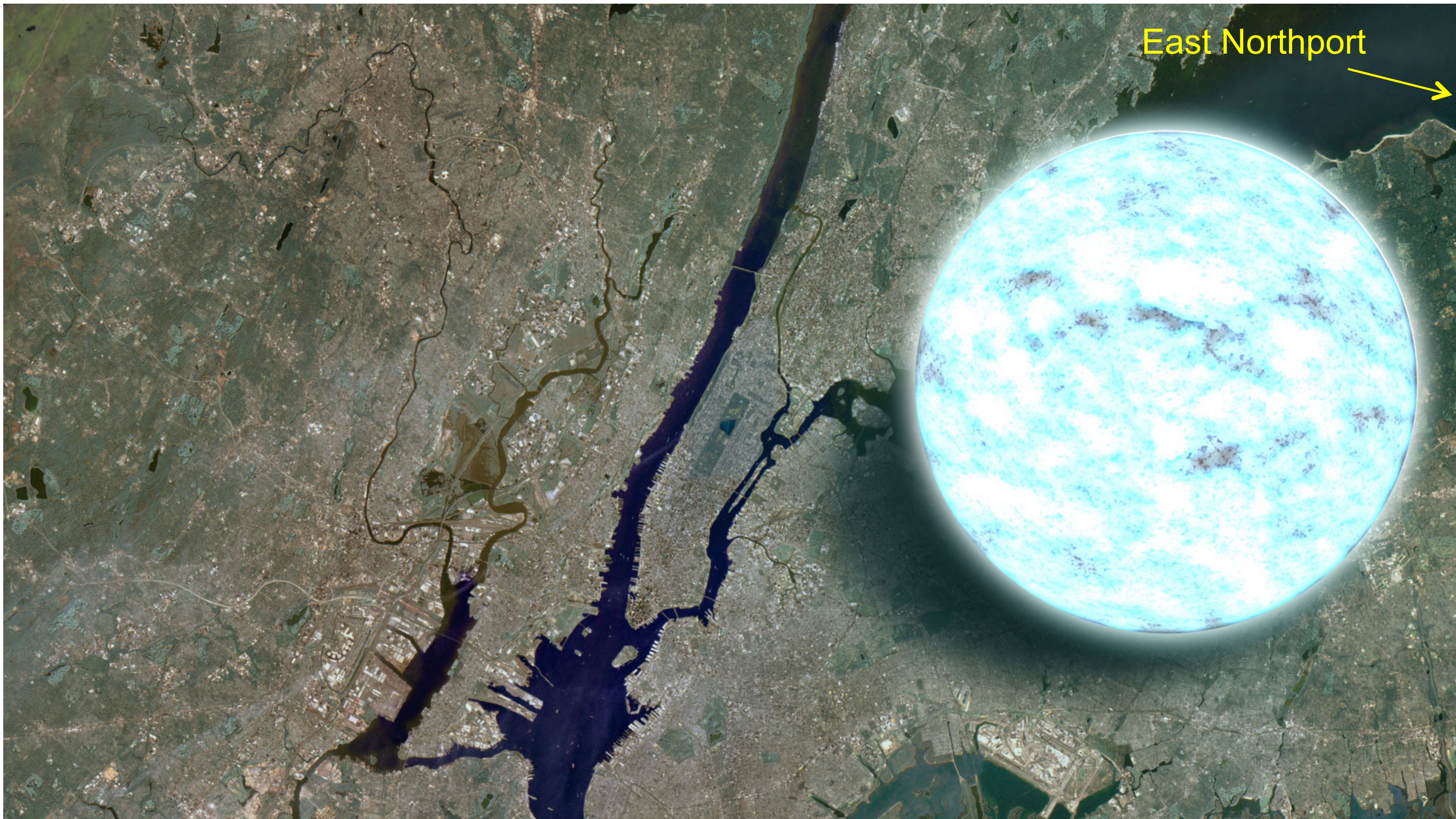
X-ray Bursts: Nuclear Physics on Neutron Stars

Tod Strohmayer, NASA's 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, crust cooling-heating 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 observations of accreting neutron stars.

Plan For Lectures

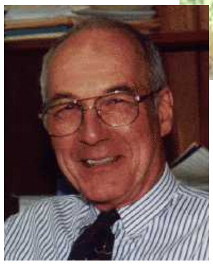
Part 1: Introduction, X-ray burst basics, comparisons with observations, new recent results.

Part 2: Moving away from Spherical Symmetry, timing observations, neutron star spin, burst ignition and spreading.

Part 3: Superbursts, X-ray probes of neutron stars; mass-radius constraints, X-ray pulsar and eclipse timing, pulse profile fitting, spectroscopy, recent results and status.

Part 4: Future prospects, missions in planning and development, summary.

Neutron Stars: A (very) Brief Introduction and History



- Neutron stars, existence predicted in the 1930's, Zwicky & Baade (1933), super-nova, neutron first discovered in 1932 (Chadwick).
- Theoretical properties and structure, Oppenheimer & Volkoff (1939), TOV eqns.
- Cosmic X-ray sources discovered, accreting compact objects, X-ray binaries (Giacconi et al. 1962). Nobel Prize, 2002.
- First firm observational detection, discovery of radio pulsars, 1967 (Bell & Hewish). Hewish wins Nobel Prize in 1974, Bell does not.
- Binary Pulsar discovered, 1974, Hulse-Taylor win Nobel Prize, 1993, gravitational radiation
- X-ray bursting neutron stars discovered (1976), Grindlay et al. Belian, Conner & Evans, predicted by Hansen & van Horn (1975).

Neutron Stars: Nature's Extreme Physics Labs

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

NASA IMAGE

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 "light-

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 1999. 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—like a gift presenting itself to ob-

Structure and Behavior of Neutron Stars

Neutron stars are the imploded cores of dead stars, in the most extr 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.

Accretion disk
Neutron star
White dwarf
Comparative size of Earth

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.

Axis of rotation
Magnetic axis
Radio beam
Magnetic field
Pulsar
D.C.

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.

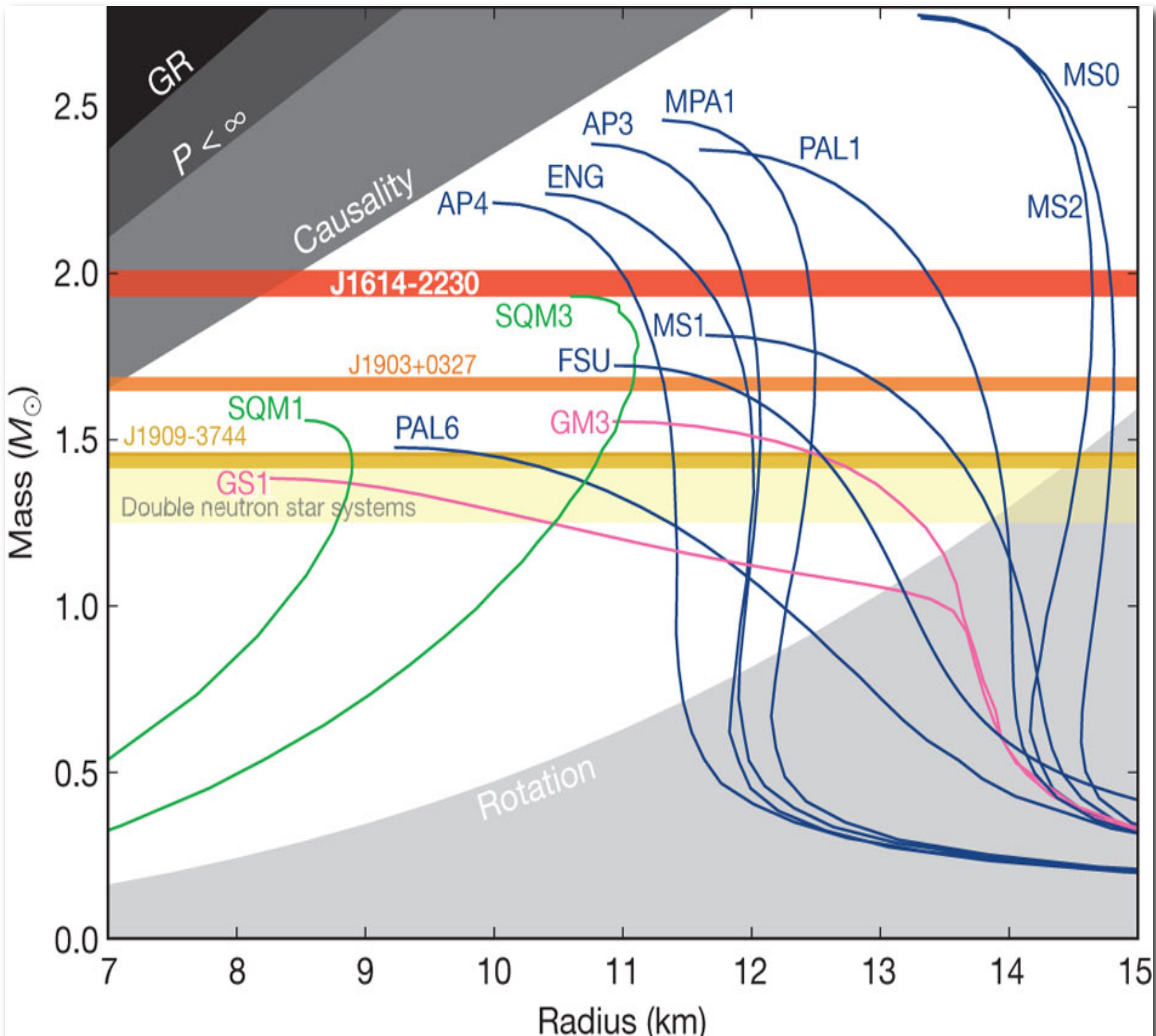
Core: Possibly superfluid neutrons (a fluid that has no resistance to flow), superconducting protons

Density (Approxim IN GRAMS PER CUBI CENTIMETER*
10,000 (surface)
4.3 trillion
200 trillion
440 trillion
10 miles

- Neutron stars, ~2 Solar masses compressed inside a sphere ~20 km in diameter.
- Highest density matter observable in universe.
- Highest "persistent" magnetic field strengths observable in the universe.
- General Relativity (GR) *required* to describe structure. Complex Physics!!
- All forces needed!

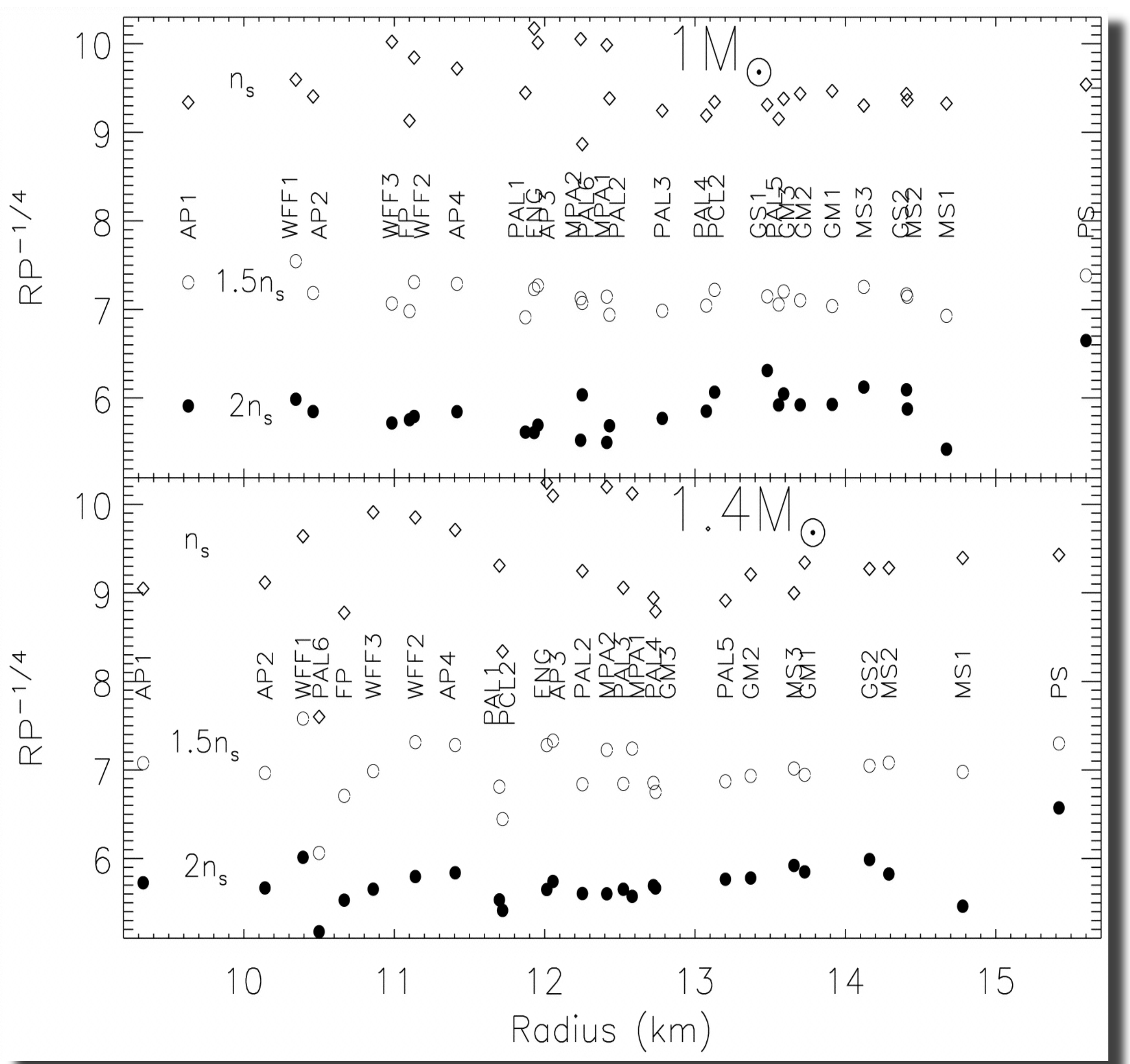
The Neutron Star Equation of State

Demorest & Ransom 2011



- High mass measurements, limit softening of EOS from hyperons, quarks, other exotic stuff.
- Most good mass measurements at low end, and systems not conducive to radius estimates, EOS not constrained strongly.
- Need either masses for higher mass systems (accretors), and/or possibility to get R (AMPs).

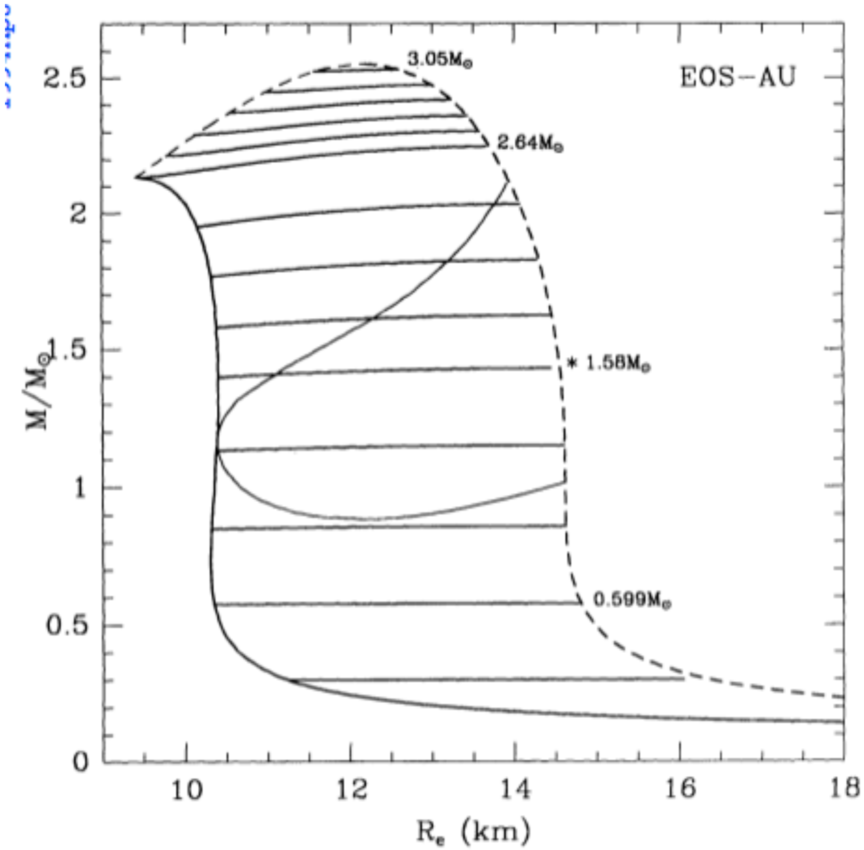
Neutron Star Radii and the Equation of State



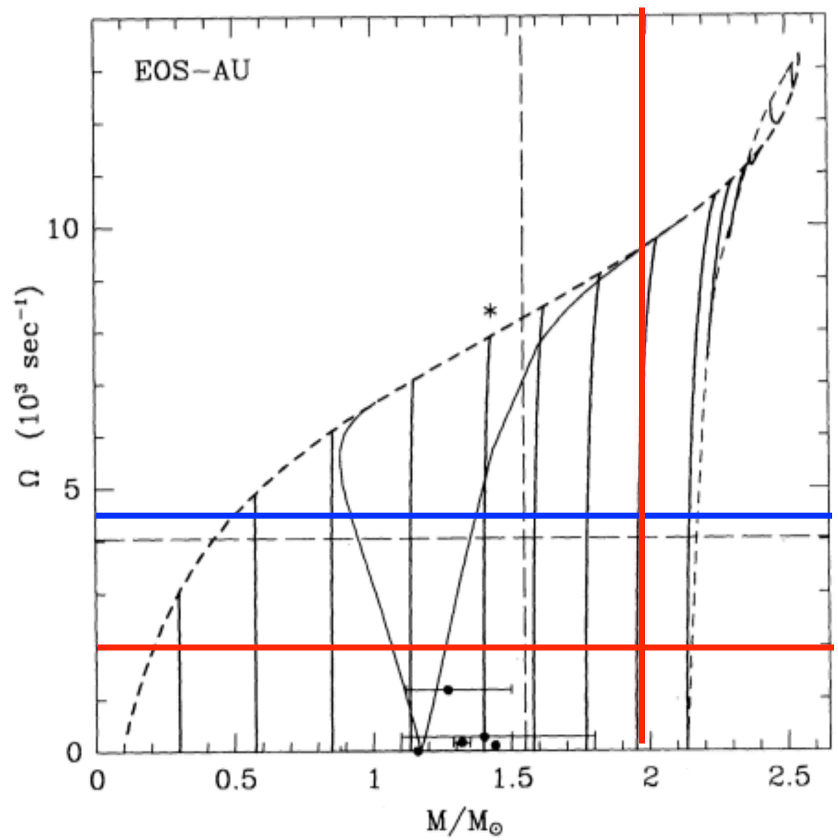
Lattimer & Prakash 2001

- 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. Pressure largely related to density dependence of symmetry energy of nuclear interaction (isospin dependence).
- More reliable in absence of softening

Rotating Neutron Stars

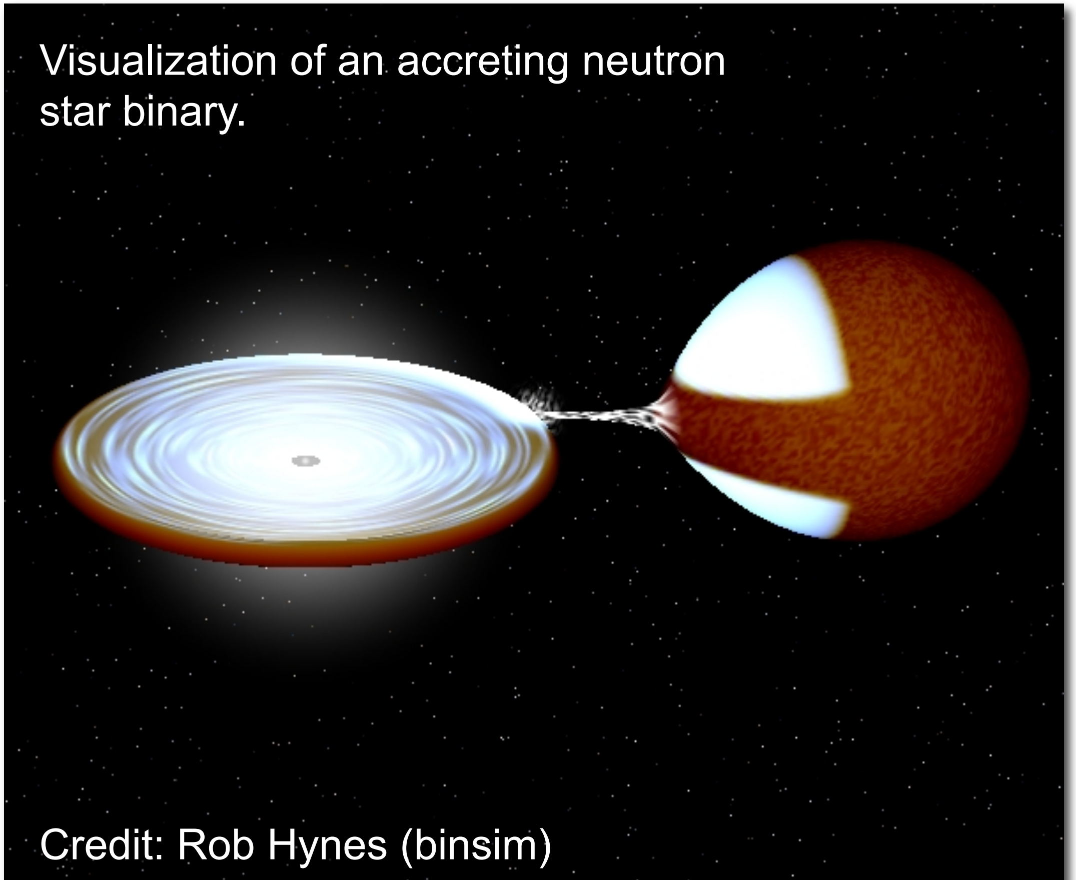


- Rotation: Increases maximum mass, centrifugal support. Max spin rate, mass shedding limit, depends on EOS (Cook, Shapiro, Teukolsky 1994).



- Rotation: Equatorial bulge, increases radius at rotational equator. Effective gravity is now function of latitude.

Compact Stars, Accretion Power



- Accretion Powered: X-ray binaries

•X-ray Binaries: neutron star or black hole with normal star.

