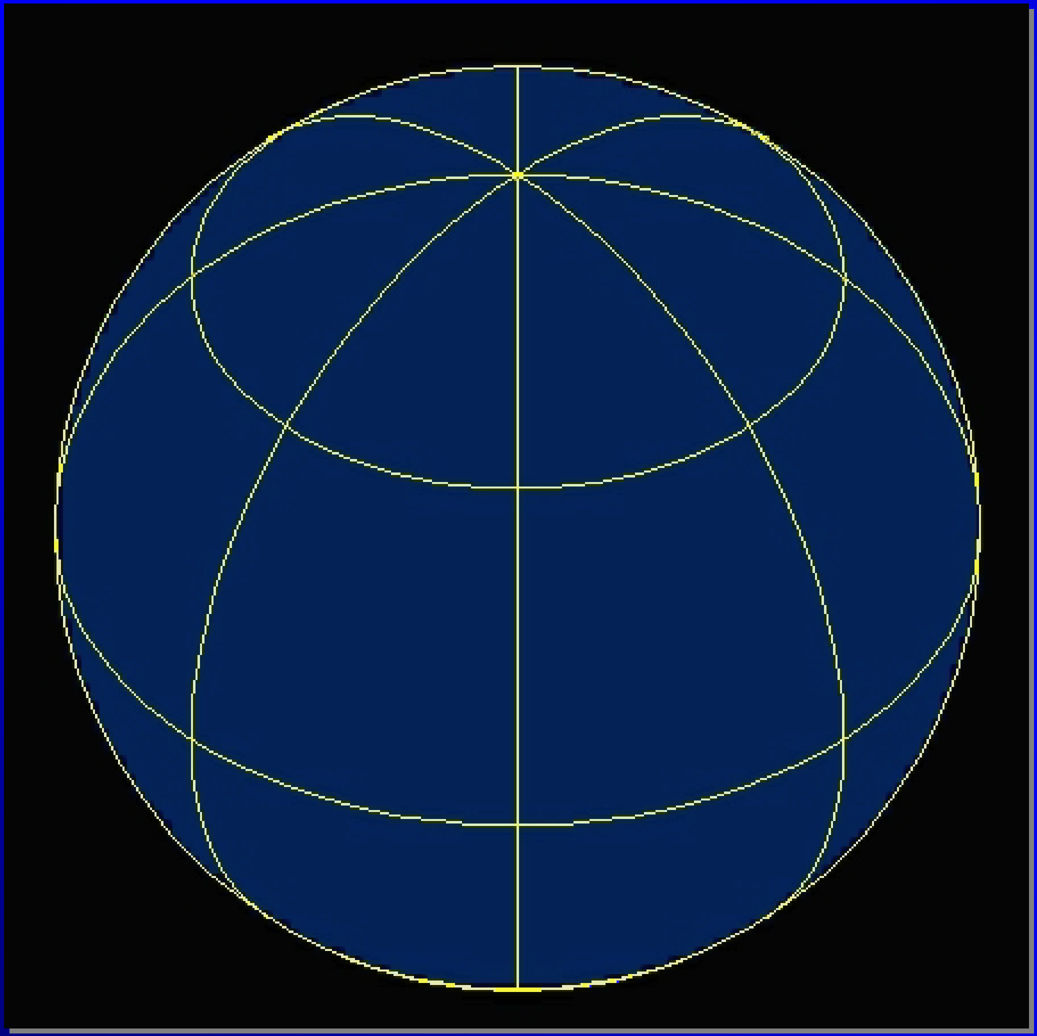
From Spitkovsky, Levin & Ushomirsky (2002)

- Spitkovsky, Levin & Ushomirsky (2002) explored burning front propagation on rotating neutron stars.
- Burst heating and Coriolis force drive zonal flows; vortices and retrograde flows may account for late time asymmetry and frequency drifts.



Goddard Space Flight Center

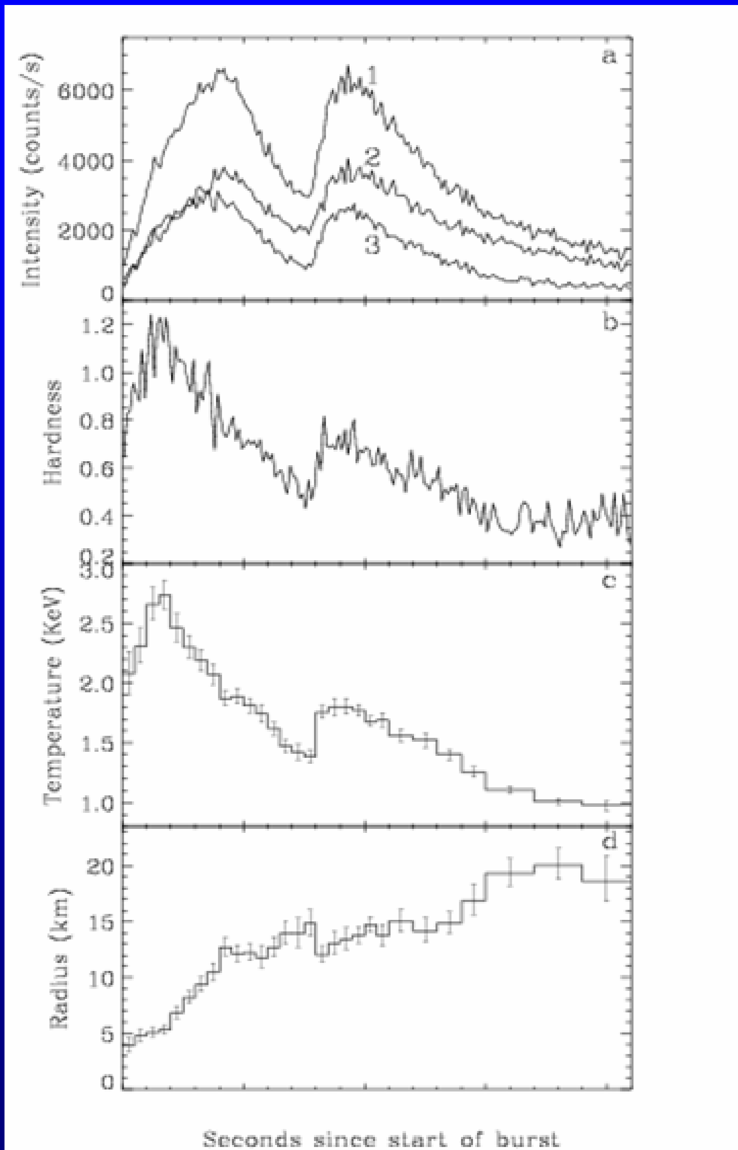
Burst Oscillations: Ignition and Spreading.



Thanks to Anatoly Spitkovsky!

- Combining spreading theory (Spitkovsky, Levin & Ushomirsky 2002), with burning calculations (Schatz, Bildsten, Cumming, Heger, Woosley…), can give detailed predictions for hot spot geometry and lightcurves.
- Comparison with precision measurements can probe various burning physics as well as the neutron star properties.

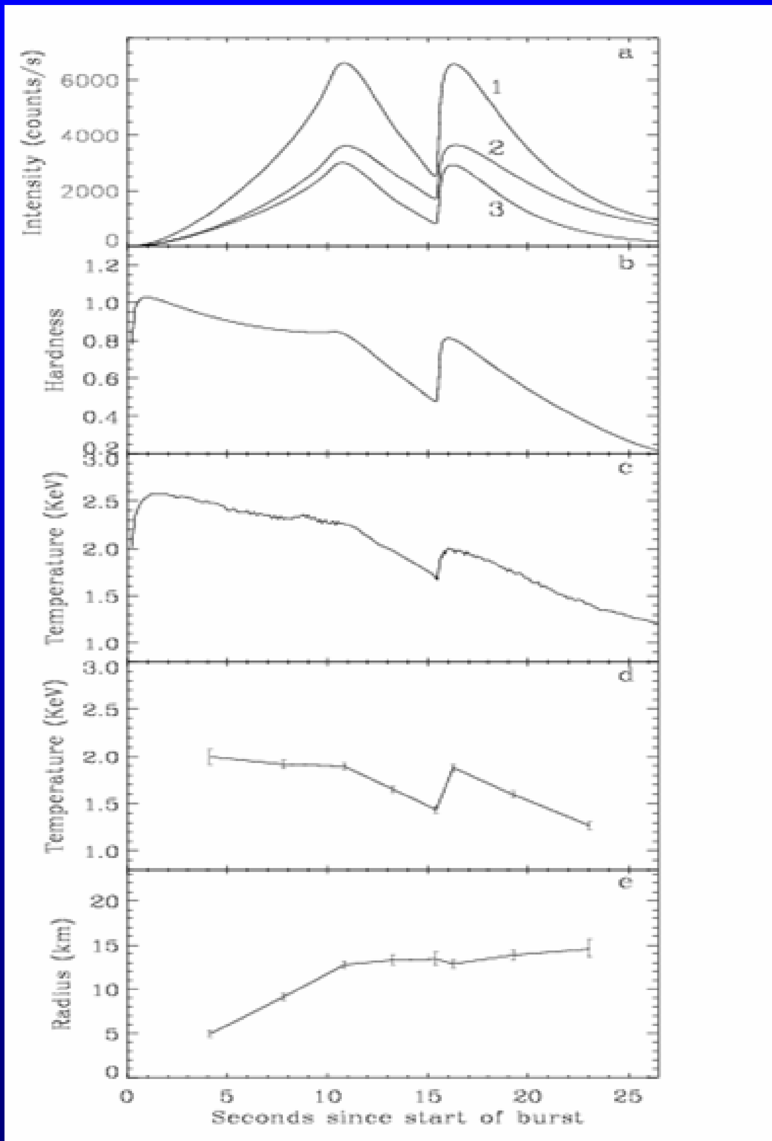
Double-peaked bursts: A Spreading Phenomenon?



- A small fraction of bursts show multiple peaks NOT associated with photospheric radius expansion (4U 1636-53, a famous example).
- These are sub-Eddington in peak flux.
- Several models proposed: 1) shear instability (Fujimoto): 2) “Delayed” nuclear energy release (Fisker et al.).
- All of these “one dimensional” in some sense

Bhattacharyya & Strohmayer (2005)

Double-peaked bursts: A Spreading Phenomenon?

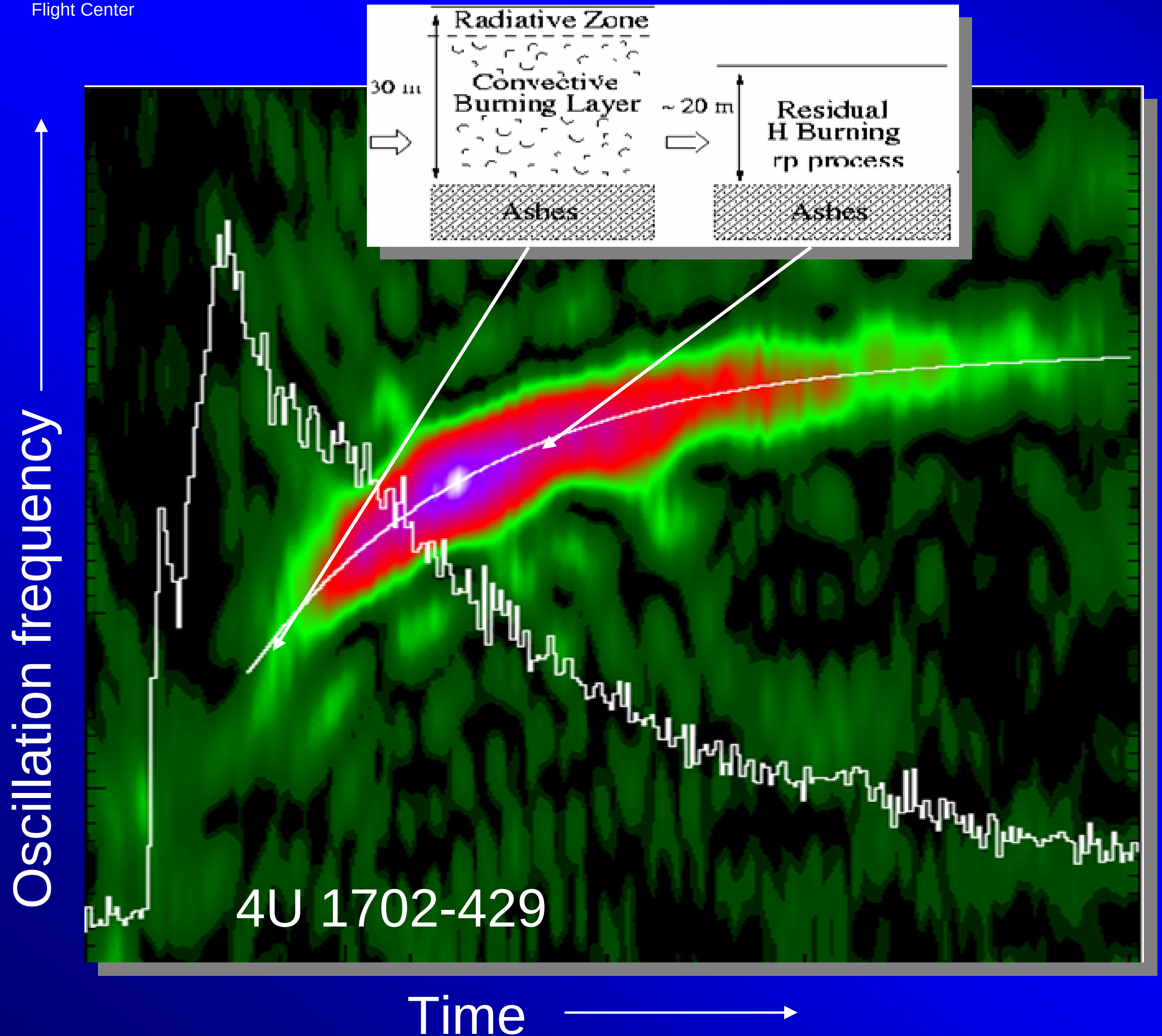


- We explore spreading in a manner analogous to Spitkovsky et al (2002).
- Using fully relativistic model of photon propagation from NS surface (Bhattacharyya et al. 2005).
- Spreading from equator appears implausible.
- Spreading from a pole with front "stalling" near equator can qualitatively explain observed properties.

Bhattacharyya & Strohmayer (2005)

Puzzle # 1: Frequency Evolution of Burst Oscillations

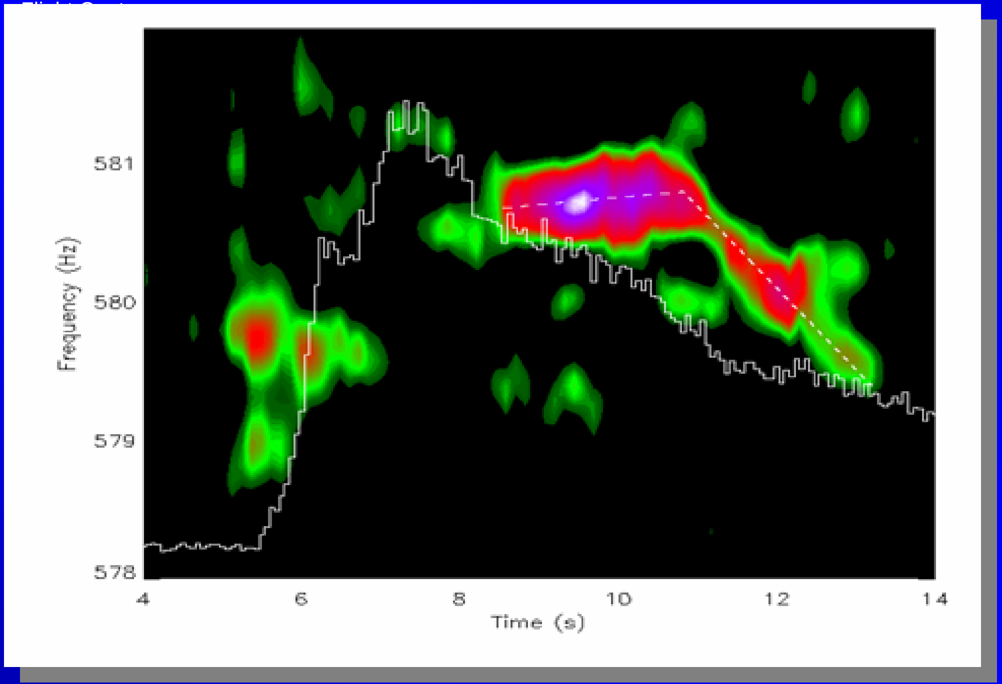
Goddard Space Flight Center

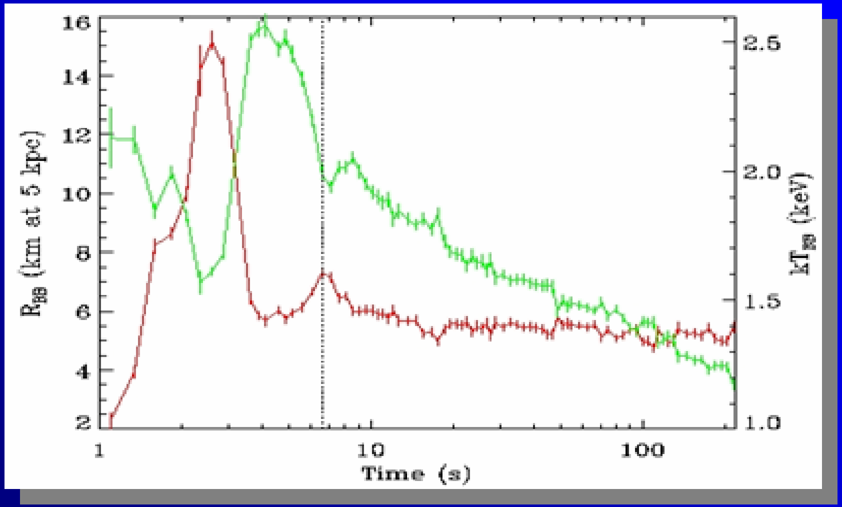


- Expanding layer slows down relative to bulk of the star.
- Change in spin frequency crudely consistent with expected height increase, but perhaps not for most extreme variations.
- X-ray burst expands surface layers by ~ 30 meters.

Goddard Space

Spin Down of Burst Oscillations in 4U1636-53



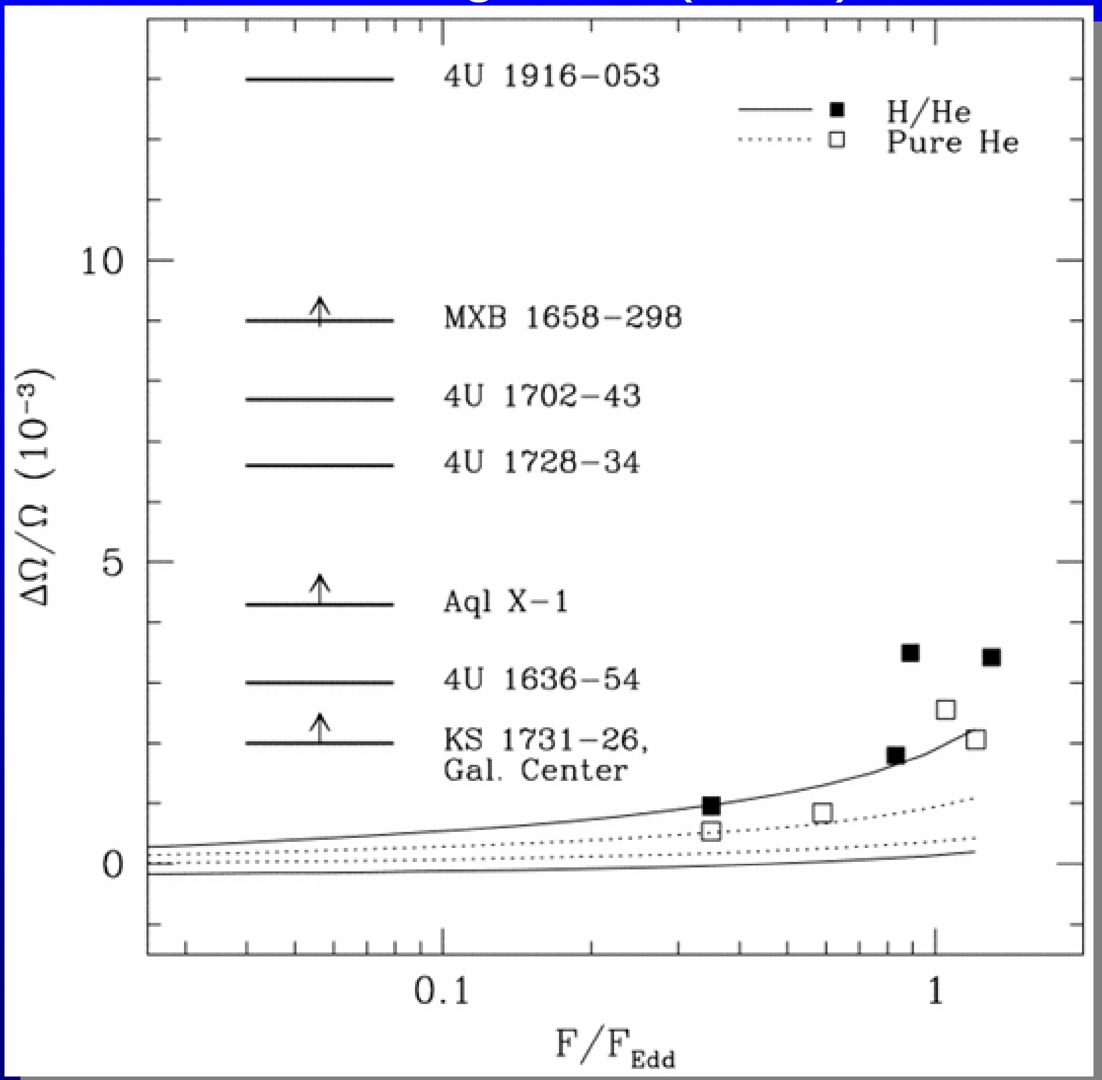


- A small fraction of bursts show episodes of spin down (Miller 1999; Strohmayer 1999).
- Spin down in 4U 1636-53 is associated with extended thermal tail and transition evident in spectral evolution.
- Magnitude of spin down may reflect an expansion of the surface layers by only 10 - 30 meters!

Frequency Drifts due to Hydrostatic Expansion

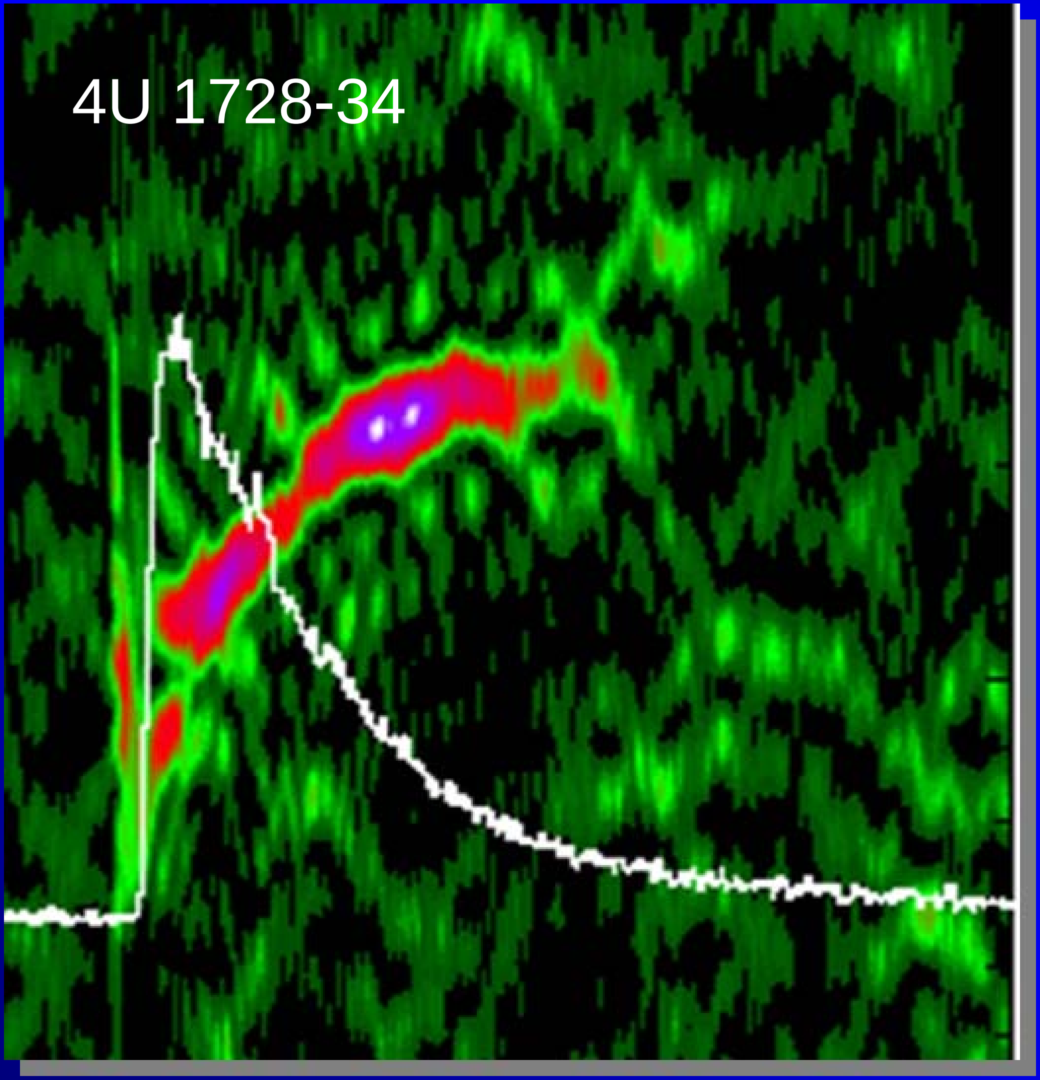
Goddard Space Flight Center

From Cumming et al. (2002)



- Fractional frequency shifts appear to be a bit too large in some sources for hydrostatic expansion alone
- If differential rotation persists, then top layers can spin down enough, but seems unlikely.
- Hydrodynamics important?

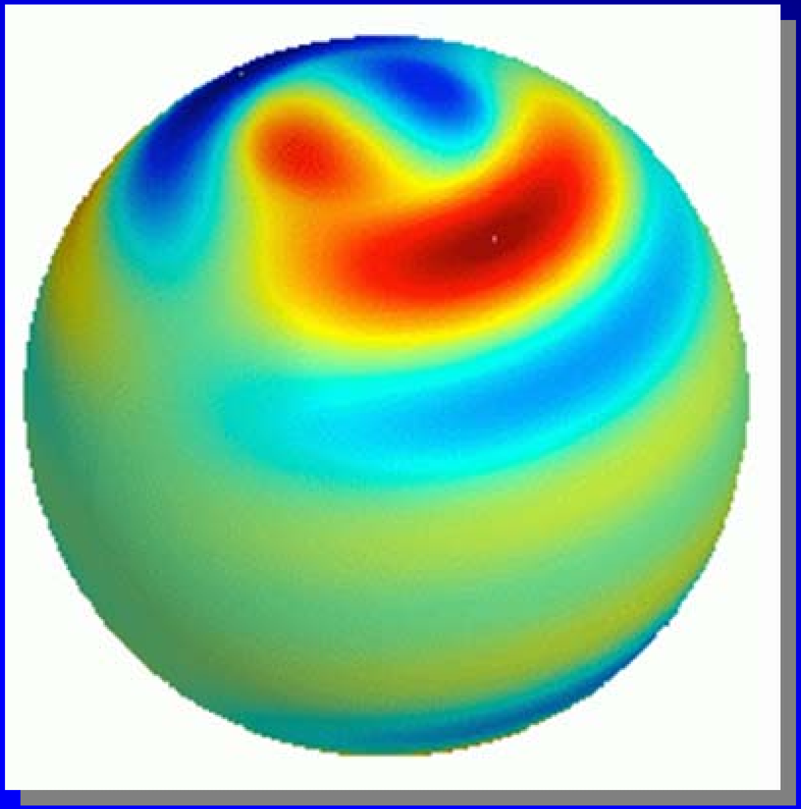
Puzzle # 2: Oscillations in the Cooling Phase



- Pulsations in the cooling tails can be as large as 15% (rms)
- If the whole surface is burned, what causes the flux asymmetry?
- Cooling time asymmetry is probably not large enough
- Oscillation modes (Heyl 2002 suggests *r*-modes; Piro & Bildsten 2005, Lee & Strohmayer 2005, Heyl 2005) ?

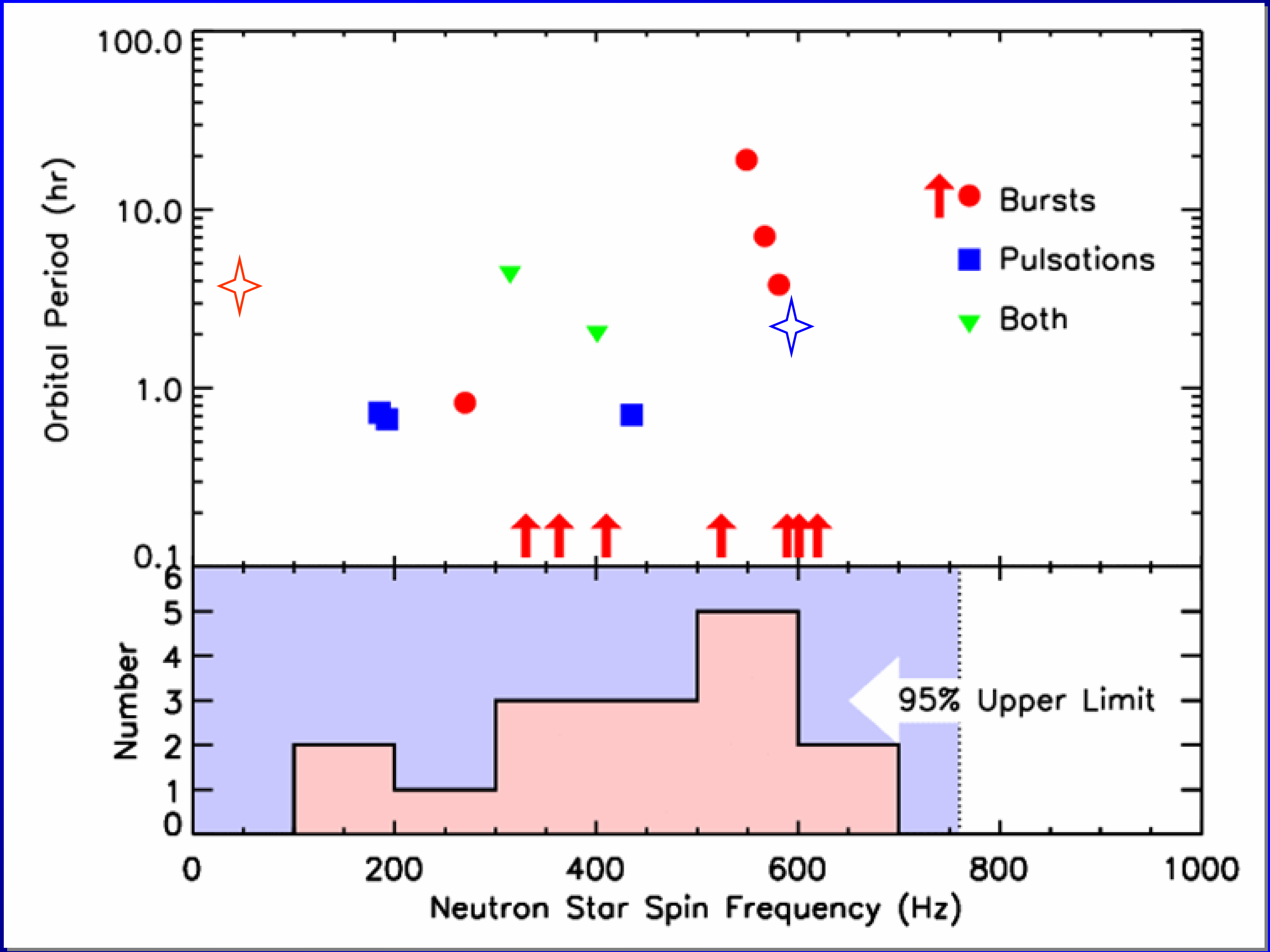
What Breaks the Symmetry?

- Global Oscillation modes could provide late time asymmetry.
- Heyl suggested r-modes. Recent work by Lee & Strohmayer (2005), Heyl (2005). Are the modes unstable?
- Piro & Bildsten (2005), suggest connection with crustal interface mode, to account for frequency stability.
- Cumming (2005) finds dynamically unstable shear modes, associated with differential rotation, perhaps “self-excited” by bursts.