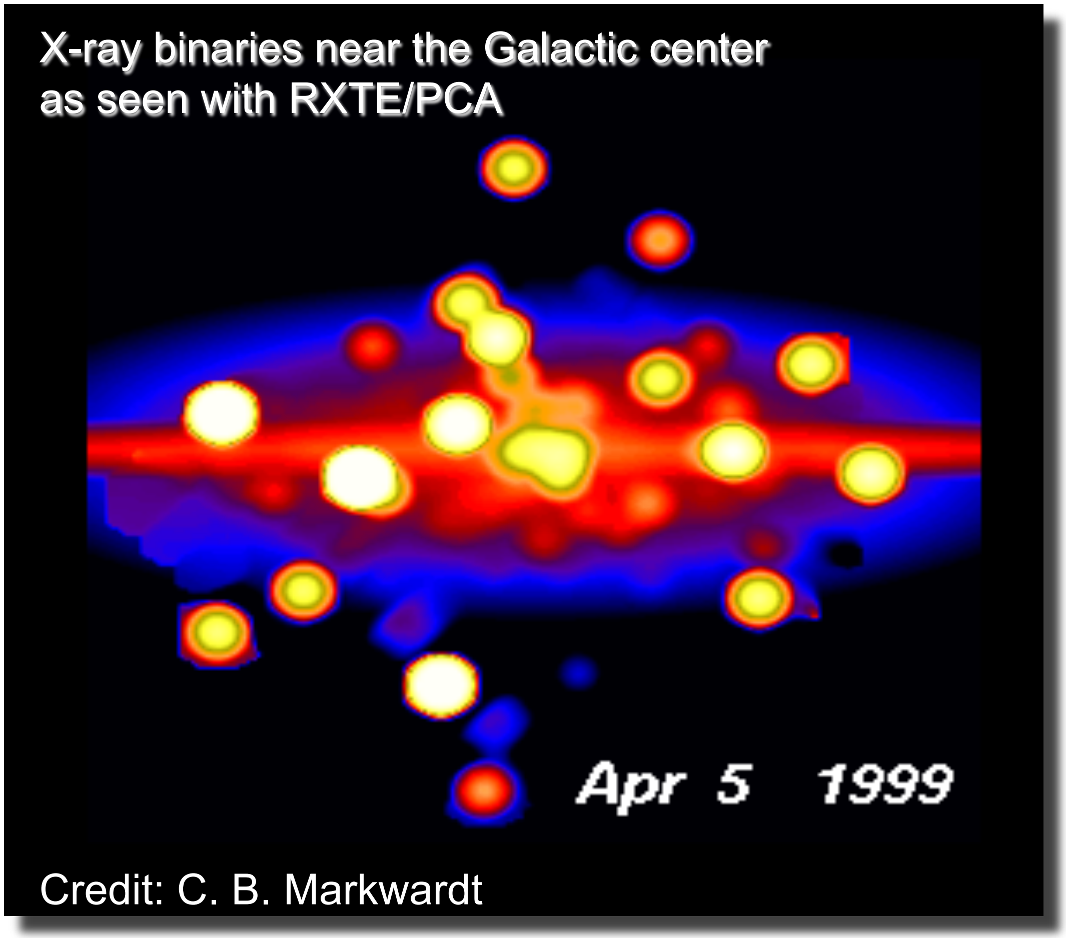
•Accretion powers X-ray emission.

•Nuclear Powered: X-ray burst sources (neutron stars only).

•$E_{grav} = GMm/R = (GM/c^2R)\ mc^2 \sim 0.2\ mc^2 \sim 200$ MeV per baryon ===> T ~ few x 10^7 K ~ keV range, X-rays!

Sources of Thermonuclear Bursts: LMXBs Containing Neutron Stars

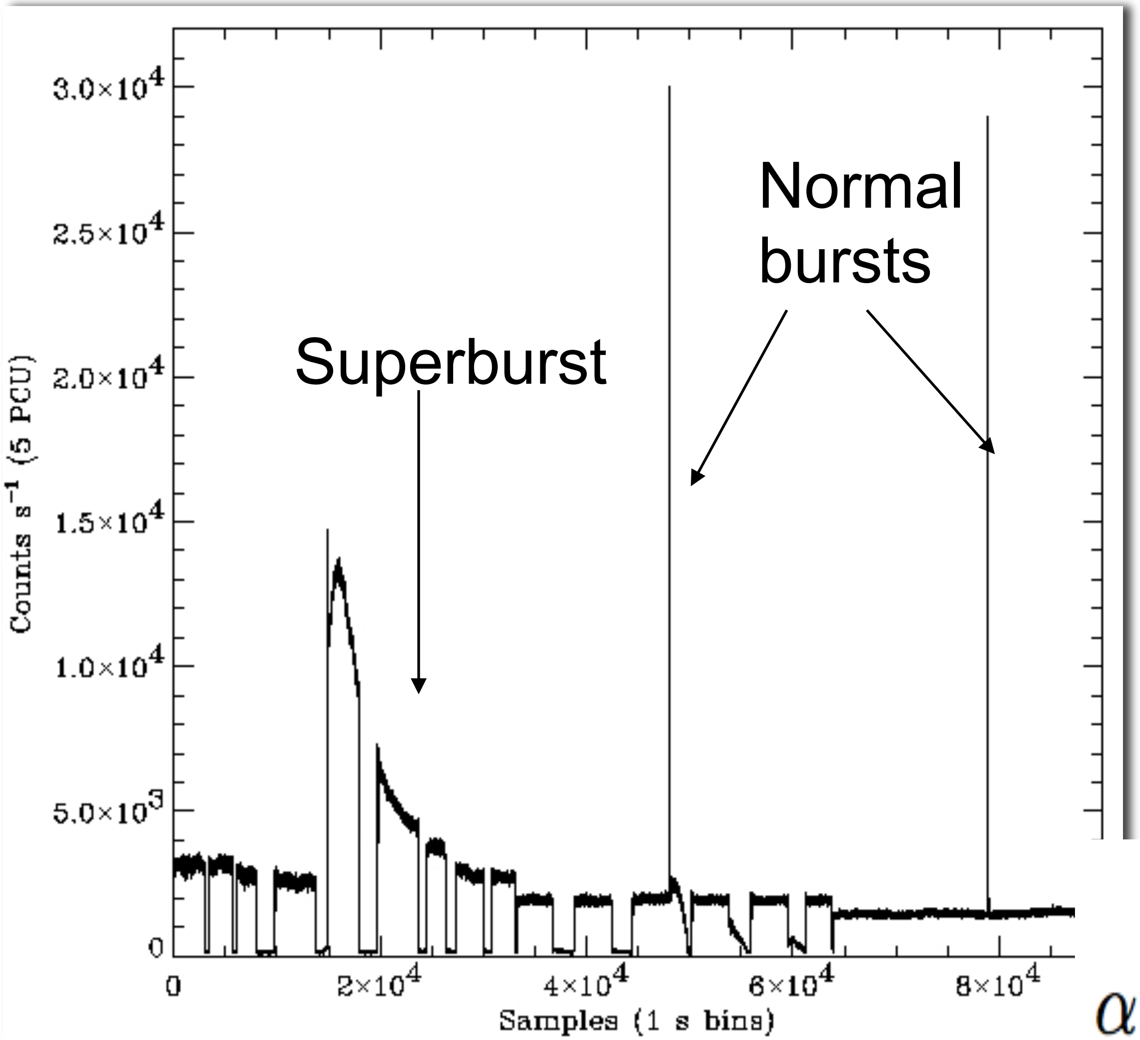
http://www.sron.nl/~jeanz/bursterlist.html



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 100 burst sources are known.
- Concentrated in the Galactic bulge.
- Bursts triggered by thermally unstable H or He burning at column of few x 10^8 g cm^{-2}
- Liberates ~ 10^{39} – 10^{43} ergs. First discovered 1976 (Grindlay et al., Belian et al. 1976
- Recurrence times of hours to a few days (or years).

Accreting Neutron Star binaries: what do we see?

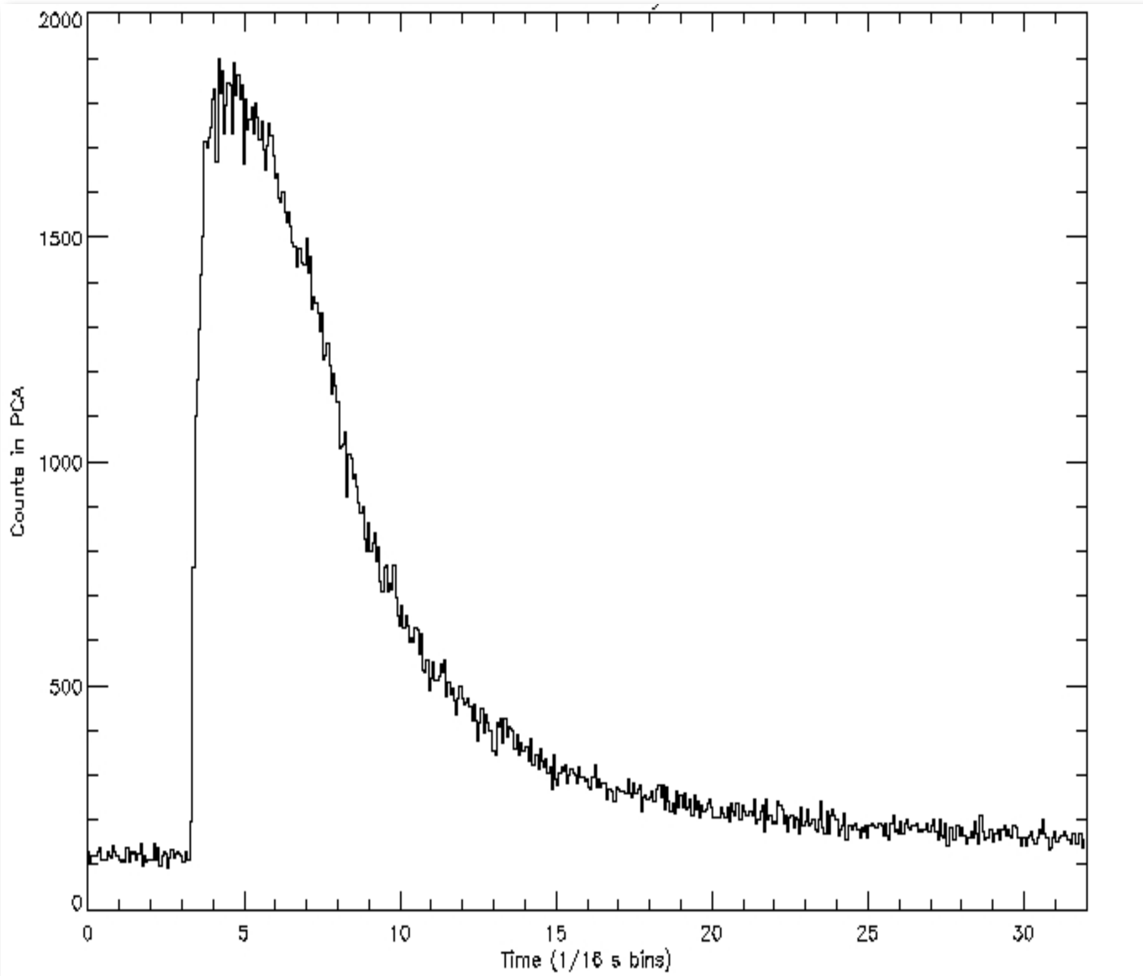


- Accretion of matter converts gravitational potential energy to radiation (X-rays, persistent flux)
- Can produce normal bursts (recur hours to days) and superbursts (years).

$$\alpha \equiv \frac{\int_0^{\Delta t} F_{\rm p}\, dt}{\int_0^{\Delta t} F_{\rm b}\, dt} \approx \frac{(GM/R)}{Q_{\rm nuc}}$$

$Q_H^{solar} \approx 5$ MeV, $Q_{He} \approx 1.6$ MeV

"Normal" Thermonuclear Bursts

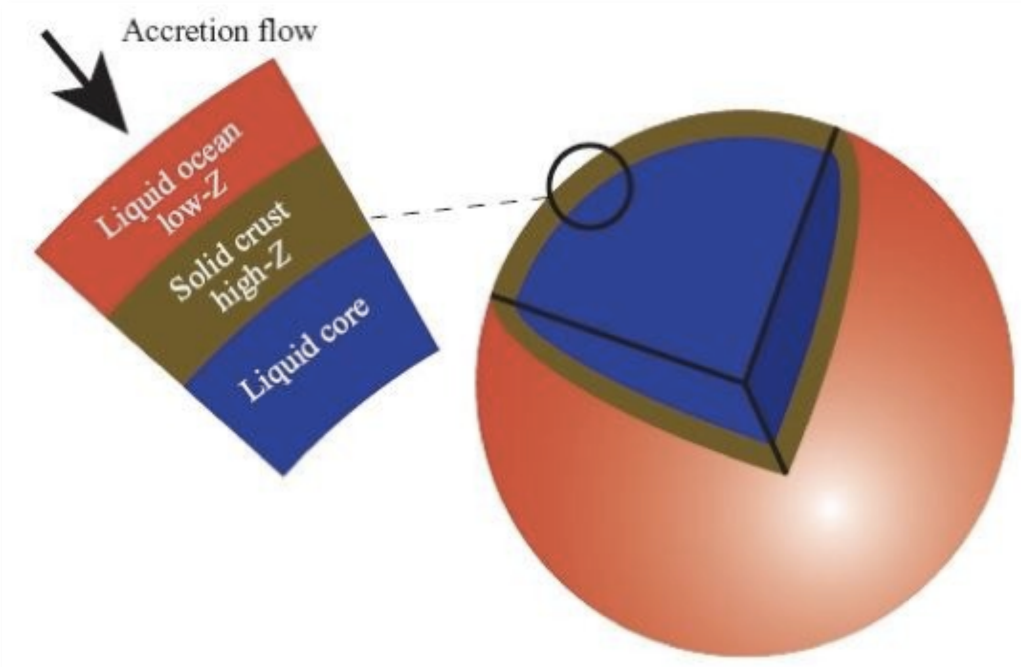


Time (s)

He ignition at a column depth of 2 x 10^8 g cm^{-2}

- 10 - 200 s flares.
- Thermal spectra which soften with time.
- 2 - 18 hr recurrence times, sometimes quasi-periodic.
- ~ 10^{39} ergs
- H and He primary fuels.

Bursts and Nuclear Burning: Theory



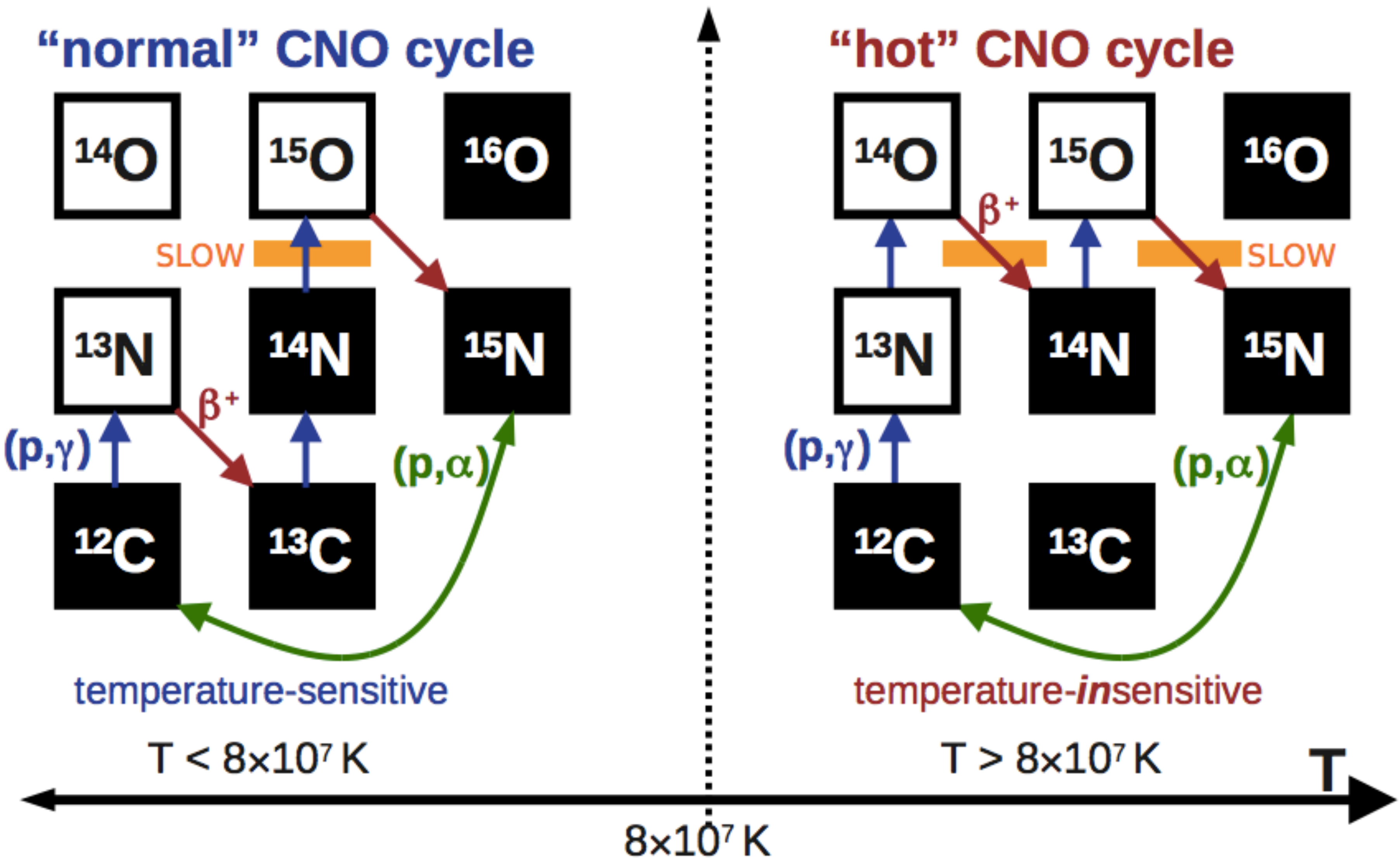
- Accreted layer, and pressure scale height, h << R, so local, plane-parallel analysis OK.
- What is the fate of a mass element as it is buried and compressed?

$$L_{\rm Edd} = \frac{4\pi G M m_{\rm p} c}{\sigma_{\rm T}}$$

$L_{acc} = G\, M\, m\, /\, R$, $m_{Edd} \sim 1.7 \times 10^{-8}\ M_{\odot}\ yr^{-1}$, local rate of, $m_{Edd}\ /\ 4\pi R^2 = \dot{m}_{Edd} = 8.6 \times 10^{4}\ g\ cm^{-2}\ s^{-1}$

Accreted matter is H and He rich with likely mix of metals (exact composition, Z, usually uncertain!). T almost always > few x 10^7 K ==> Hot (beta-limited) CNO cycle dominates H burning.

CNO H burning



Thanks to Alex Heger!

Burst Theory Con't

Hot CNO cycle, Fowler & Hoyle (1965)

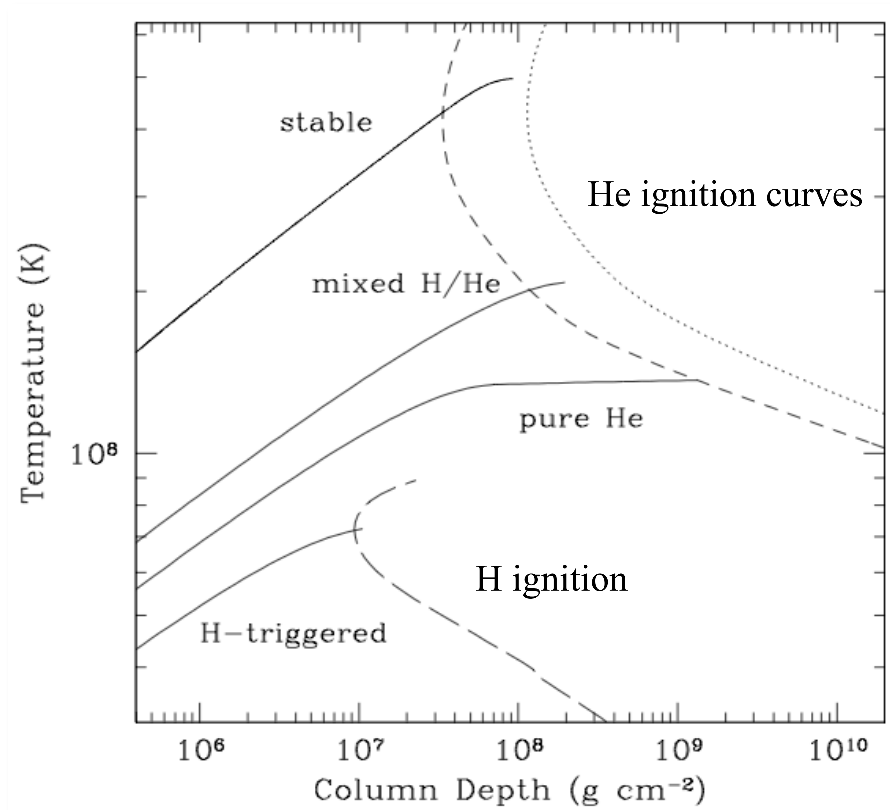
$$^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}(p,\gamma)^{14}\mathrm{O}(\beta^{+})^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}(\beta^{+})^{15}\mathrm{N}(p,\alpha)^{12}\mathrm{C},$$

- For $\dot{m}$ > 900 g cm^{-2} s^{-1} $(Z_{CNO}/0.01)^{1/2}$, temperatures and densities in the accumulating layer are such that the proton captures proceed more rapidly than the β decays, leading to thermal stability (an increase in temperature does not raise the energy generation rate, which is limited to, $\varepsilon \sim 6 \times 10^{15}$ $(Z_{CNO} / 0.01)$ ergs g^{-1} s^{-1} (Fujimoto, Hanawa & Miyaji 1981; Fushiki & Lamb1987; Cumming & Bildsten 2000; Cooper & Narayan 2007).
- EXERCISE: Show that the time to burn all the H in a fluid element is about a day (for Z_{CNO}=0.01, and X_0 = 0.7).
- At lower $\dot{m}$ the CNO cycle becomes temperature sensitive and H burning can trigger instability.

Burst Ignition: Thin Shell Instability

- Bursts caused by thin shell thermal instability, Schwarzchild & Härm (1965), Hansen & Van Horn (1975).
- Ignition at; $d\varepsilon_{nuc}/dT > d\varepsilon_{cool}/dT$; $\varepsilon_{cool} \propto T^4$ (radiative cooling of thin shell). Strong T-dependence of triple-alpha reaction can induce ignition.

Cumming & Bildsten (2000)



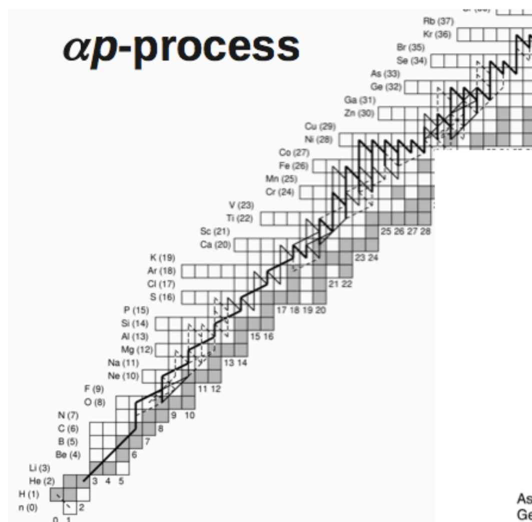
$\dot{m}$ increasing

- H, He burning stabilizes (no bursts).
- He ignition in a mixed H/He shell (case I).
- He ignition in a pure He environment (case II).
- H ignition in a mixed H/He environment (case III).

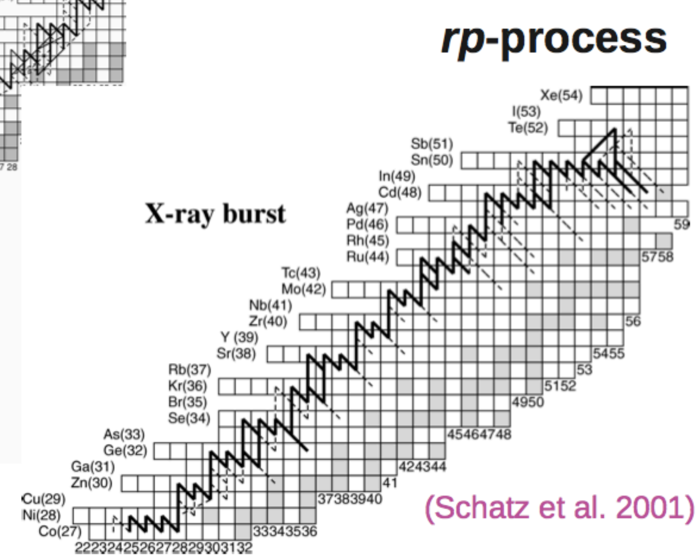
Mixed H/He Burning: rp Process

- For mixed H/He burning with He ignition, the ignition column does not depend strongly on $\dot{m}$, ==> $t_{rec} \propto \dot{m}^{-1}$ (case I, $\dot{m}$ > 2,000 g cm^{-2} s^{-1})
- For pure He shell burning, the ignition column decreases as $\dot{m}$ increases, so t_{rec} drops more steeply, $\propto \dot{m}^{-3}$ (case II, 900 g cm^{-2} s^{-1} < $\dot{m}$ < 2,000 g cm^{-2} s^{-1})
- Above rates are with Z_{CNO} = 0.01

- H burning proceeds via αp and rp-processes (rapid proton captures and betas).
- Increases and delays the energy release ===> longer light curves.