Cumming (2005)

Neutron Star Spins

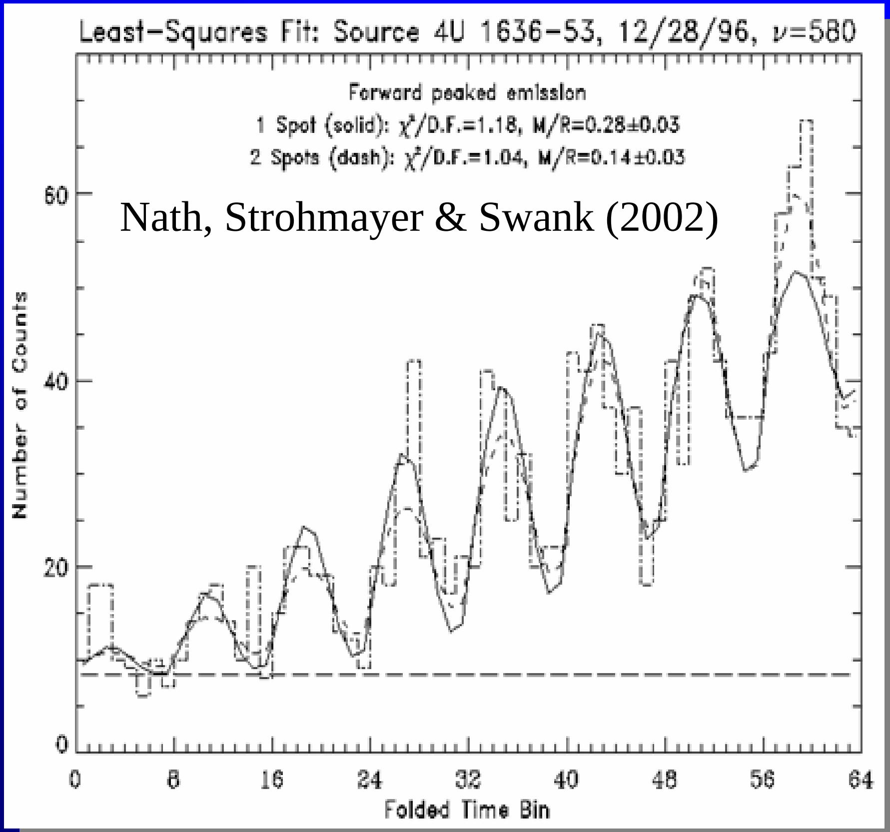


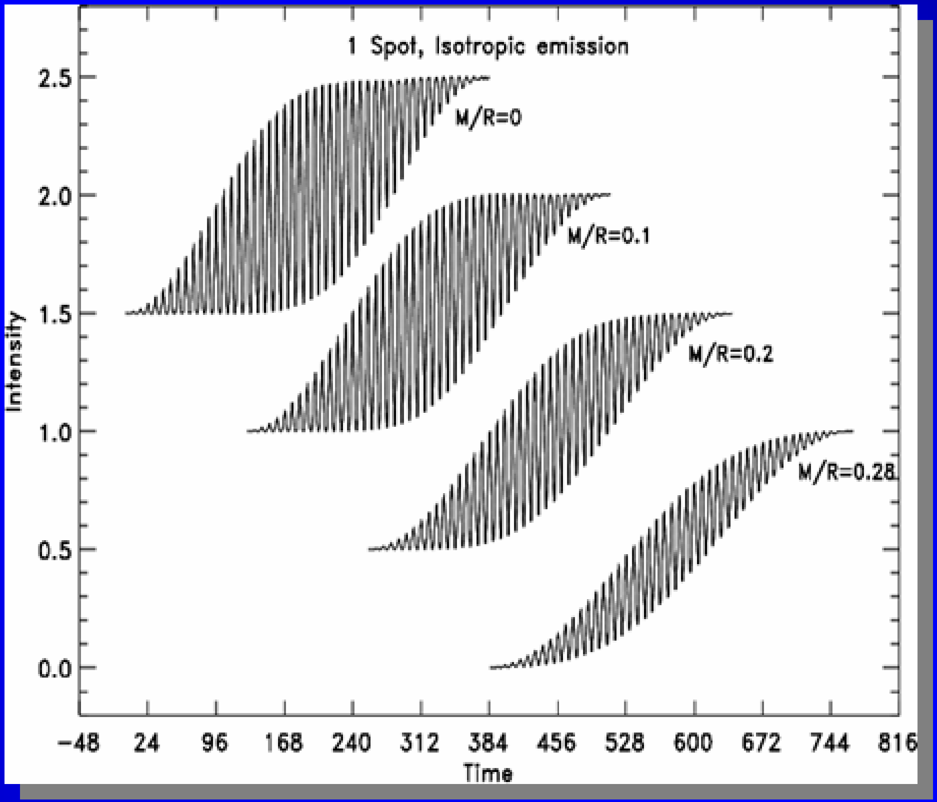
Chakrabarty et al. (2003) suggest upper limit to neutron star spin frequencies

Burst Oscillations Probe the Structure of Neutron Stars

Goddard Space Flight Center

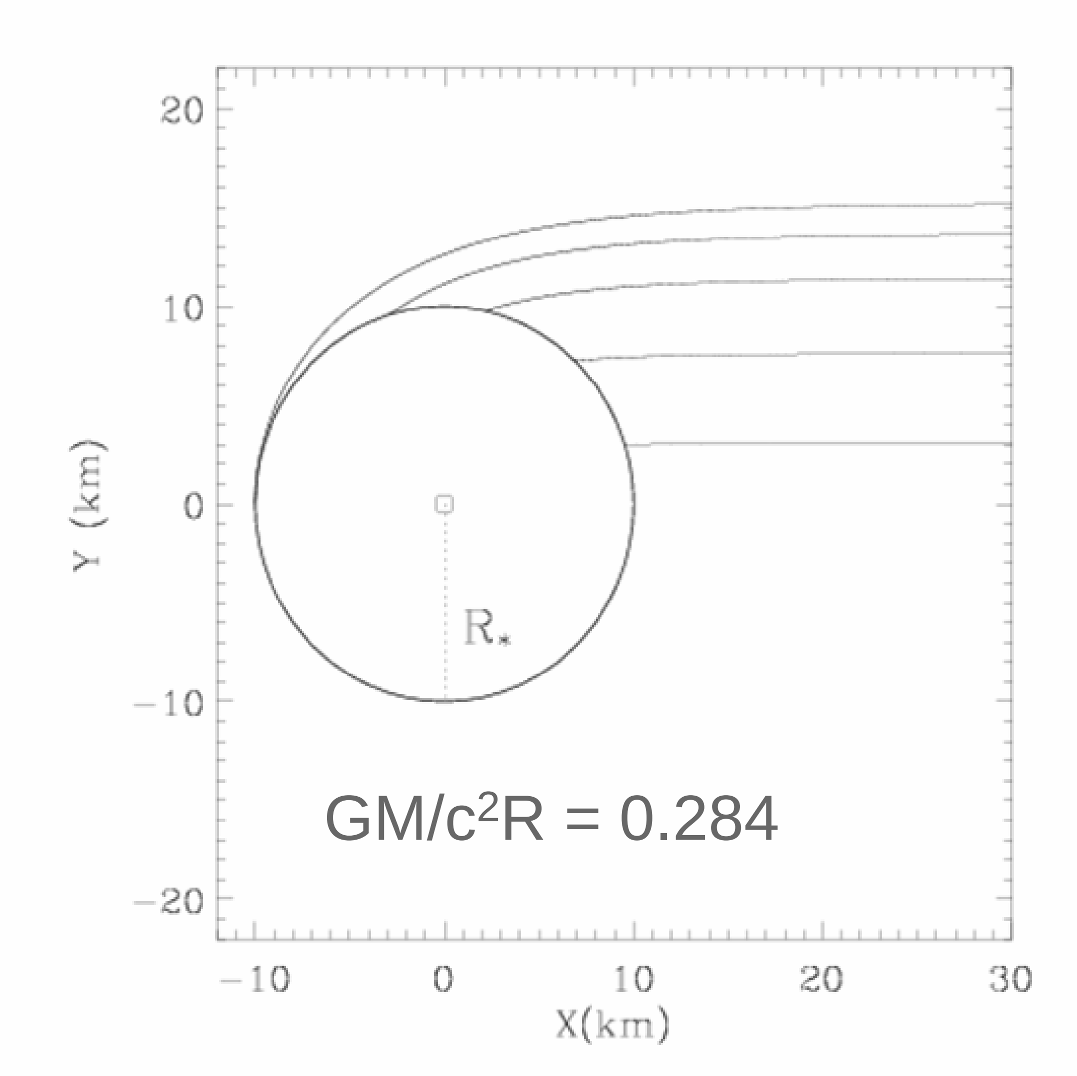
- Pulse strength and shape depends on M/R or ‘compactness’ because of light bending (a General Relativistic effect).
- More compact stars have weaker modulations.
- Pulse shape (harmonic content) depends on relativistic rotational speed, which depends on R (ie. spin frequency known).





Rotational Modulation of Neutron Star Emission: The Model

Goddard Space Flight Center

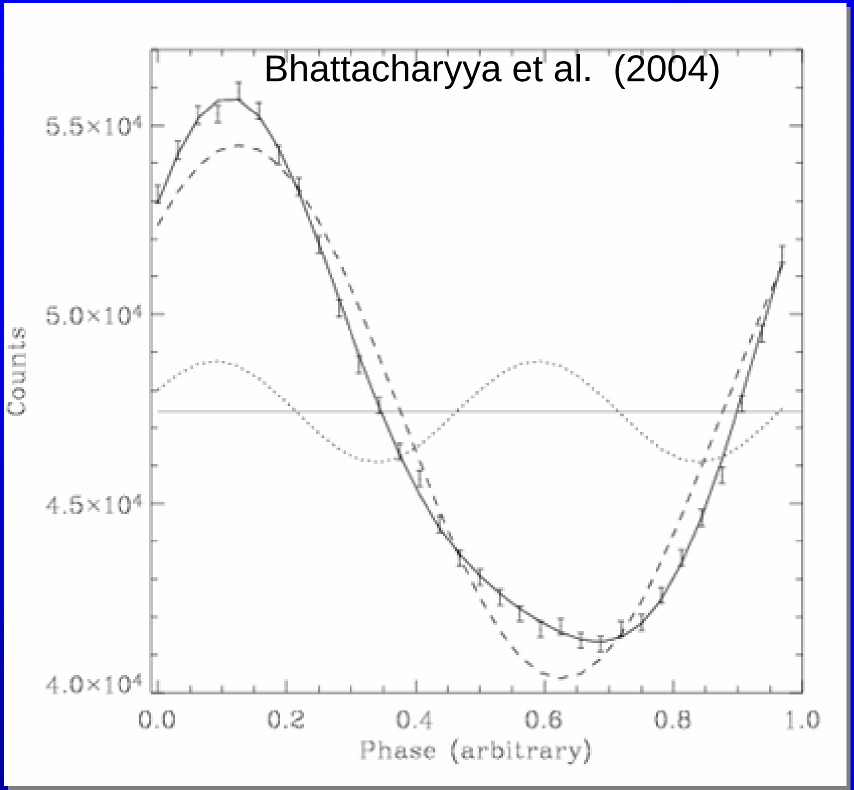


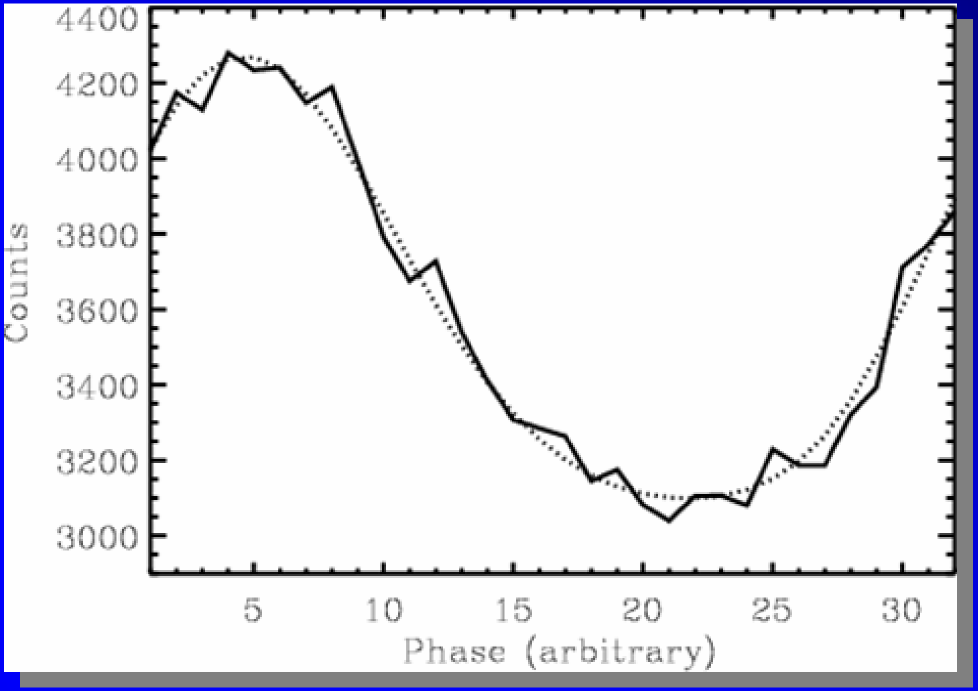
- Gravitational Light Deflection: Kerr metric with appropriate angular momentum.
- Gravitational redshift
- Rotational doppler shifts and aberration of the intensity.
- "Beaming" of intensity in NS rest frame.
- Arbitrary geometry of emission regions.
- Self-consistent neutron star structure (several EOSs).

Bhattacharyya, Strohmayer, Miller & Markwardt (2005).

Goddard Space Flight Center

Mass – Radius Constraints: Recent Results: XTE J1814-338





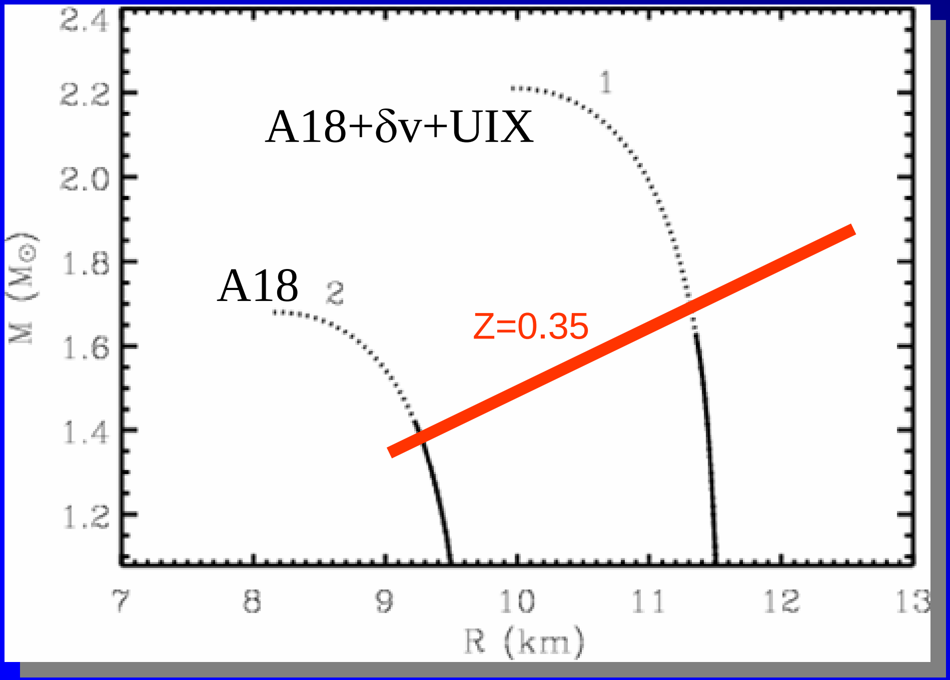
- 27 X-ray bursts from XTE J1814-338 (ms pulsar).
- High signal to noise burst oscillation profiles, with first ever harmonics.
- Phase resolved profiles in 5 energy bands.

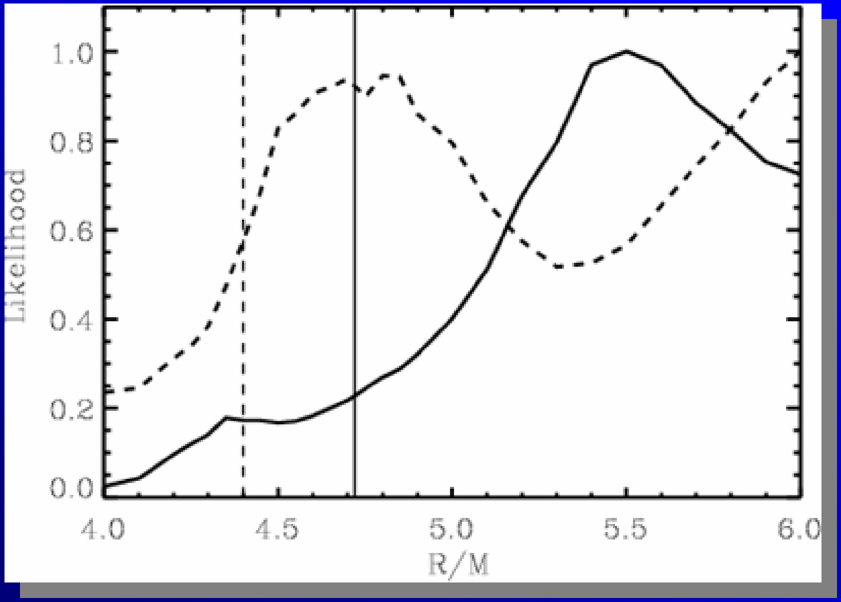
- Use Bayesian method, determine likelihoods for each combination of parameters (uniform priors).
- Parameters: R/M, spot location and size (2), beaming exponent, observers inclination angle. Fix surface temperature (BB).

Compactness limits from pulse fitting in XTE J1814-338

Goddard Space Flight Center

- Results for two representative EOSs (soft and stiff).
- Model provides an acceptable fit in the χ^2 sense.
- R/M distributions peak in "reasonable" range. R/M > 4.2.
- Likelihoods do not yet favor a particular EOS.

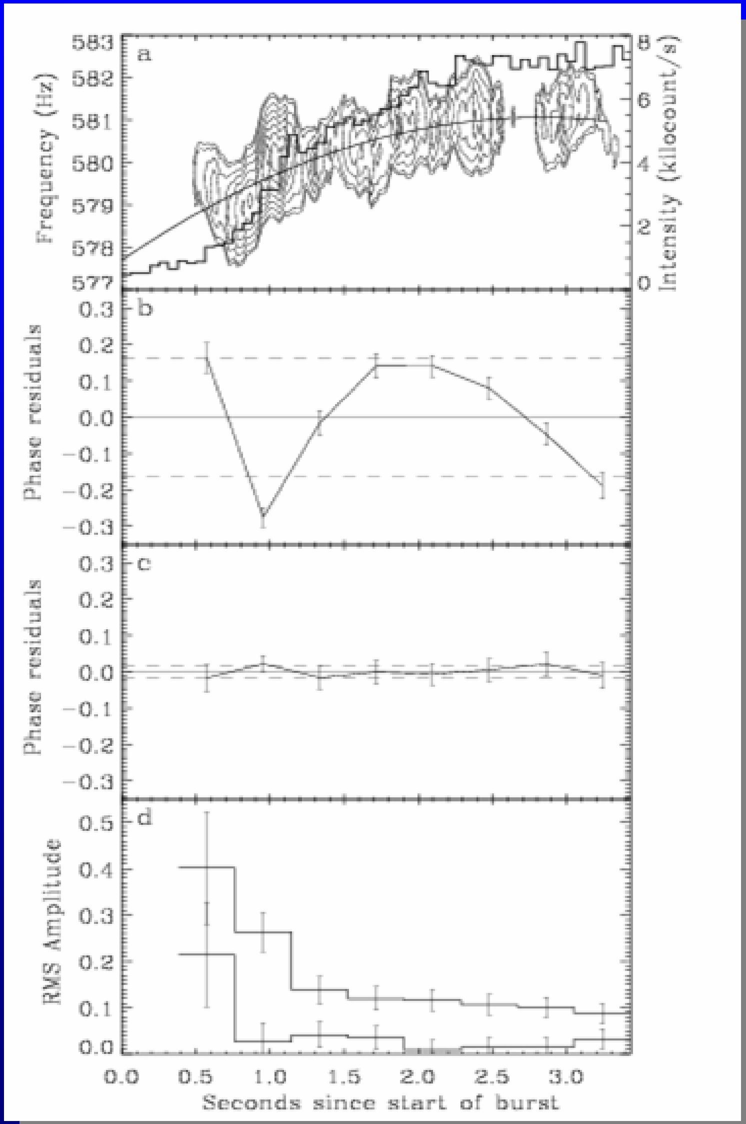


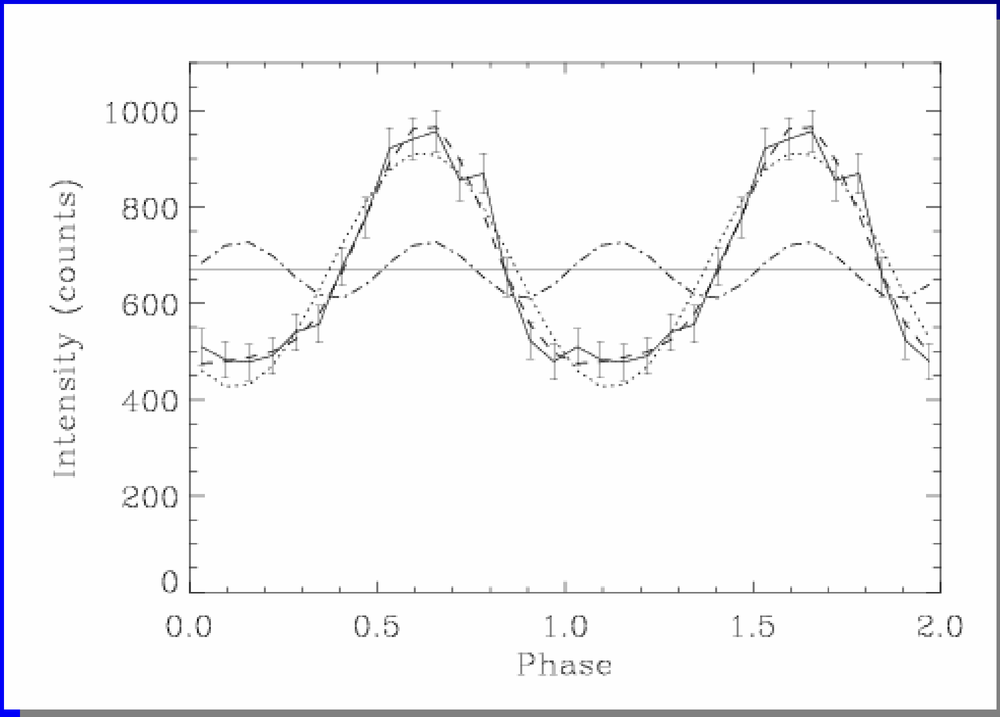


- Lattitude of hot spot near rotational equator (+- 30 degrees).
- Moderately low inclination (30 – 50 degrees)
- Some evidence for spot size evolution during outburst.

Oscillations at Burst Onset (4U 1636-53)

Goddard Space Flight Center



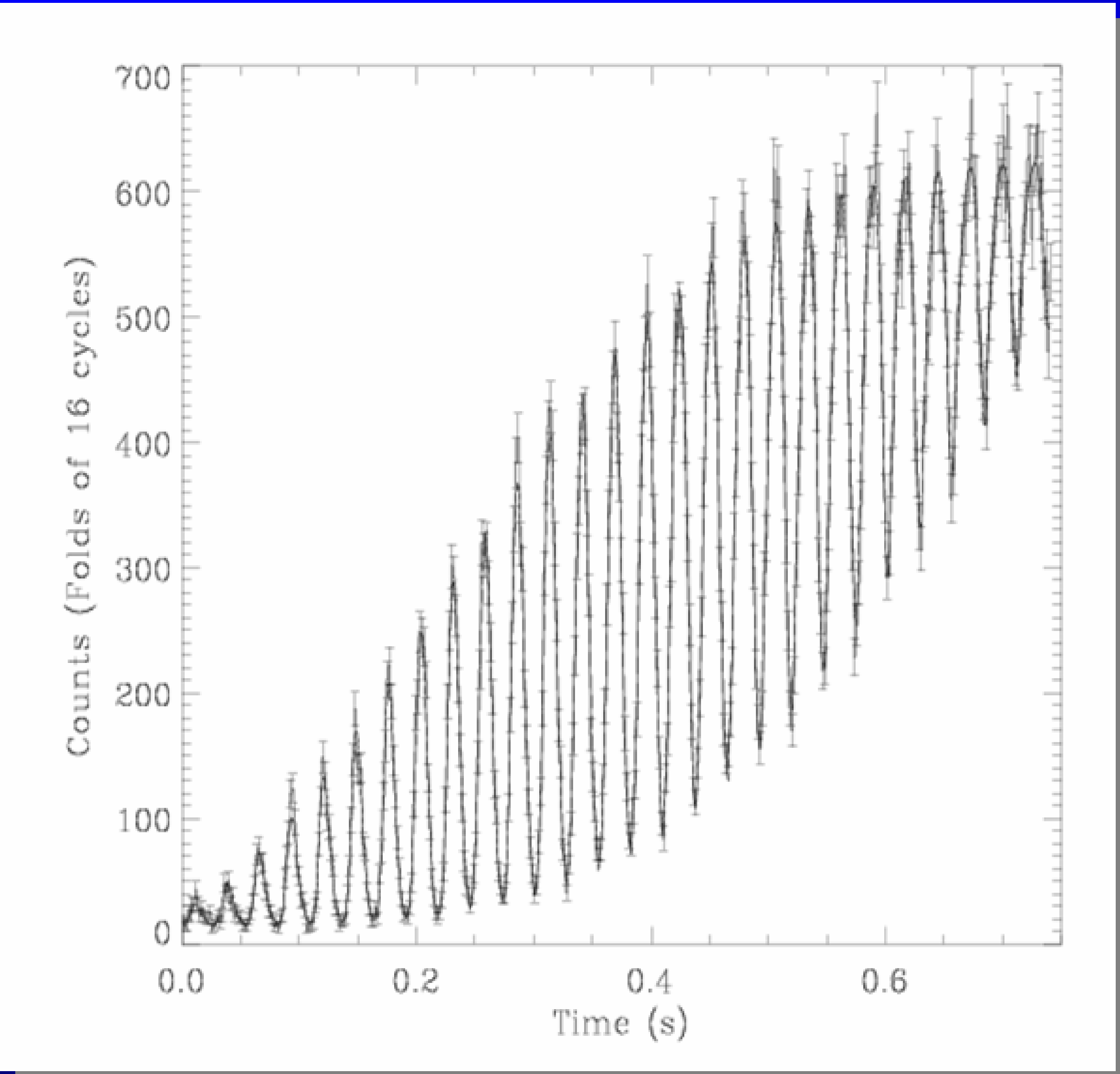


Bhattacharyya & Strohmayer (2005)

- Frequency drifts during the rise.
- Evidence for harmonic structure in first few tenths of a second of burst.
- Insights into nature of flame spreading.

Goddard Space Flight Center

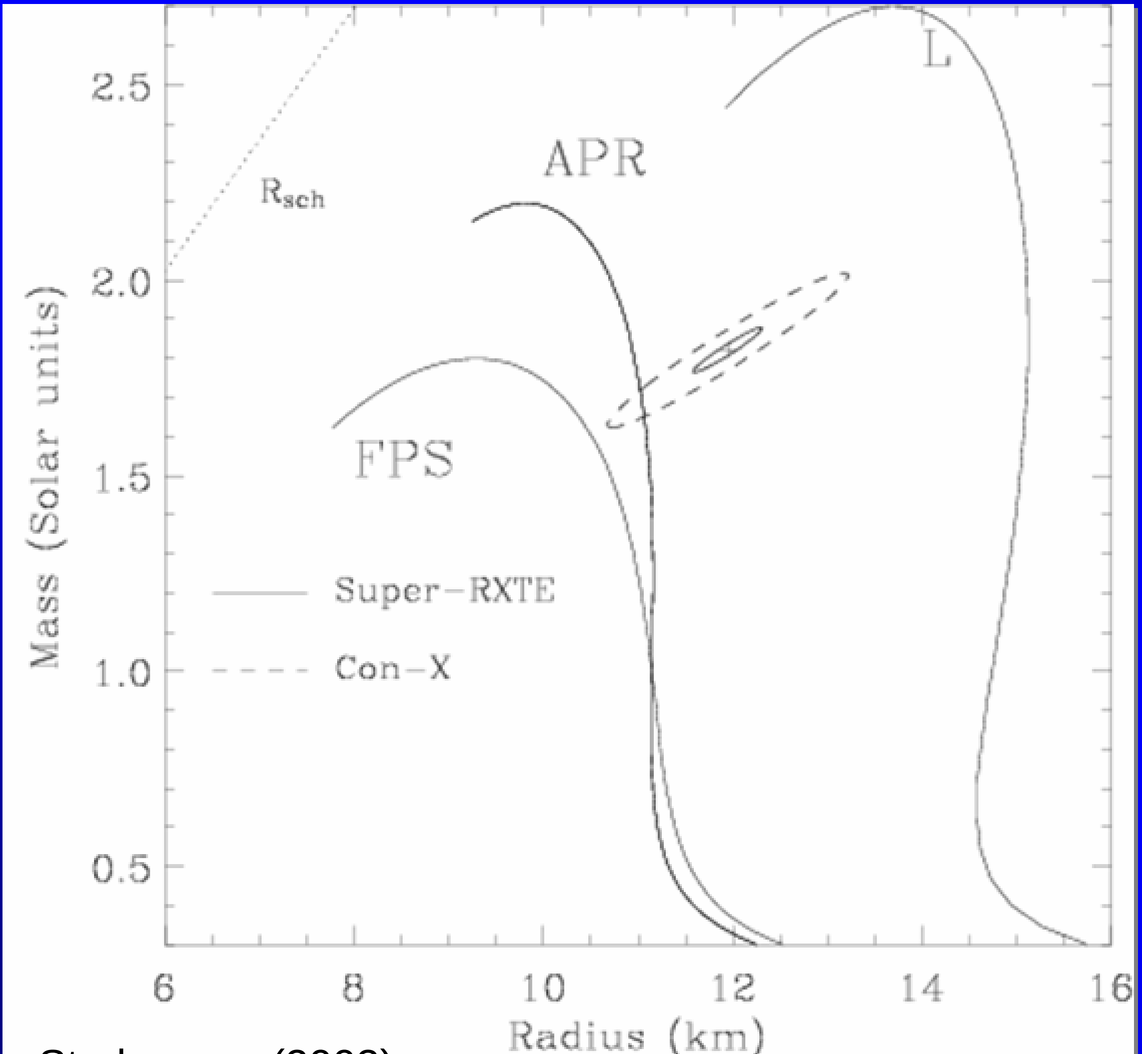
Future: Simulated Lightcurve: 10x RXTE/PCA



- Use blackbody emission from Neutron star surface.
- Circular hot region which grows linearly with time.
- Flux and spin rate for bursts from 4U 1636-53.

Burst Oscillations and M - R Constraints for Neutron Stars

Goddard Space Flight Center



Strohmayer (2003)

- Pulse shapes of burst oscillations encode information on the neutron star mass and radius.
- Modulation amplitude sensitive to compactness, M/R.
- Pulse sharpness (harmonic content) sensitive to surface velocity, and hence radius for known spin frequency.
- Geometry and evolution of the hot region can be a complicating factor.
- Statistical limits for future missions look promising.

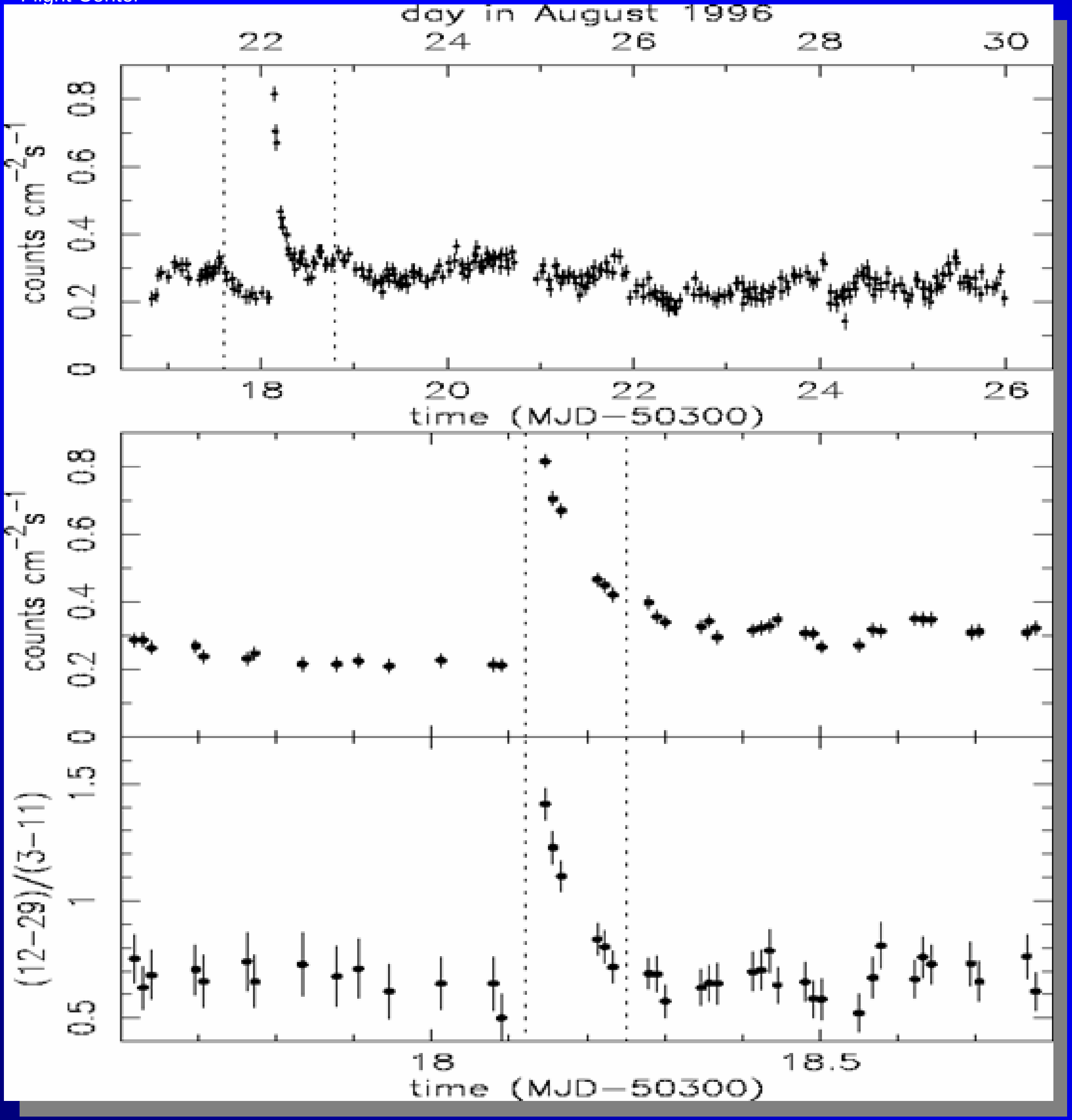
Goddard Space Flight Center

Burst Modeling: A Theoretical Opportunity

- To capitalize on current and future observations, we need a detailed, multi-dimensional model of the X-ray flux from bursting neutron stars:
- Input physics: nuclear energy release; reaction networks, etc.
- Atmospheric physics, transfer of nuclear energy to photon flux.
- Flame spreading; time dependence of flame propagation.
- Propagation of flux at surface to the observer, including all relativistic physics.
- Fitting of models to the data to derive neutron star properties (M, R, sin i, etc.), and perhaps constrain nuclear physics.
- This is a substantial collaborative effort. Something JINA could support?
- Synergistic with astrophysics community; could support future observing efforts.