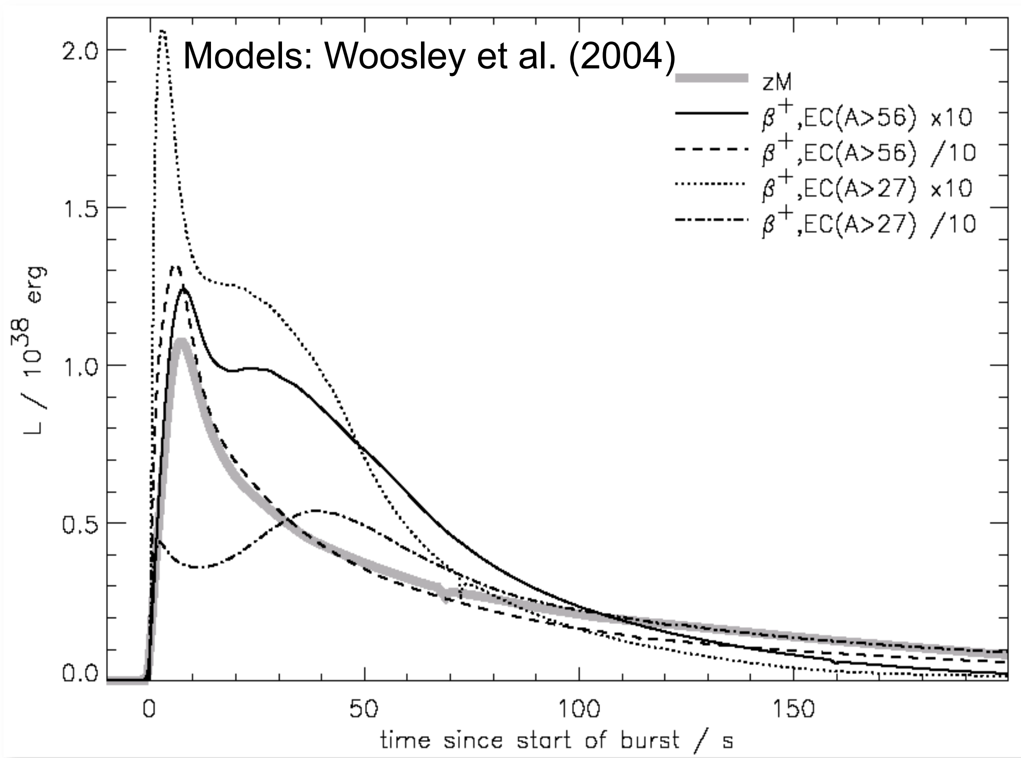


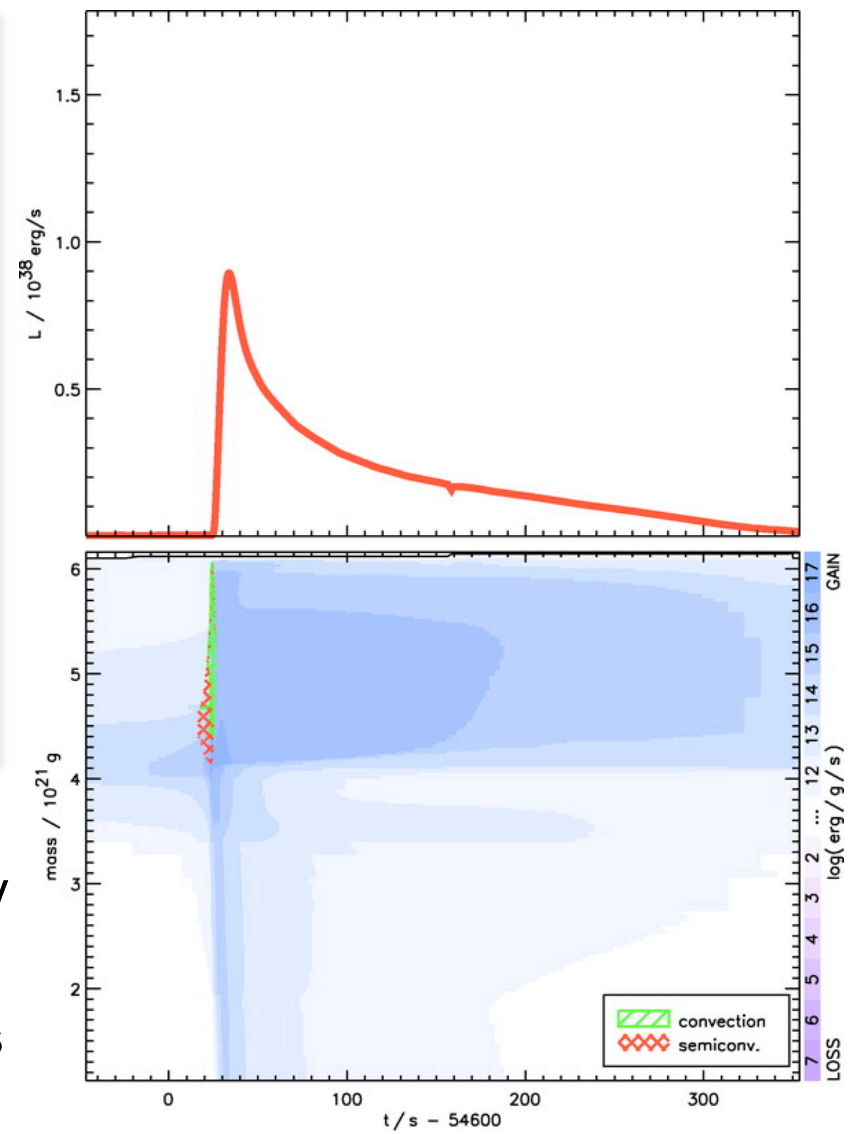
(Schatz, Bildsten, & Cumming 1999)



(Schatz et al. 2001)

X-ray Bursts: Nuclear Physics and Burst Profiles





- Multi-zone numerical hydro models with sophisticated reaction networks (Woosley et al. 2004)
- Uncertainties of rp-process reaction rates can dramatically effect light curves.

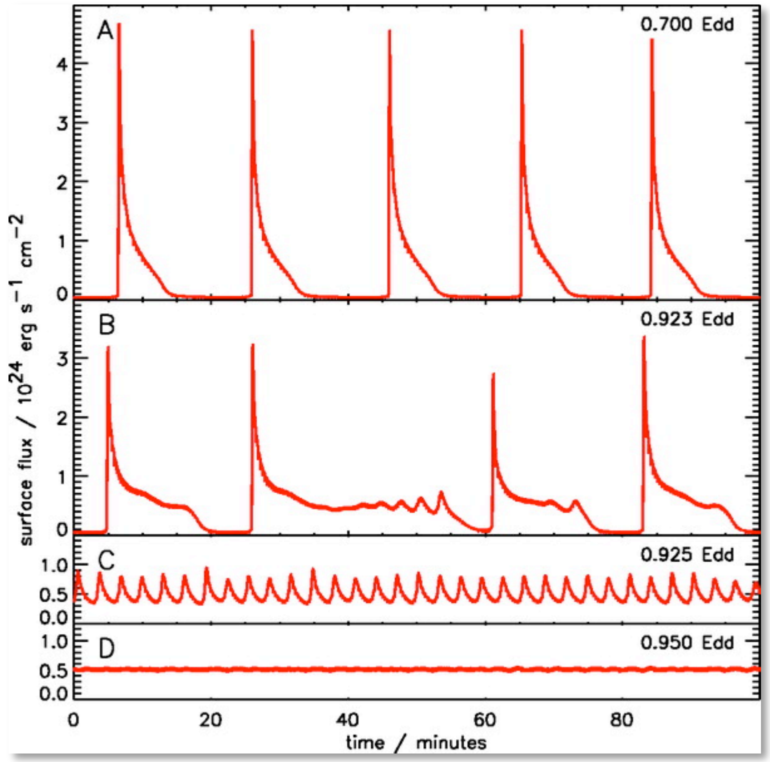
Marginally Stable Burning: mHz Oscillations

f prop δT/T
α =dln(ε)/dln(T)

$$\frac{\partial^2 f}{\partial t^2} + \left(\frac{4-\alpha}{t_{\rm therm}} - \frac{1}{t_{\rm accr}}\right)\frac{\partial f}{\partial t} + \frac{2\alpha}{t_{\rm accr}t_{\rm therm}} f = 0.$$

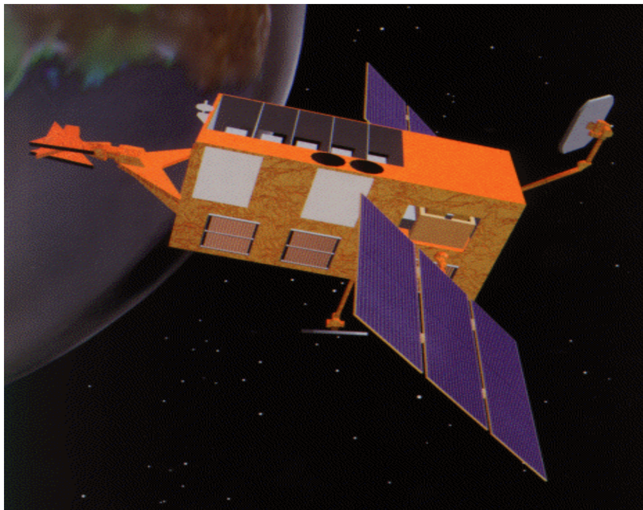
EXERCISE: Show that for a one-zone model the temperature fluctuations satisfy the equation for a damped harmonic oscillator (van der Pol oscillator).

- Typically $t_{therm} << t_{accr}$, and the middle term dominates (bursts). But near stability ($\alpha \approx 4$) the oscillatory term can dominate (oscn's with $\omega^2 = 2\alpha/t_{accr}t_{therm}$)
- Multi-zone modeling (Heger et al. 2007) shows mHz QPOs with few minute periods.
- Periods sensitive to surface gravity, H fraction! Potential probes of these quantities.



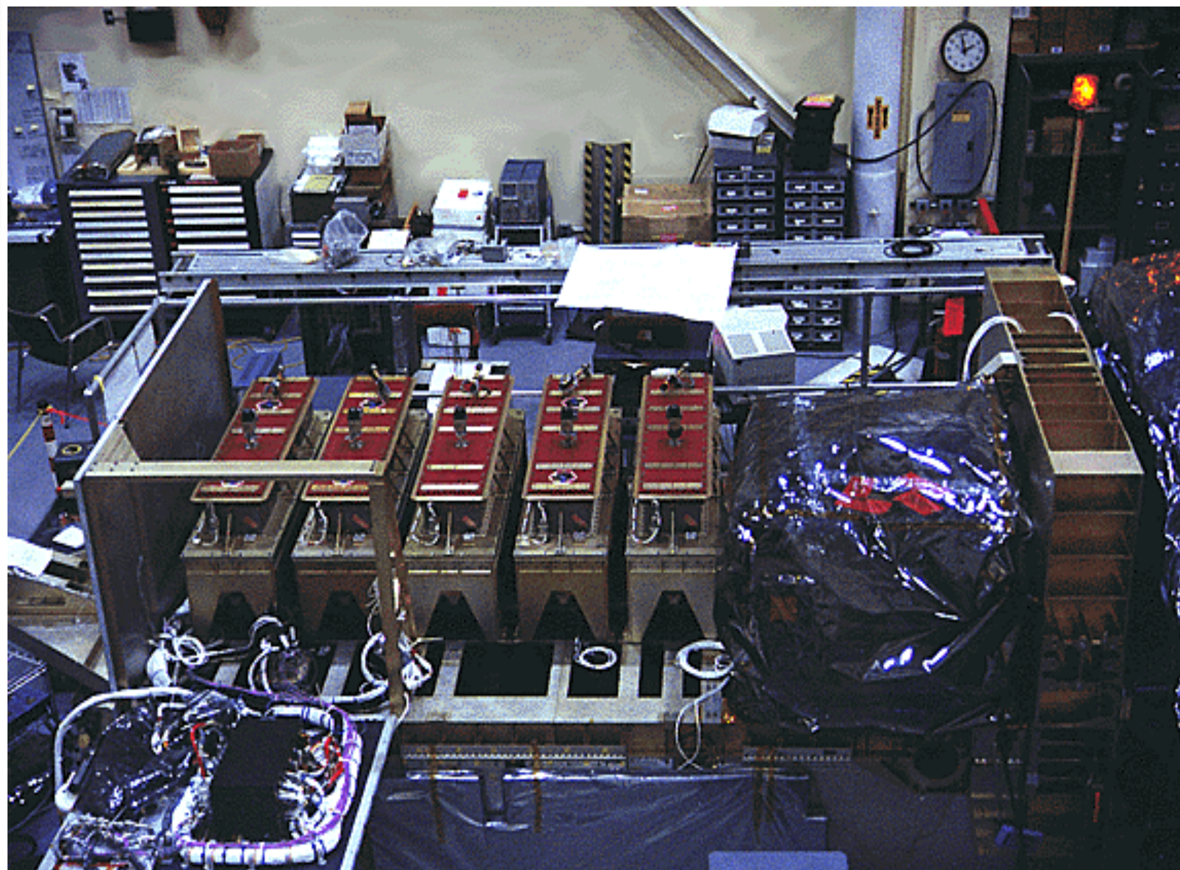
Heger et al. (2007)

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



Launched in December, 1995, science operations concluded on January 5, 2012, after 16 years of discovery!   Huge and rich X-ray burst archive.

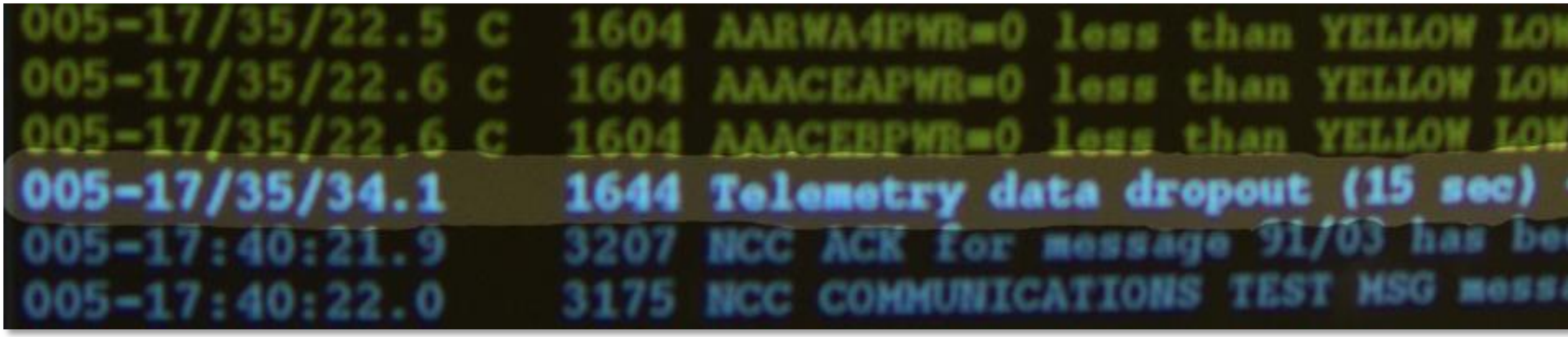
http://heasarc.gsfc.nasa.gov/docs/xte/xte_1st.html

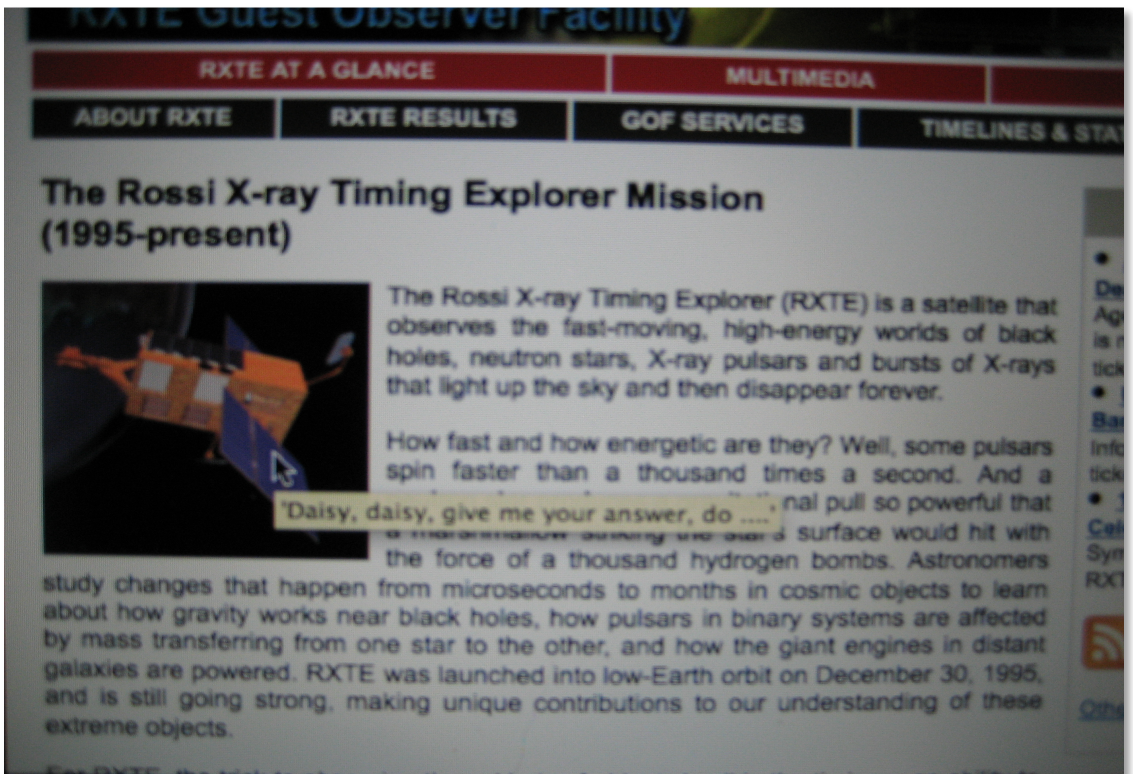


RXTE's Unique Strengths

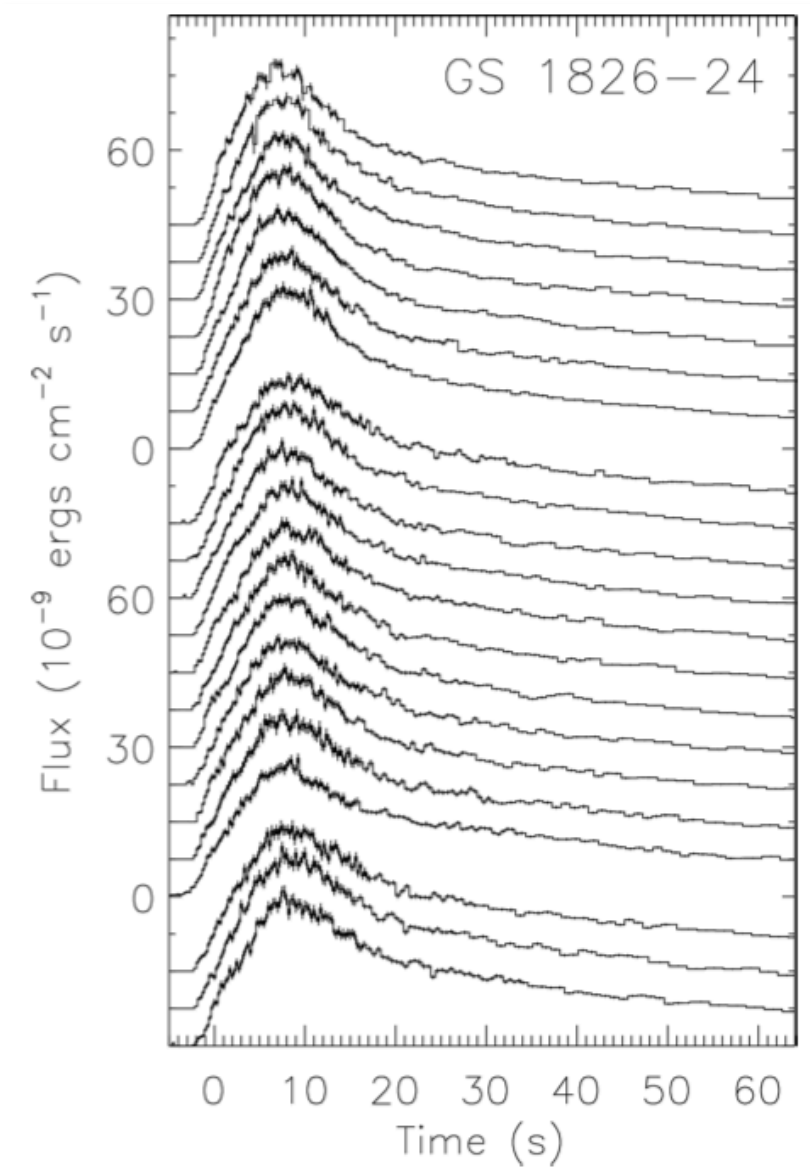
- Large collecting area
- High time resolution
- High telemetry capacity
- Flexible observing

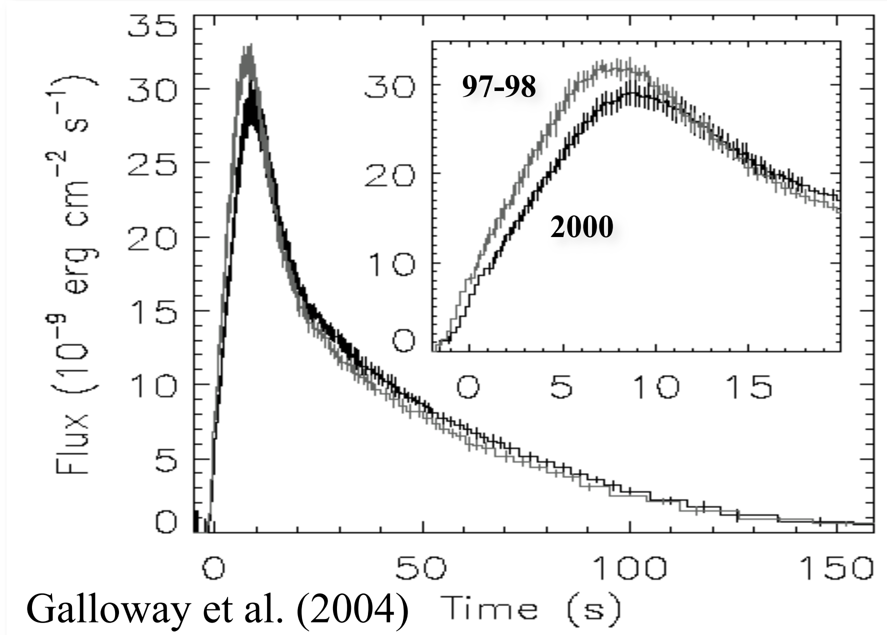
Last Contact With RXTE Spacecraft





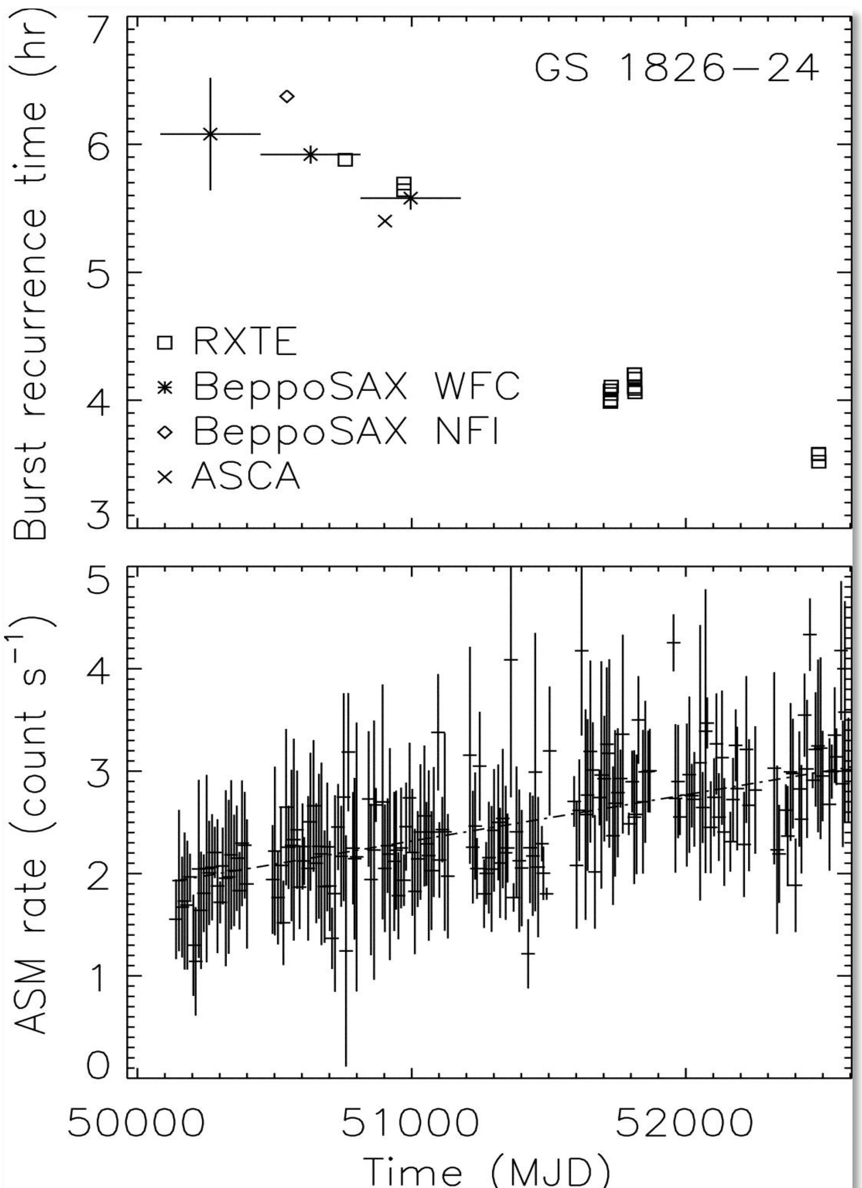
GS 1826-24: A "Textbook" Burster?