First Superburst from 4U 1735-44 (BeppoSAX/WFC)

Goddard Space Flight Center

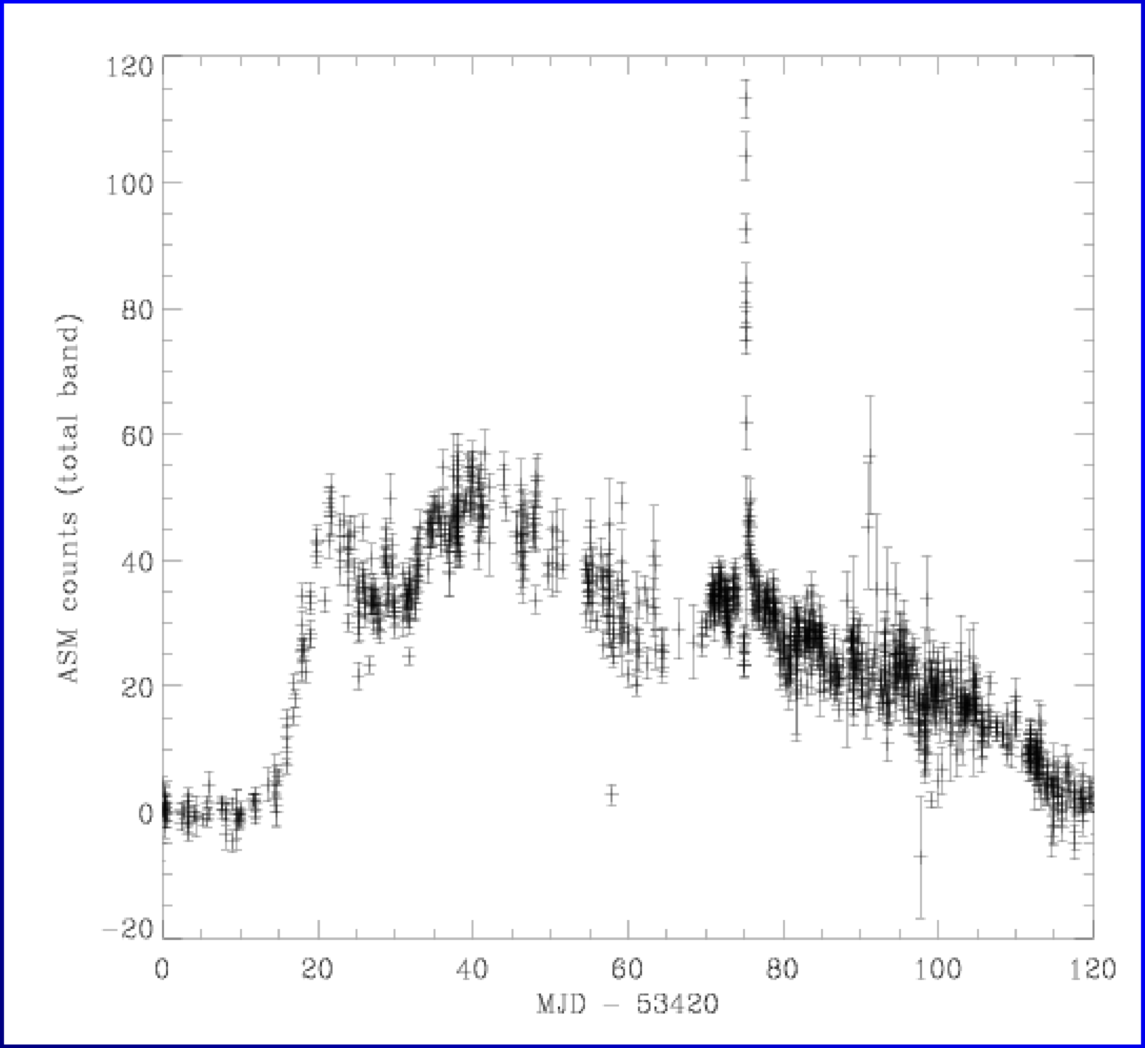


Cornelisse et al. (2000)

- Long, 3 - 5 hr flares seen to date from 9 low mass X-ray binaries (LMXB).
- Spectra consistent with thermal, show softening with time.
- Two superbursts from 4U 1636-53, 4.7 yr apart.
- 1,000 x more energy than standard Type I bursts.

New Superburst from 4U 1608-522 (RXTE/ASM)

Goddard Space Flight Center



Levine et al. (2005)

- Seen in the transient source 4U 1608-522.
- Spectrum consistent with thermal, shows softening with time.
- Observed during the most recent outburst.
- RXTE and XMM programs to observe superbursts. ASM notice was not disseminated, missed this one!

Goddard Space Flight Center

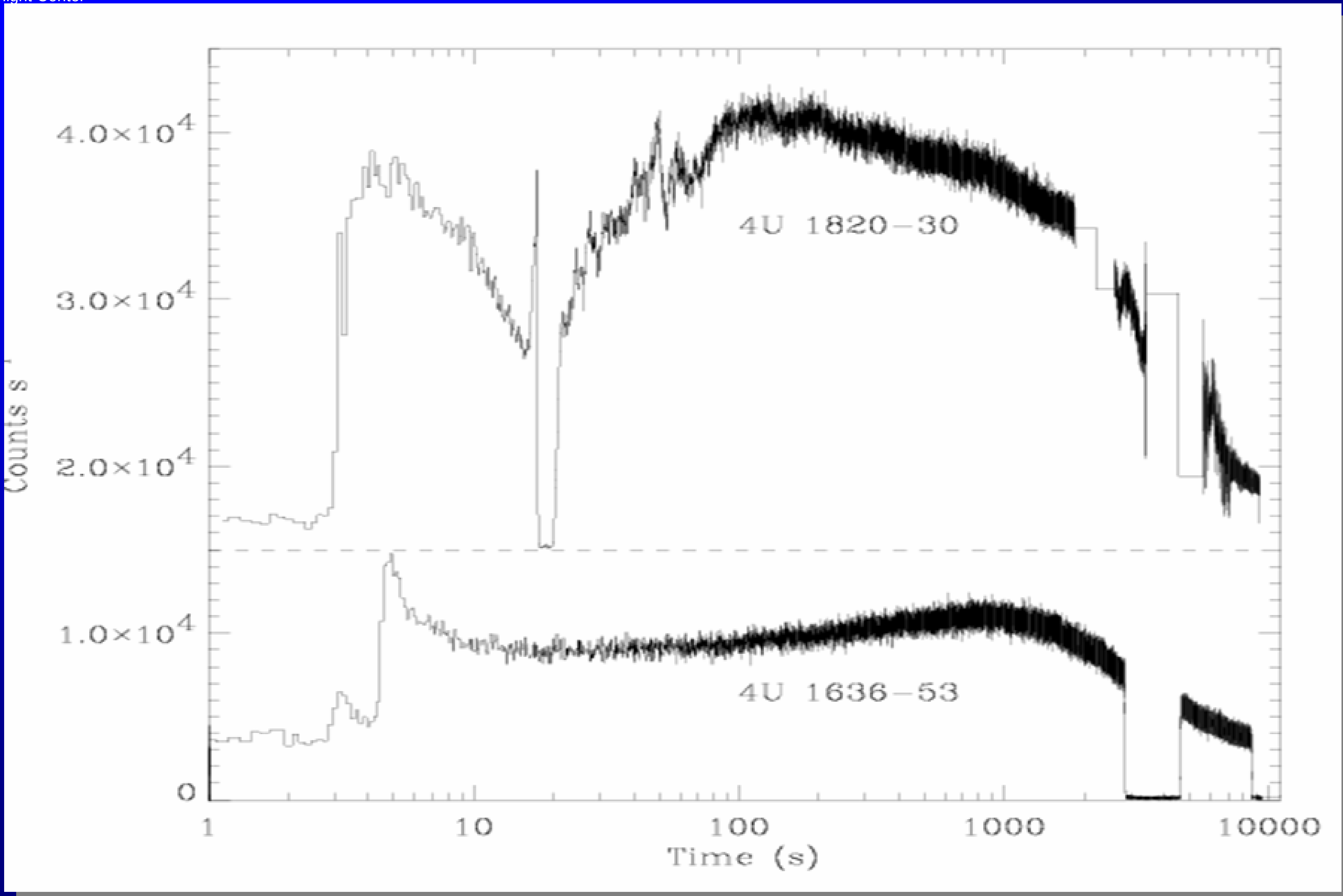
Superburst Sources

Sources	Observations	Number (recurrence)
4U 1735-44	SAX - WFC	1
4U 1820-30	RXTE - PCA	1
4U 1636-53	RXTE - ASM, PCA	2 (4.7 yr)
KS 1731-260	SAX - WFC	1
Serpens X-1	SAX - WFC	1
GX 3+1	RXTE – ASM	1
4U 1254-69	SAX-WFC	1
4U 0614+091	RXTE-ASM	1
4U 1608-522	RXTE-ASM	1

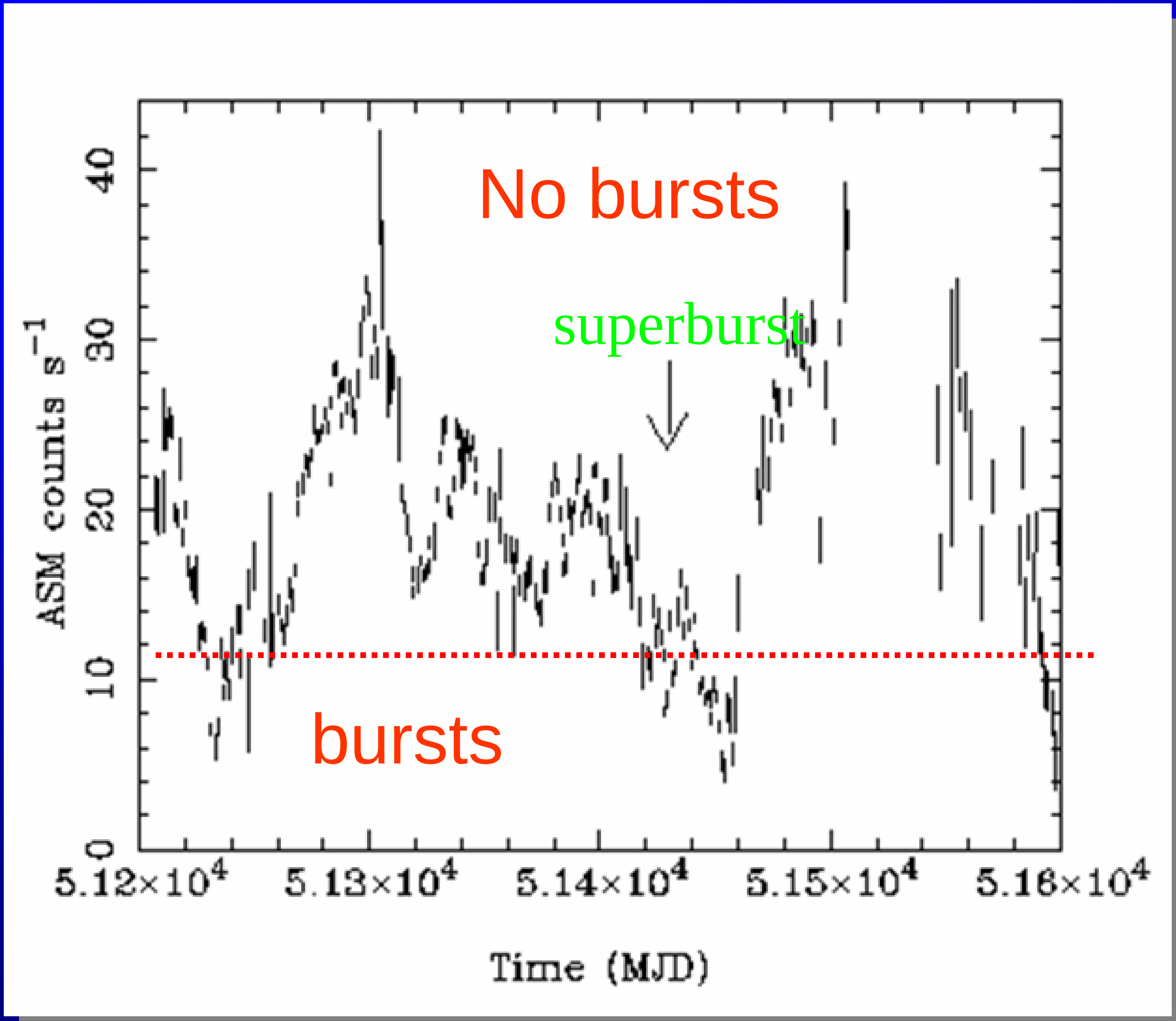
4U 1728-34	GX 9+9	Aql X-1
4U 1702-429	GX 9+1	
Cyg X-2	GX 13+1	
GS 1826-238	4U 1705-440	

Superbursts observed with RXTE/PCA

Goddard Space Flight Center



Superburst from 4U 1820-30: Carbon Production

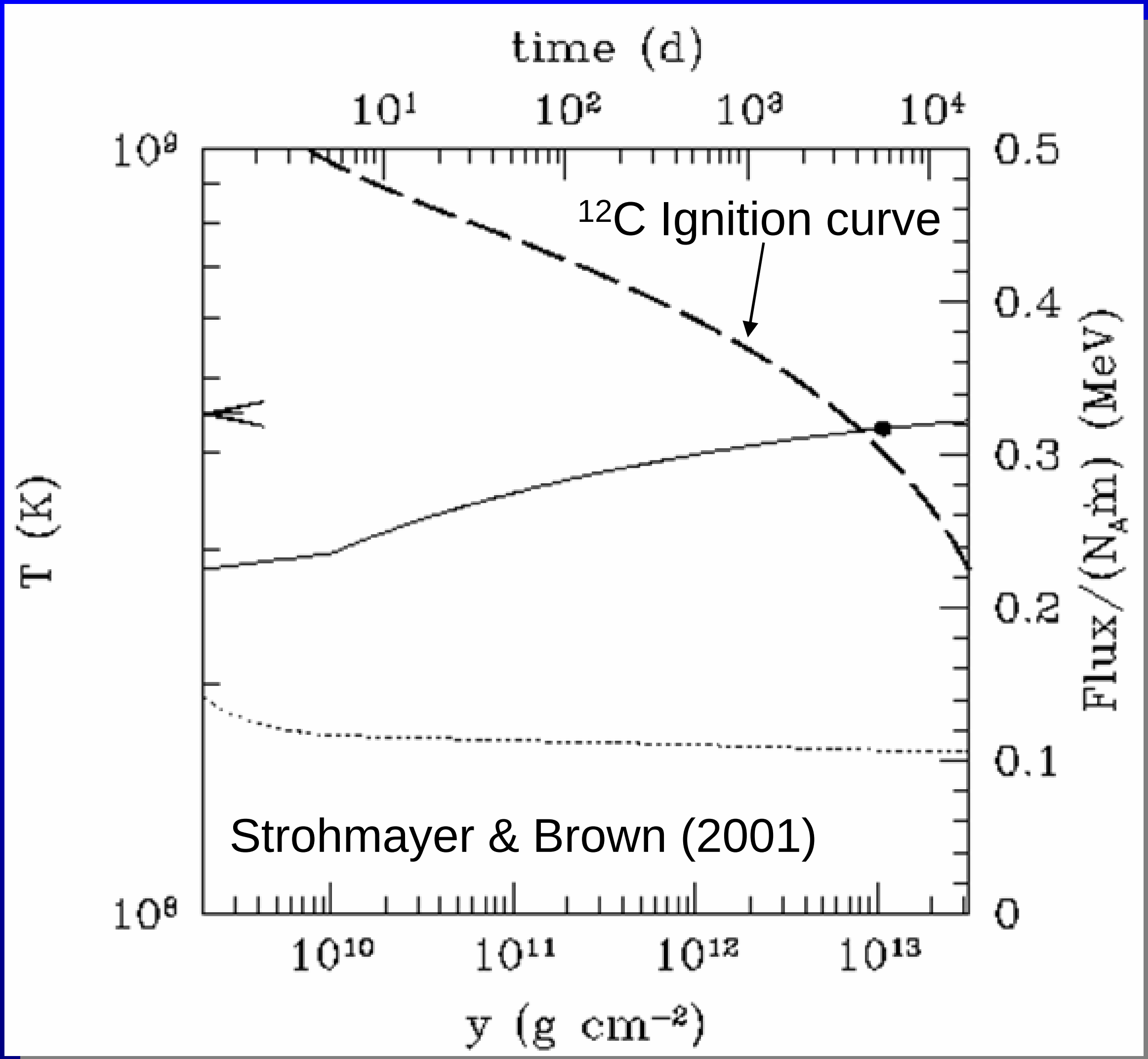


- Thermonuclear (helium) burning is stabilized at high accretion rates (ie. no normal bursts).
- Lower peak burning temperatures will likely synthesize lots of Carbon.
- Higher temperature during unstable burning yields little Carbon

Strohmayer & Brown (2002)

A Carbon "bomb" on a Neutron Star

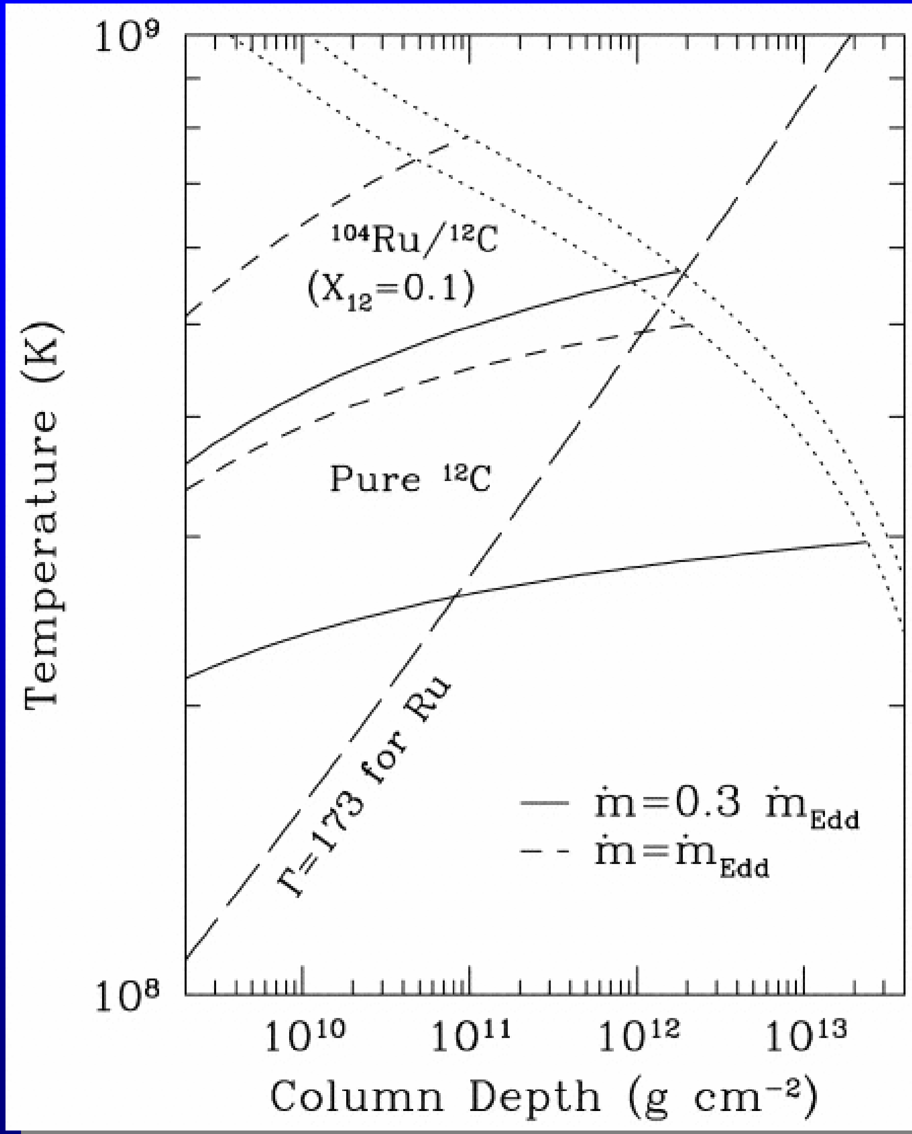
Goddard Space Flight Center

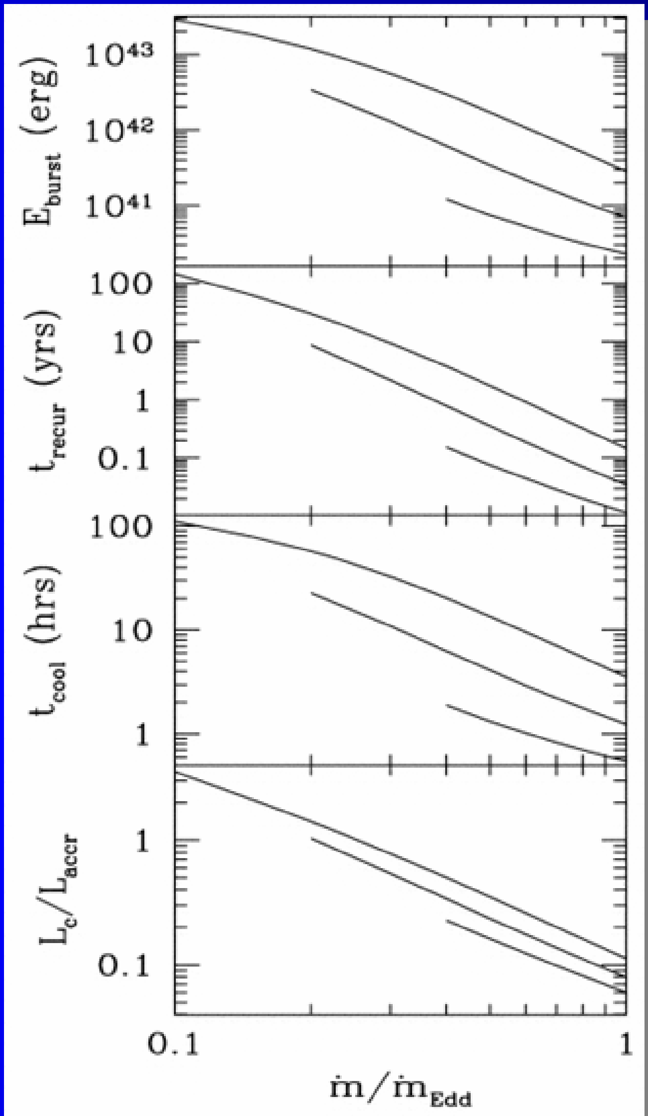


- Too much energy for unstable helium burning
- Carbon burning can supply total energy, recurrence time ~ 10 years.
- Carbon produced during stable burning of accreted helium.
- Carbon ignites at 10^{13} g cm^{-2}. Total energy is ~10-20 times greater than X-ray fluence.
- Significant energy loss to neutrinos, energy will flow inward to be released on longer timescale.

Carbon Flashes on Neutron Stars: Mixed Accretors

Goddard Space Flight Center

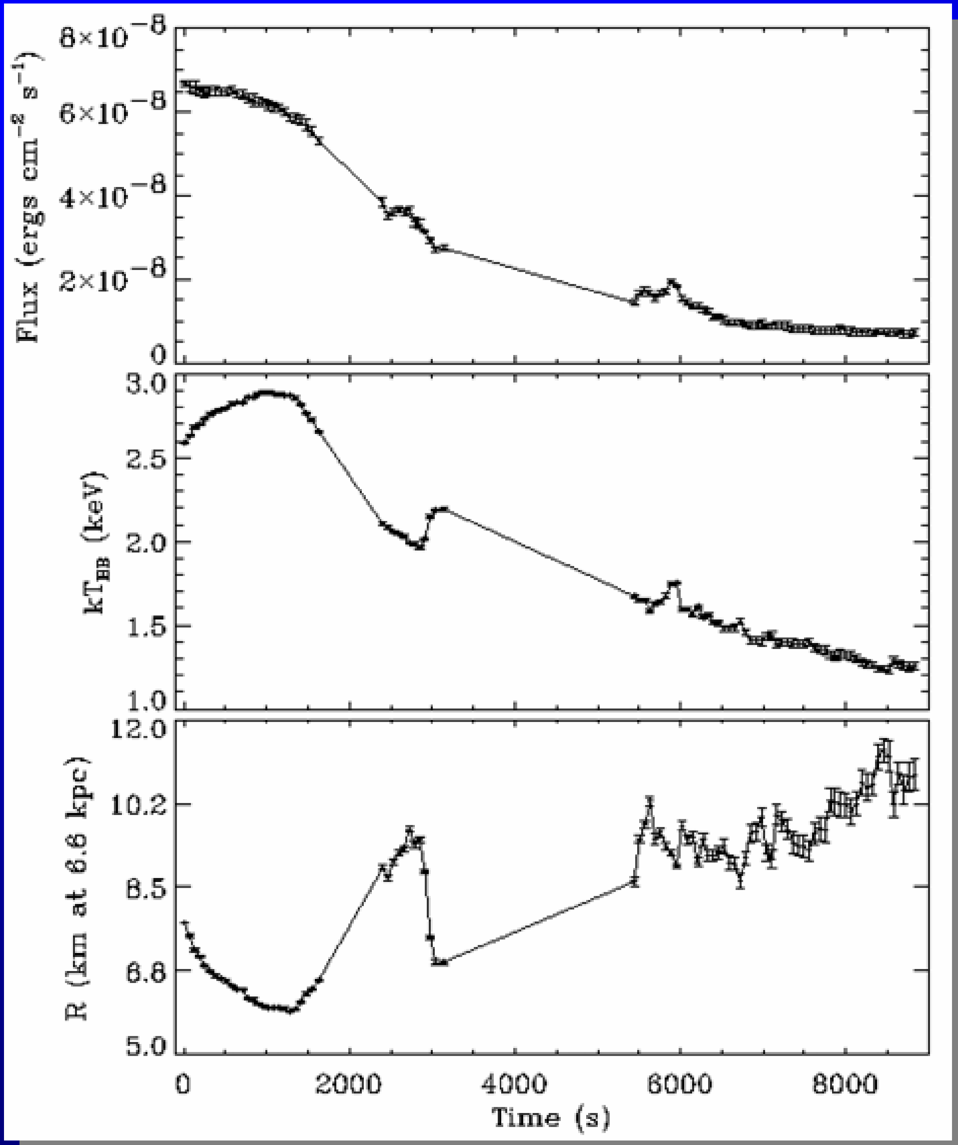


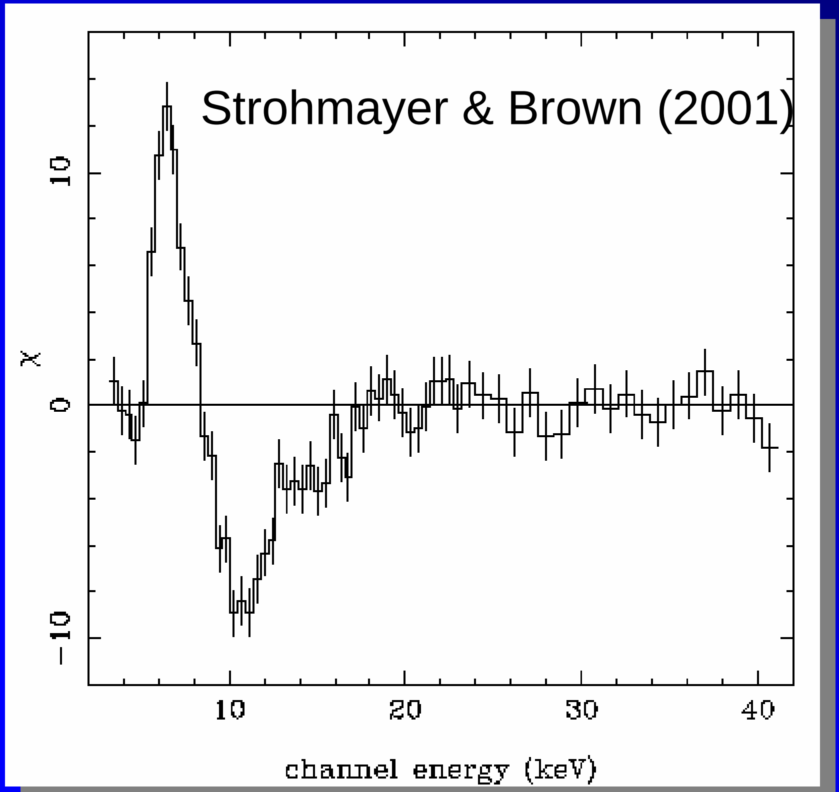


Cumming & Bildsten 2001

RXTE Observes Three Hour Burst from a Neutron Star (4U 1820-30)

Goddard Space Flight Center

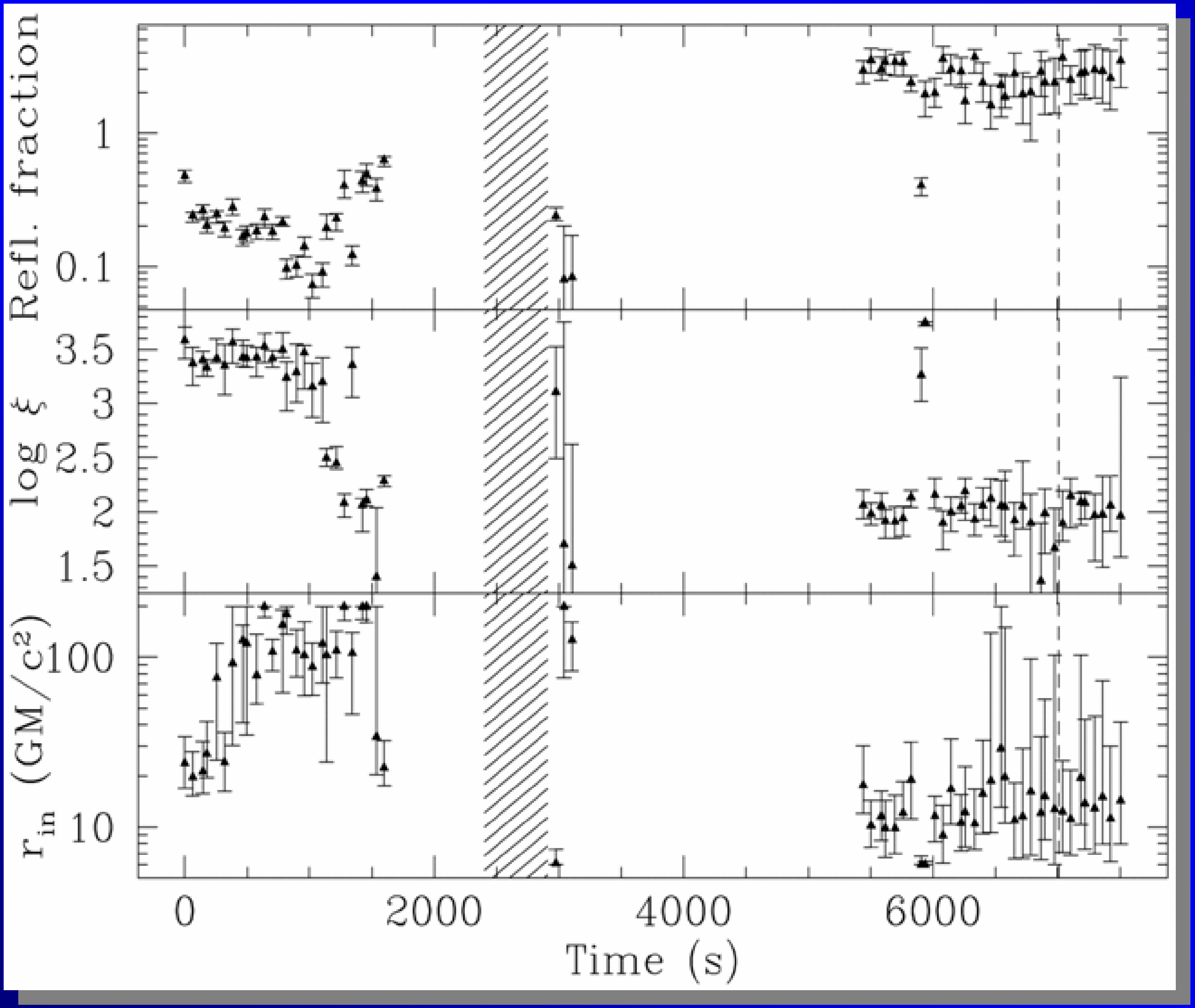




- Peak flux consistent with Eddington limit from neutron star.
- Broad ~6 keV line and ~9 keV edge from reflection off inner disk.
- New probes of disks and neutron star.

Superburst from 4U 1820-30: Disk Reflection

Goddard Space Flight Center

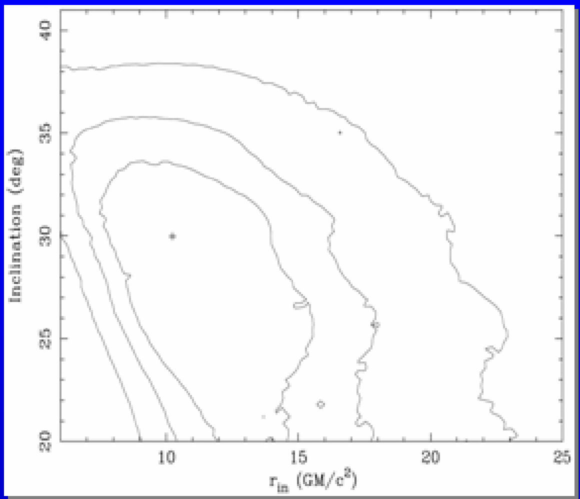


- Discrete spectral components likely due to reflection of burst flux from disk.
- Broad Fe Kα line and smeared edge.
- Line and edge parameters vary significantly through burst.
- Broad Fe line gives evidence for relativistic disk.

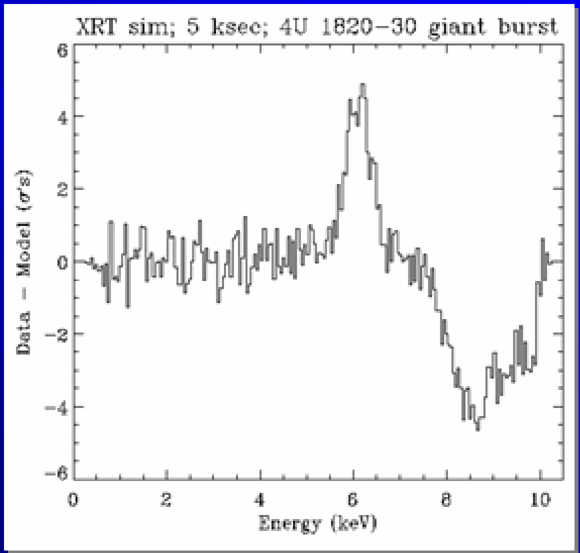
Ballantyne & Strohmayer (2004)

Goddard Space Flight Center

Superburst from 4U 1820-30: Evolution of the Disk



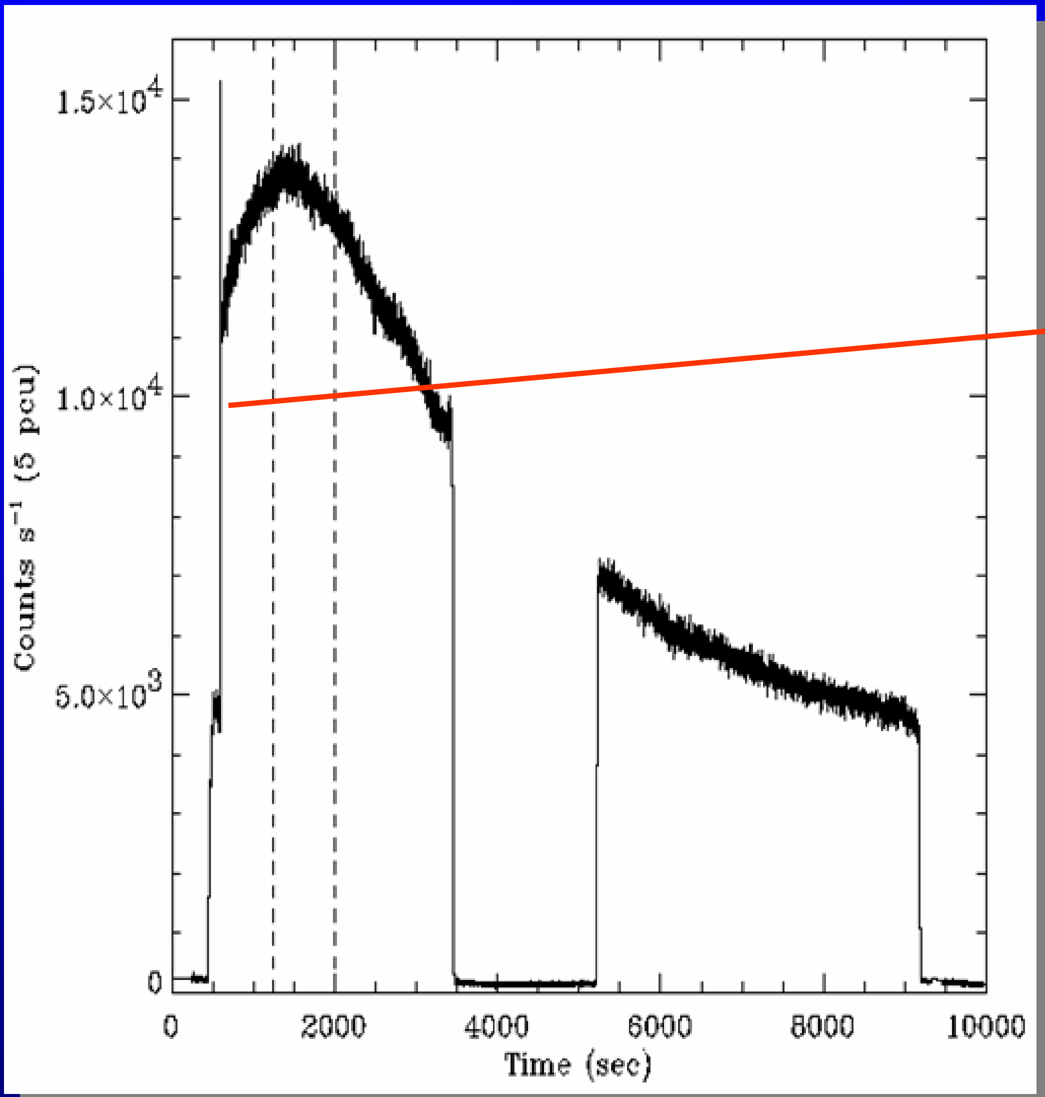
Reflection model fits constrain the system inclination. Important for dynamical mass studies.

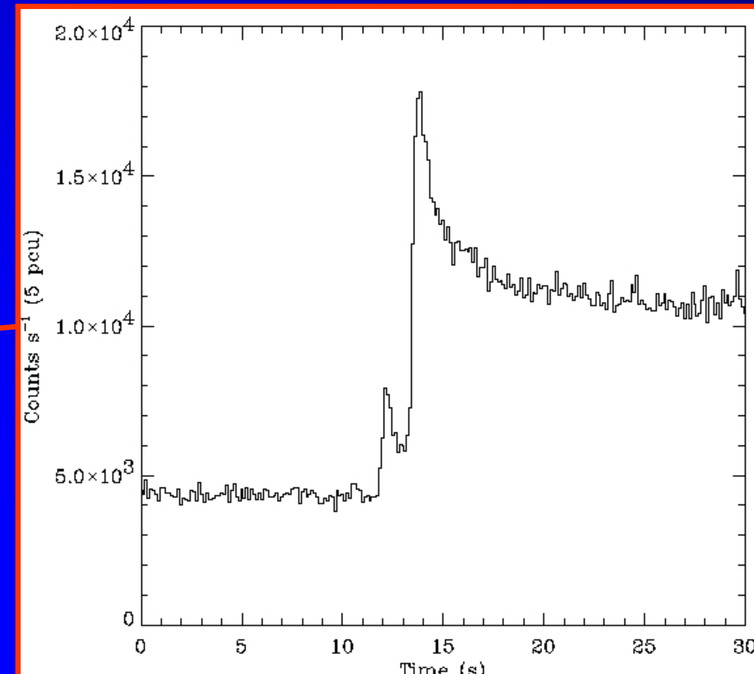


SWIFT studies

RXTE/PCA Observes Superburst from 4U 1636-53

Goddard Space Flight Center

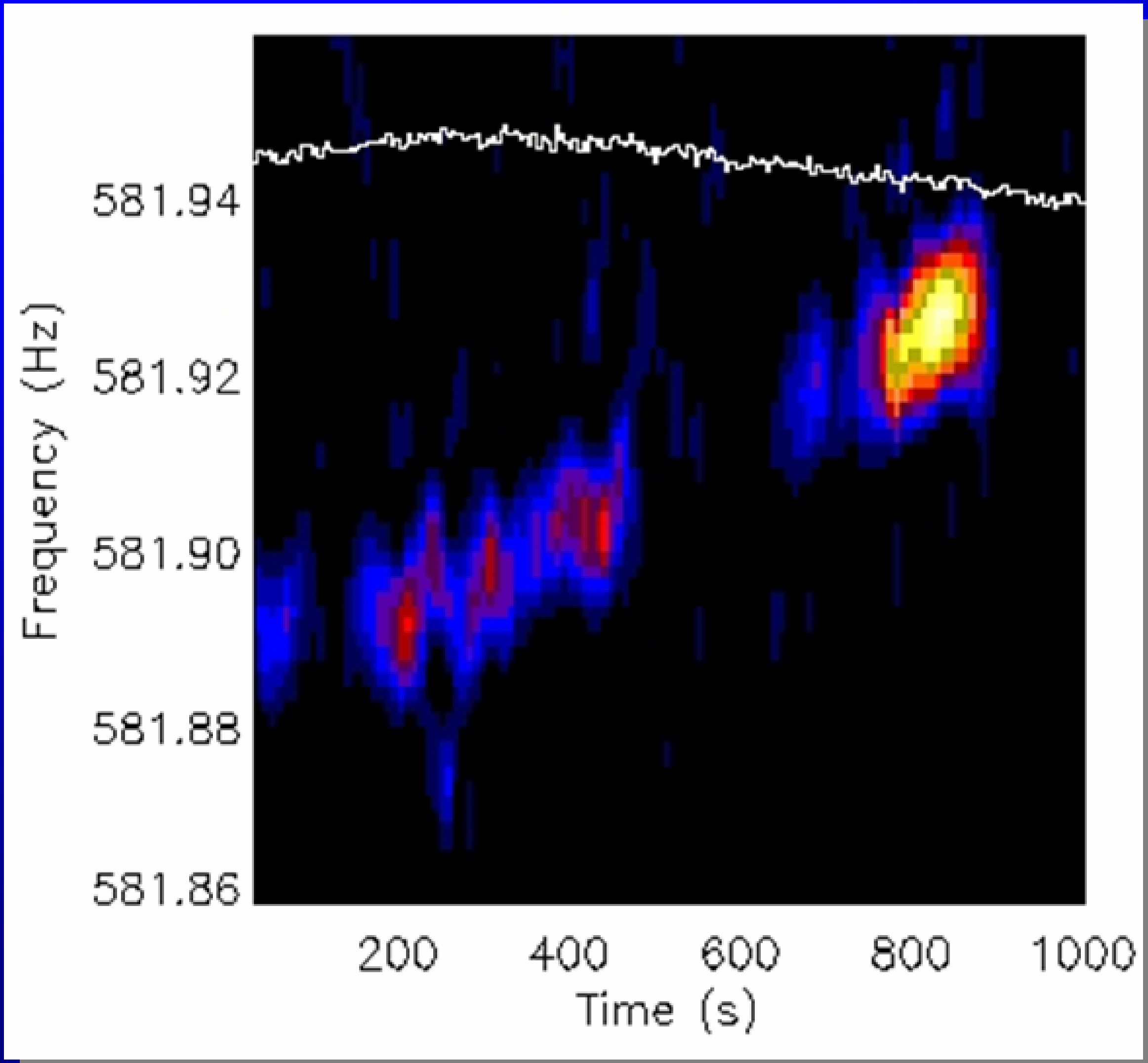




- Unique double precursor near rise of the burst.
- Heat flow from below may trigger H/He layer.

Time Dependence of the Pulsation Frequency

Goddard Space Flight Center

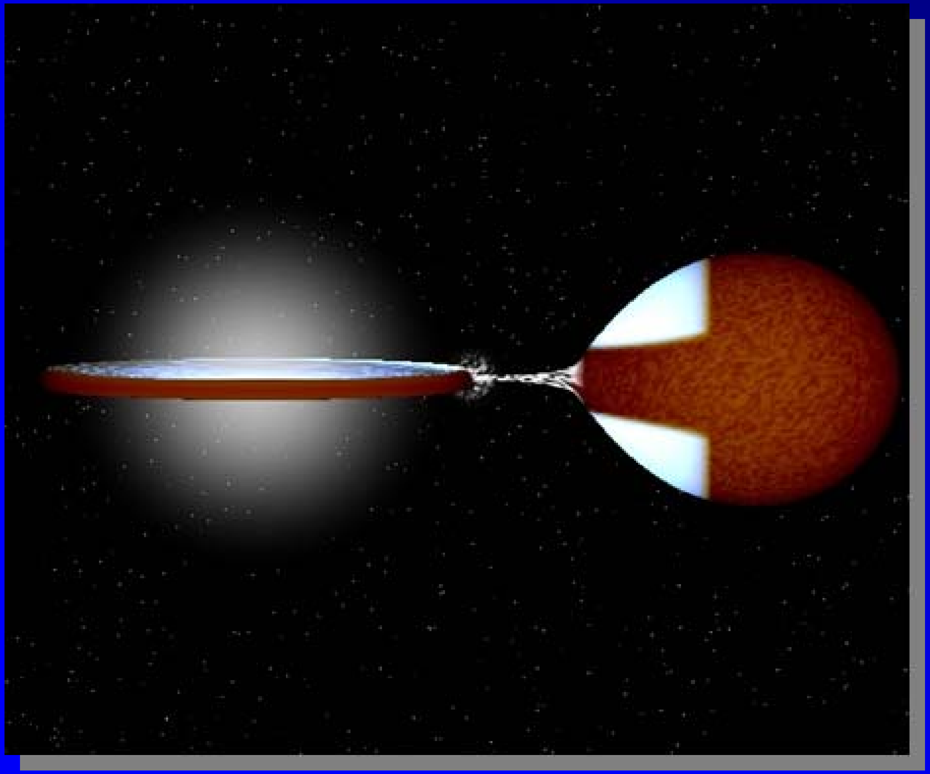


- Pulse train lasts ~1000 seconds. Much longer than in normal bursts.
- Frequency drifts by about 0.03 Hz in 800 s. Much smaller than drift in normal bursts.
- Orbital modulation of neutron star spin frequency.

EXO 0748-676 Summary

Goddard Space Flight Center

- Eclipsing – dipping LMXB, discovered by EXOSAT.
- Orbital period of 3.82 hours.
- Eclipses and orbit period indicate high inclination: $75 < i < 82$ degrees.
- X-ray bursts indicate neutron star accretor.
- ~1 Hz QPOs and so far only 1 observed kHz QPO.

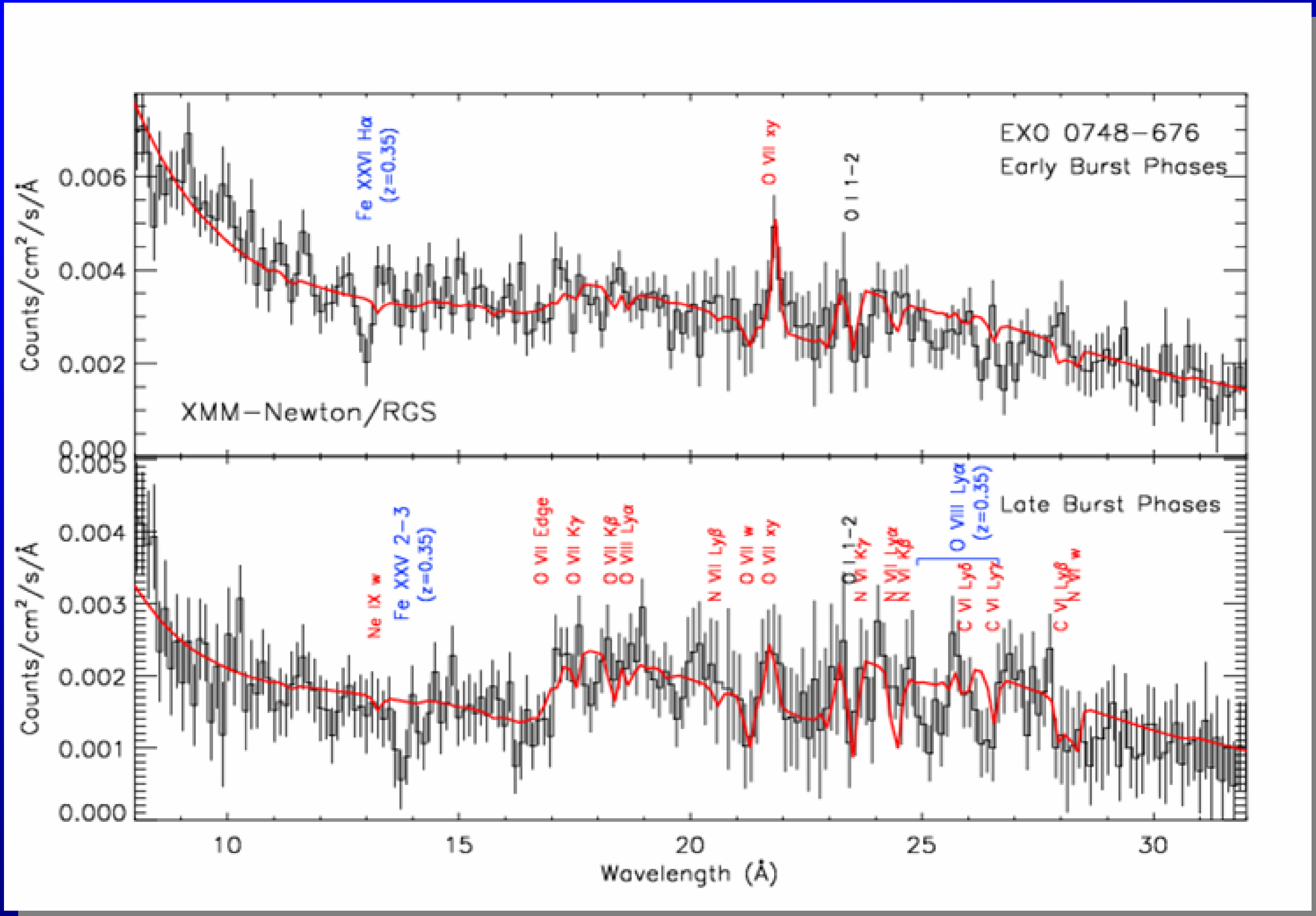


- Evidence for gravitationally redshifted absorption lines (Cottam et al. 2002), z = 0.35.

X-ray Spectroscopy of Neutron Stars: Recent Results

Goddard Space Flight Center

XMM/Newton grating observations of X-ray bursts from an accreting neutron star (EXO 0748-676); Cottam, Paerels, & Mendez (2002).



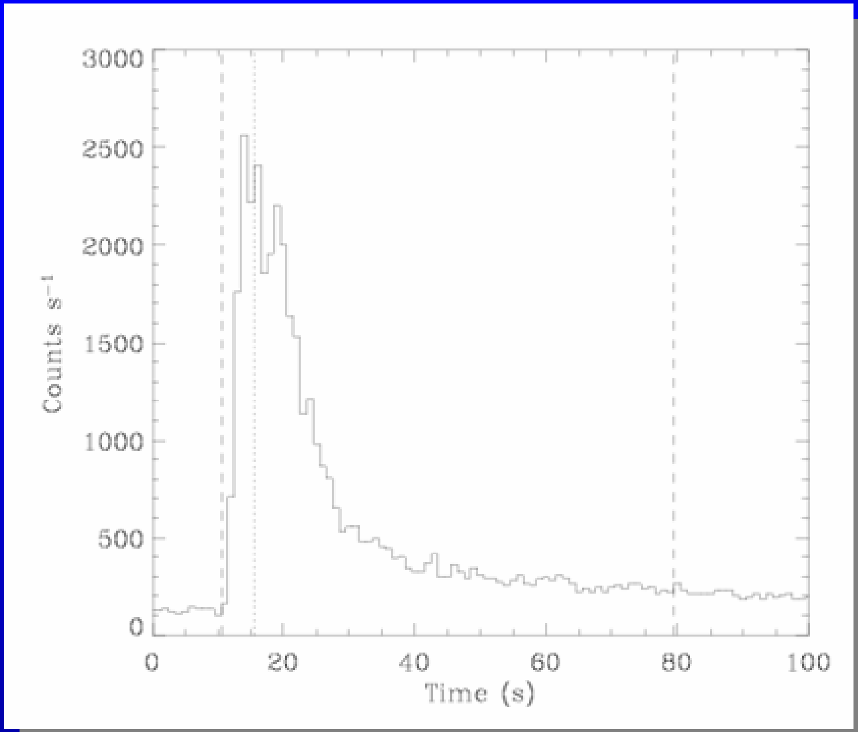
Goddard Space Flight Center

EXO Absorption Lines: Caveats

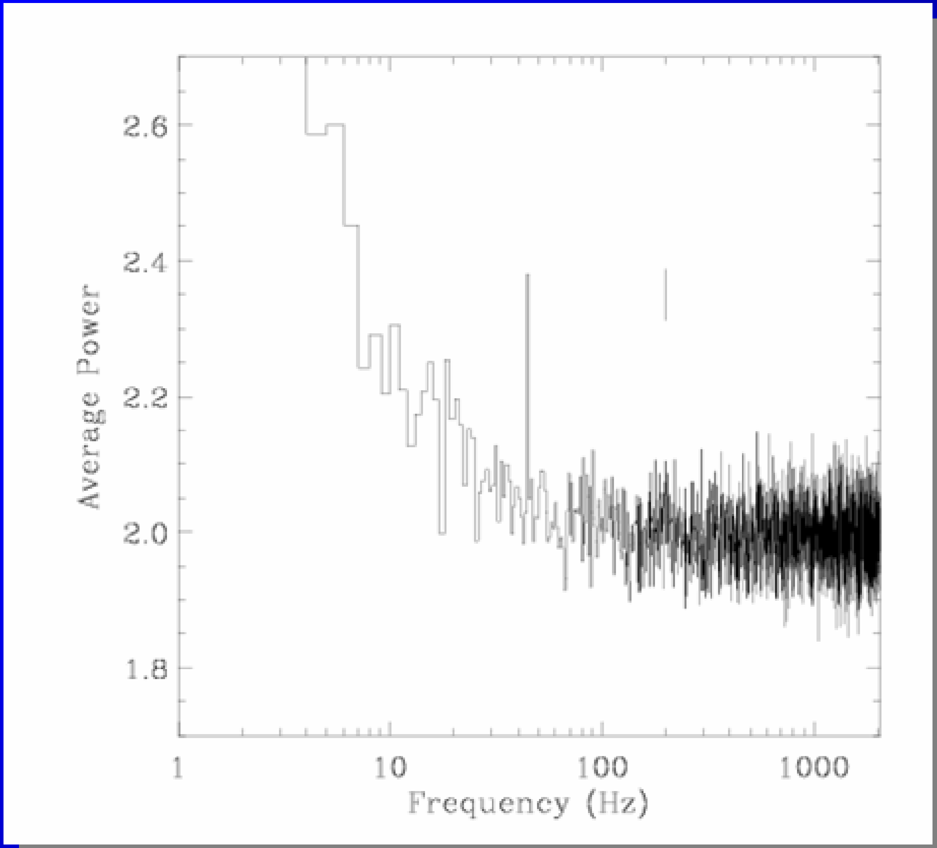
- Line Identifications not completely secure.
- Any single line feature is not detected with extremely high statistical significance.
- Indications of several (weak) features at consistent redshift, perhaps mitigates these concerns somewhat.
- Such narrow lines were not expected. Presumption that the NS is spinning at hundreds of Hz, like other LMXB bursters.
- Equivalent widths; are they compatible with reasonable Fe abundances; maybe (see Chang, Bildsten & Wasserman 2005).

Search for Burst Oscillations

Goddard Space Flight Center

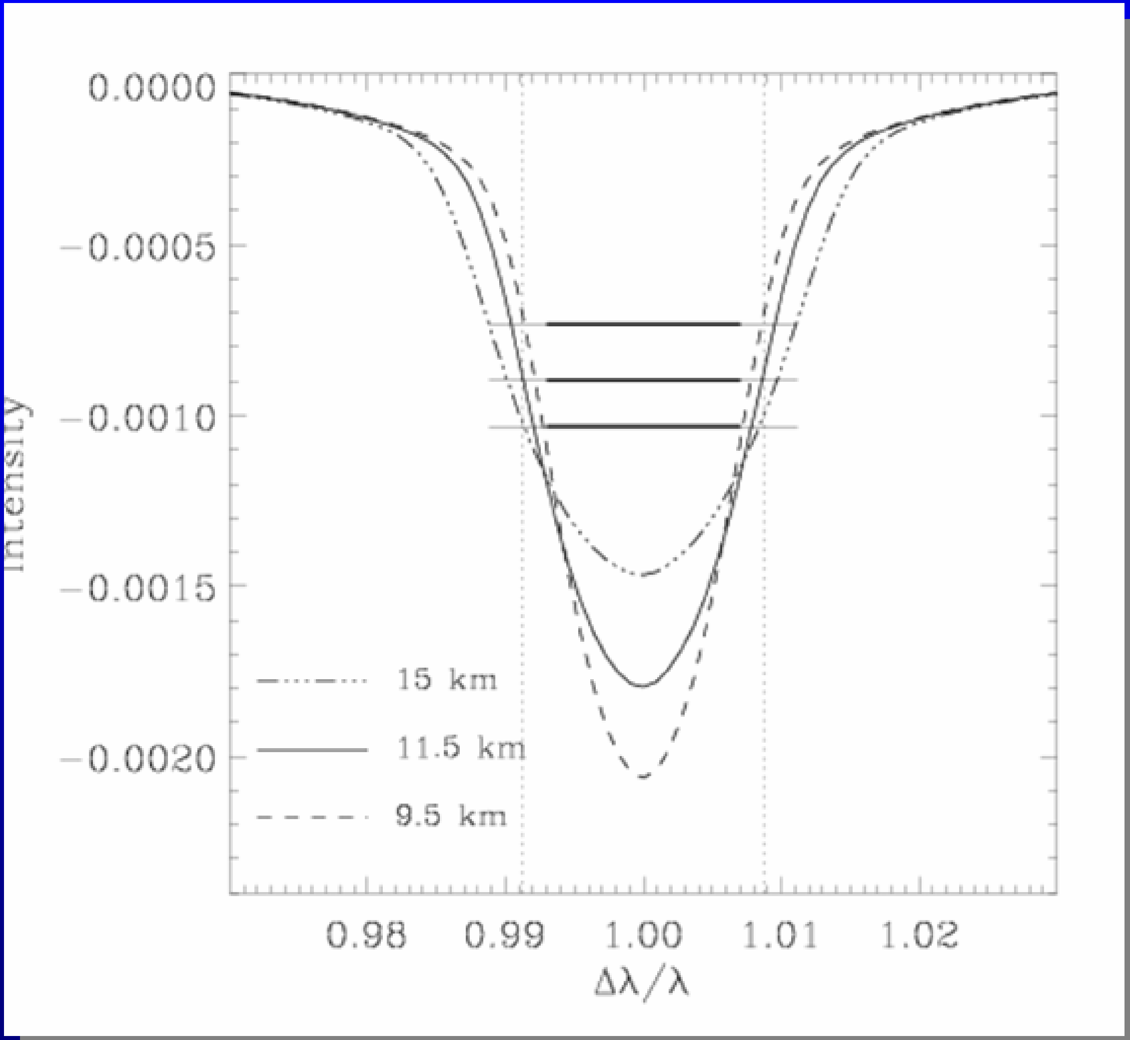


- 38 RXTE X-ray bursts.
- Calculated Power spectra for rise and decay intervals



- Averaged (stacked) all 38 burst power spectra.
- 45 Hz signal detected in decay intervals.

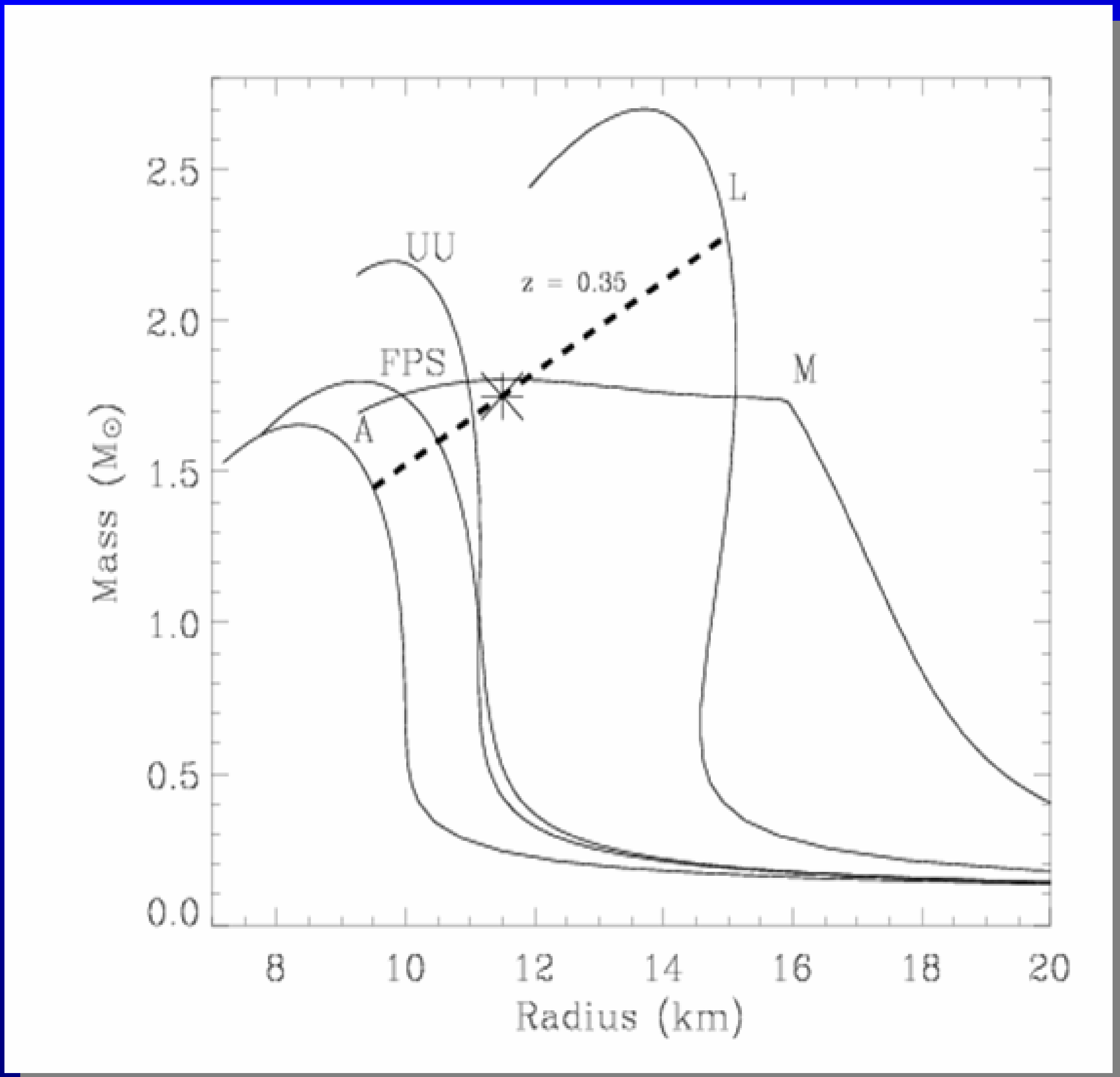
Rotational Doppler Broadening of Lines



- Surface rotational velocity gives Doppler shift.
- Dominates over thermal Doppler and pressure (Stark) broadening.
- Line widths from Cottam et al. (2002) consistent with 45 Hz spin, and constrain the neutron star radius (9.5 < R < 15) km.