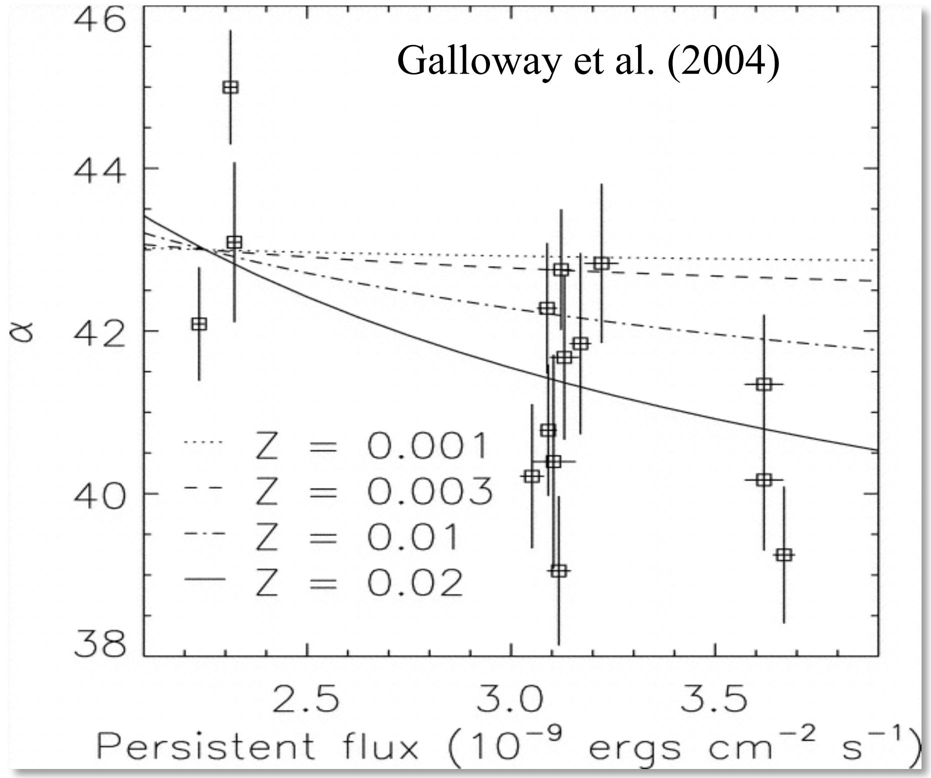




- Very steady X-ray flux, and thus mass accretion rate.
- Regular "clocked" bursts (Cocchi et al., Ubertini et al.)
- Long duration and $\alpha \approx 40$ ==> mixed H/He burning.
- $\dot{m}$ comfortably in the mixed ignition regime

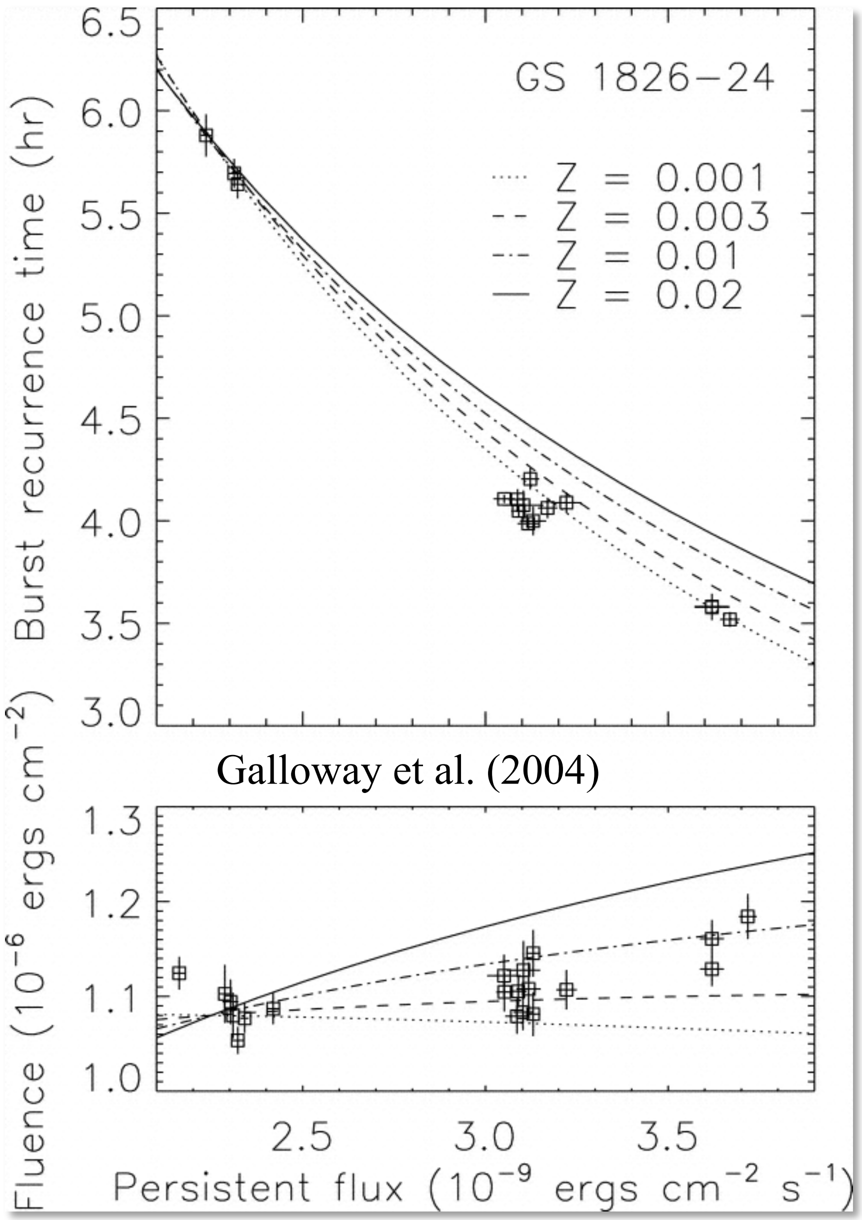
GS 1826-24: A "Textbook" Burster?





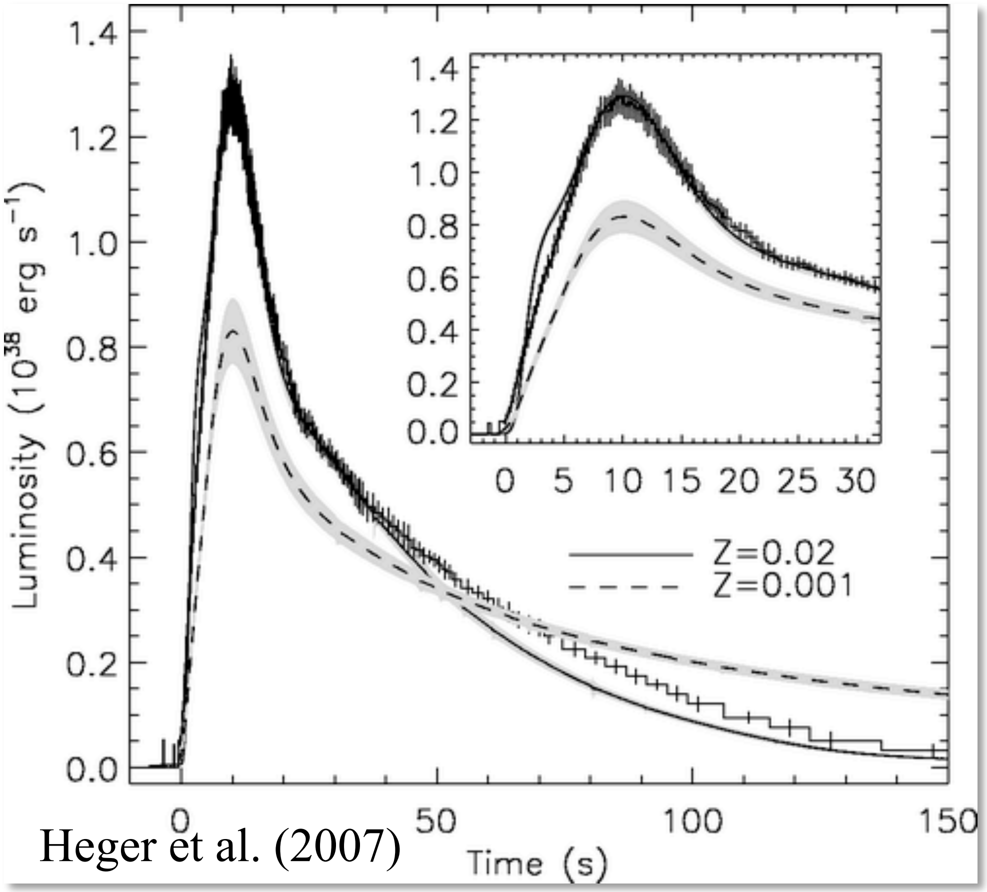
- Recurrence time drops as flux increases with expected f^{-1} behavior
- Drop in α with f_{per} favors solar-like abundance of CNO. More H present, higher Q_{nuc} ===> lower α.
- Can "see" the stable CNO burning!

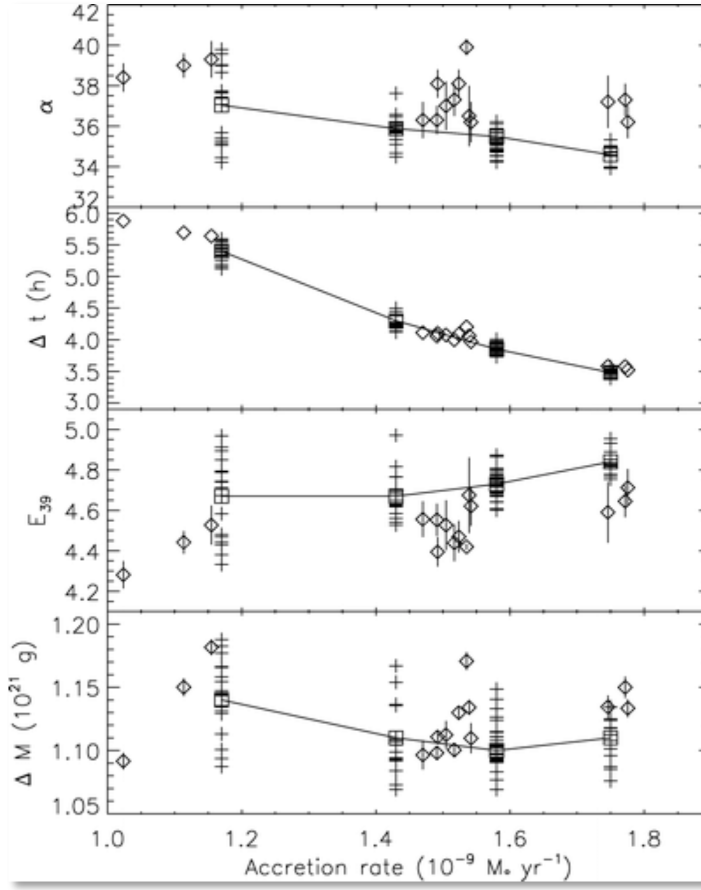
GS 1826-24: A "Textbook" Burster?



- But one zone models with solar abundances over predict the recurrence time and burst fluence.
- In these models as t_{rec} drops less H burning ➔ less He present and ignition mass increases.
- Additional heating (thermal inertia from prior bursts).
- Maybe local accretion rate changes (fuel covering factor)?
- Need more realistic multi-zone, multi-D models.

GS 1826-24: Multi-zone Modeling

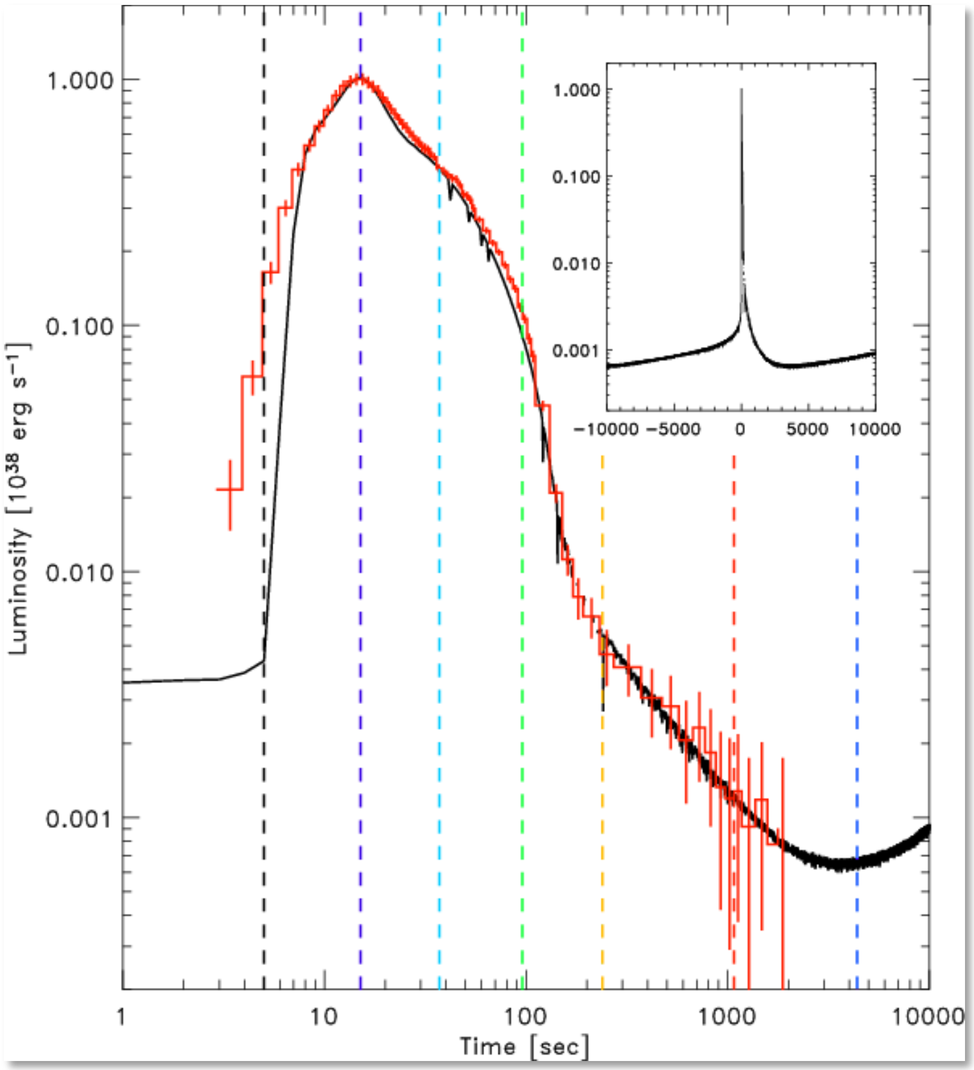




Heger et al. (2007)

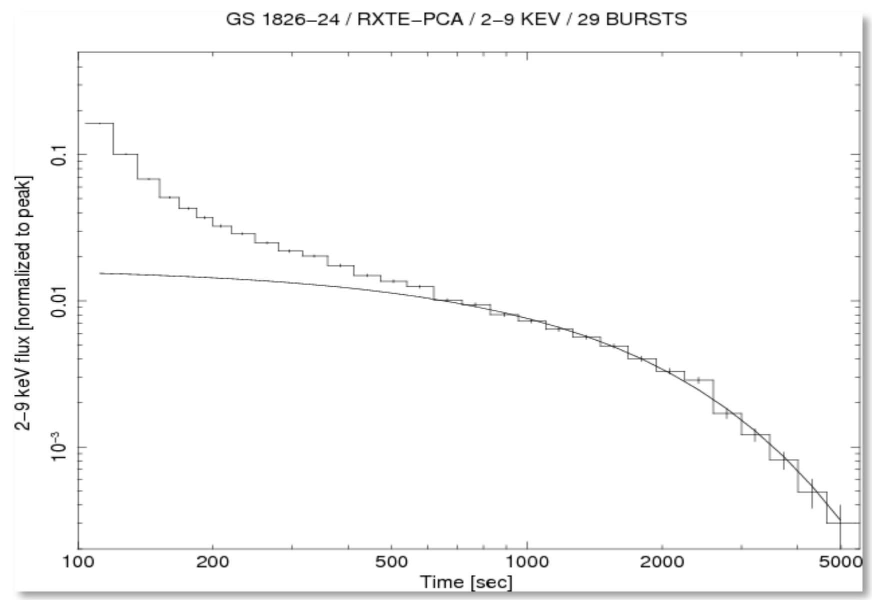
- Detailed multi-zone modeling (Heger et al. 2007) shows that $Z \approx 0.02$ needed to match average burst light curves. Also now matches t_{rec} (thermal inertia).
- Rise light curve does not match precisely. Models show two-stage rise.

GS 1826-24: Multi-zone Modeling and Long Tails

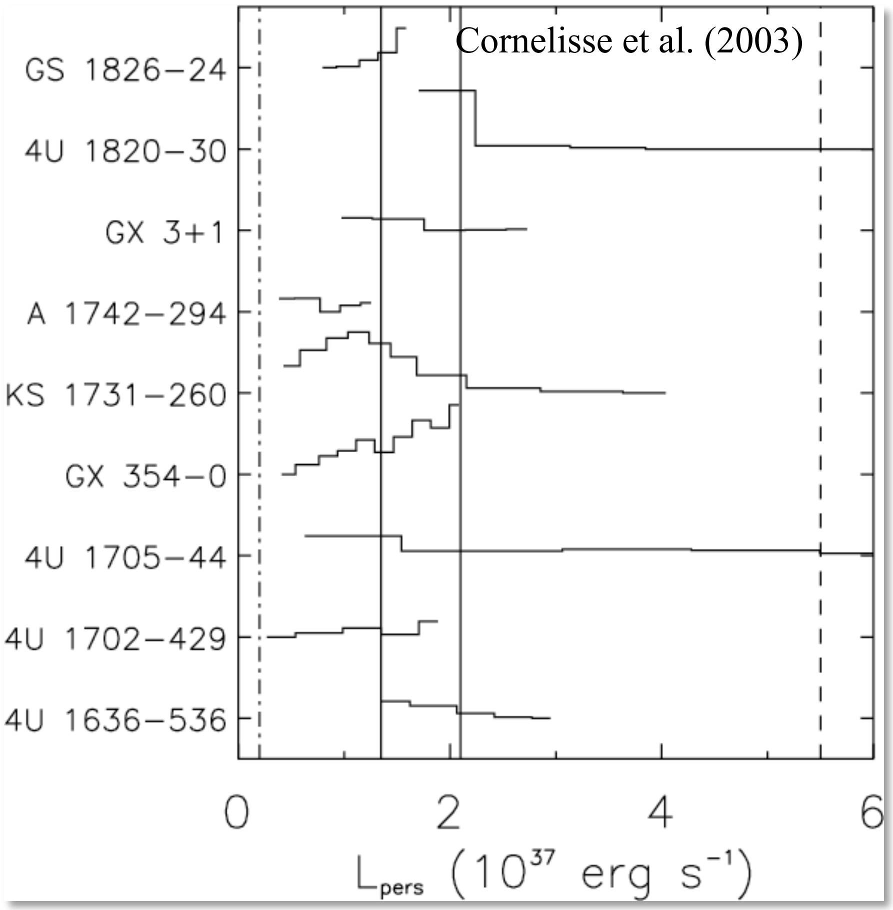


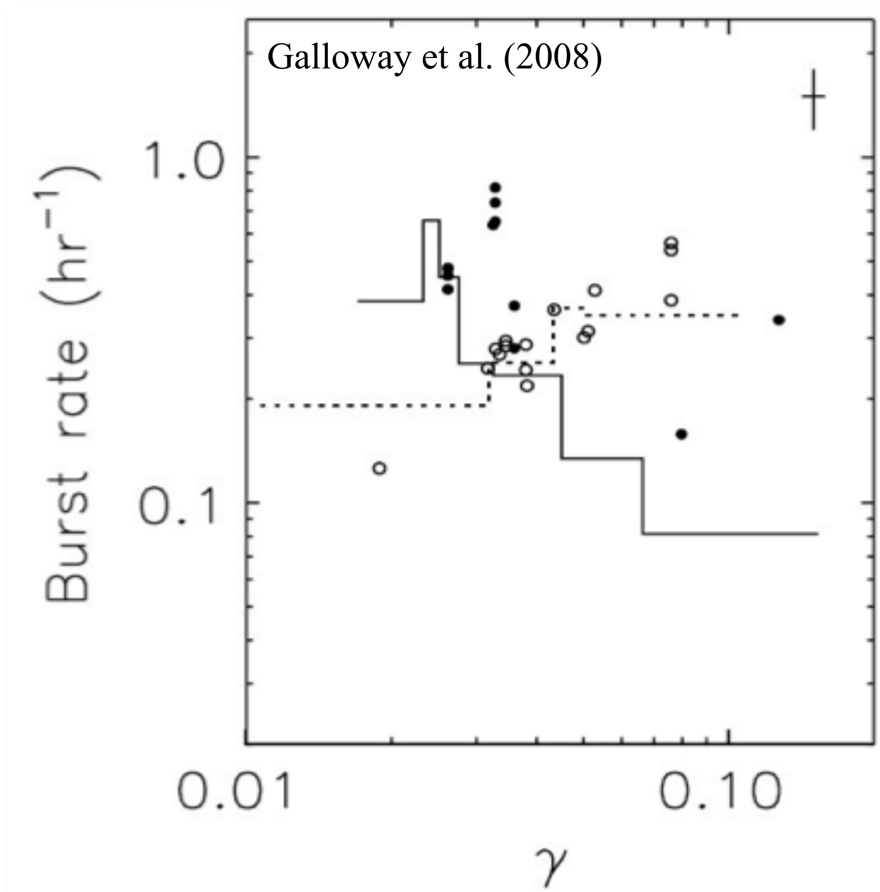
in 't Zand et al. (2009)

- In 't Zand et al. averaged many (~30) bursts from GS 1826, after subtracting off persistent (pre-burst) data. Faint exponential tail evident.
- Multi-zone modeling matches light curve, tail from cooling of deeper layers heated by burning.