Goddard Space Flight Center

Fundamental Physics: The Neutron Star Equation of State (EOS)



- EXO 0748-676 now an excellent candidate for precise neutron star Mass and Radius measurements.
- Can constrain the dense matter EOS.
- Need better line profile measurements; and models (including fine structure splitting, Chang et al.) to narrow radius range

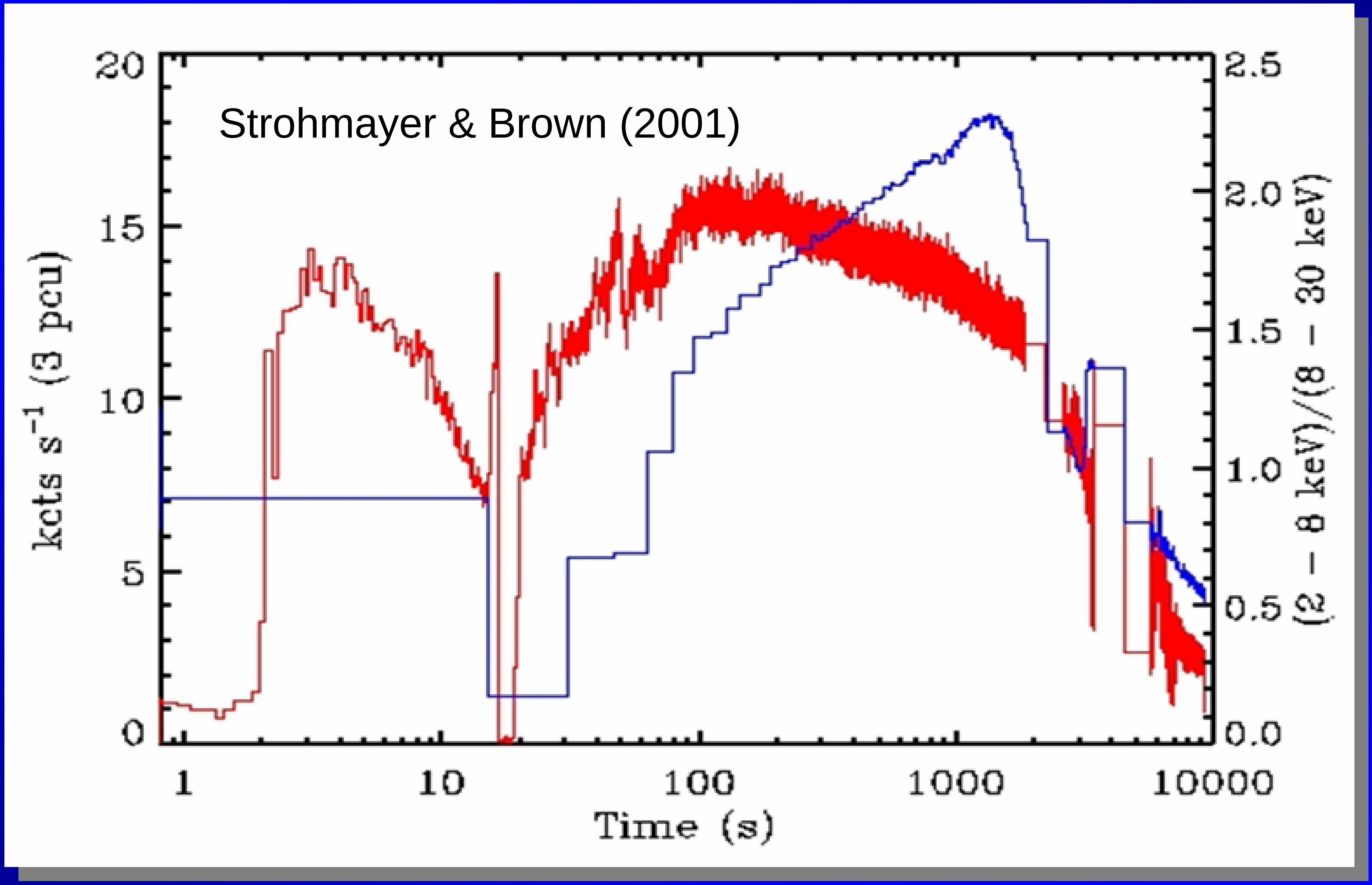
Goddard Space
Flight Center

EXO 0748-676 Burst Oscillations: The Movie

psbavg_burst.mov

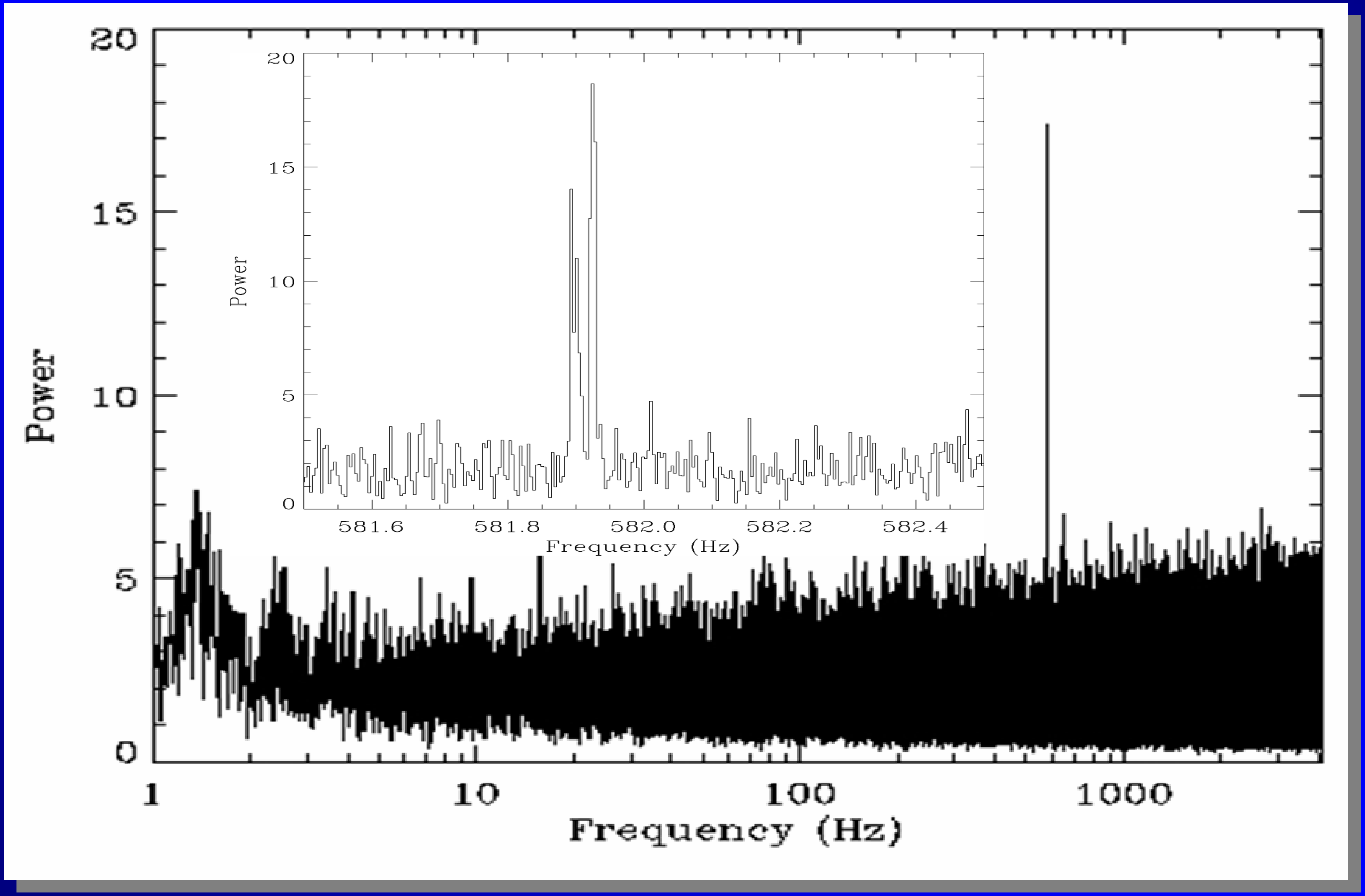
RXTE Observes Three Hour Thermonuclear Burst from a Neutron Star (4U 1820-30)

Goddard Space Flight Center



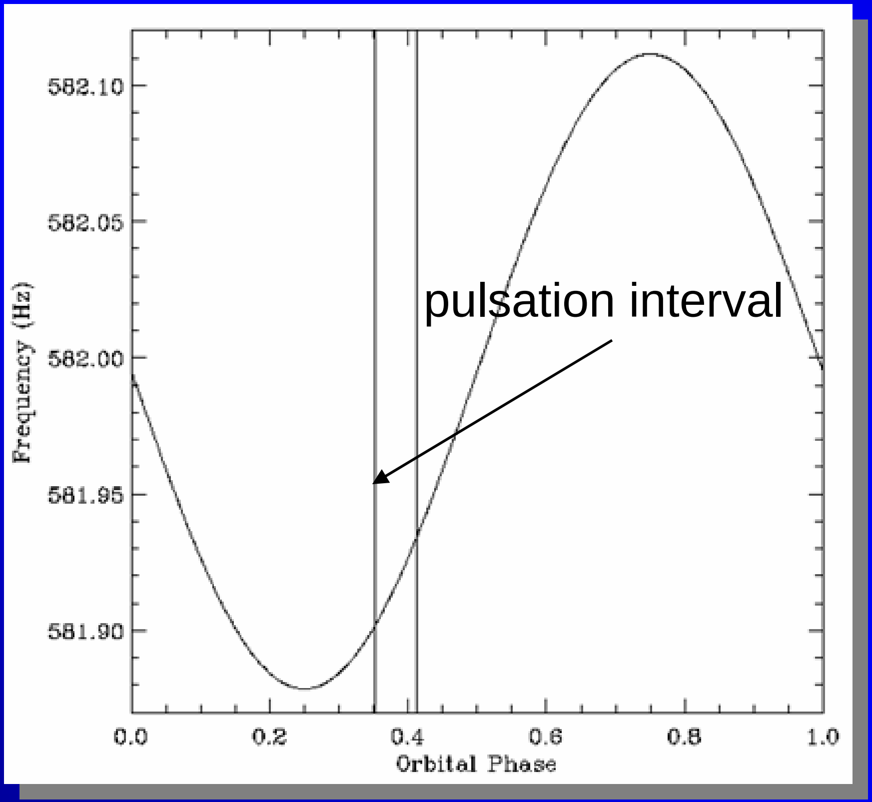
- Burst produced ~ 2 *x* 10^{42} ergs in X-rays, perhaps 10x more energy not seen (neutrinos; heat flowing into the crust).
- Energy source likely carbon burning at great depth (~10^{13} g cm^{-2}).

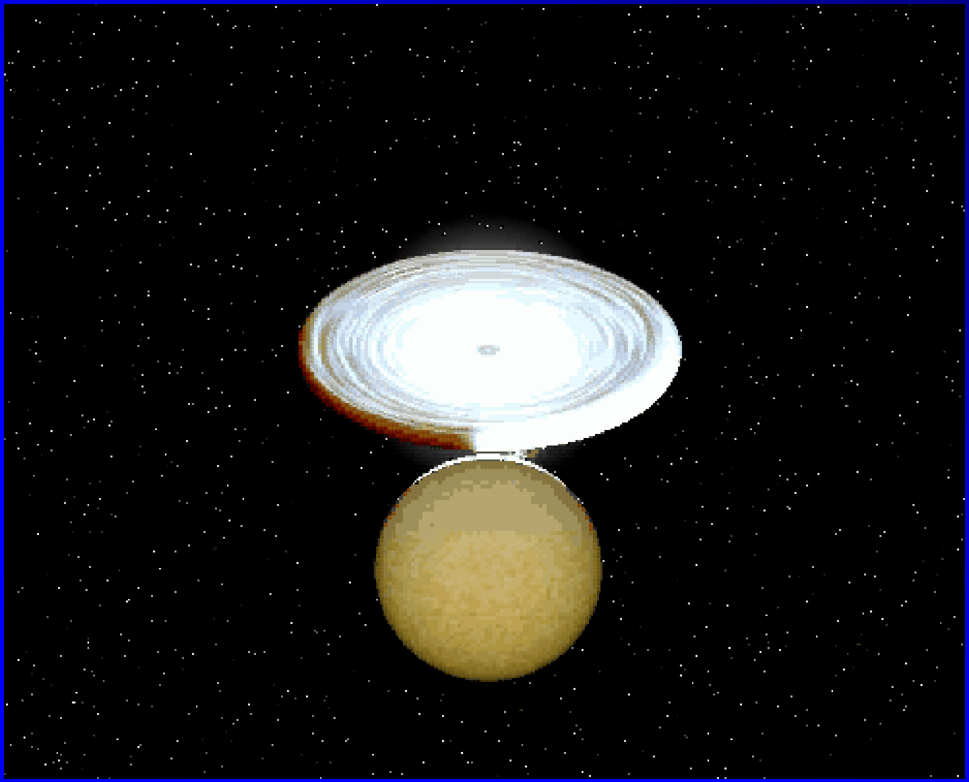
Pulsations During the Superburst from 4U 1636-53



Predicted Orbital Modulation from Optical Ephemeris for 4U 1636-53

Goddard Space Flight Center

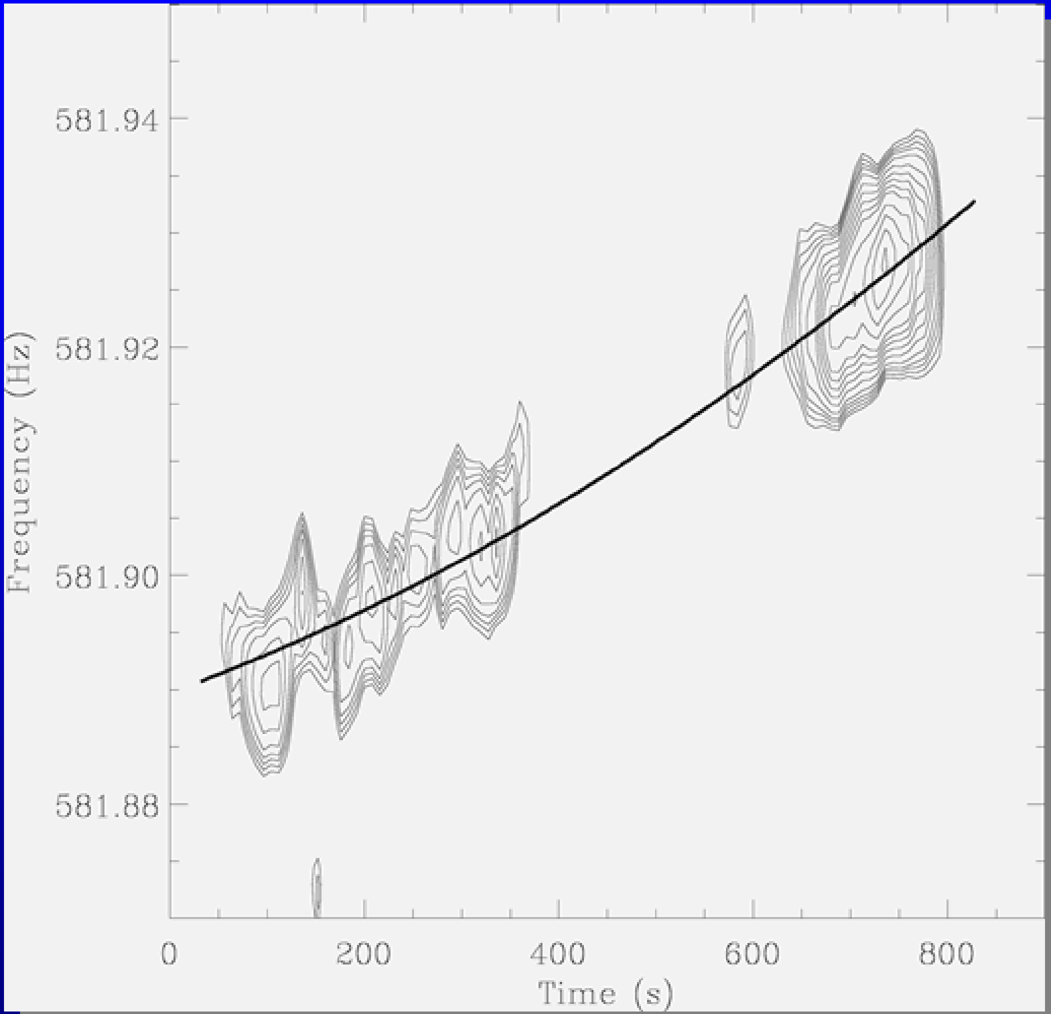


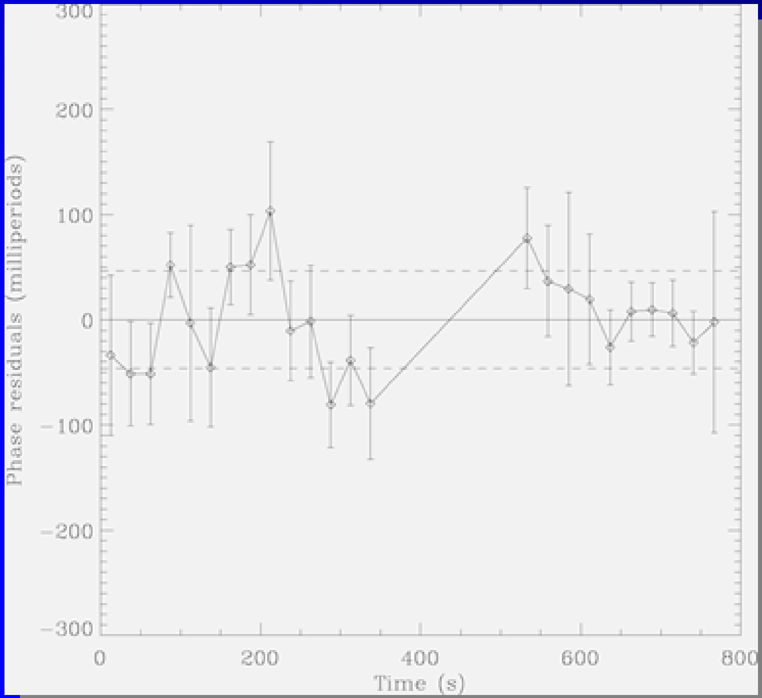


- 3.8 hr orbital period. Ephemeris from Augusteijn et al. (1998) and Giles et al. (2002).
- Only assumption, optical maximum corresponds to superior conjunction of the optical secondary.

Phase Coherent Timing with Circular Orbit Model

Goddard Space Flight Center

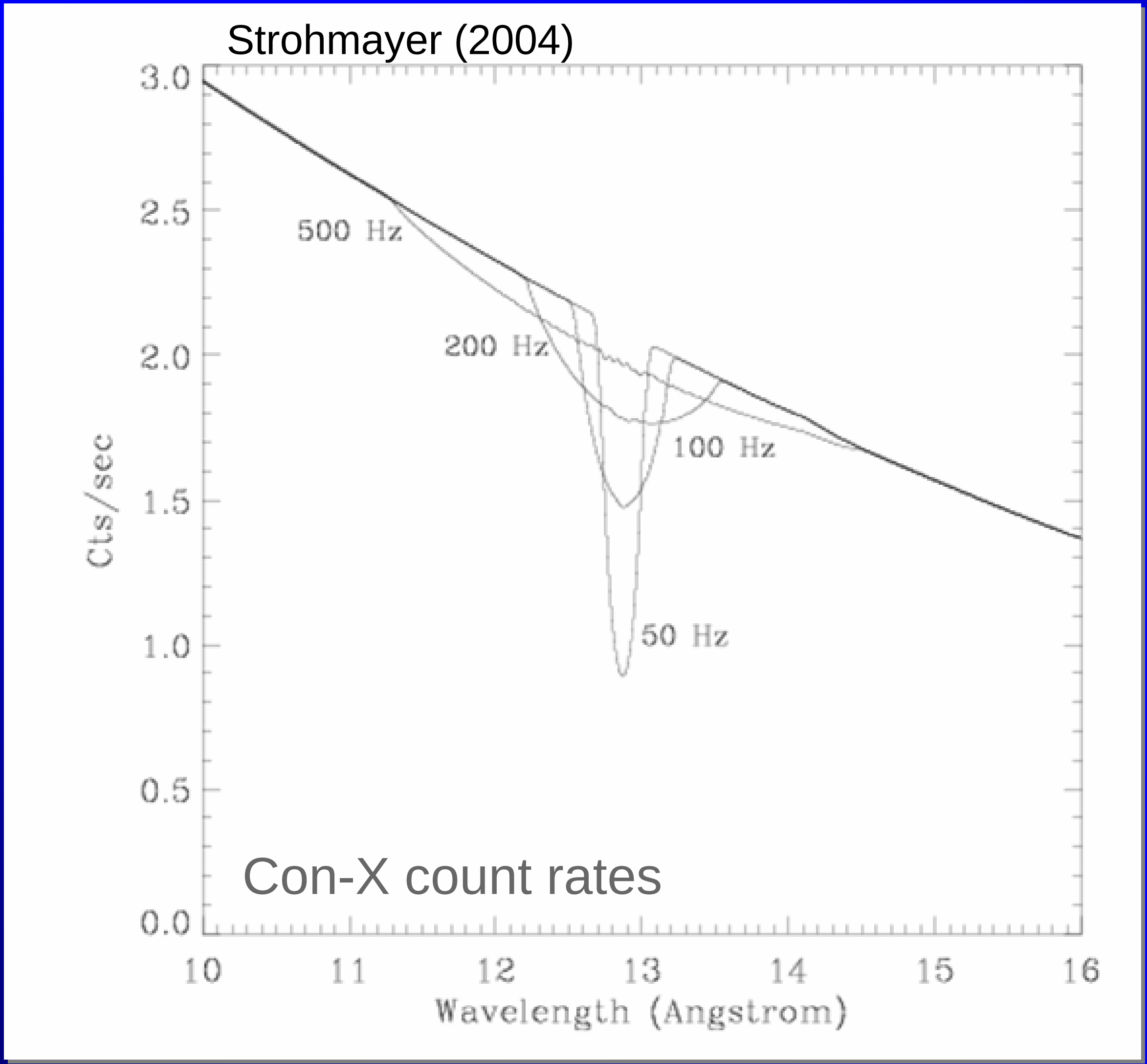




- Circular orbit describes the frequency and phase evolution very well.
- Range of parameters allowed due to short data segment.

Line Spectroscopy and M - R Constraints for Neutron Stars

Goddard Space Flight Center

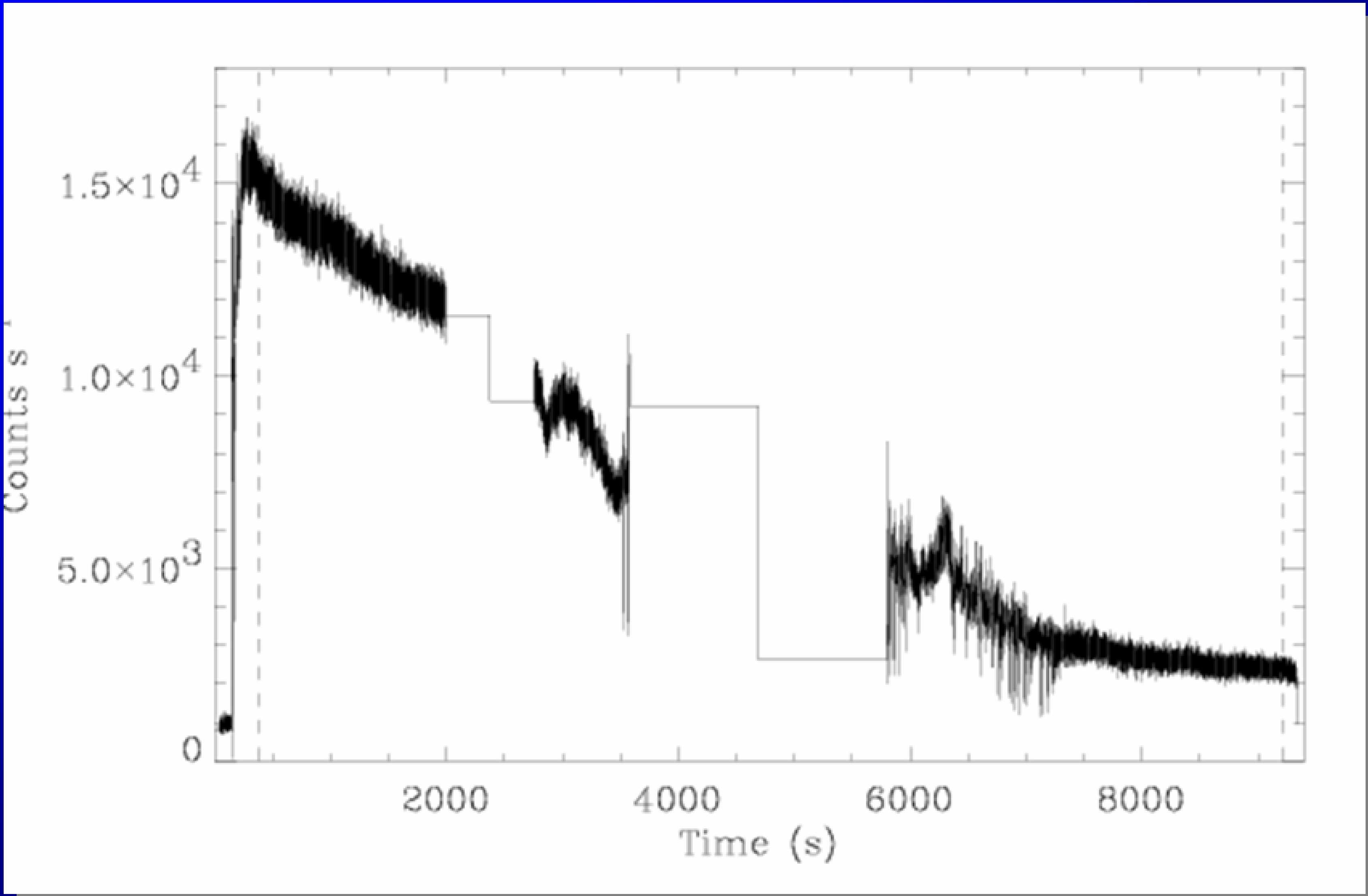


- Lines features from NS surface will be broadened by rotational velocities.
- For many sources, the rotational broadening will dominate (for example, Stark broadening).
- For known spins, velocity gives radius information.
- Asymmetric and double-peaked shapes possible, can constrain emitting surface.

Ozel, Psaltis, Datta, Kapoor, Bildsten, Chang, Paerels.

Probing the Accretion disk in 4U 1820-30: Reflection Spectra

Goddard Space Flight Center

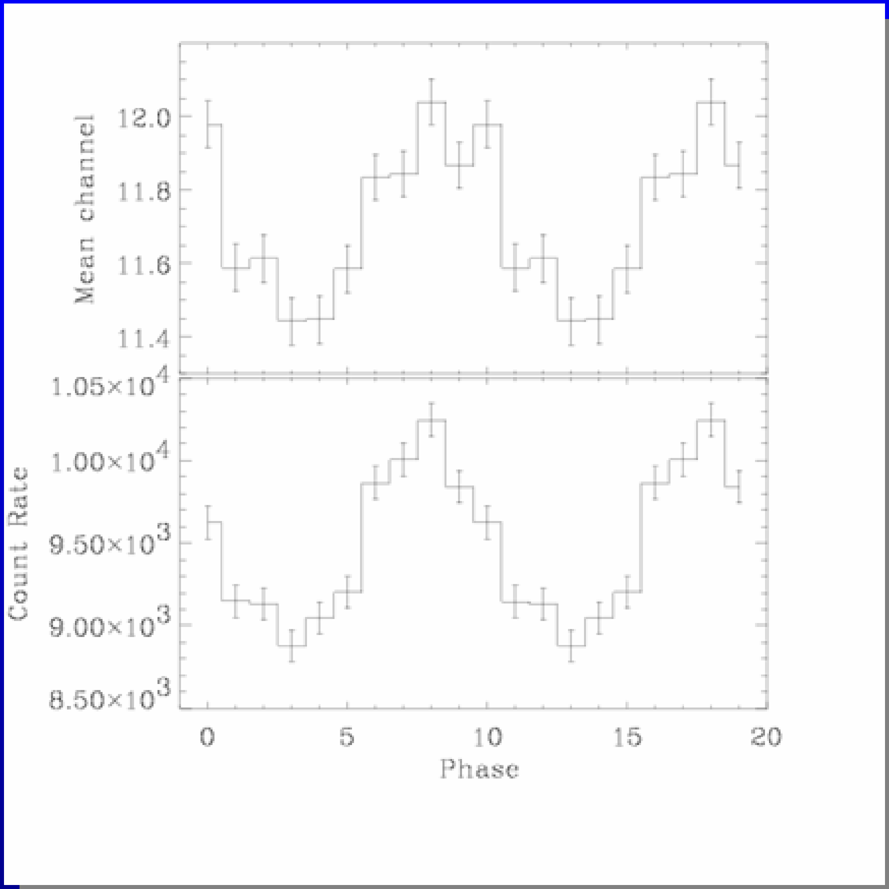


Phase Resolved Spectroscopy

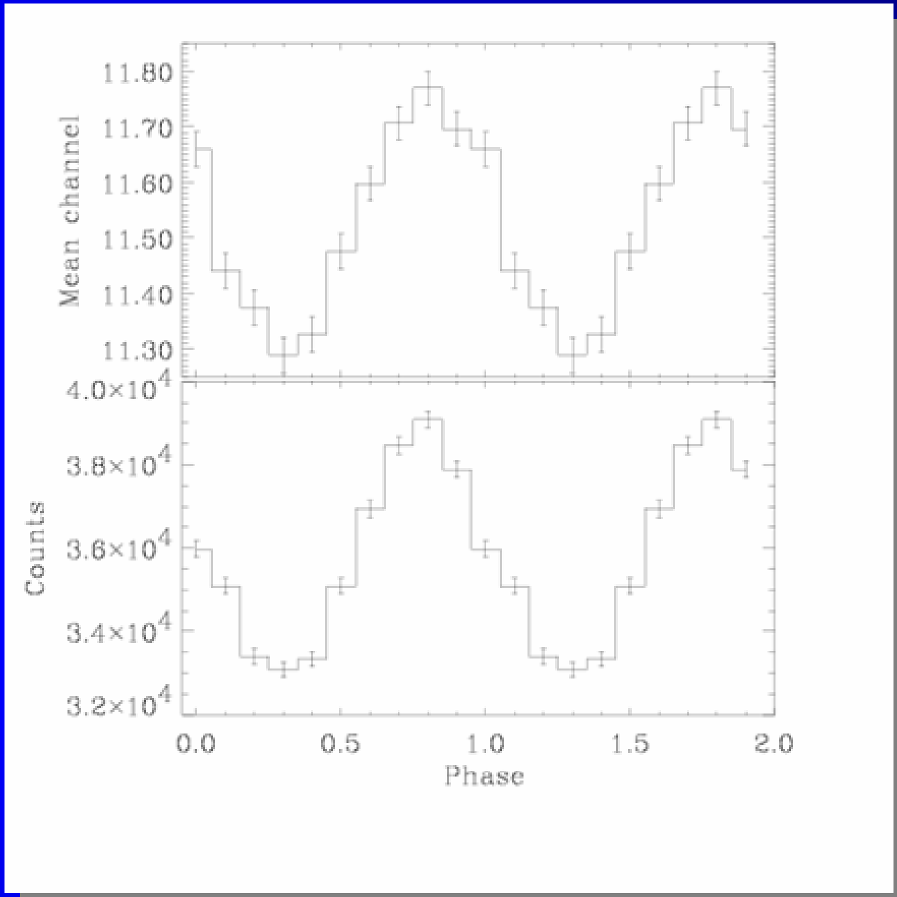
Goddard Space Flight Center

4U 1702-429

Rises: 4 bursts



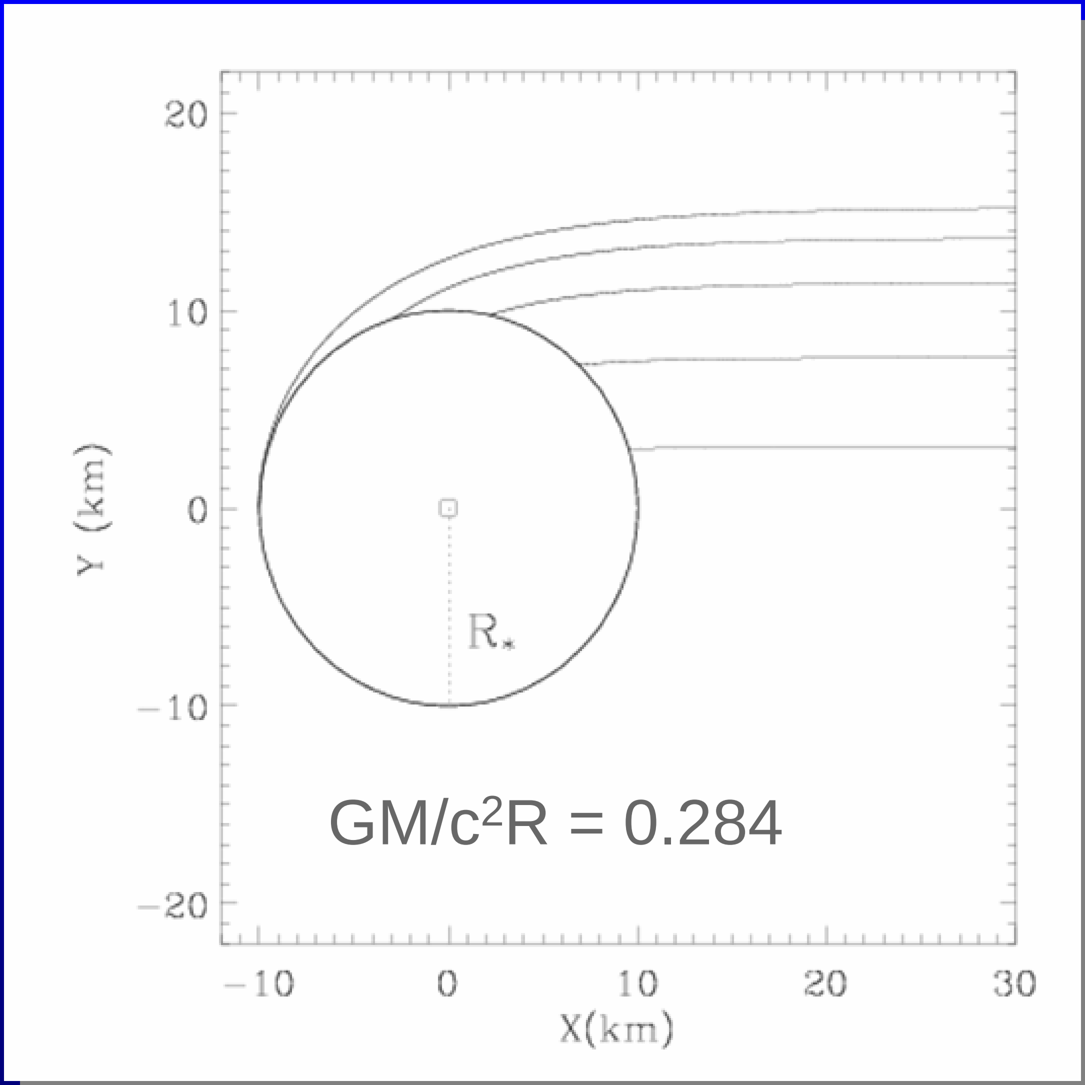
Tails: 4 bursts



- Spectra (or average hardness) with pulse phase show modulations consistent with temperature asymmetry.