Global Burst Rates: Where are the Bursts at Higher F_p ?



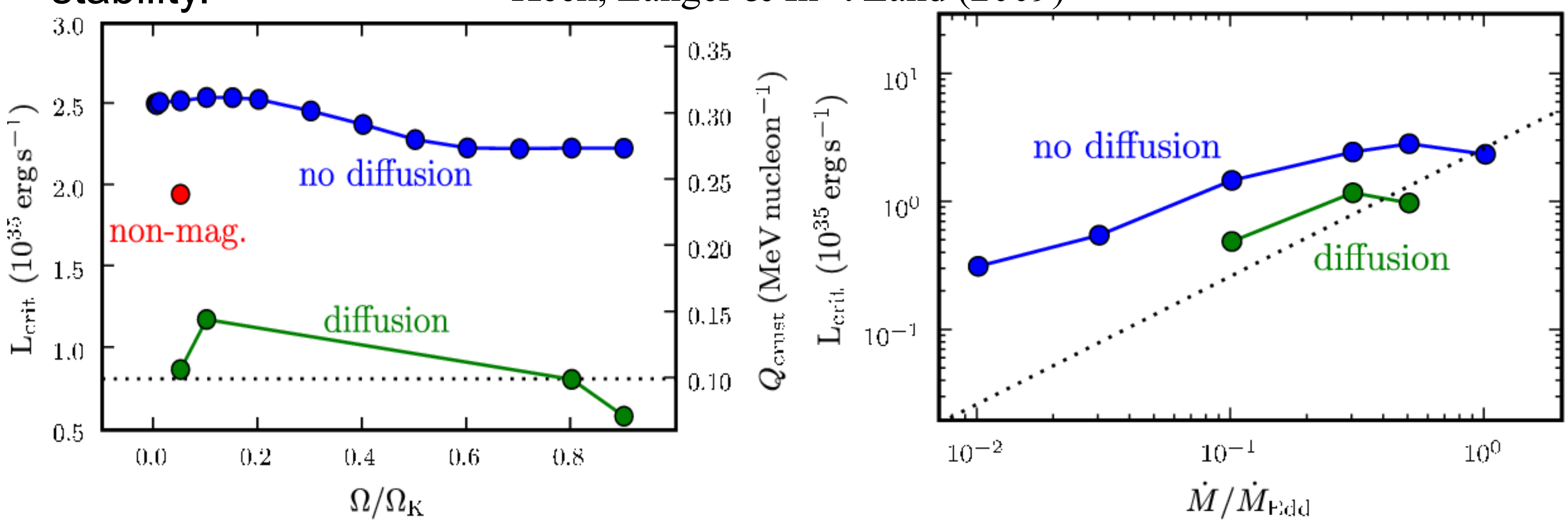


- Simple theory would predict bursting should continue (though with higher rates and smaller fluences) to the stability regime at $\dot{m}$ ~ Eddington.
- Large samples of bursts (RXTE and BeppoSAX/WFC) suggest burst rates drop, and few bursts seen above ~0.2 $\dot{m}_{edd}$?

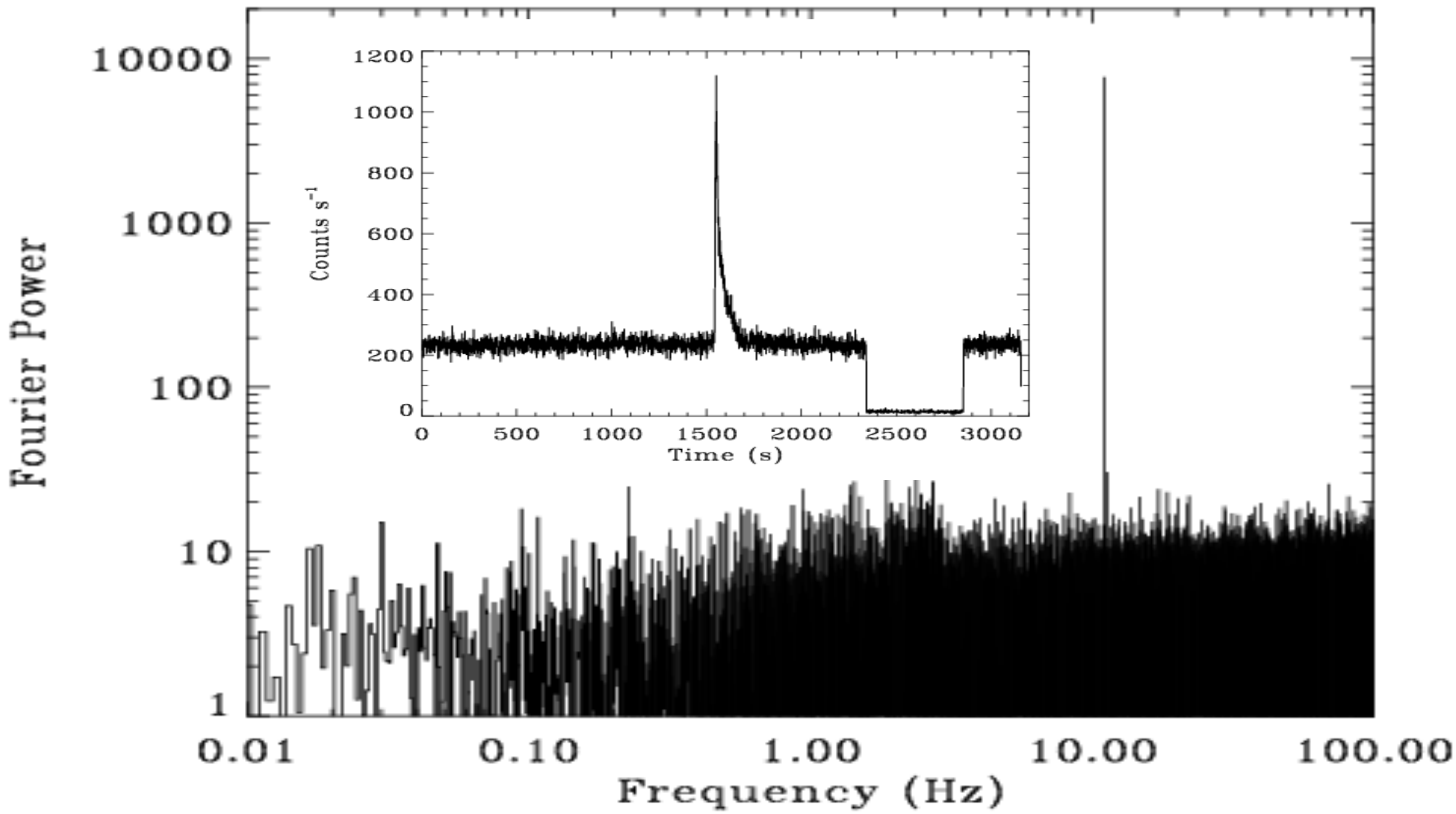
Global Burst Rates: Where Does the Fuel Go?

- Observed persistent flux related to global accretion rate; could the fuel coverage be limited to a portion of the star, so that local rate near stability? Bildsten (2000). Non-spherical behavior.   Additional heating would stabilize too.
- What about spin and angular momentum of accreted matter; mixing of accreted fuel?   Shear instabilities can mix fuel to deeper, hotter layers, where it could burn stably. Keek et al. (2009), rotationally induced B-fields give strong magnetic diffusivity, lowers accretion rate at which expect stability.

Keek, Langer & In ‘t Zand (2009)



New NS Transient in Ter 5: IGR J17480--2446

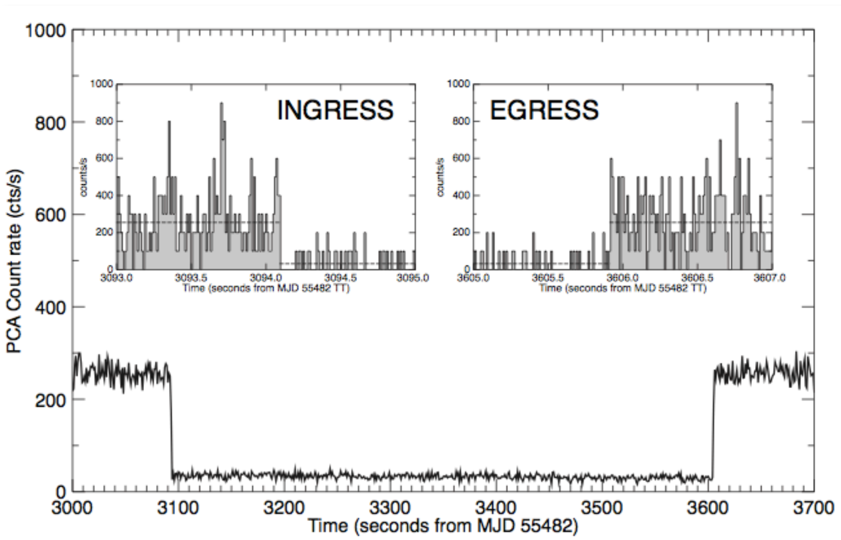


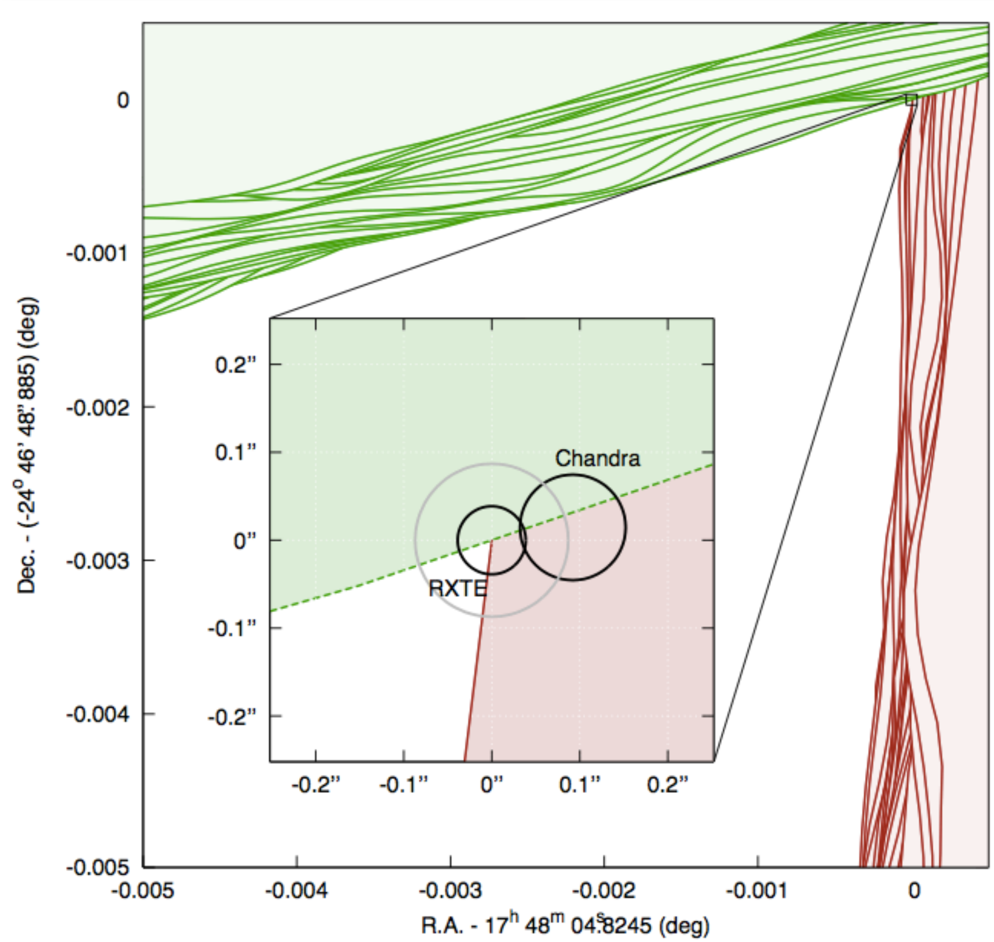
- New X-ray transient found by INTEGRAL (Oct. 2010), in GC Ter 5.
- Subsequent RXTE observations find 11 Hz pulsar (Strohmayer & Markwardt 2010), and 21.3 hr circular orbit, and extensive thermonuclear behavior.

Aside: Lunar Occultation of IGR J17480--2446 with RXTE

- Precision timing of eclipse ingress and egress (< 10 ms).
- Accurate Lunar ephemerides.
- Lunar topography data.
- Enable sub-arcsecond position determination!

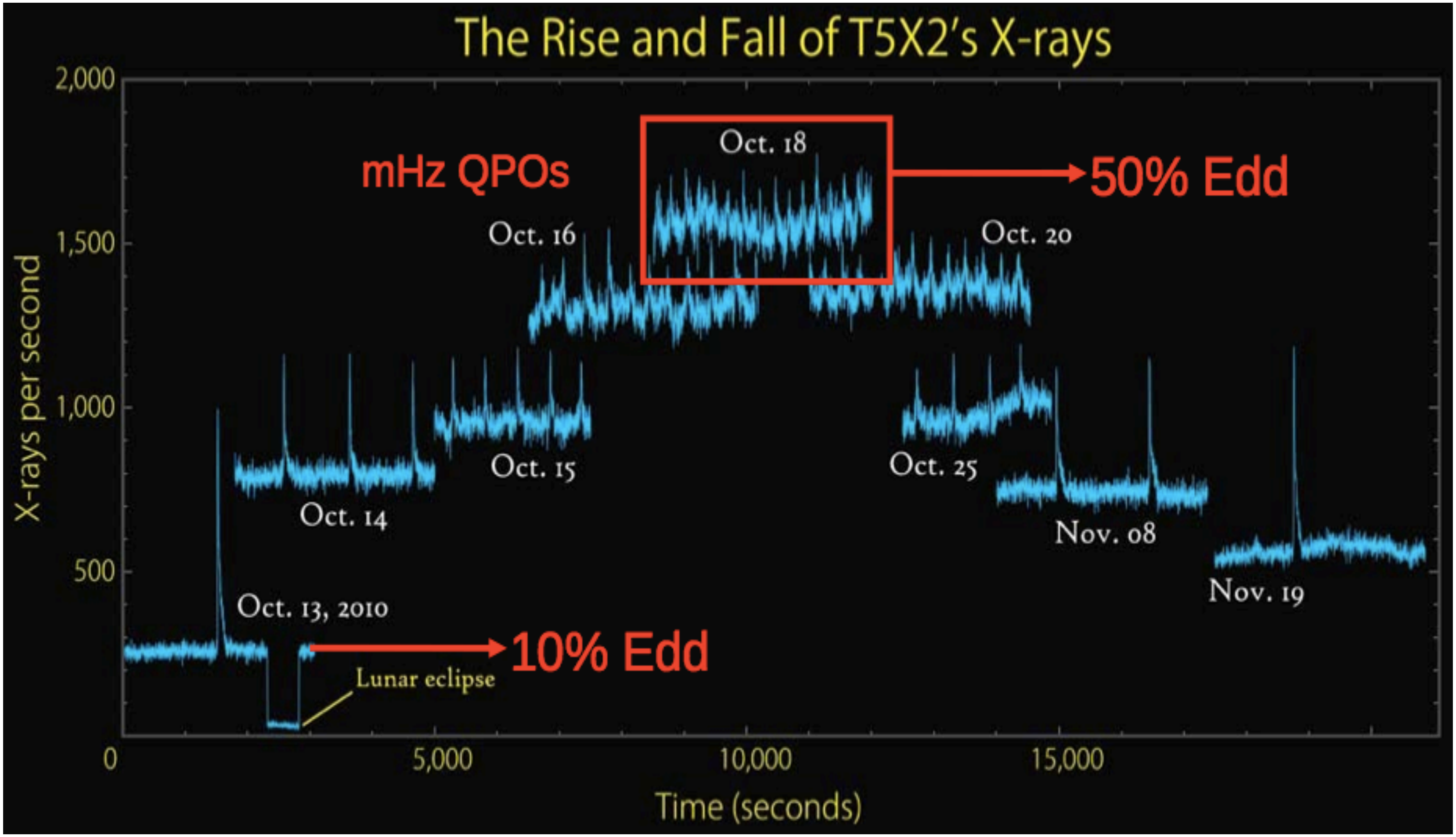
Riggio et al. (2012)





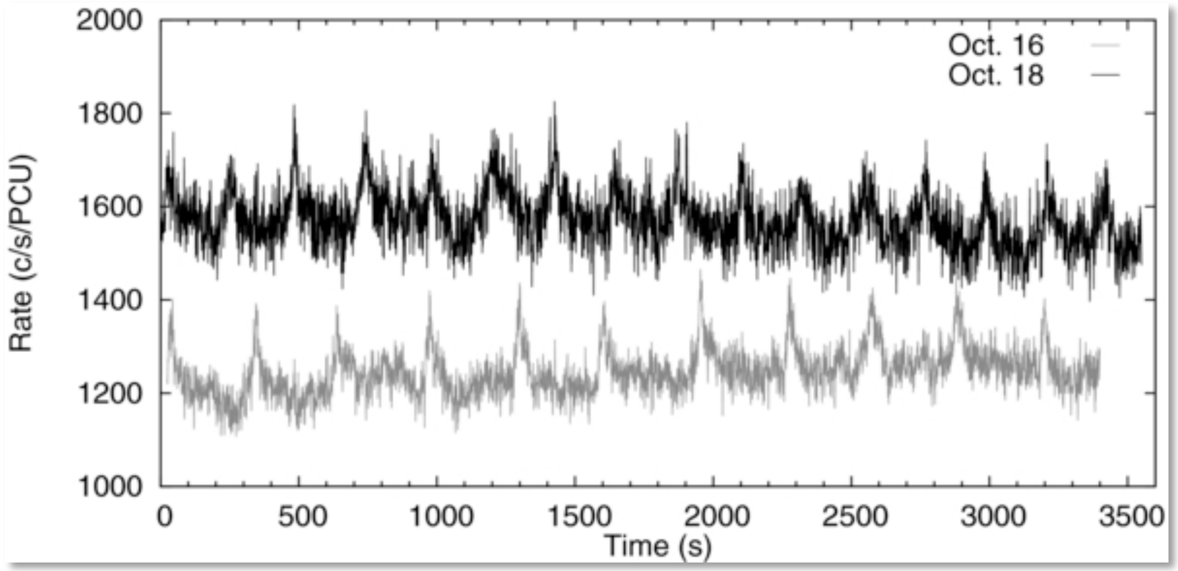
Never underestimate the power of **timing**!

T5X2: 11 Hz pulsar transient

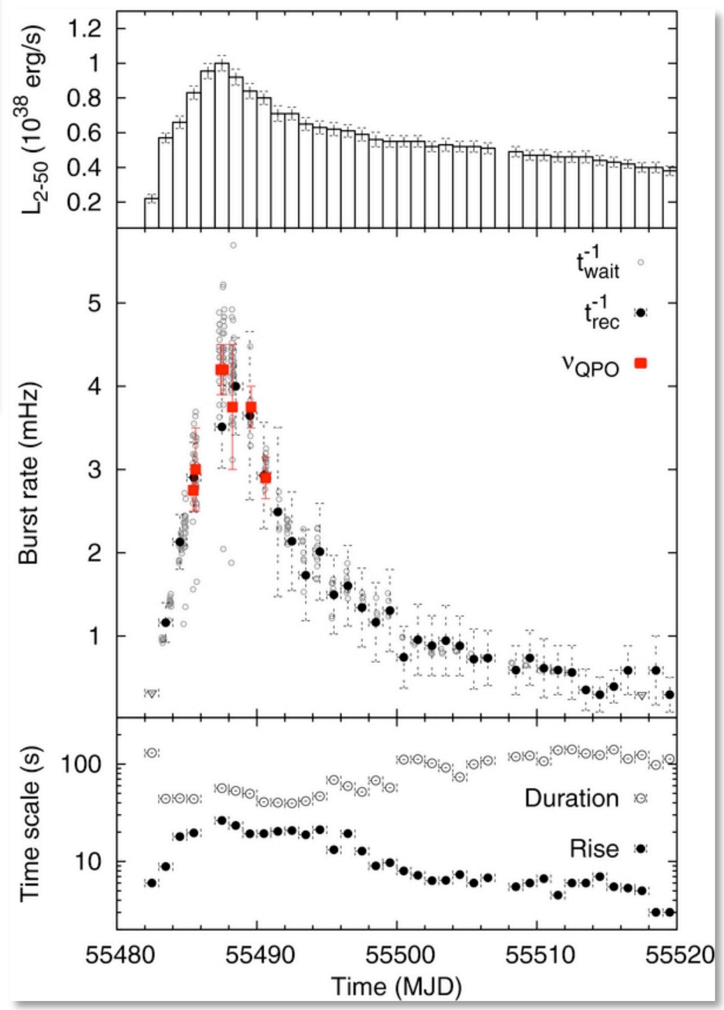


Linares et al. (2012)

T5X2: 11 Hz Pulsar Transient

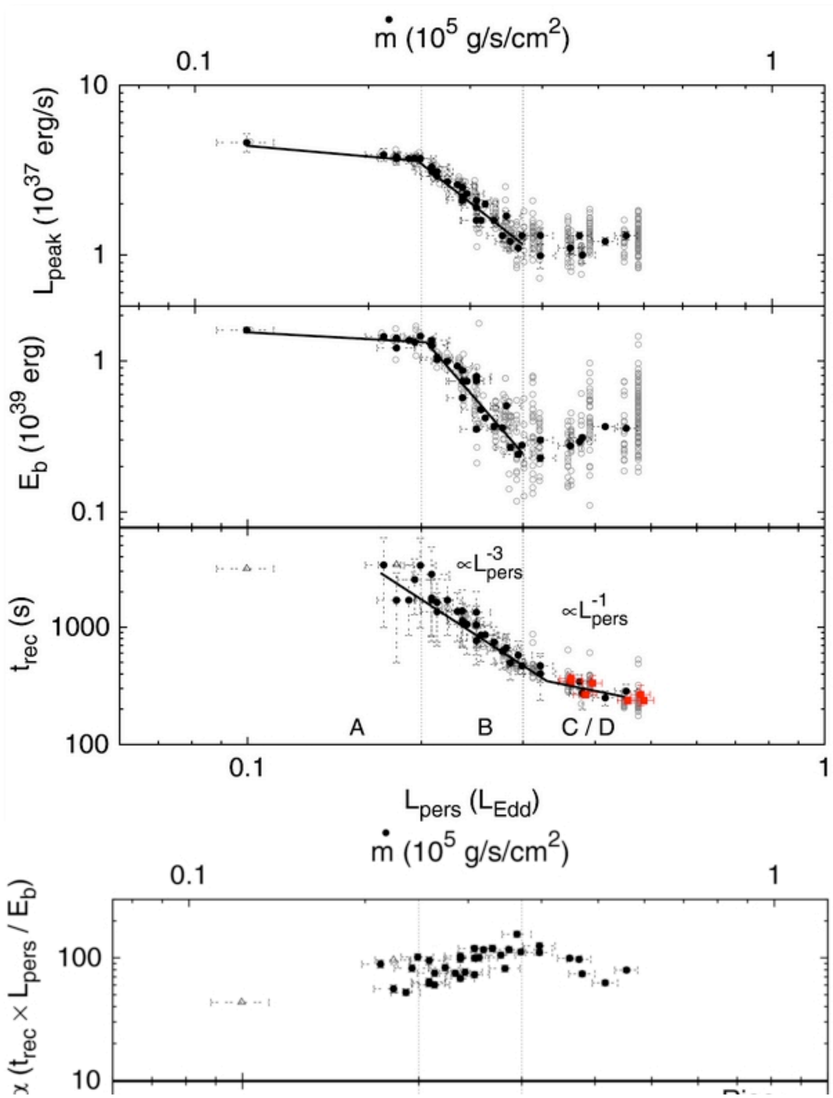


Linares et al. (2012)

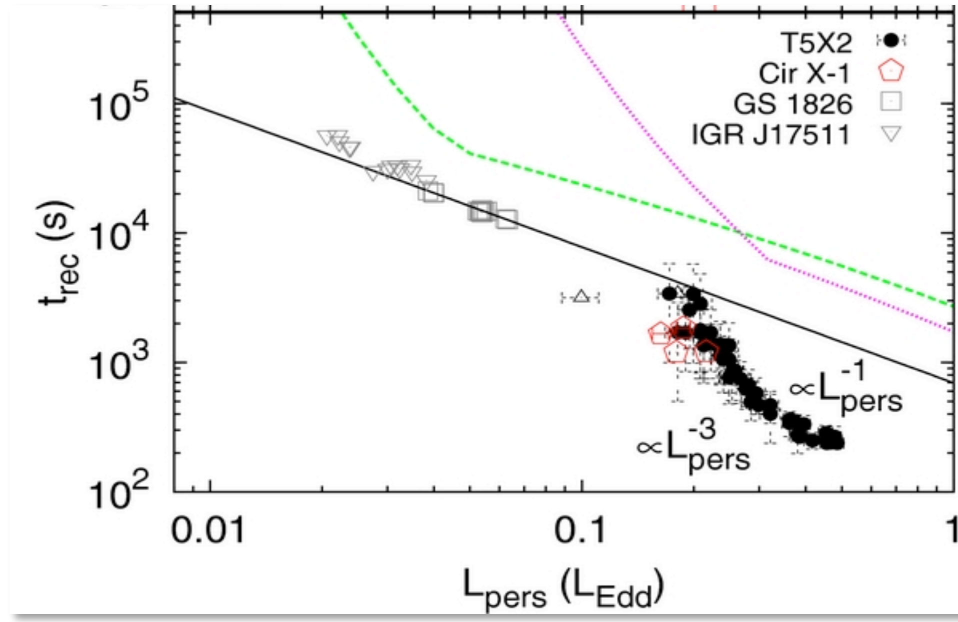


- Smooth variation of burst rate with mass accretion rate
- Bursting continued to high $\dot{m}$
- mHz QPOs, marginally stable burning.
- Several burning regimes identifiable.

T5X2: 11 Hz pulsar transient

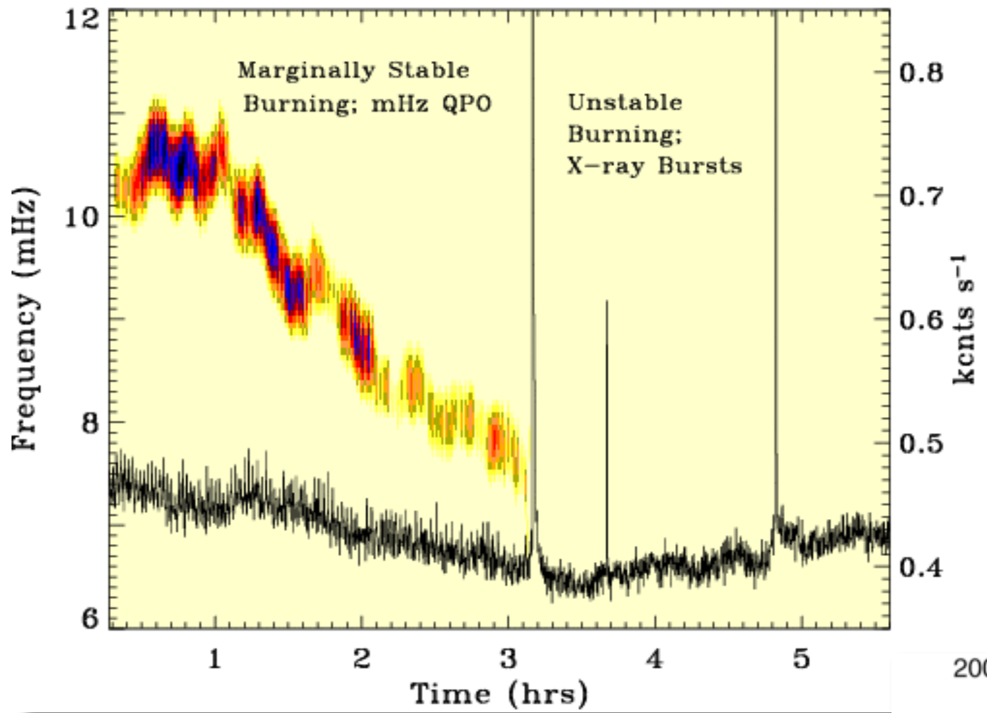


Linares et al. (2012)

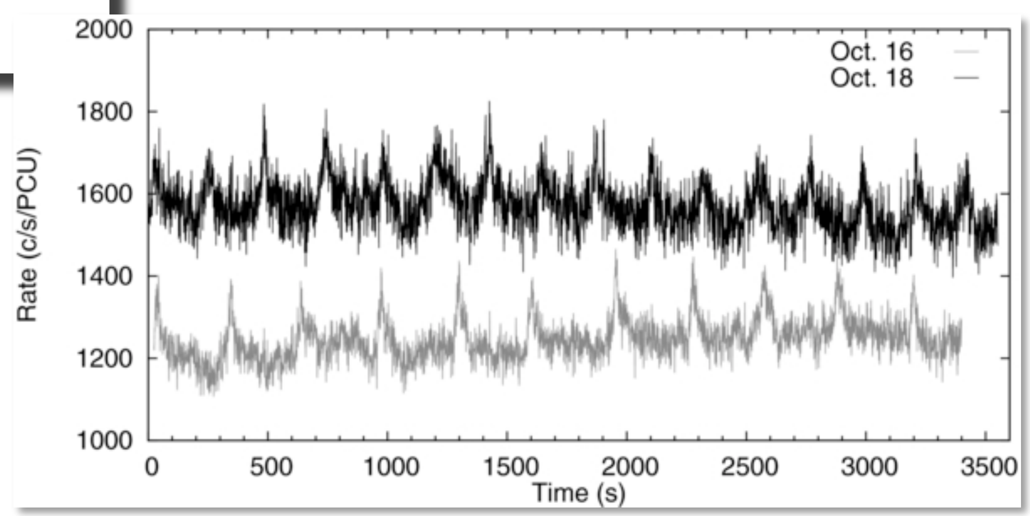


- Several bursting regimes identified, He to H/He (B to C), shows correct t_{rec} dependence
- However, would need low H to match the inferred transition
- And one-zone models don't match the short recurrence times and smaller burst energies (Extra Heat?)

Marginally Stable Burning: Observed mHz QPOs

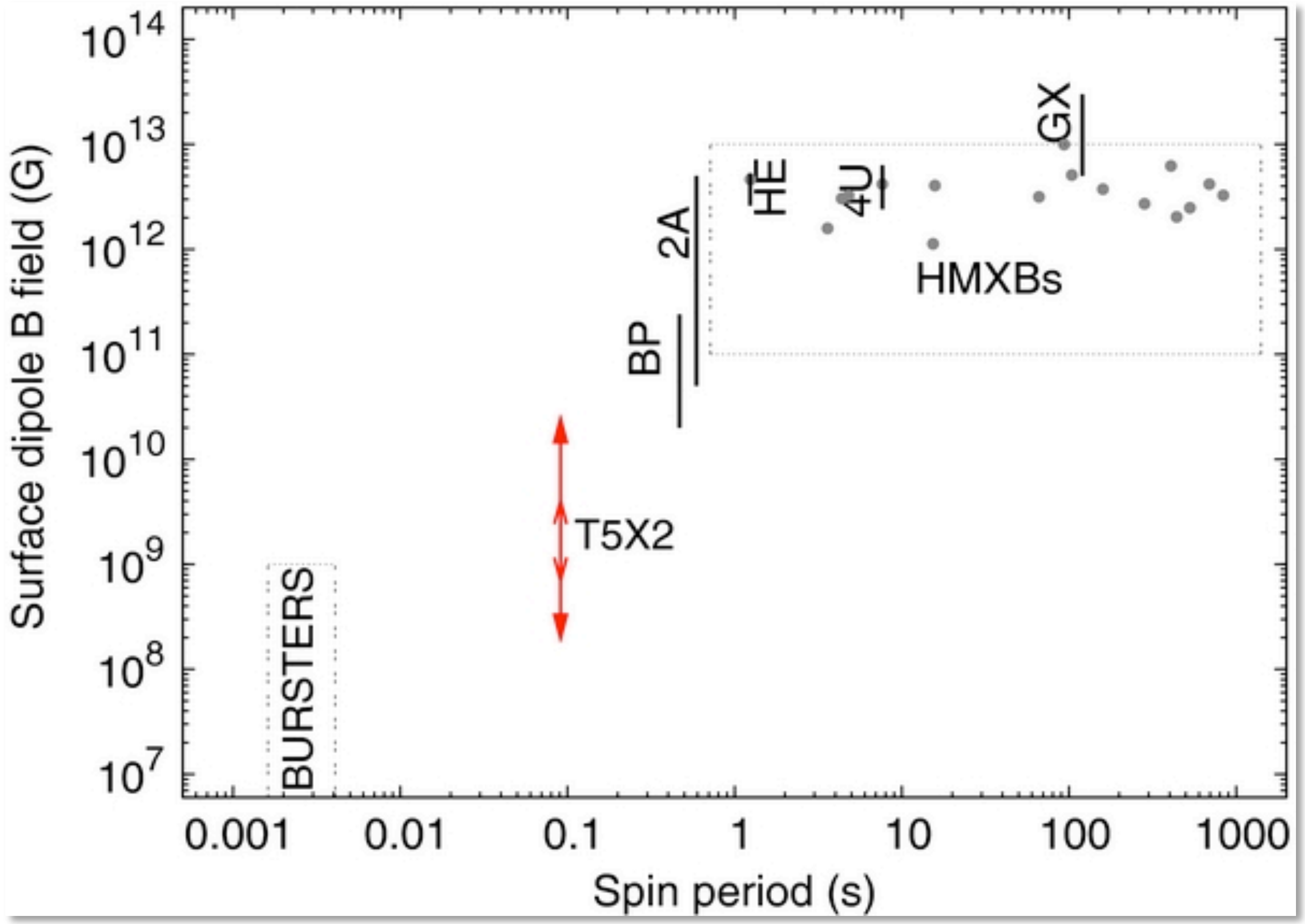


- mHz QPO behavior in 4U 1636-53, when frequency drops below ~8 mHz, then bursting is seen. QPOs at < 0.1 Eddington, Altamirano et al. (2008).
- Inferred accretion rate is again apparently to low for He stability limit by ~ x10.



- QPO frequency in T5X2 lower by factor ~2-3.
- Perhaps behavior in T5X2 is related to He stability limit (matches models), and other sources related to H stability limit?

Magnetic Fields and Spin of Accreting Neutron Stars

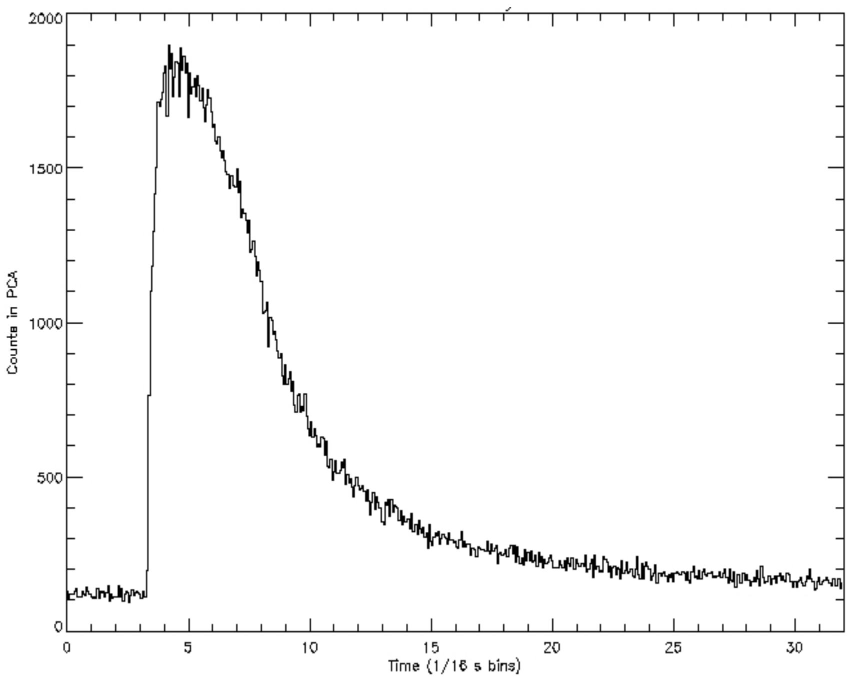


T5x2 fills a gap in the B – spin frequency distribution for accreting NS

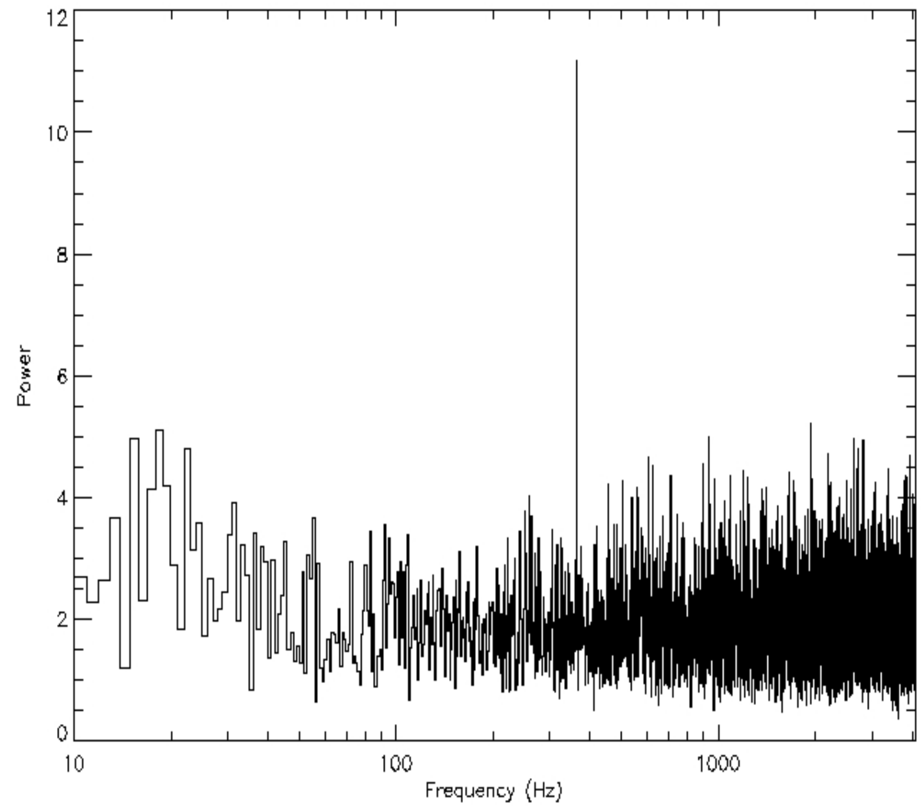
Linares et al. (2012)

Part 2
The end of Spherical Symmetry

Burst Oscillations: Neutron Star Spins

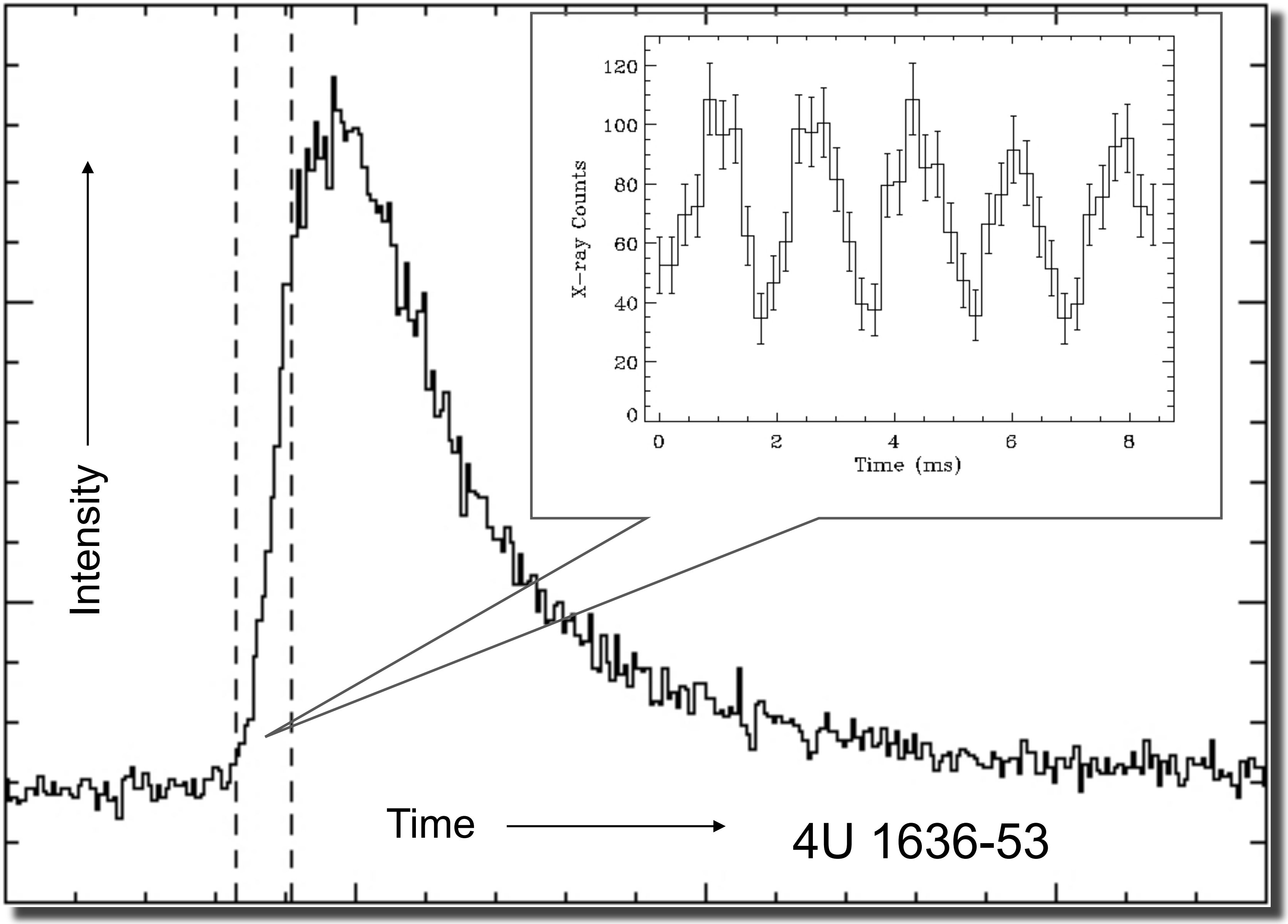


- Discovered in Feb. 1996, shortly after RXTE's launch (Strohmayer et al, 1996)
- First indication of ms spins in accreting LMXBs.

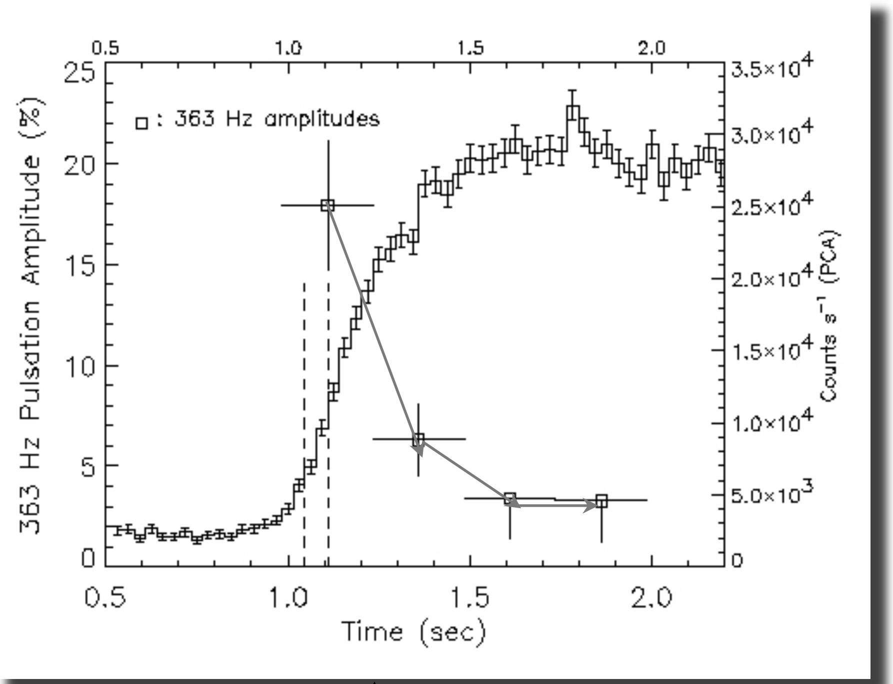


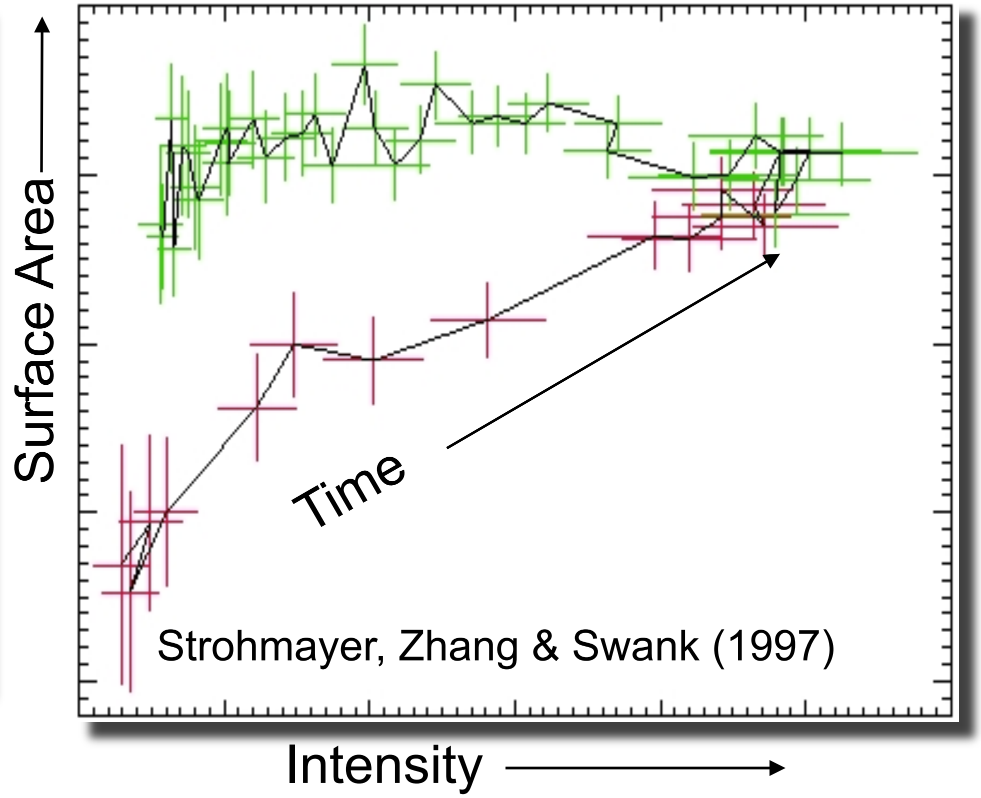
- 4U 1728-34, well known, frequent burster.
- Power spectra of burst time series shows significant peak at 363 Hz.