Rotational Modulation of Neutron Star Emission: The Model

Goddard Space Flight Center

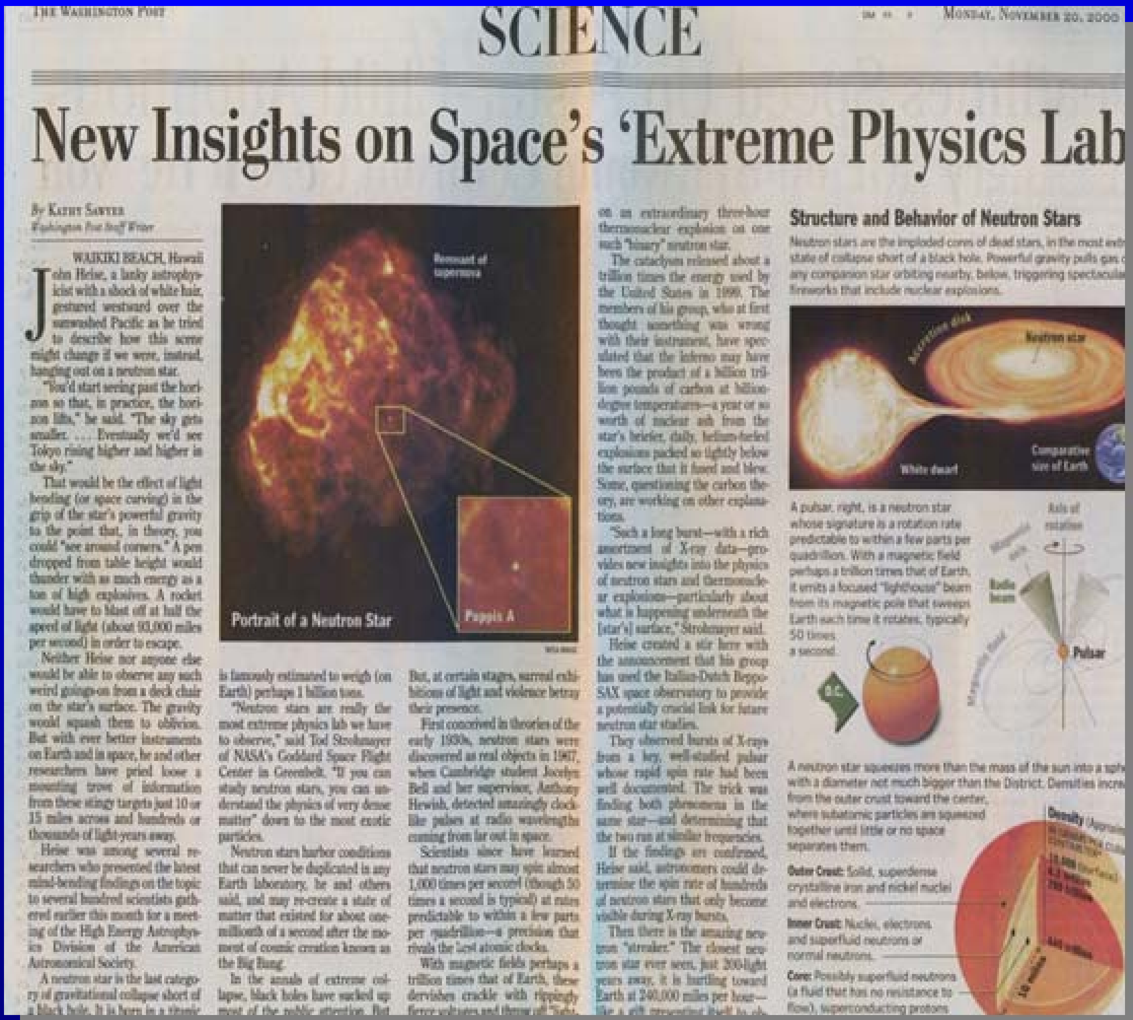


- Gravitational Light Deflection: Schwarzschild metric.
- Gravitational redshift
- Rotational doppler shifts and aberration of the intensity.
- "Beaming" of intensity in NS rest frame.
- Arbitrary geometry of emission regions.
- Observed response using various detector response matrices.

Miller, Bhatacharya, Muno, Ozel, Psaltis, Braje, Romani, Nath, etc.

RXTE and BeppoSAX Observe "Superbursts" from Accreting Neutron Stars

Goddard Space
Flight Center



THE WASHINGTON POST — SCIENCE — MONDAY, NOVEMBER 20, 2000

New Insights on Space's 'Extreme Physics Lab'

By Kathy Sawyer
Washington Post Staff Writer

WAIKIKI BEACH, Hawaii

John Heise, a lanky astrophysicist with a shock of white hair, gestured westward over the sunwashed Pacific as he tried to describe how this scene might change if we were, instead, hanging out on a neutron star.

"You'd start seeing past the horizon so that, in practice, the horizon lifts," he said. "The sky gets smaller. . . . Eventually we'd see Tokyo rising higher and higher in the sky."

That would be the effect of light bending (or space curving) in the grip of the star's powerful gravity to the point that, in theory, you could "see around corners." A pen dropped from table height would thunder with as much energy as a ton of high explosives. A rocket would have to blast off at half the speed of light (about 93,000 miles per second) in order to escape.

Neither Heise nor anyone else would be able to observe any such weird goings-on from a deck chair on the star's surface. The gravity would squash them to oblivion. But with ever better instruments on Earth and in space, he and other researchers have pried loose a mounting trove of information from these stingy targets just 10 or 15 miles across and hundreds or thousands of light-years away.

Heise was among several researchers who presented the latest mind-bending findings on the topic to several hundred scientists gathered earlier this month for a meeting of the High Energy Astrophysics Division of the American Astronomical Society.

A neutron star is the last category of gravitational collapse short of a black hole. It is born in a titanic

Portrait of a Neutron Star

Remnant of supernova

Puppis A

is famously estimated to weigh (on Earth) perhaps 1 billion tons.

"Neutron stars are really the most extreme physics lab we have to observe," said Tod Strohmayer of NASA's Goddard Space Flight Center in Greenbelt. "If you can study neutron stars, you can understand the physics of very dense matter" down to the most exotic particles.

Neutron stars harbor conditions that can never be duplicated in any Earth laboratory, he and others said, and may re-create a state of matter that existed for about one-millionth of a second after the moment of cosmic creation known as the Big Bang.

In the annals of extreme collapse, black holes have sucked up most of the public attention. But

But, at certain stages, surreal exhibitions of light and violence betray their presence.

First conceived in theories of the early 1930s, neutron stars were discovered as real objects in 1967, when Cambridge student Jocelyn Bell and her supervisor, Anthony Hewish, detected amazingly clock-like pulses at radio wavelengths coming from far out in space.

Scientists since have learned that neutron stars may spin almost 1,000 times per second (though 50 times a second is typical) at rates predictable to within a few parts per quadrillion—a precision that rivals the best atomic clocks.

With magnetic fields perhaps a trillion times that of Earth, these dervishes crackle with rippingly fierce voltages and throw off

on an extraordinary three-hour thermonuclear explosion on one such "binary" neutron star.

The cataclysm released about a trillion times the energy used by the United States in 1998. The members of his group, who at first thought something was wrong with their instrument, have speculated that the inferno may have been the product of a billion trillion pounds of carbon at billion-degree temperatures—a year or so worth of nuclear ash from the star's briefer, daily, helium-fueled explosions packed so tightly below the surface that it fused and blew. Some, questioning the carbon theory, are working on other explanations.

"Such a long burst—with a rich assortment of X-ray data—provides new insights into the physics of neutron stars and thermonuclear explosions—particularly about what is happening underneath the [star's] surface," Strohmayer said.

Heise created a stir here with the announcement that his group has used the Italian-Dutch BeppoSAX space observatory to provide a potentially crucial link for future neutron star studies.

They observed bursts of X-rays from a key, well-studied pulsar whose rapid spin rate had been well documented. The trick was finding both phenomena in the same star—and determining that the two ran at similar frequencies.

If the findings are confirmed, Heise said, astronomers could determine the spin rate of hundreds of neutron stars that only become visible during X-ray bursts.

Then there is the amazing neutron "streaker." The closest neutron star ever seen, just 200 light-years away, it is hurtling toward Earth at 240,000 miles per hour—

Structure and Behavior of Neutron Stars

Neutron stars are the imploded cores of dead stars, in the most ext
state of collapse short of a black hole. Powerful gravity pulls gas o
any companion star orbiting nearby, below, triggering spectacula
fireworks that include nuclear explosions.

A pulsar, right, is a neutron star whose signature is a rotation rate predictable to within a few parts per quadrillion. With a magnetic field perhaps a trillion times that of Earth, it emits a focused "lighthouse" beam from its magnetic pole that sweeps Earth each time it rotates, typically 50 times a second.

A neutron star squeezes more than the mass of the sun into a sph
with a diameter not much bigger than the District. Densities incre
from the outer crust toward the center, where subatomic particles are squeezed together until little or no space separates them.

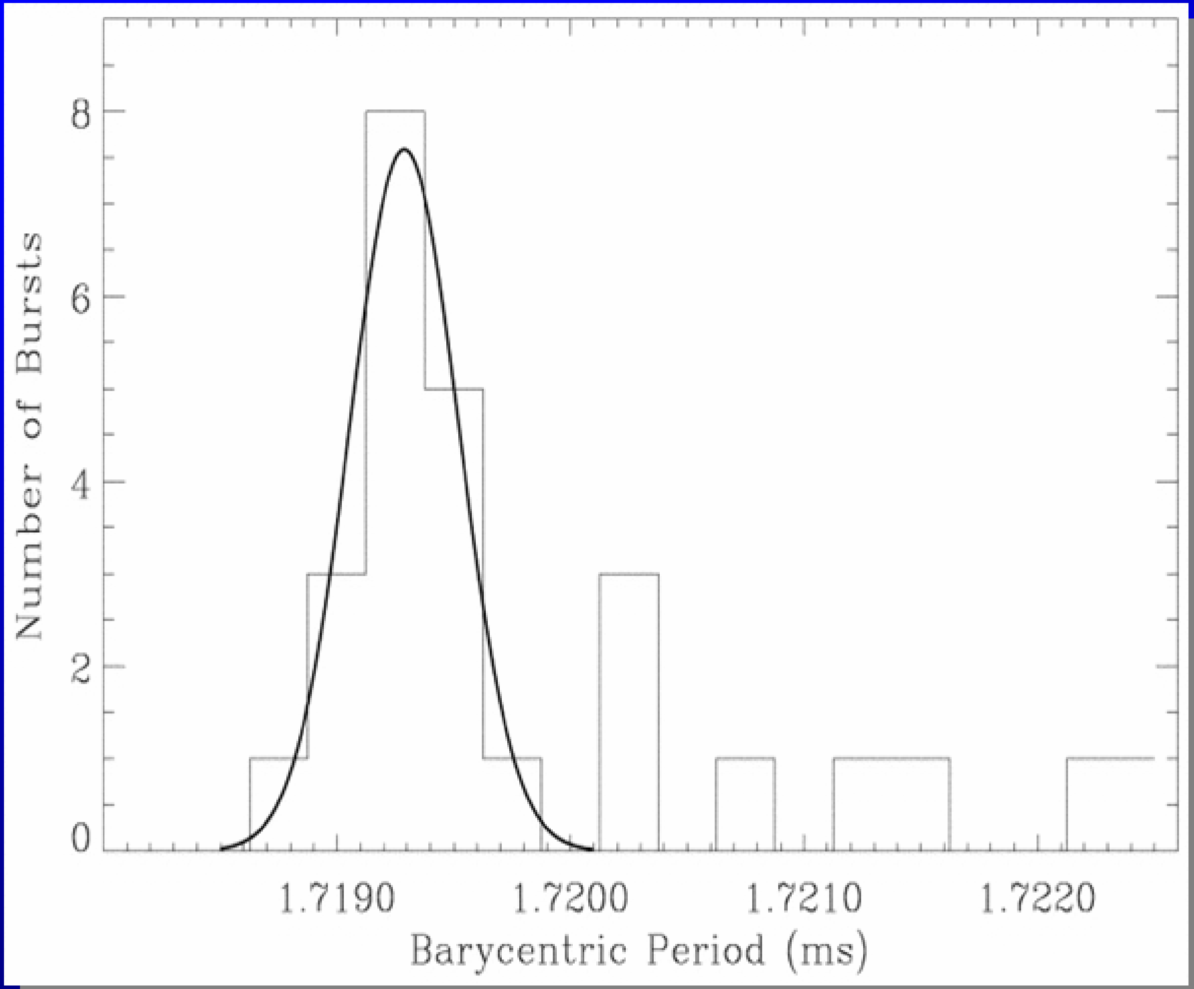
Outer Crust: Solid, superdense crystalline iron and nickel nuclei and electrons.

Inner Crust: Nuclei, electrons and superfluid neutrons or normal neutrons.

Core: Possibly superfluid neutrons (a fluid that has no resistance to flow), superconducting protons

- Long, 3-5 hr. X-ray bursts observed from 5 accreting neutron star binaries (Heise et al. 2000; Strohmayer 2000; Wijnands 2001).
- Bursts reveal new regime of nuclear burning. 1,000 times more energy release than normal bursts.
- Stories made headlines in national papers, Washington Post, NY Times.

Stability of Burst Oscillations

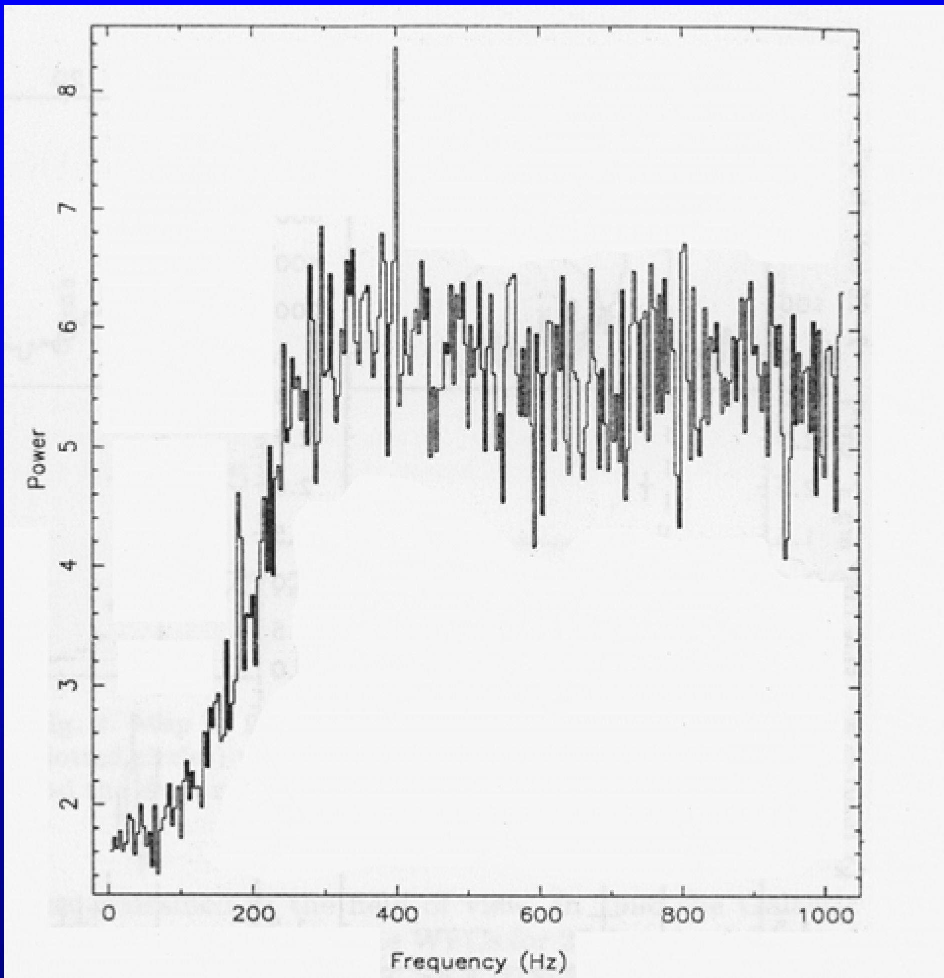


- Burst oscillation frequencies in 4U 1636-53 have δf/f ~ 0.003
- No apparent correlation with orbital phase.
- Difficult to infer orbital parameters from sample of bursts, for example, neutron star velocity.

4U 1636-53: Giles et al. (2002)

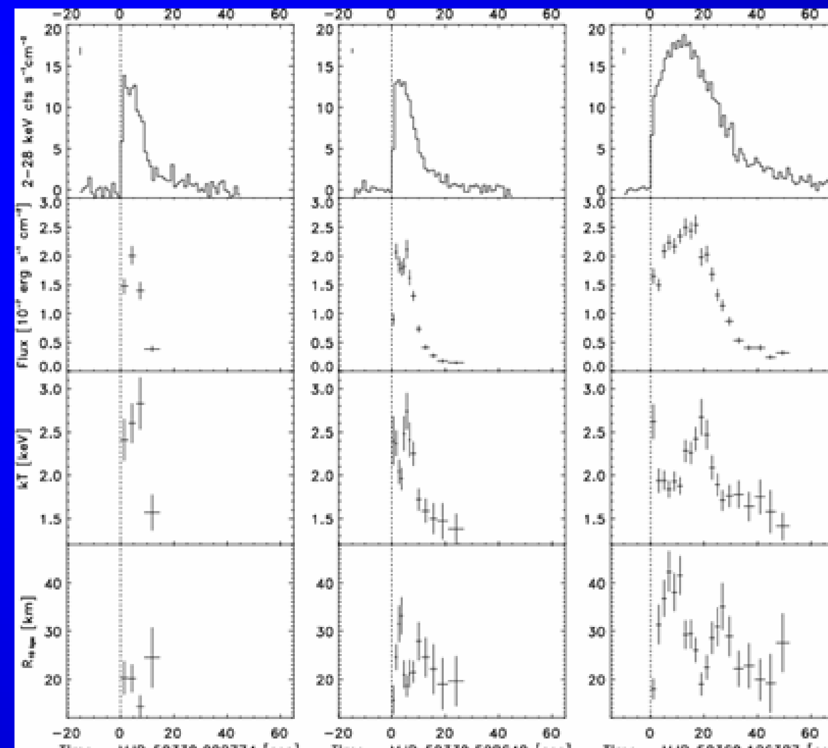
Goddard Space Flight Center

*SAX J1808.4-3658 (401 Hz Pulsar)



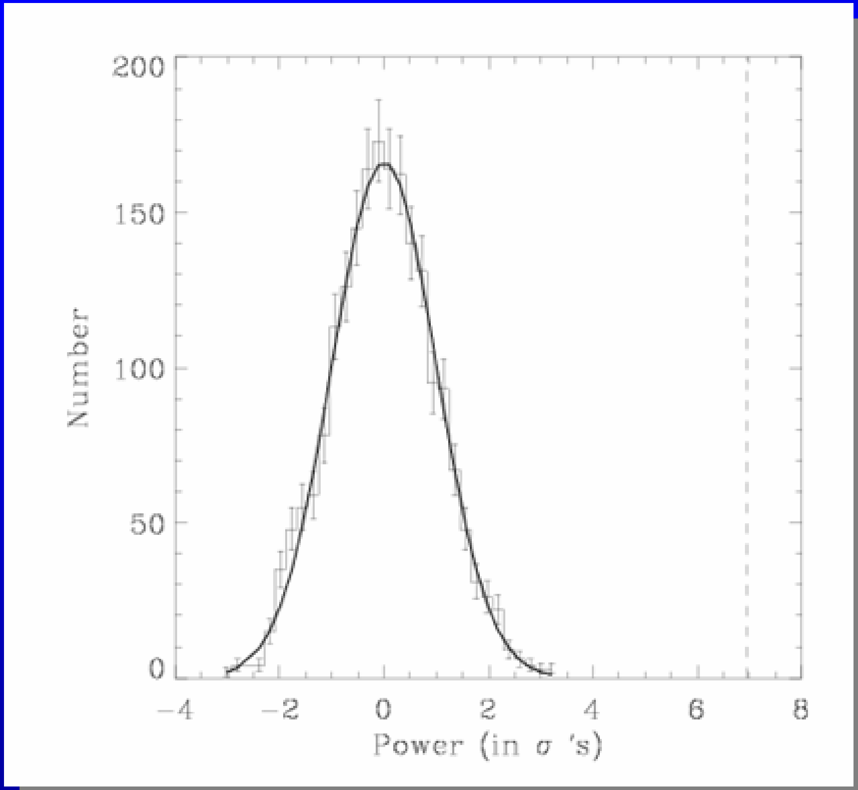
From in ‘t Zand et al. (2001)

- In ‘t Zand et al. (2001) using BeppoSAX/WFC, find evidence for 401 pulsations in bright burst from SAX J1808

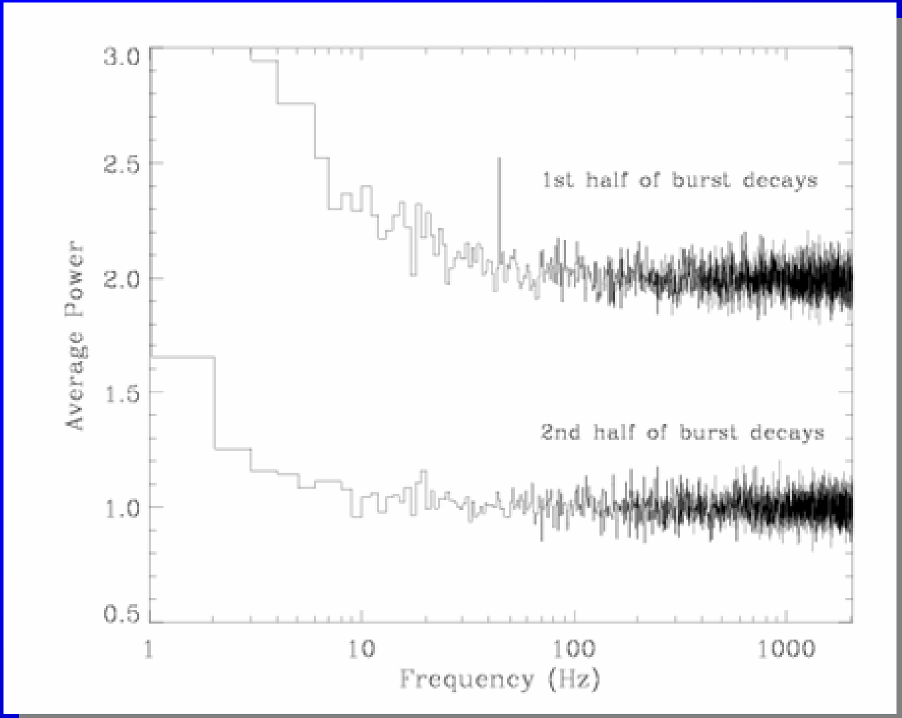


45 Hz Signal: Summary

Goddard Space Flight Center



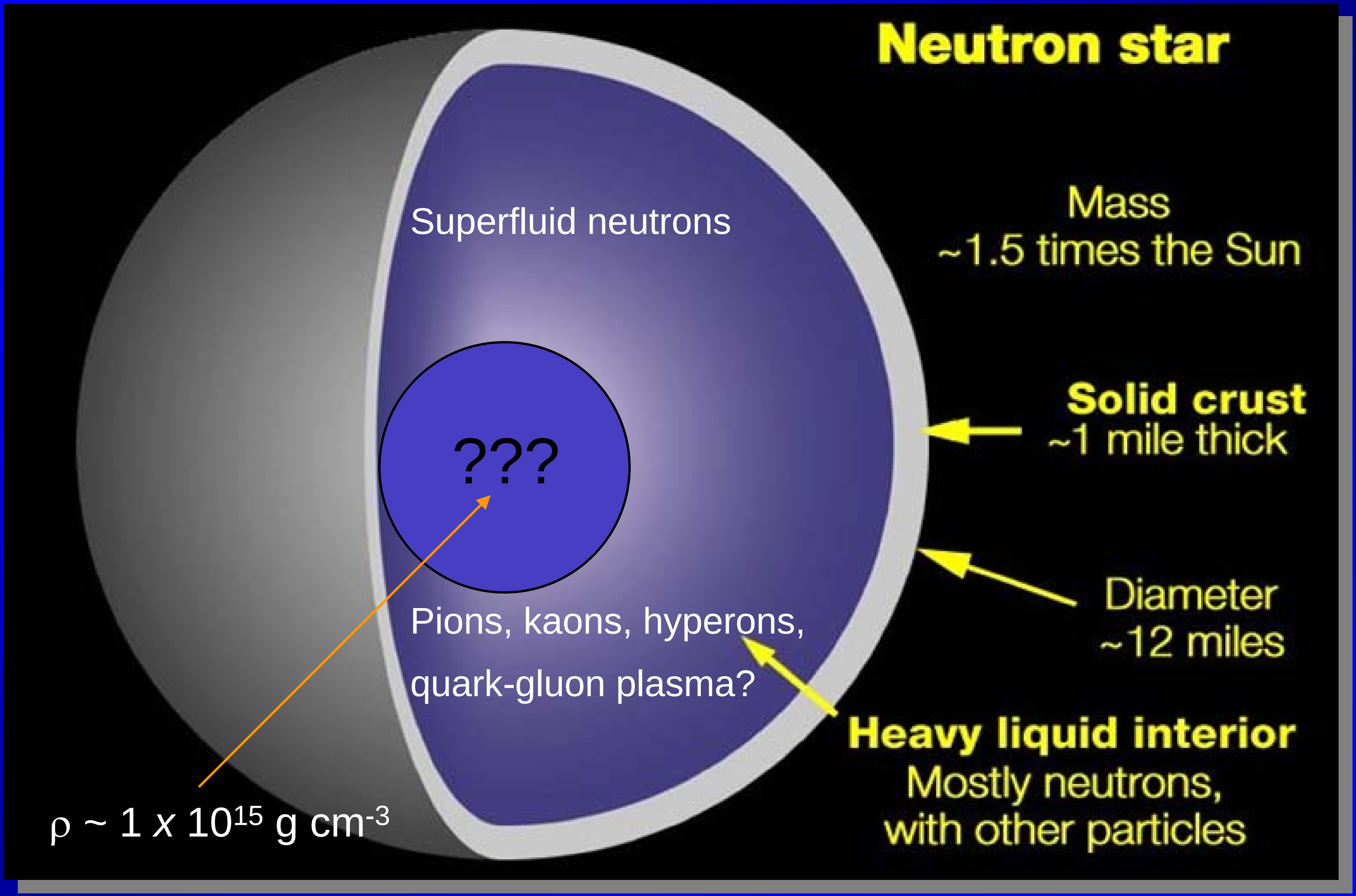
- Signal significant at 4 x 10^{-8} level.
- Average amplitude of 3% (rms).



Signal definitely associated with brightest parts of the X-ray bursts.

Inside 'Extreme' Neutron Stars

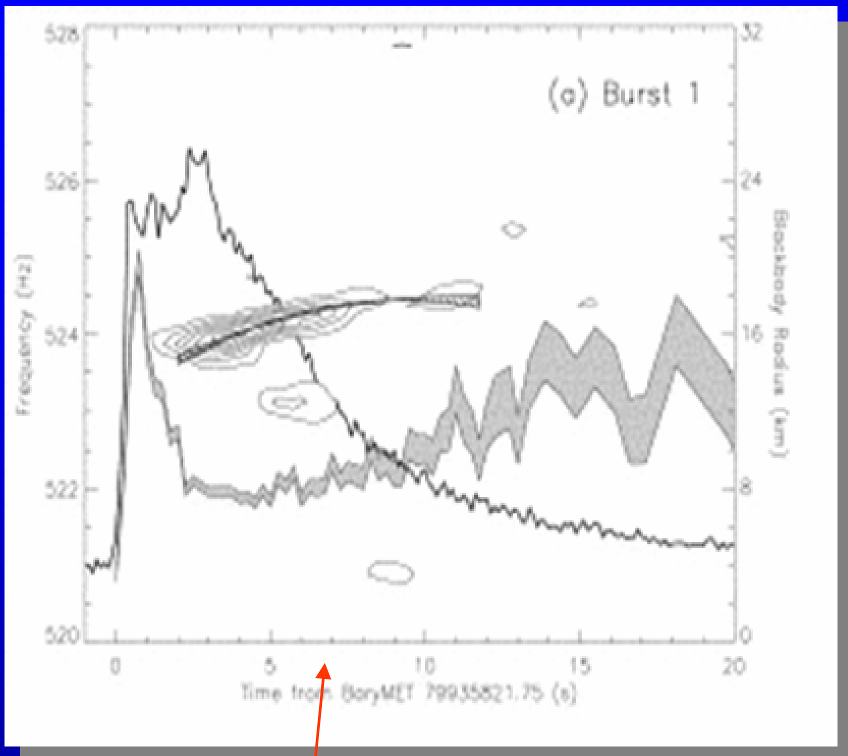
Goddard Space Flight Center



- The physical constituents of neutron star interiors remain a mystery after 35 years.