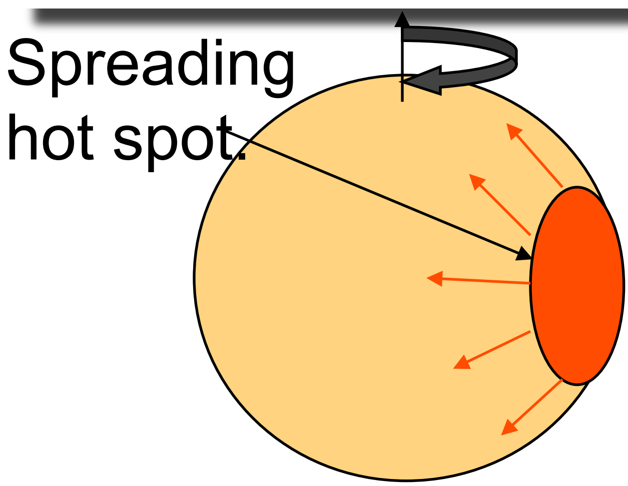
Oscillations at Burst Onset



Timing and Spectral Evidence for Rotational Modulation



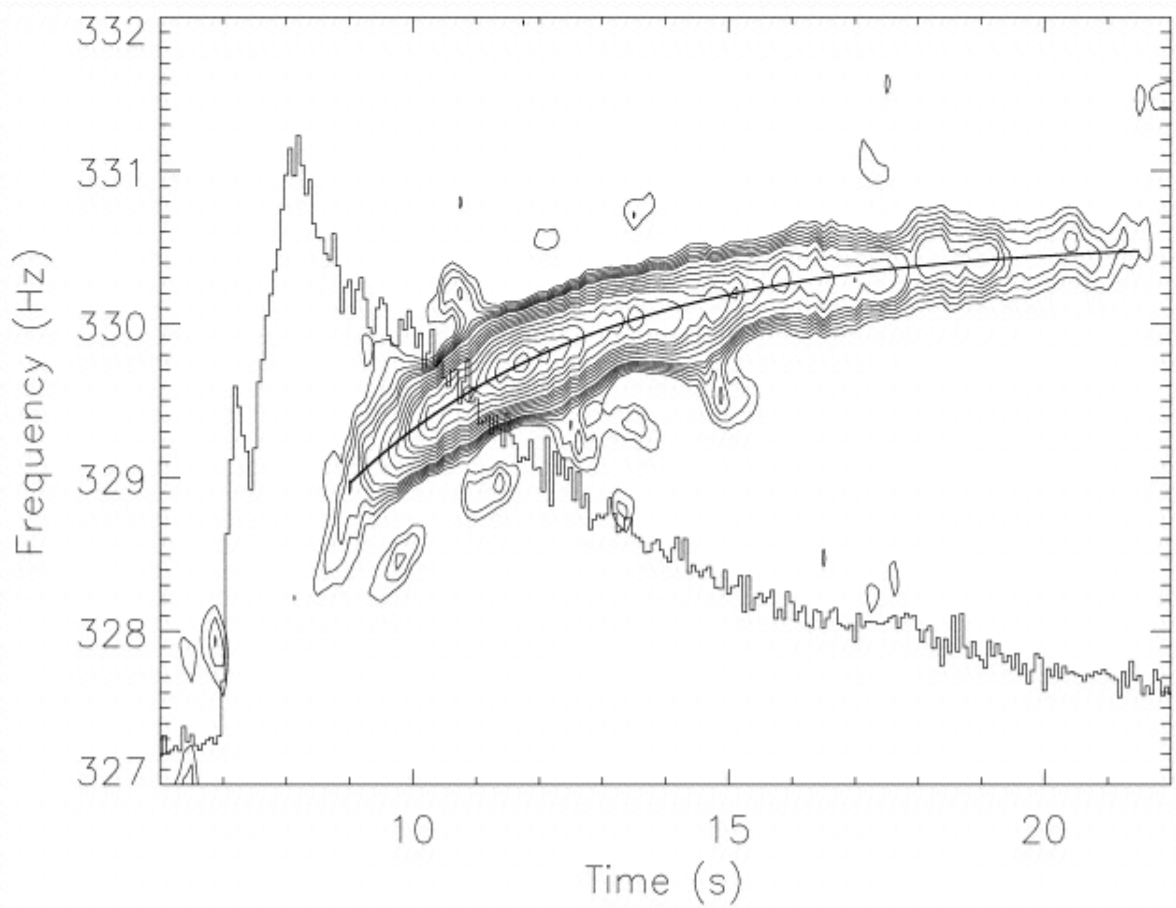


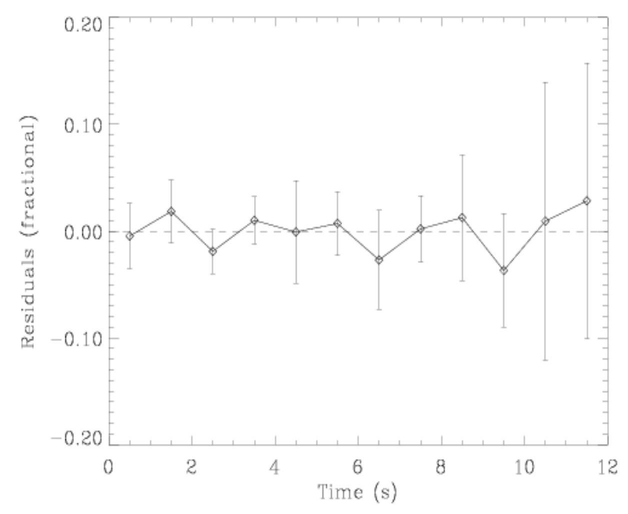


- Oscillations at onset caused by hot spot on rotating neutron star
- Modulation amplitude drops as spot grows.
- Spectra track increasing size of X-ray emitting area on star.

Coherence of Burst Oscillations

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

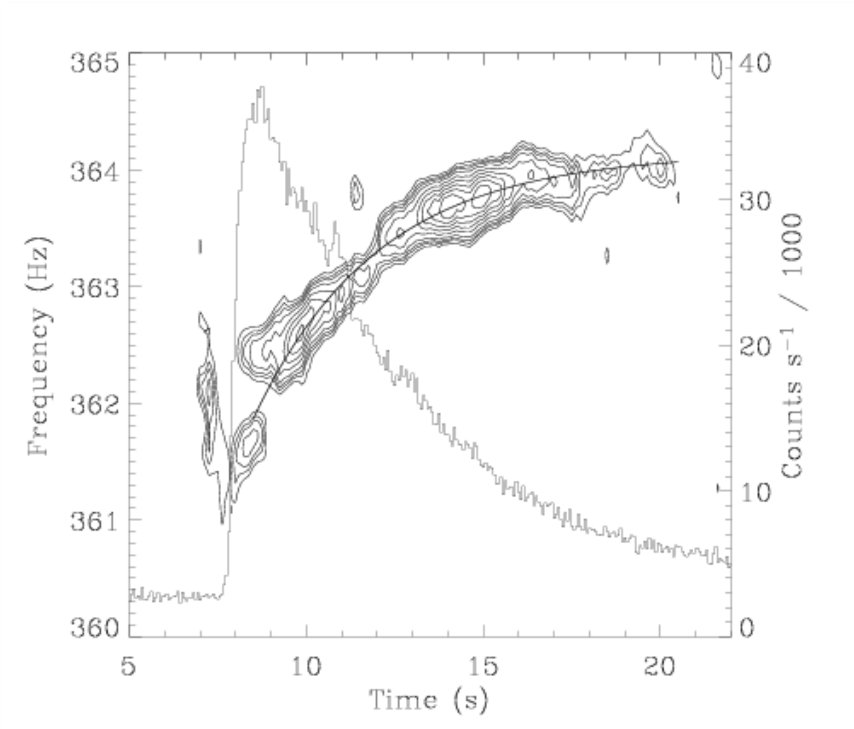


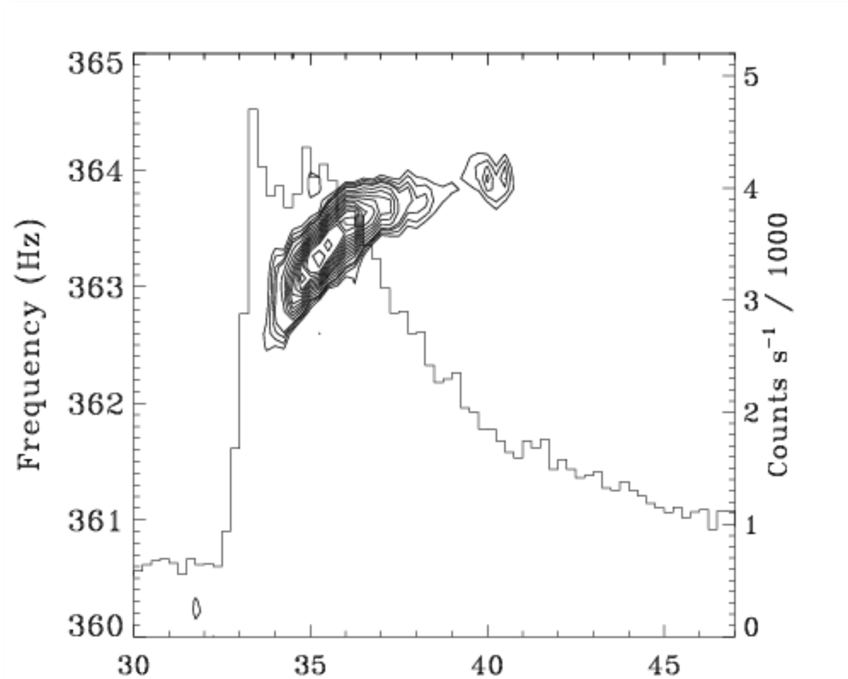


- Burst oscillations generally have high coherence (Q > 4,000)
- exponential recovery in some bursts.

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

Long Term Stability of Oscillation Frequency



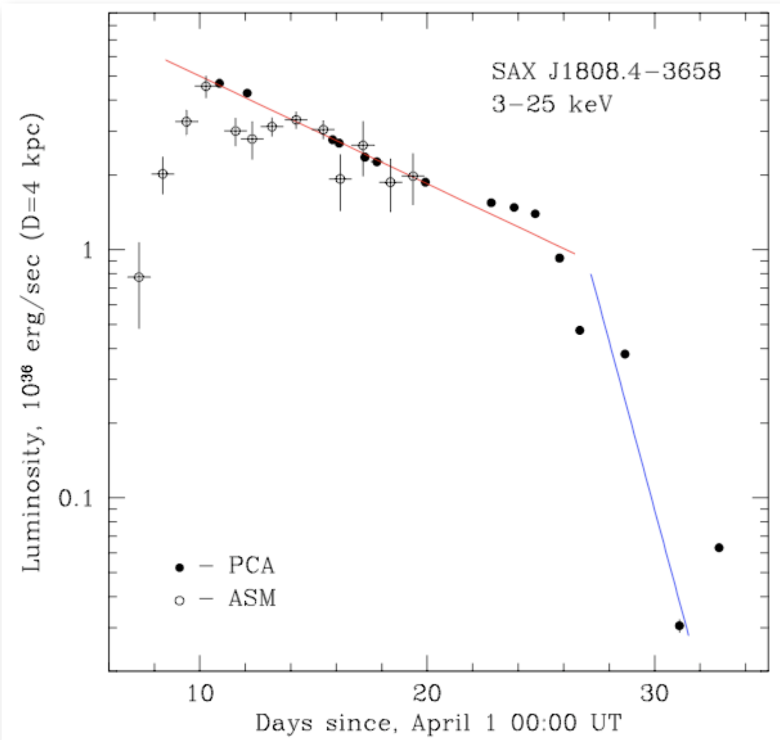


Strohmayer (2012)

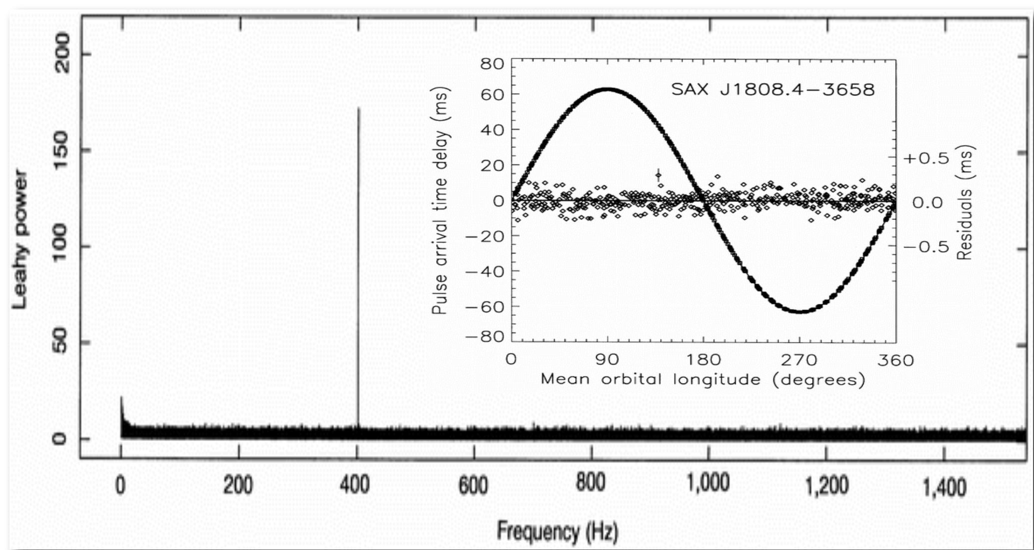
- Bursts from 4U 1728-34 separated by ≈ 16 years have the same asymptotic oscillation frequency.
- Indicative of highly stable process such as rotation.
- Nuclear-powered pulsars.

SAX J1808.4-3658: The First Accreting Millisecond Pulsar

Gilfanov et al. (1999)

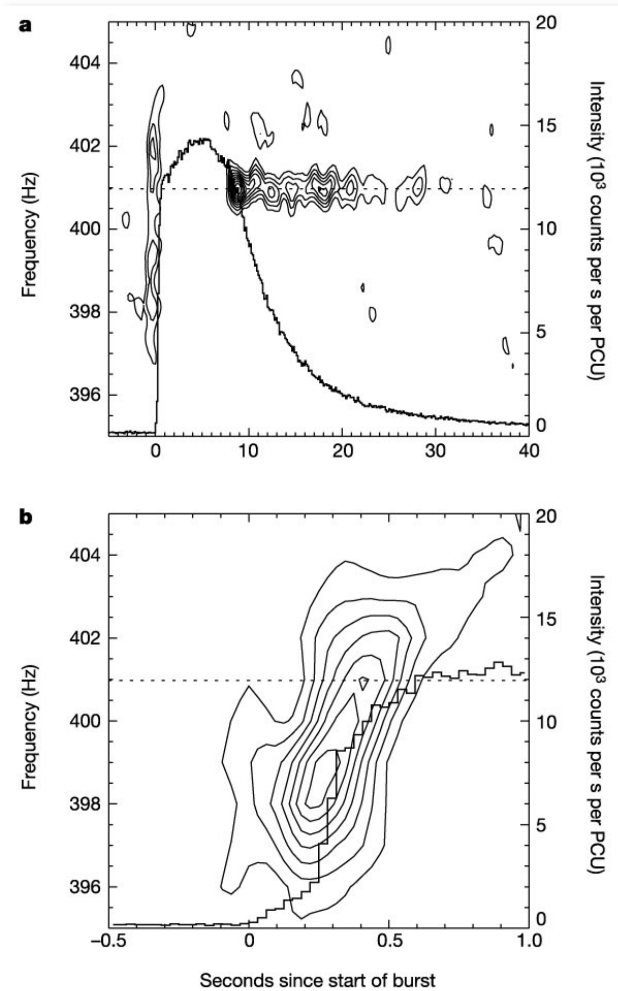


- Source first discovered in 1996 with BeppoSAX, LMXB burster (in 't Zand et al. 1998).
- New outburst in 1998 found with RXTE/PCA
- Subsequent observations reveal binary millisecond pulsar (Wijnands & van der Klis 1998; Chakrabarty & Morgan 1998)



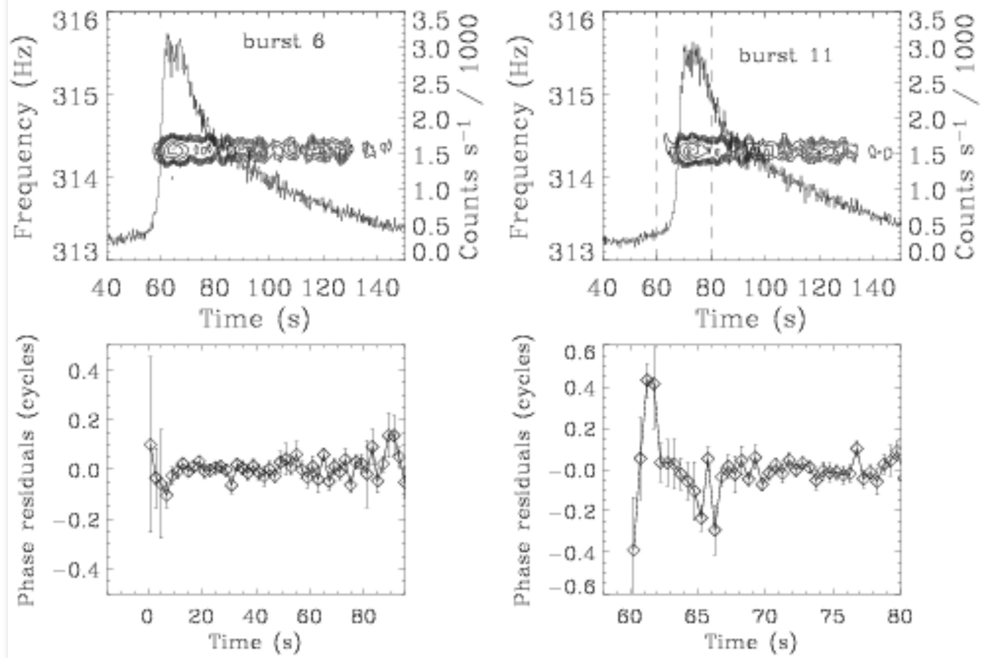
- 401 Hz pulsar
- 2 hr orbital period
- Low mass companion (~0.1 M_{sun})

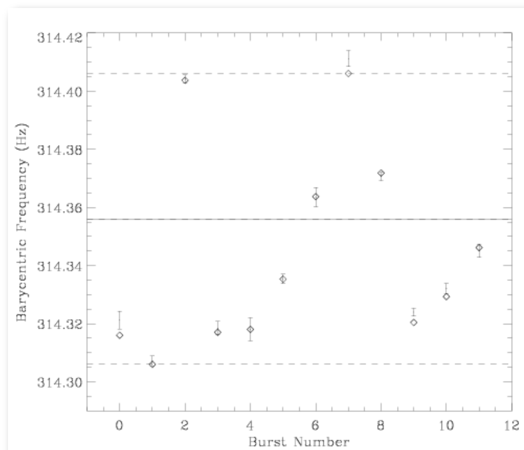
X-ray Bursts from Accreting ms Pulsars: SAX J1808 and XTE J1814-338

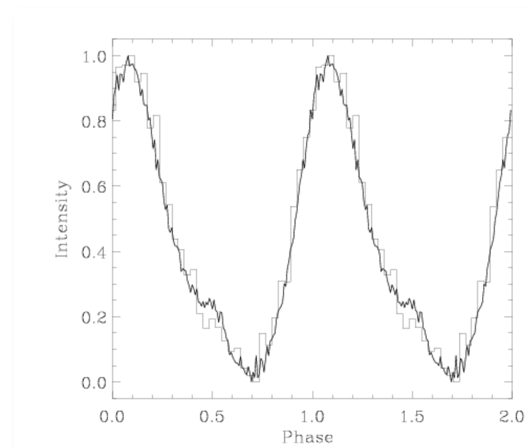


SAX J1808: Chakrabarty et al. (2003)

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







NS Spin Distribution: A Speed Limit for Neutron Stars?

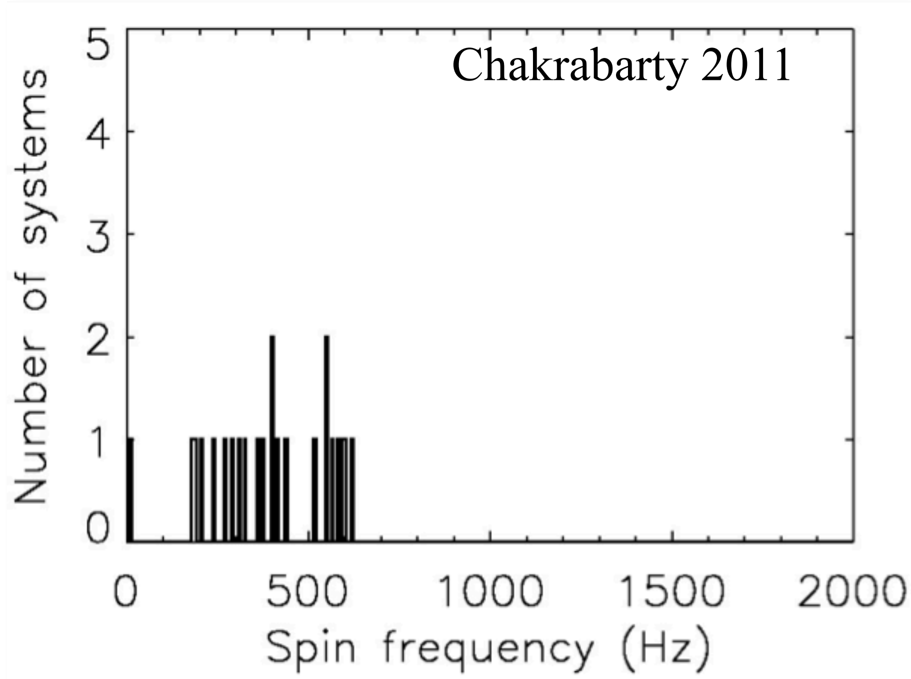
TABLE 7
ACCRETION AND NUCLEAR POWERED MILLISECOND PULSARS

Source Name	Spin Frequency [Hz]
Swift J1756-2508	182
XTE J0929-314	185
XTE J1807-294	190
NGC 6440	205
IGR J17511	245
IGR J17191-2821	294
MXB 1730-335	306
XTE J1814-338	314
4U 1728-34	363
HETE J1900.1-2455	377
SAX J1808.4-3658	401
4U 0614+09	415
XTE J1751-305	435
SAX J1748.9-2021	442
SAX J1749.4-2807	518
KS 1731-260	526
Aql X-1	550
EXO 0748-676	552
MXB 1659-298	556
4U 1636-536	581
IGR J00291-5934	599
SAX J1750.8-2900	601
4U 1608-52	620

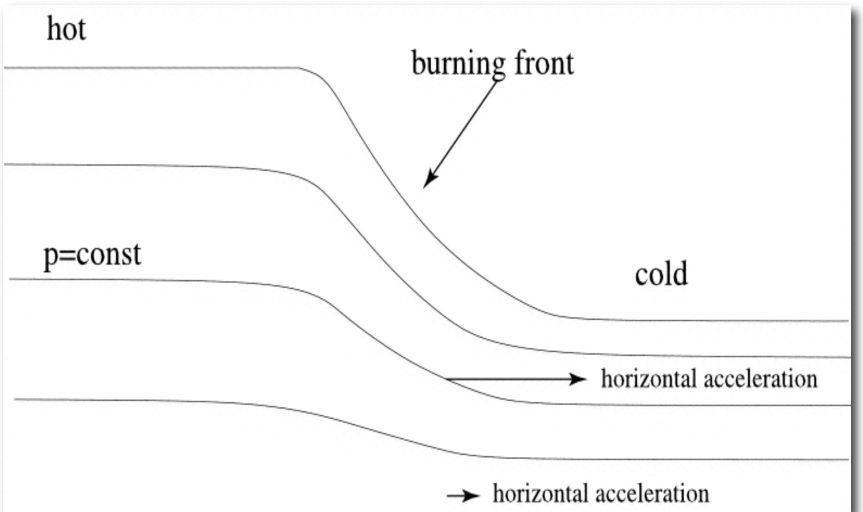
Patruno (2010)

•RXTE pulsation sensitivity extends well above NS break-up limit., but no spin detection above 620 Hz

•If intrinsic distribution were flat out to break-up (2 kHz), then expect to see some sub-ms pulsars, ==> ~730 Hz cutoff (Chakrabarty et al. 2003). Highest spin frequency 716 Hz (Hessels 2007).