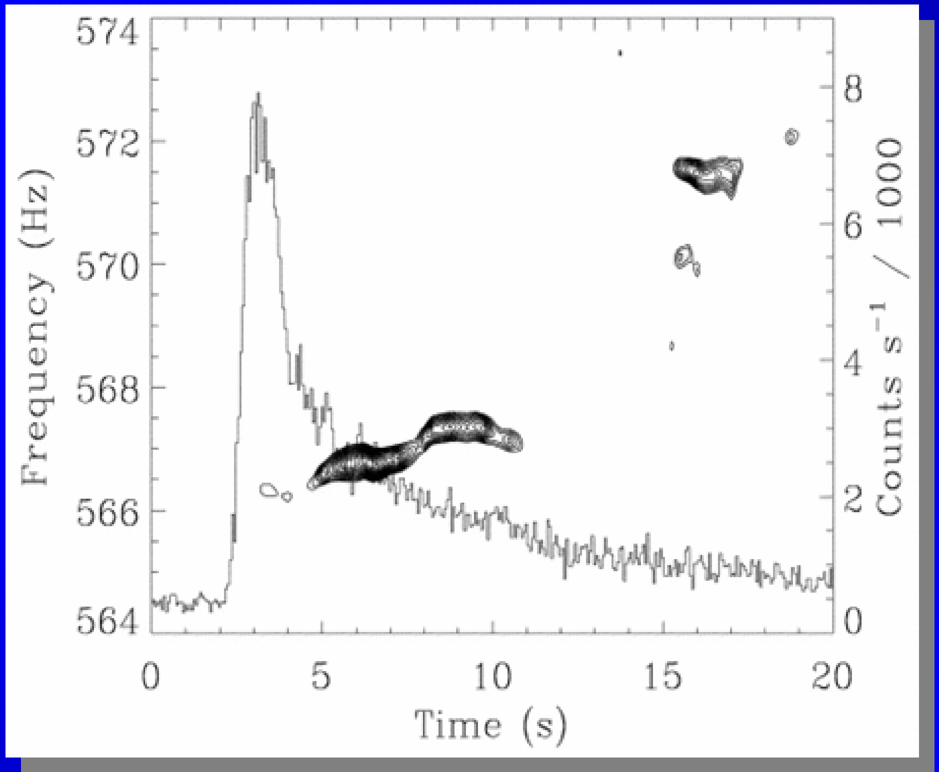
Goddard Space Flight Center

Coherence of Burst Oscillations con't



KS 1731-260: Muno et al. (2000)

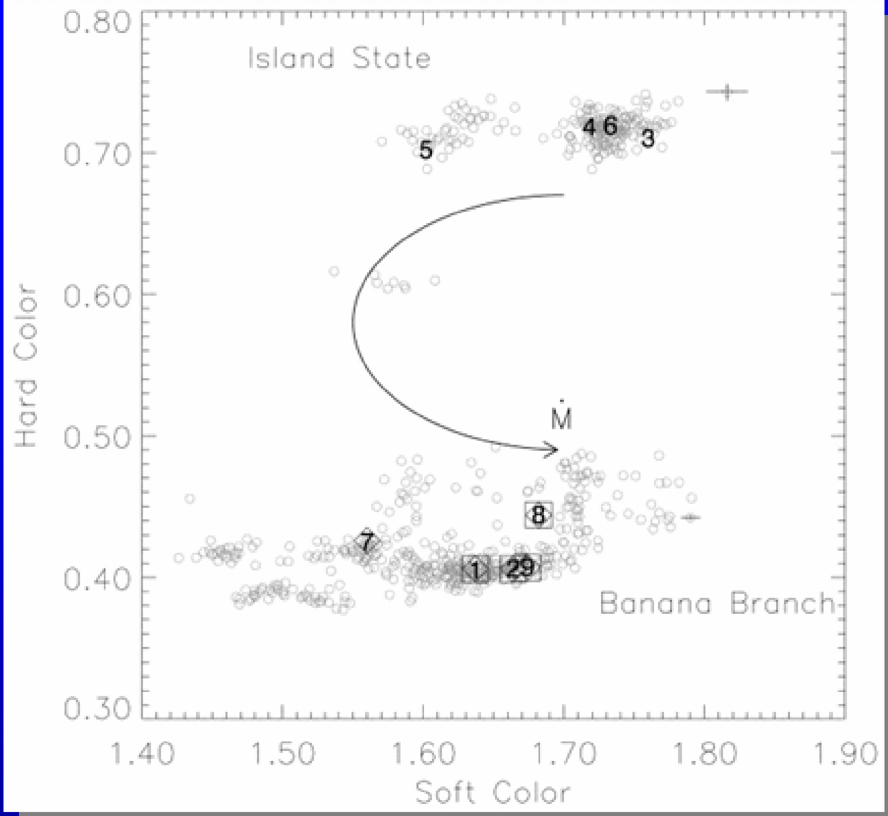
- Some bursts require higher order polynomials to fit evolution.
- Some phase jitter (Muno et al. 2000).



X1658-298: Wijnands, Strohmayer & Franco (2001)

Burst Oscillations and Source State

Goddard Space Flight Center

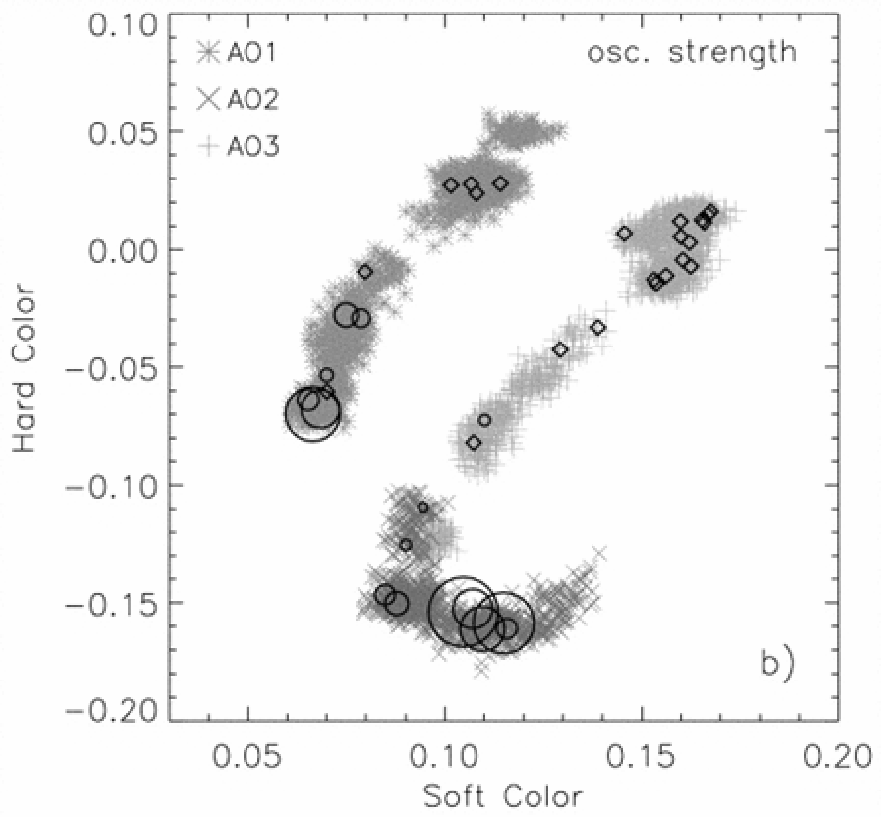


KS 1731-260: Muno et al (2000)

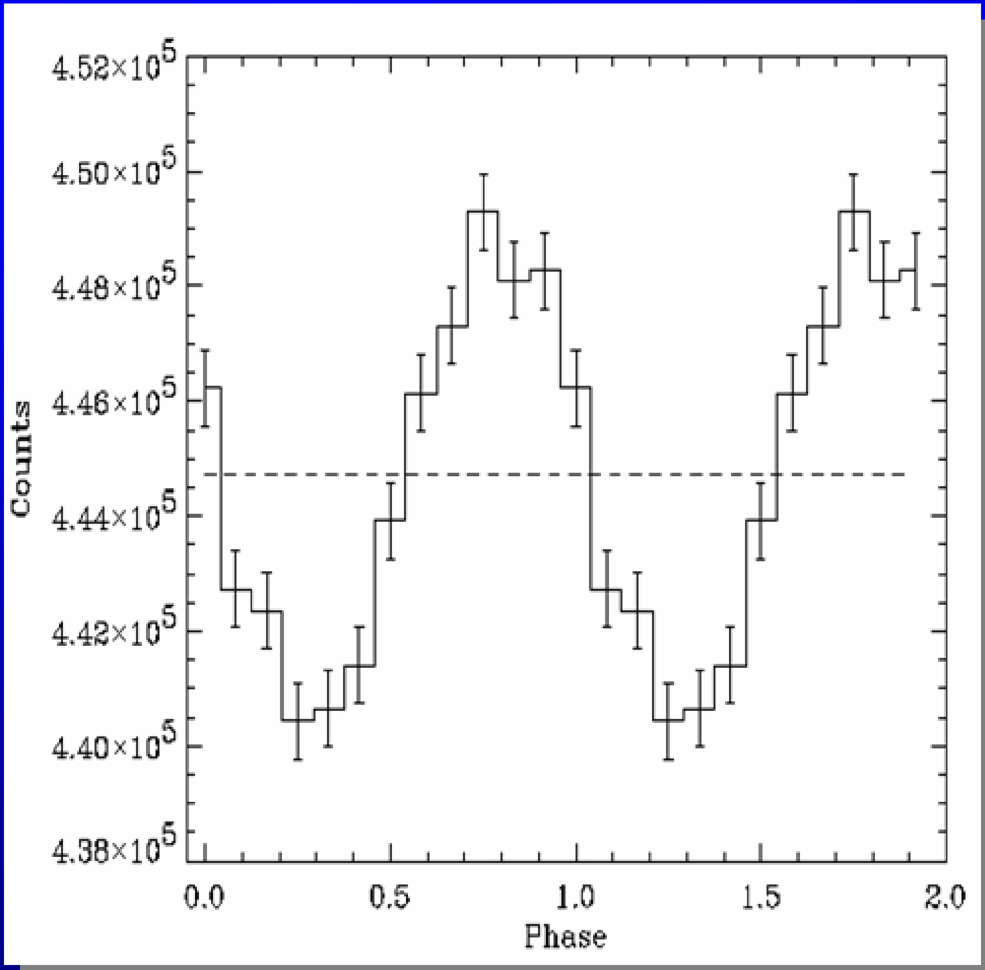
- Connection with mass accretion rate dependence of nuclear burning

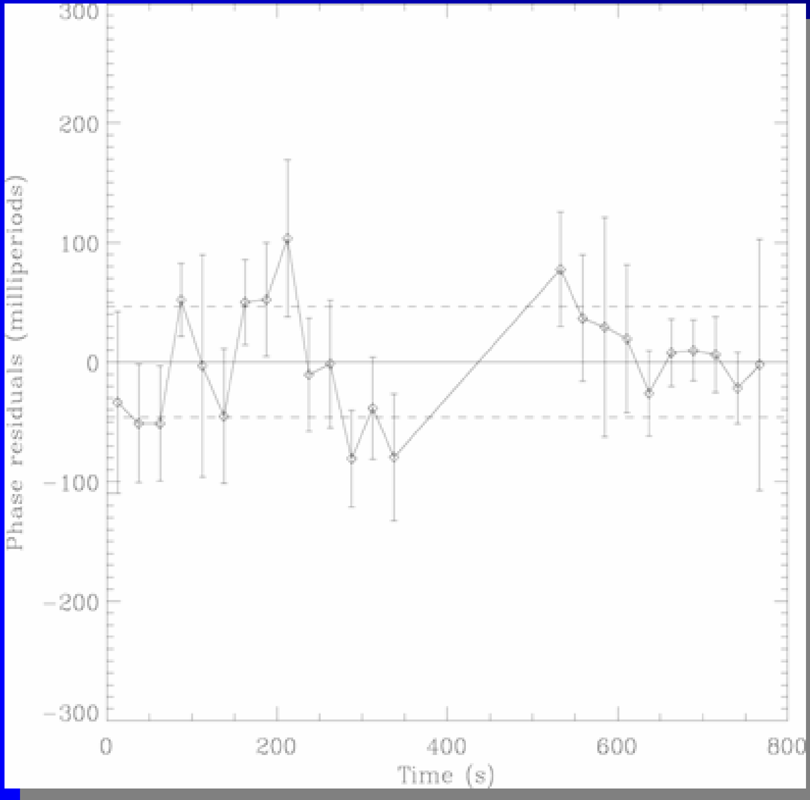
- Bursts with oscillations correlated with position in the X-ray CC diagram

4U 1728-34: Franco (2001)



Pulse Profile and Phase Residuals

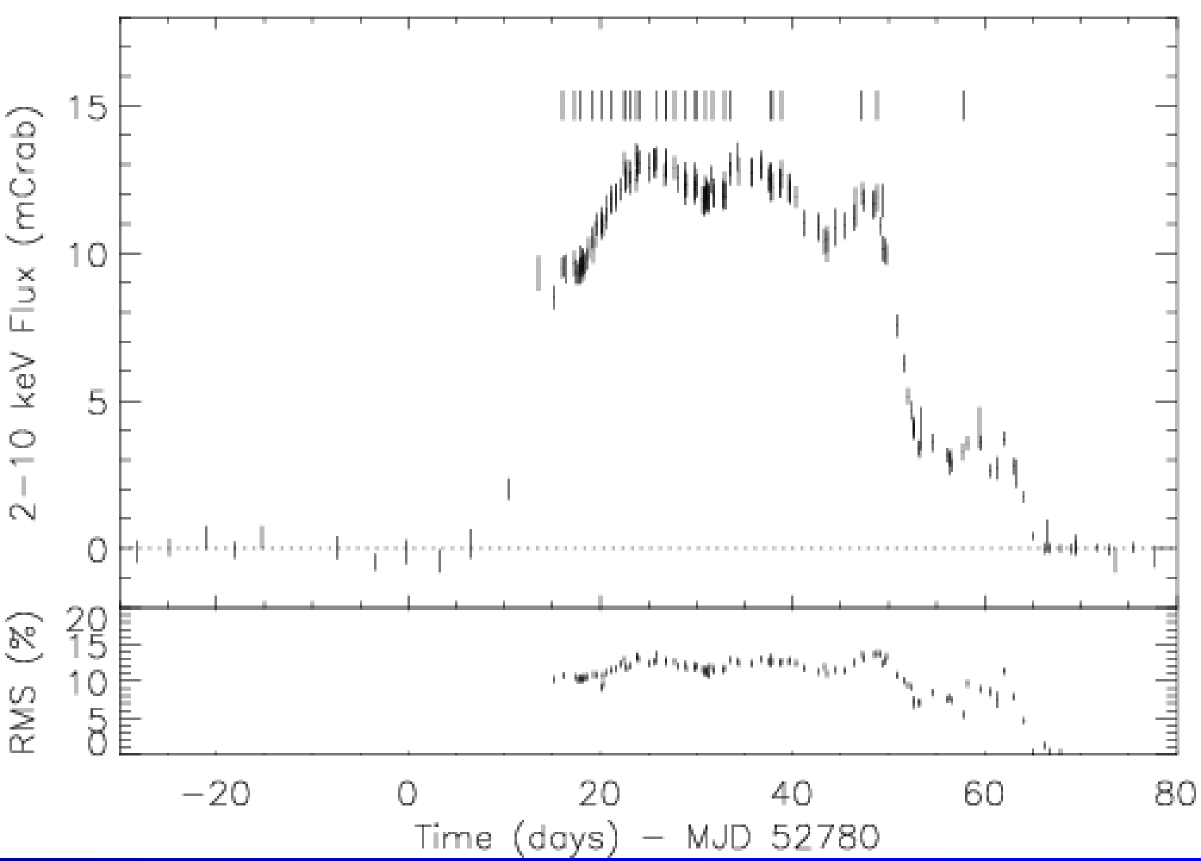




- 1% pulse amplitude (mean)
- ~30 μsec (rms)

Goddard Space Flight Center

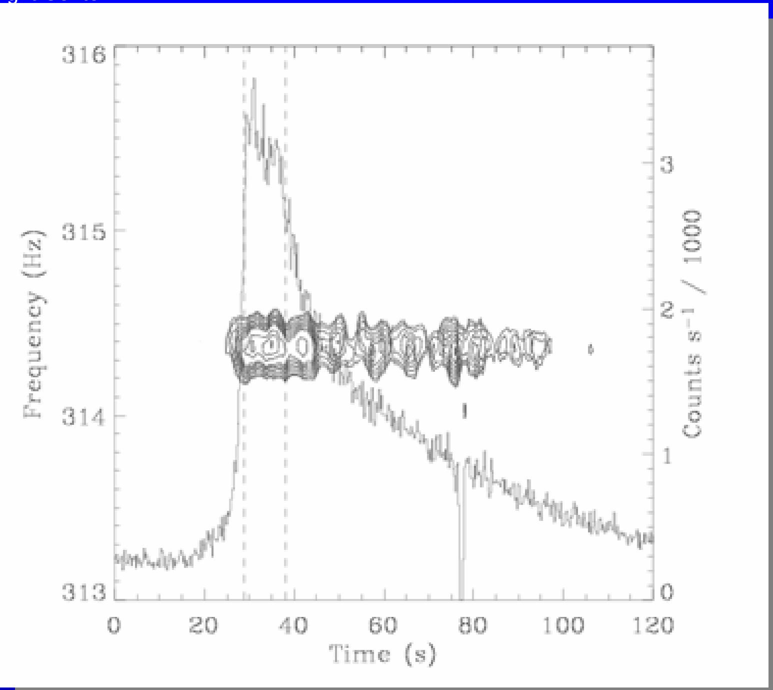
Discovery of XTE J1814-338

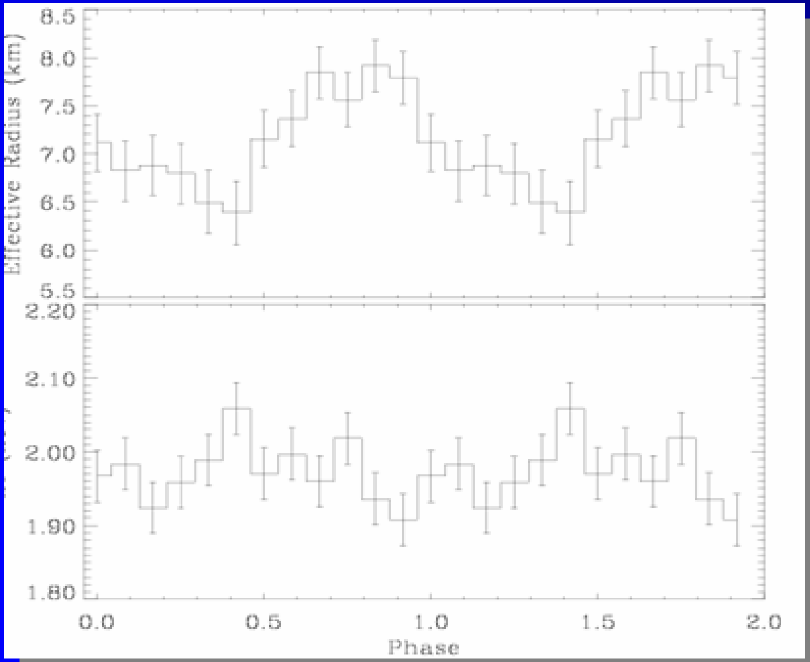


- 1% pulse amplitude (mean)
- ~30 μsec (rms)

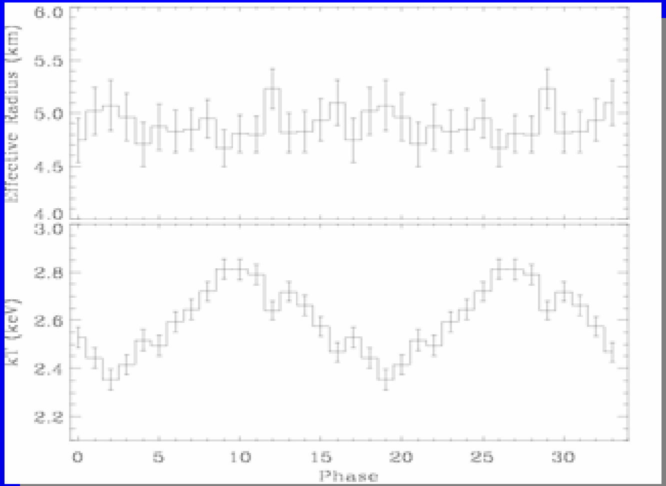
Goddard Space Flight Center

Pulse Phase Spectroscopy: XTE J1814-338



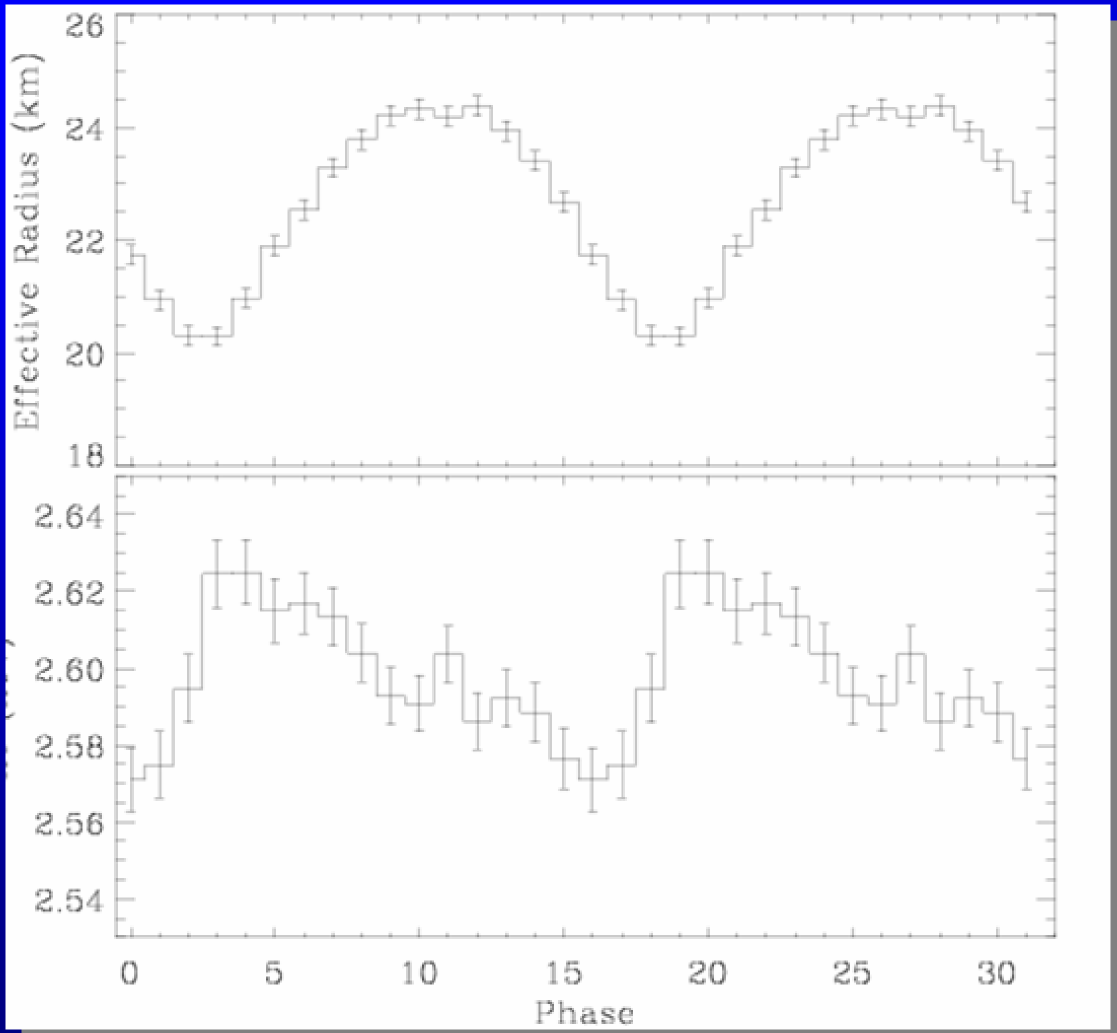


- Modulation consistent with varying projected area, at ~constant temperature
- This is not what would be seen from a “mode” where kT varied with some angular dependence



Pulse Phase Spectroscopy: Seeing the Surface Velocity.

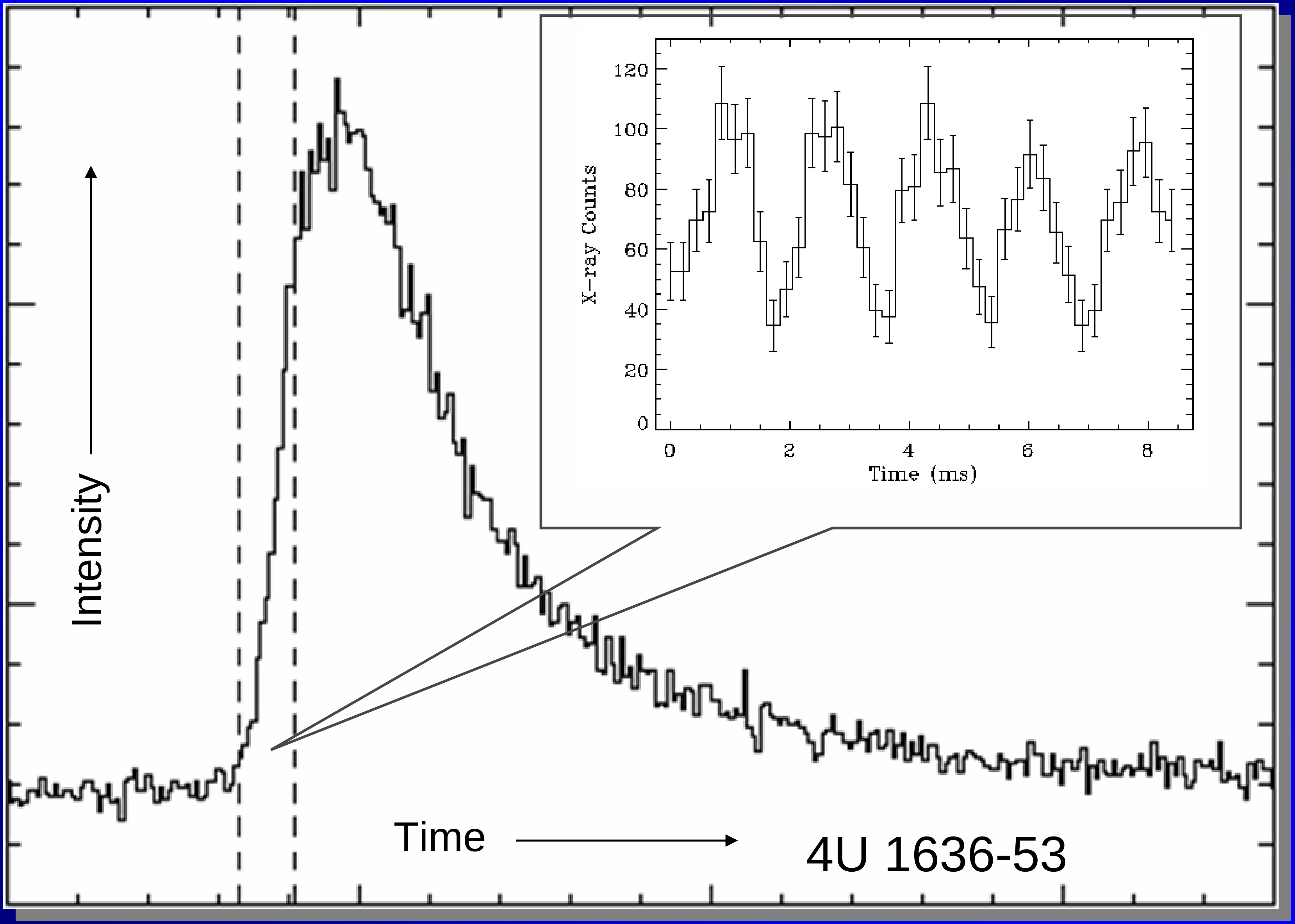
Goddard Space Flight Center



- Simulation for J1814-like burst, with 10x RXTE/PCA.
- The rotational doppler shift can be seen in the phase dependence of the fitted kT.
- Could provide a measurement of radius.

Oscillations at Burst Onset

Goddard Space Flight Center



Amplitudes at Onset: Rotational Model

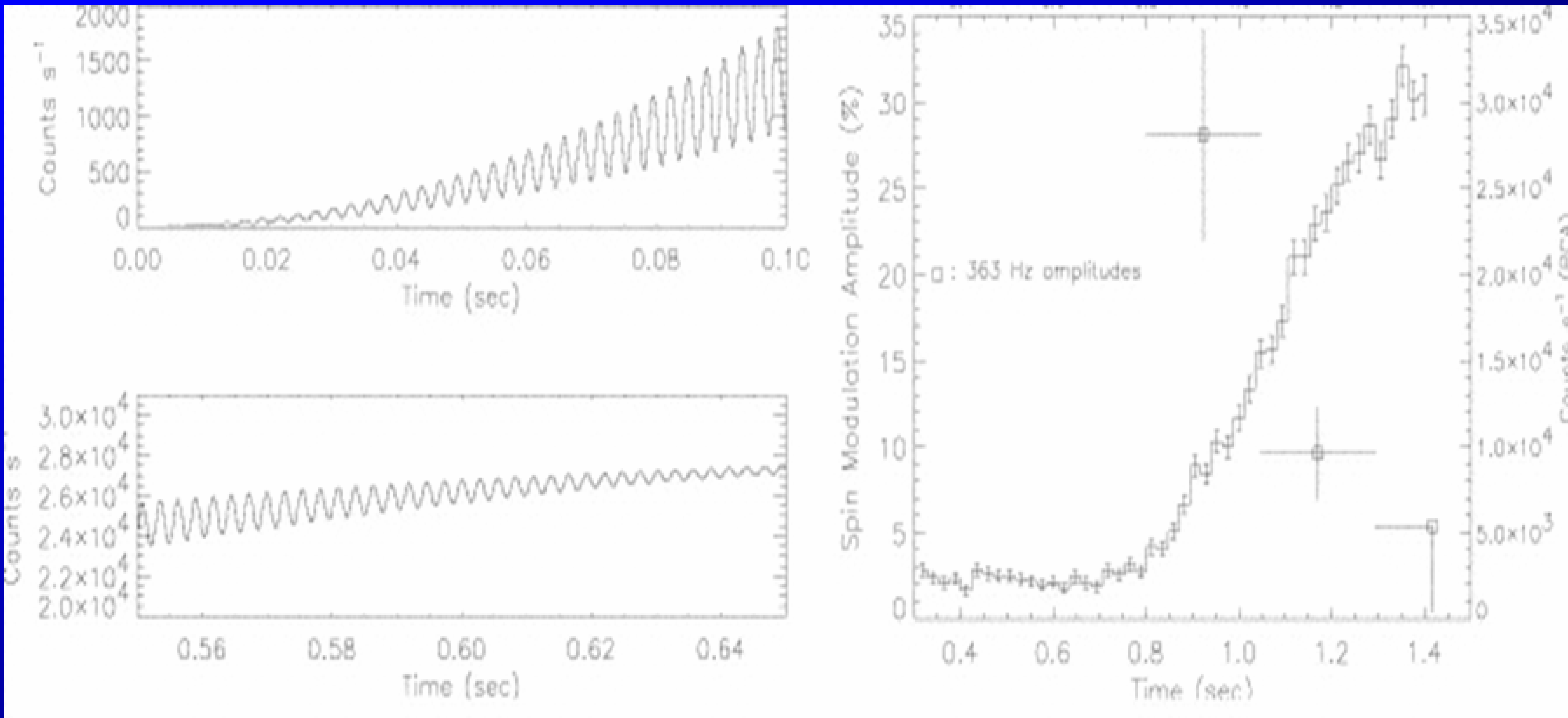


FIG. 4*a*

FIG. 4*b*

- Simple expanding hot spot on rotating neutron star, including GR light deflection, can account for amplitudes and trend.

Strohmayer, Zhang & Swank (1997)

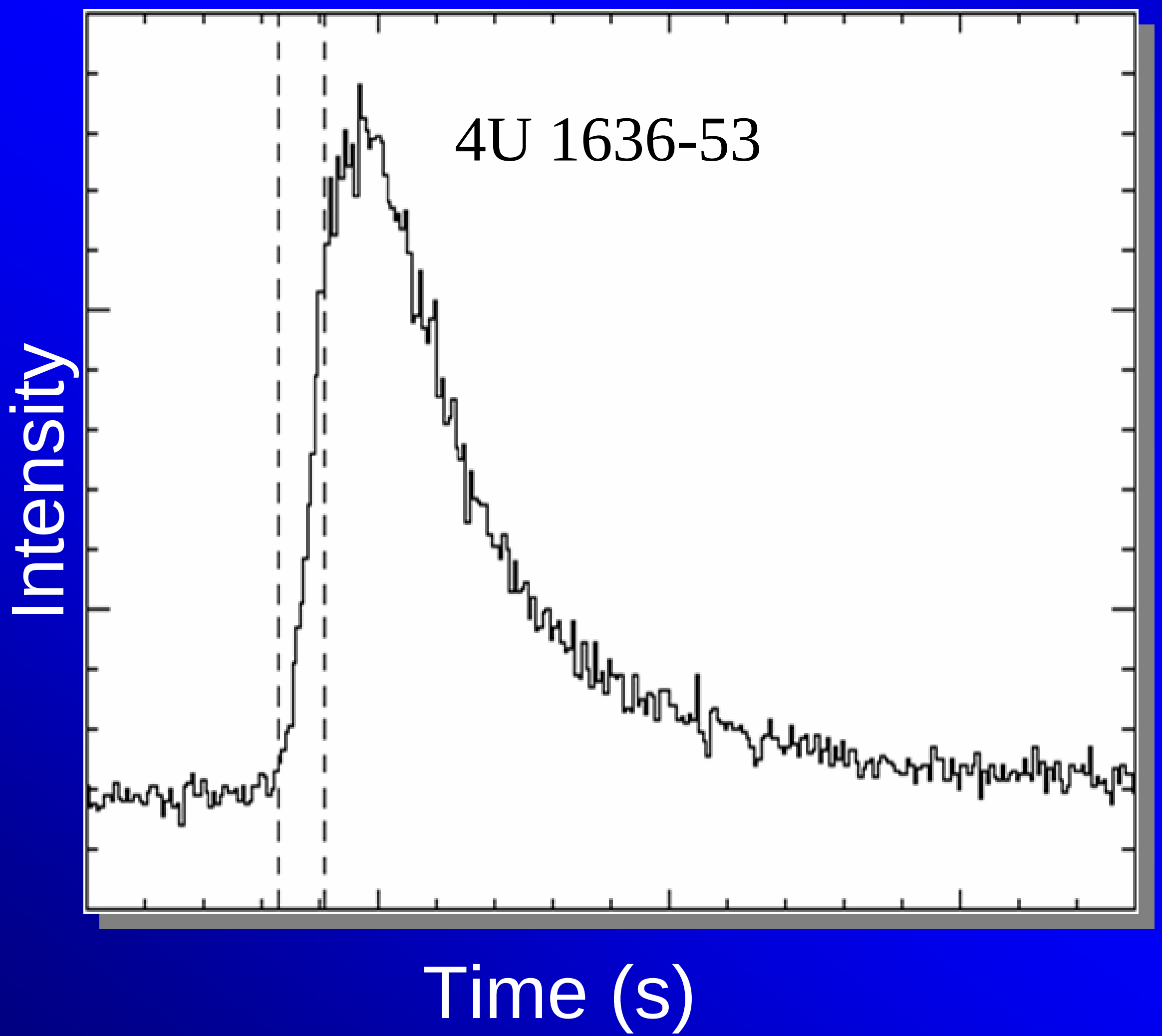
Goddard Space Flight Center

Outline

- Motivation: Precise Mass and Radius measurements, constraining EOS.
- Accreting Neutron stars: X-ray burst sources (X-ray emission from surface). Why study accreting sources?
- Fast timing of X-ray bursts (with RXTE): “burst oscillations”
- Burst oscillations. Bursts from accreting ms pulsars. => Spin modulation
- Using burst oscillations to constrain neutron star parameters
- Pulsation amplitudes, Pulse shapes (profile fitting). Recent results on XTE J1814-338 (Bhattacharyya et al 2004). Pulsars too (SAX J1808; Poutanen & Gierlinski 2002);
- Using high-res spectroscopy and timing (to get spin). Recent results on EXO 0748-676 (Cottam et al. 2002; Villarreal & Strohmayer 2004).
- Is there an upper limit to neutron star spin rates? If so, what is it telling us?

“Normal” Thermonuclear Bursts

Goddard Space Flight Center

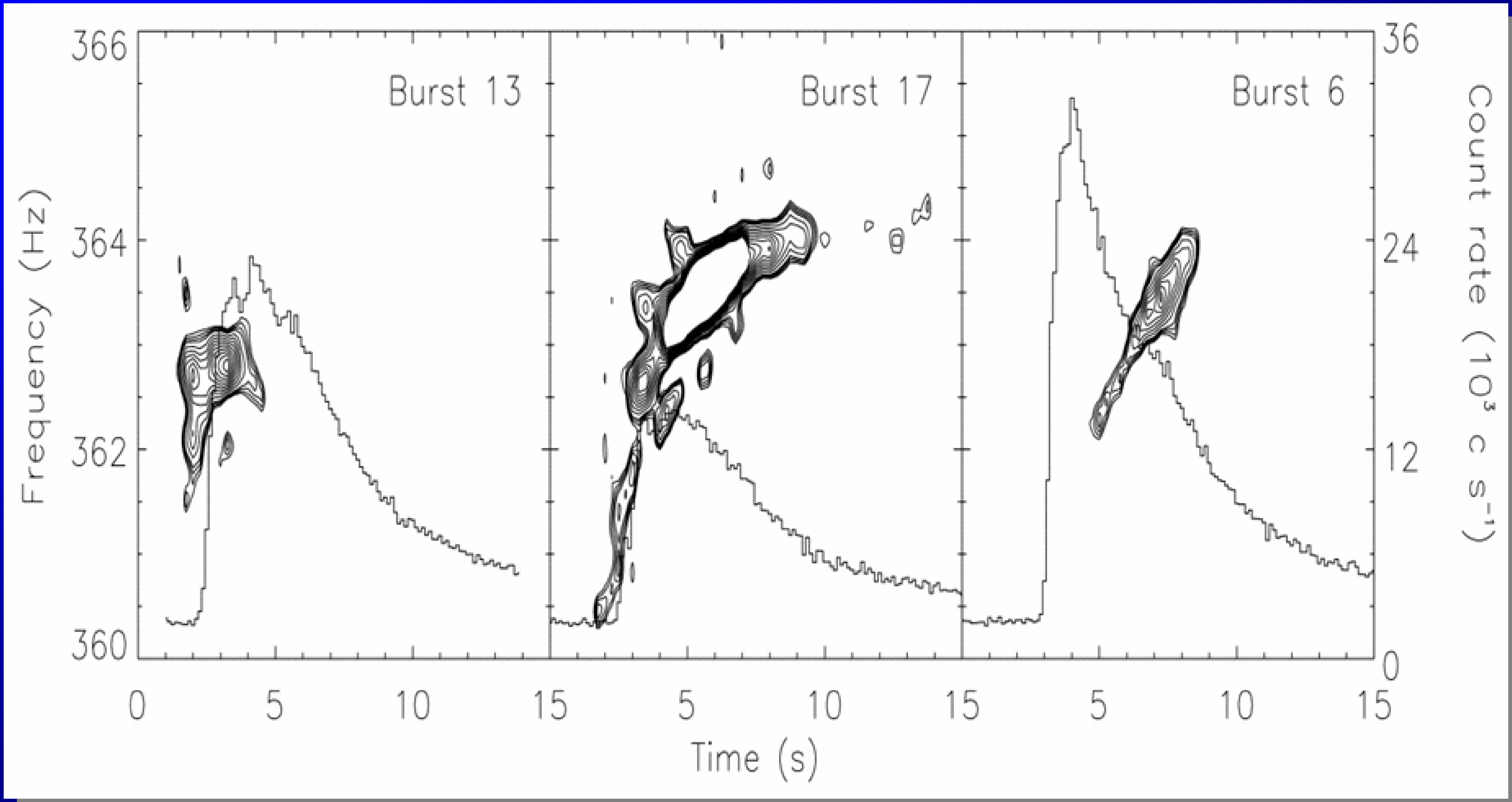


He Ignition at a column depth of 2×10^6 kg cm^{-2}

- 10 - 200 s flares.
- Thermal spectra which soften with time.
- 3 - 12 hr recurrence times, sometimes quasi-periodic.
- ~ 10^{39} ergs
- H and He primary fuels

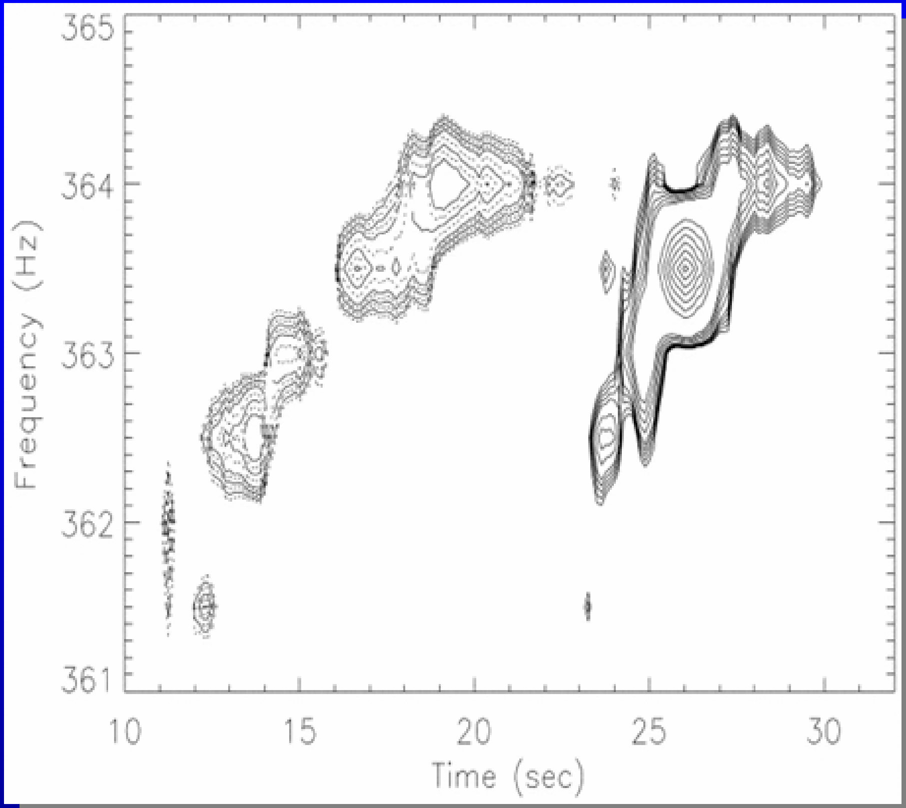
Properties of Burst Oscillations

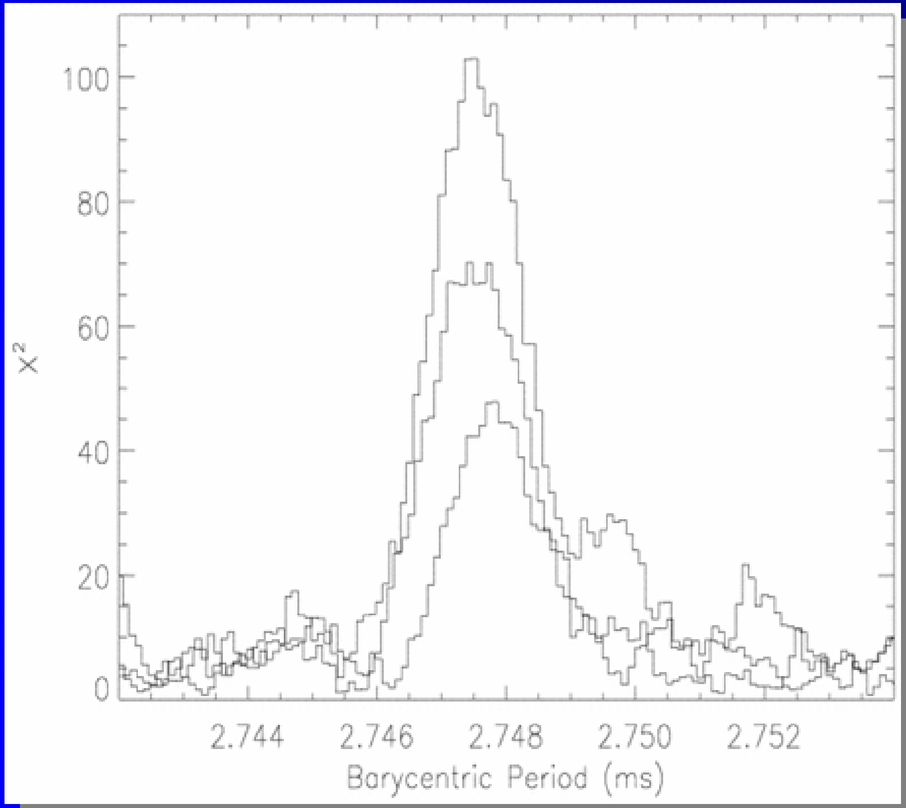
Goddard Space Flight Center



A Sample of Bursts from 4U 1728-34

Long term Stability of the Oscillation Frequency



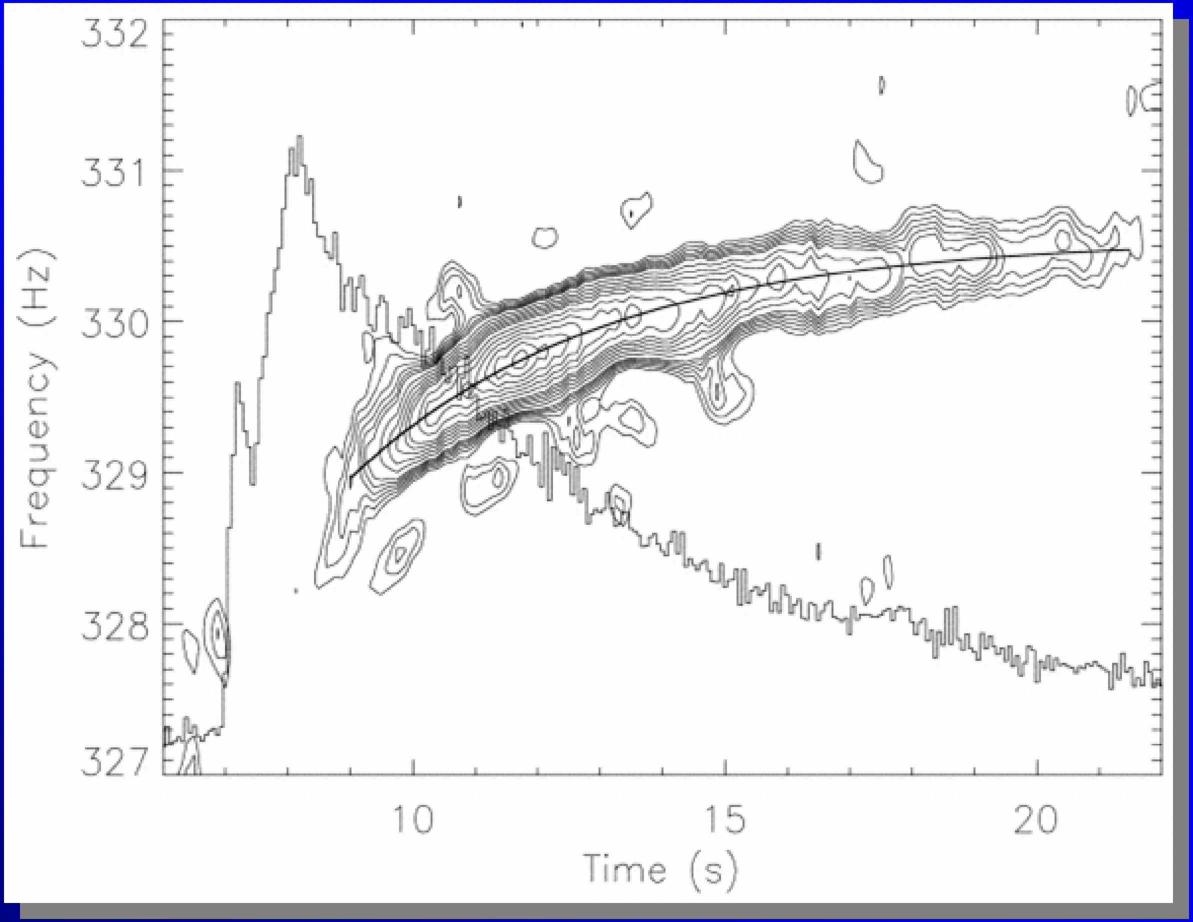


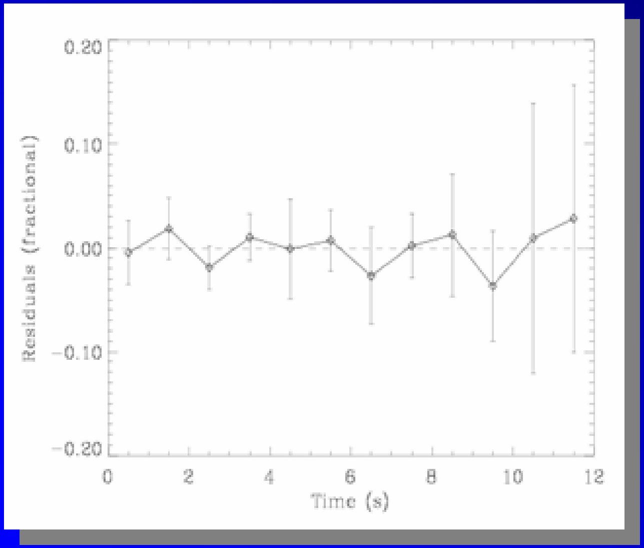
- Bursts from 4U 1728-34 separated by years have the same oscillation frequency
- for 4U 1728-34 timescale to change period ~ 2.3 x 10^4 yr

Coherence of Burst Oscillations

Goddard Space Flight Center

4U 1702-429: Strohmayer & Markwardt (1999)



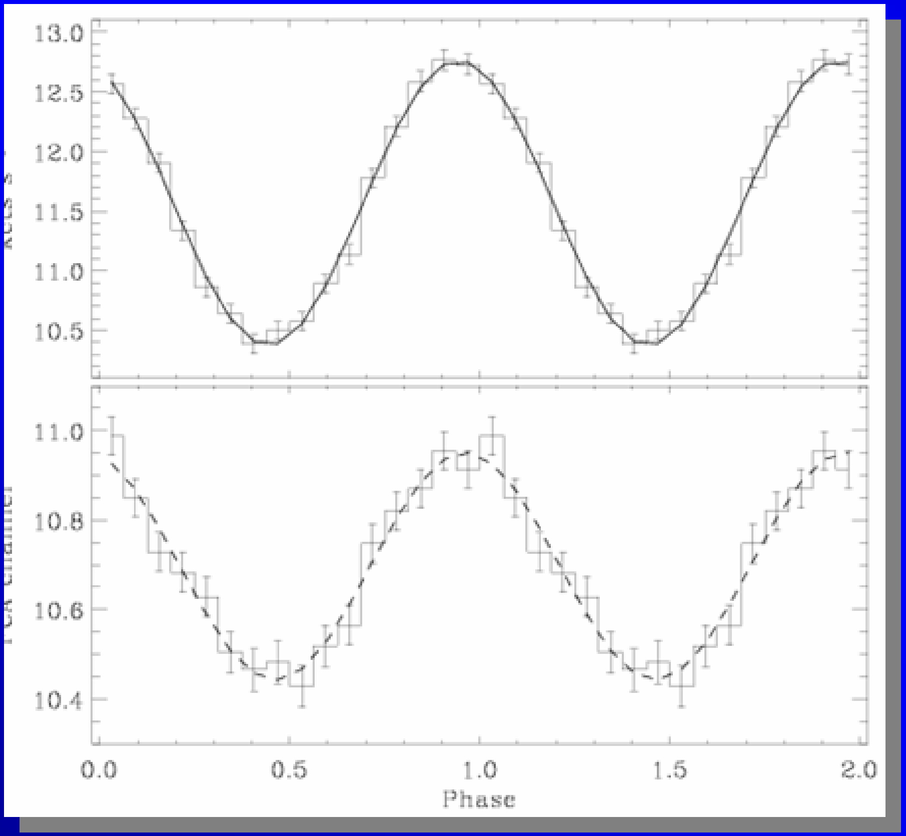


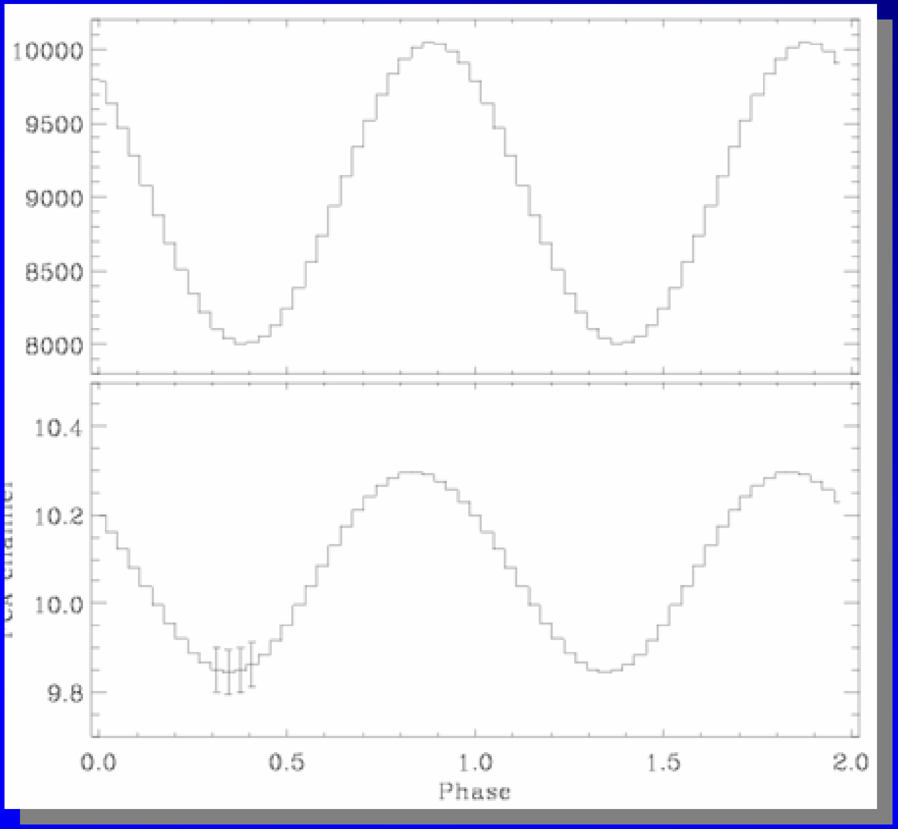
- Burst oscillations generally have high coherence (Q > 4,000)
- exponential recovery in some bursts.

Model: $f(t) = f_0 \, (1 - \delta e^{(-t/\tau)})$

Goddard Space Flight Center

Phase Resolved Spectroscopy: Rotational Doppler shifts, 4U 1636-53

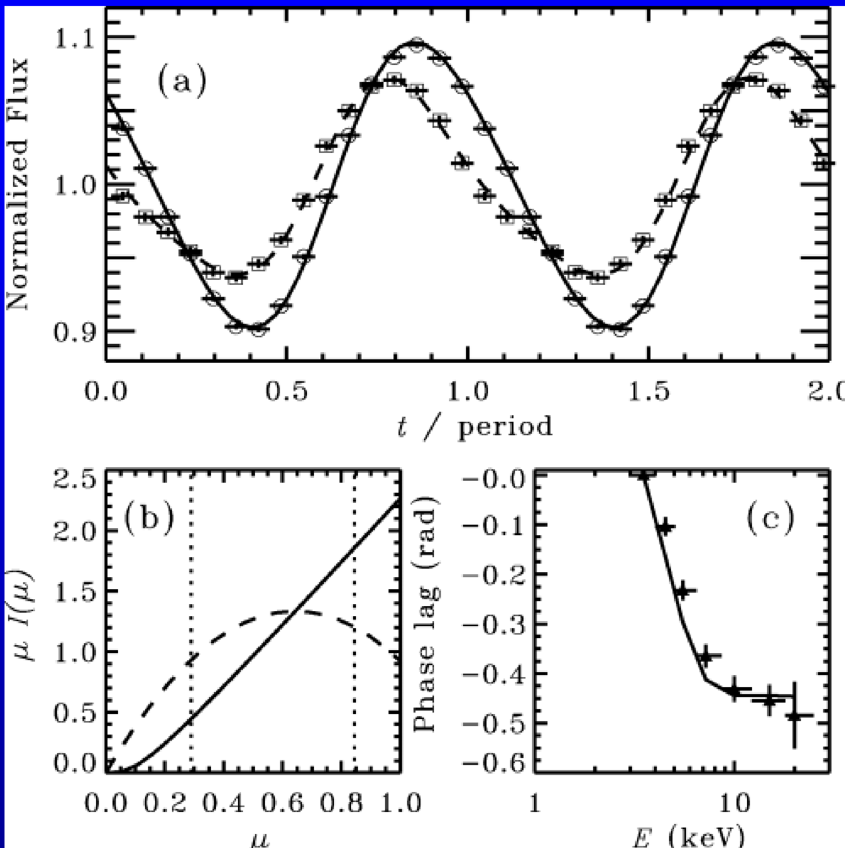




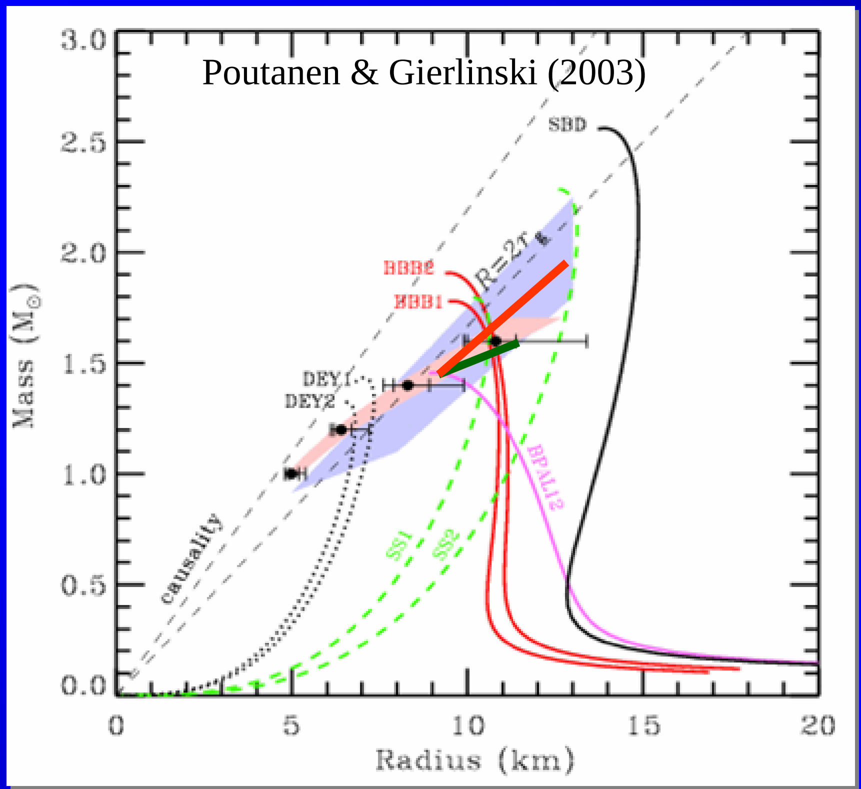
- Spectra (or average hardness) with pulse phase show modulations consistent with temperature asymmetry.
- Attempt to constrain emission geometry (is an angular mode present).
- Model fitting in progress: stay tuned…

Mass – Radius Constraints: Persistent Pulse Profiles

Goddard Space Flight Center



- Comparison of constraints from SAX J1808.4-3658 (Poutanen & Gierlinski 2003, red), and XTE J1814-338 (Bhattacharyya et al. 2005, green line).

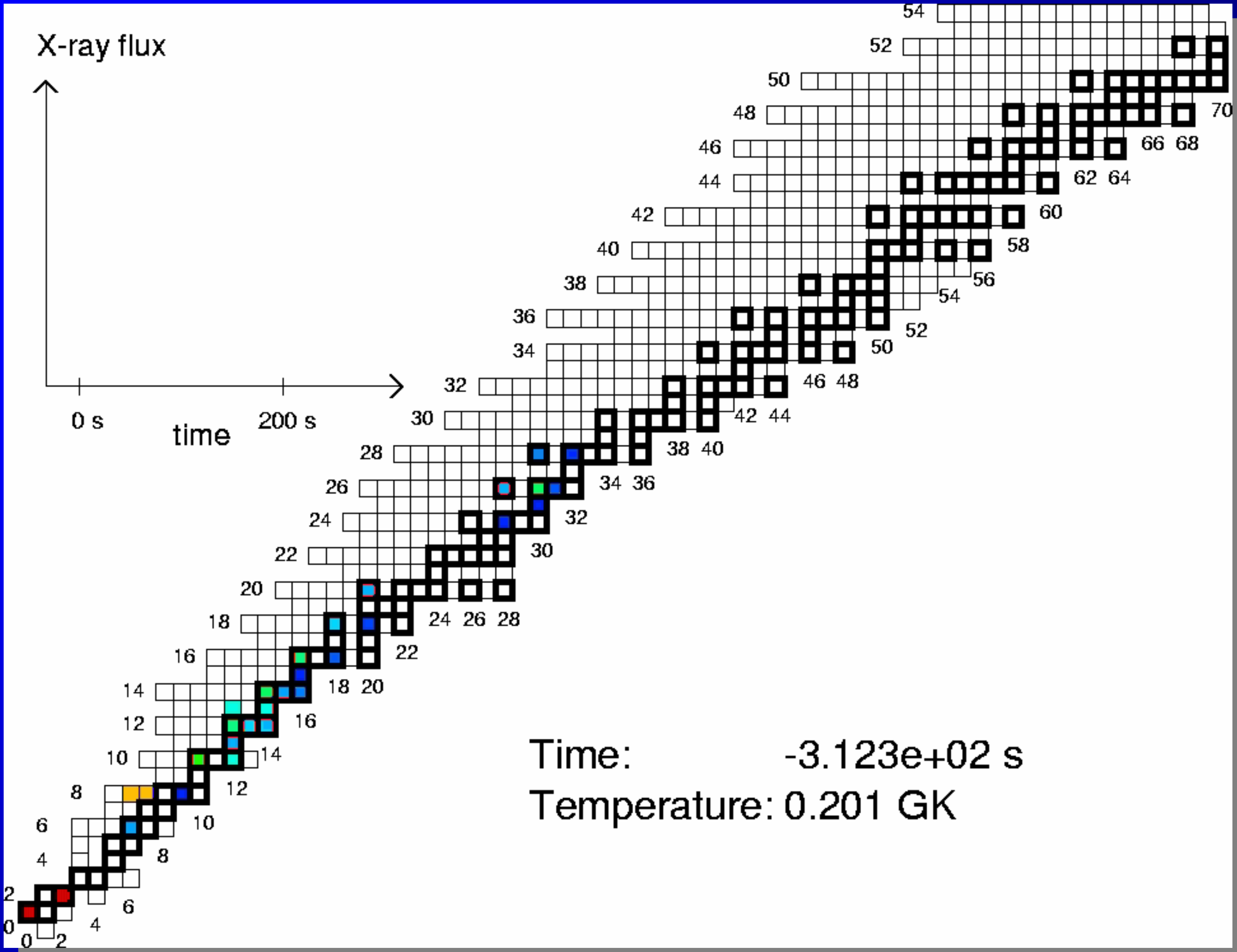


- Two component model: Thermal spot (soft); comptonized (hard).
- Very high signal to noise pulse profile.

Nuclear flows during X-ray Bursts: With Hydrogen

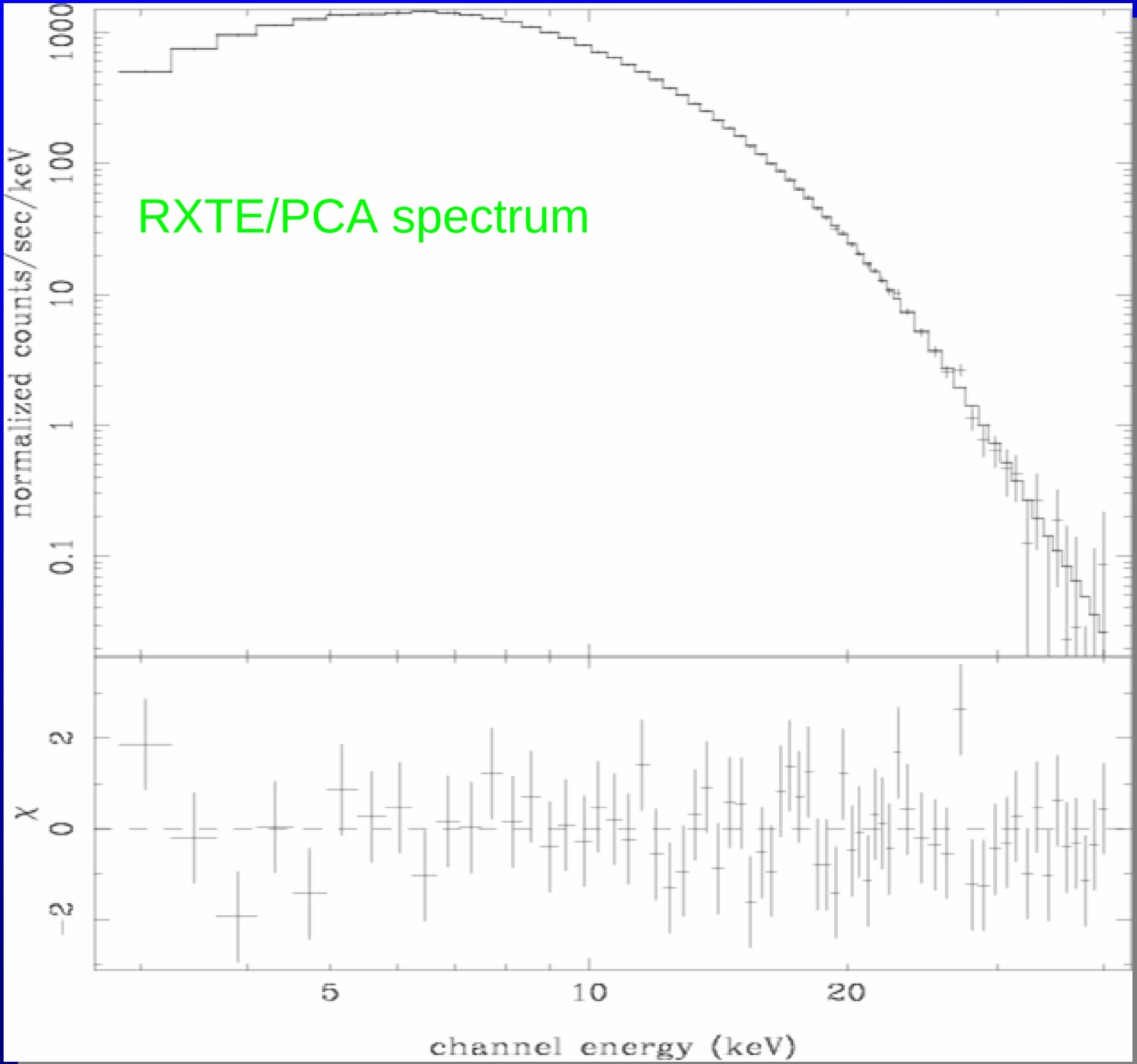
Goddard Space Flight Center

- Composition is important for superbursts.
- With hydrogen around, carbon tends to be destroyed by rp process burning.
- Is enough carbon left over to account for superbursts?



Thanks to Hendrik Schatz (MSU) for the movie

Superburst from 4U 1820-30: Spectral Modelling



- Long decay timescale gives high signal to noise spectra.
- Thermal (black body) spectrum strongly preferred for continuum.
- Discrete components, ~ 6 keV broad line, and 9 keV edge required.