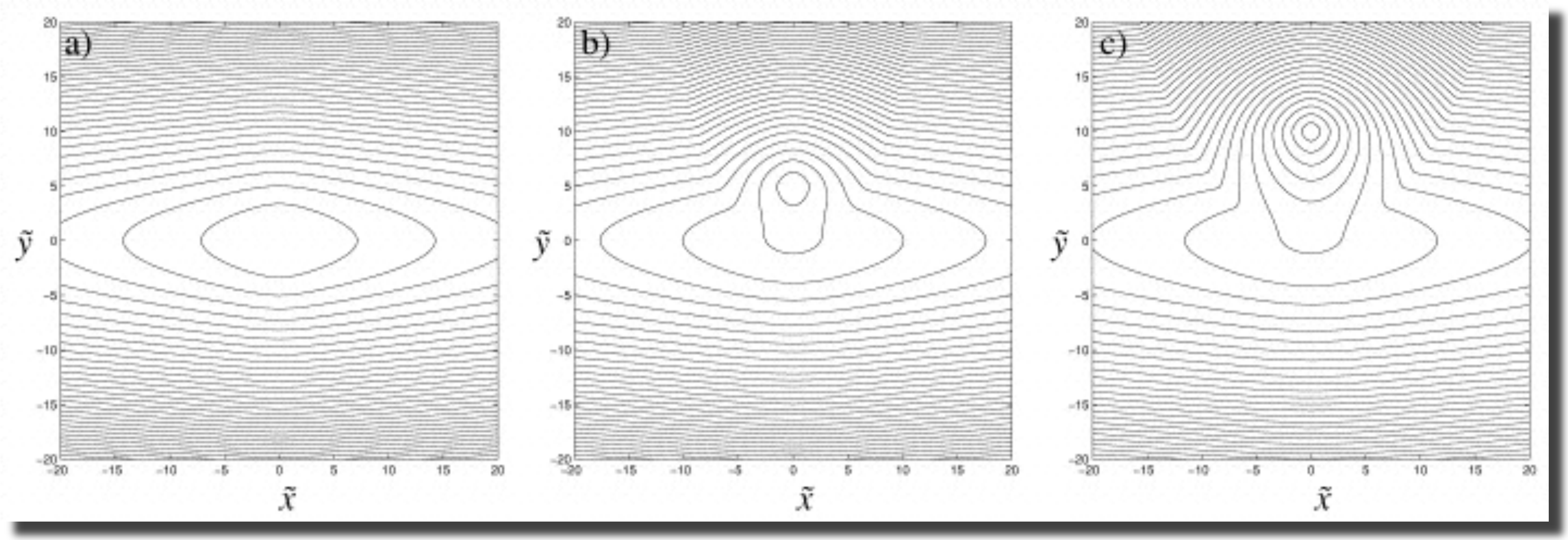


Ignition: Extreme Weather on Neutron Stars

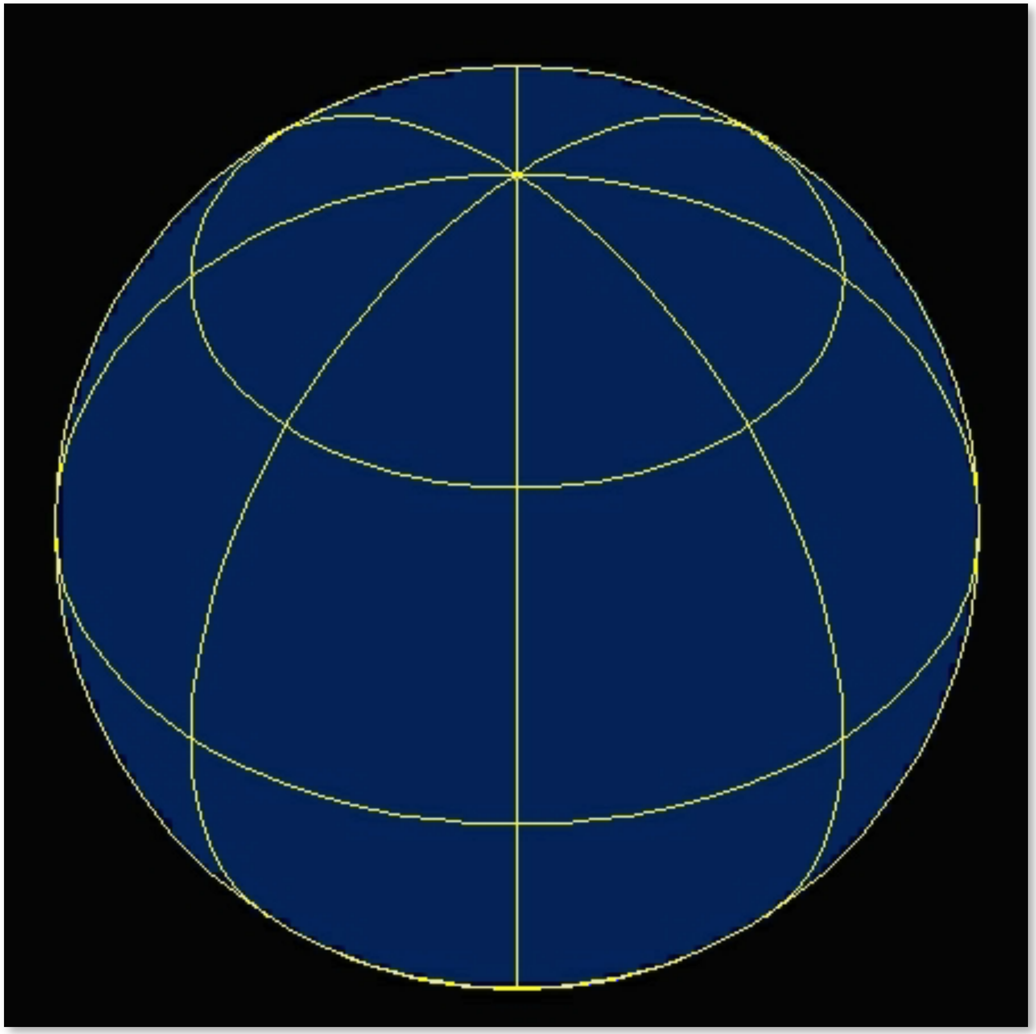


Spitkovsky, Levin & Ushomirsky (2002)

- 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.
- Cross front circulation (ageostrophic)



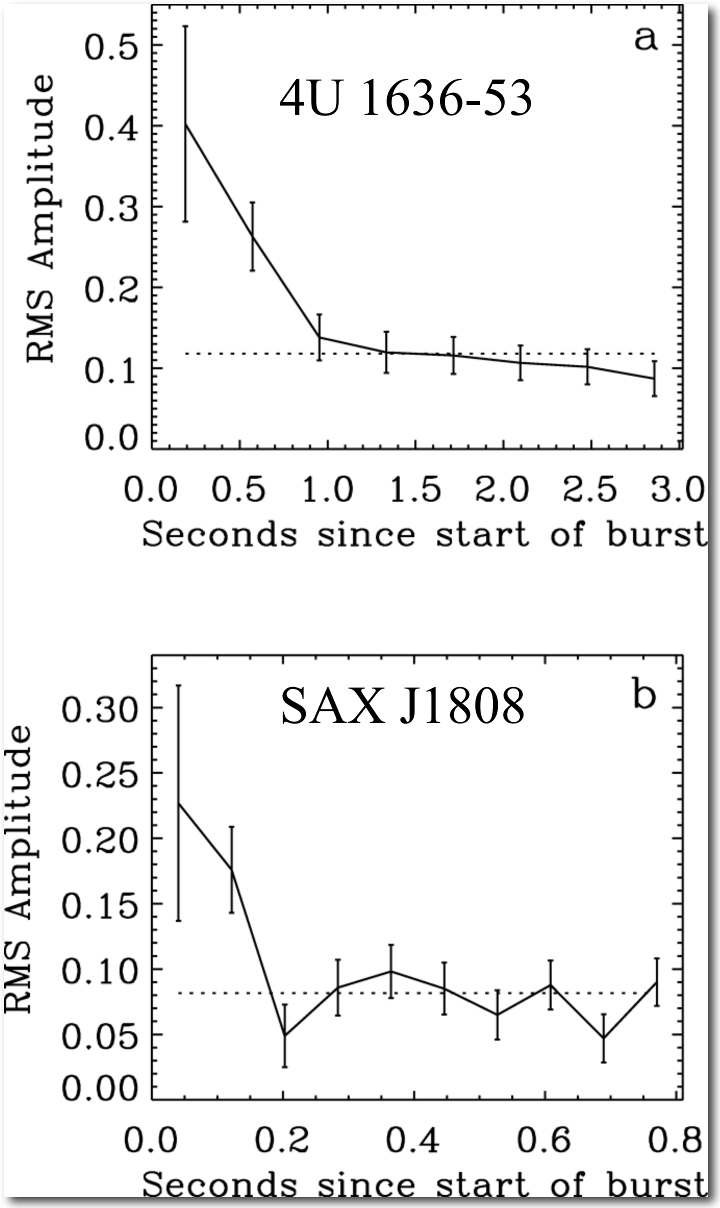
Burst Oscillations: Ignition and Spreading



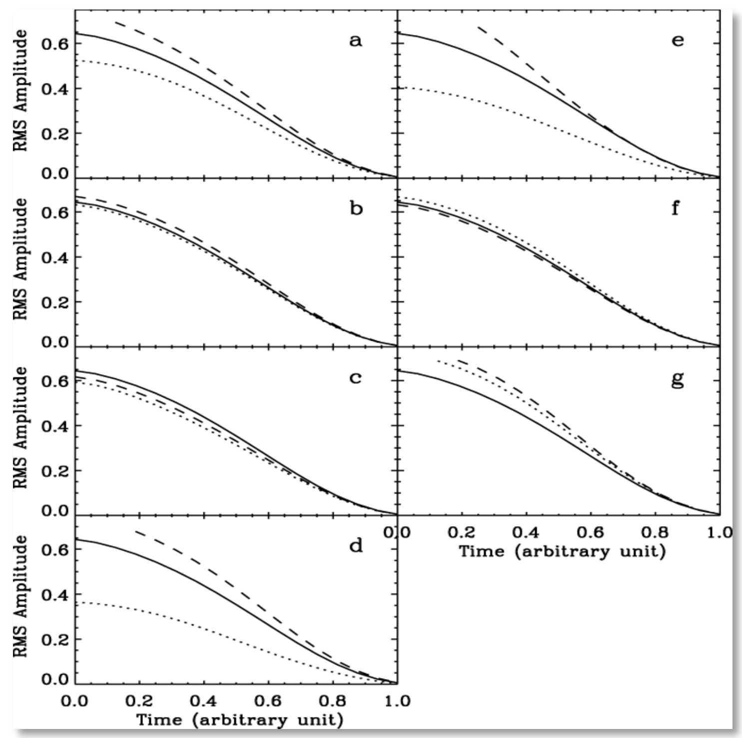
Thanks to Anatoly Spitkovsky!

- Rotation allows for “confinement” of the hot-spot, “Rossby adjustment radius.”
- Localized nuclear heating drives transverse pressure gradients, coupled with spin (coriolis force) leads to “nuclear hurricanes.”
- Similarity with weather systems, pressure gradients balanced by coriolis forces (geostrophic balance).
- Front speed depends on latitude, slower at the poles.

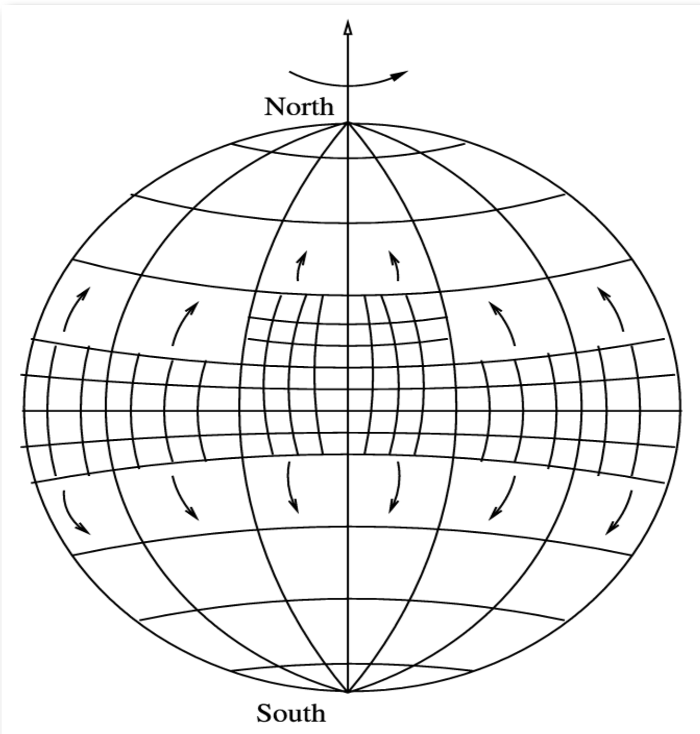
Burst Rise: Amplitude Evolution



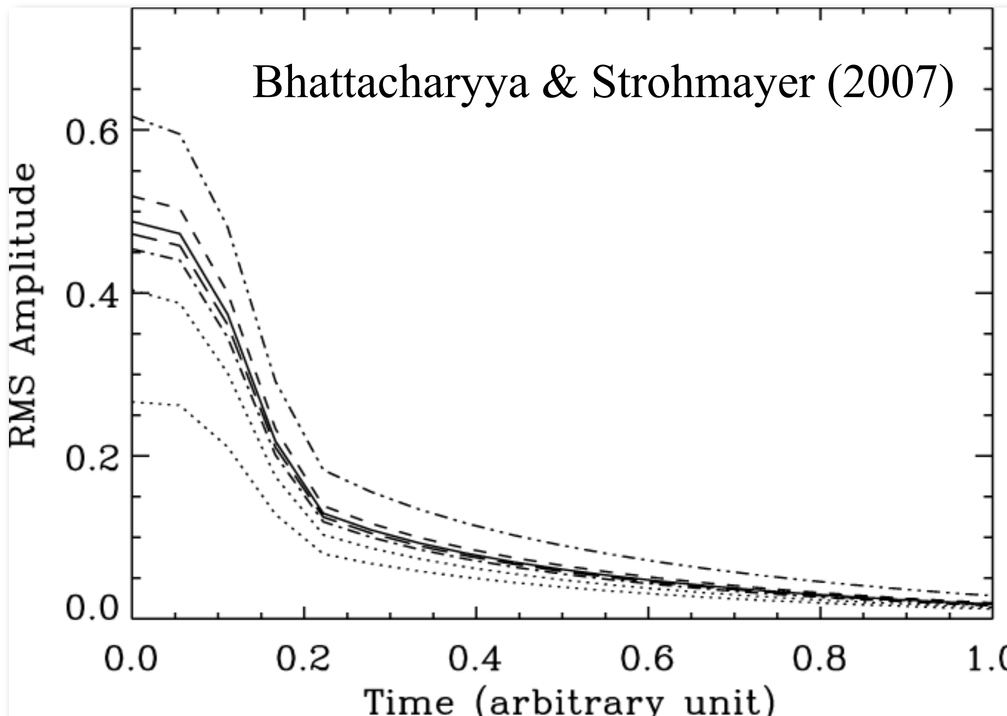
- Amplitude evolution during burst rise, encodes information on nature of flame spreading.
- Some bursts show high initial amplitude, rapid decrease, and then persist at lower amplitude.



Coriolis Force influences spreading speed

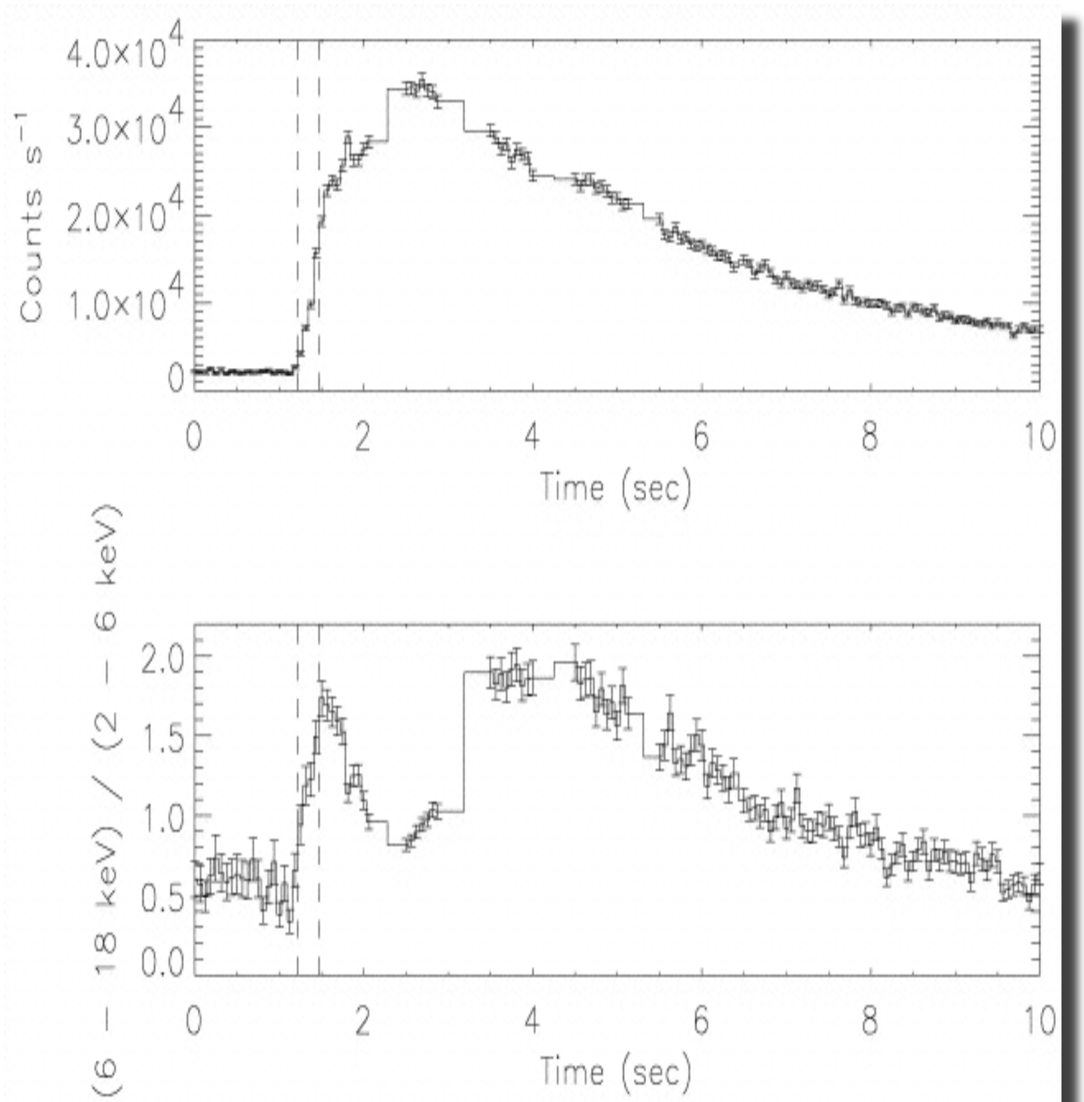


- Spitkovsky, Levin & Ushomirsky (2002) showed Coriolis force relevant to ignition and spreading.
- Flame speed faster at equator, slows with increasing lattitude.



Modelling of near-equatorial ignition, and Coriolis dependent spreading, can better explain amplitude evolution of some bursts.

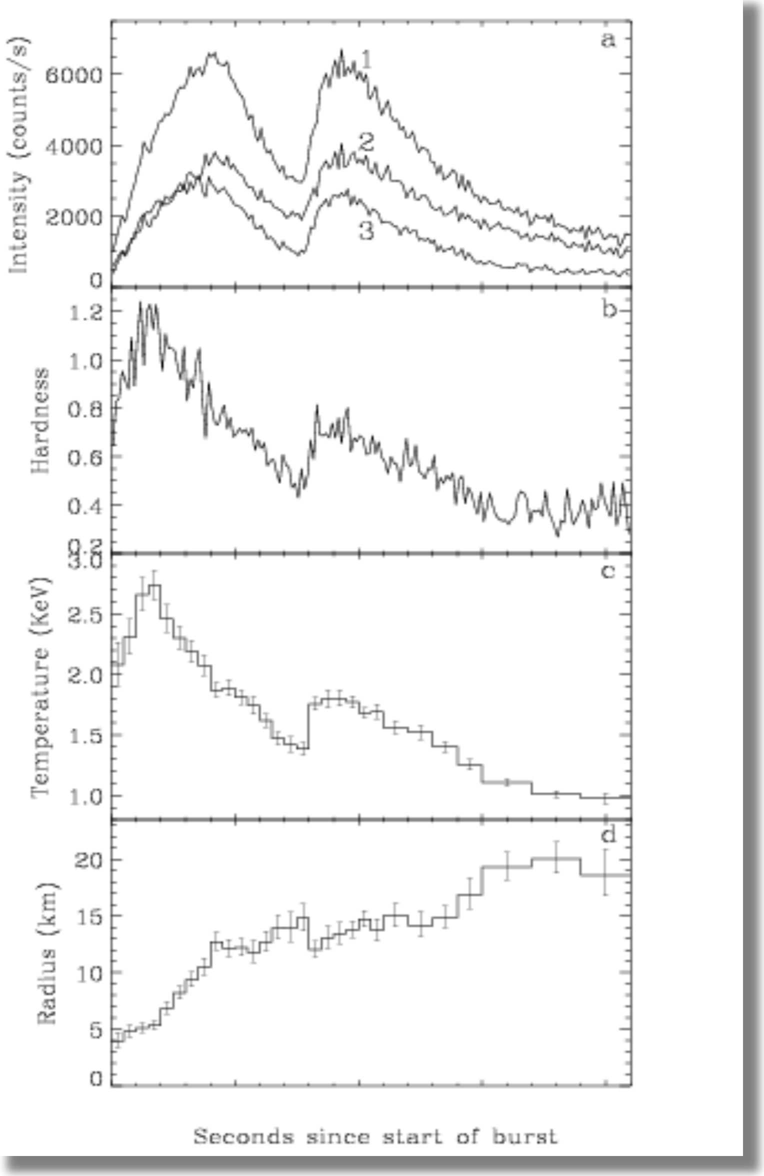
Photospheric Radius Expansion



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

- Local atmospheric flux can reach Eddington limit.
- Radiation pressure drives wind, expands photosphere.
- Models indicate L stays constant. R increases, Teff drops, spectrum softens.

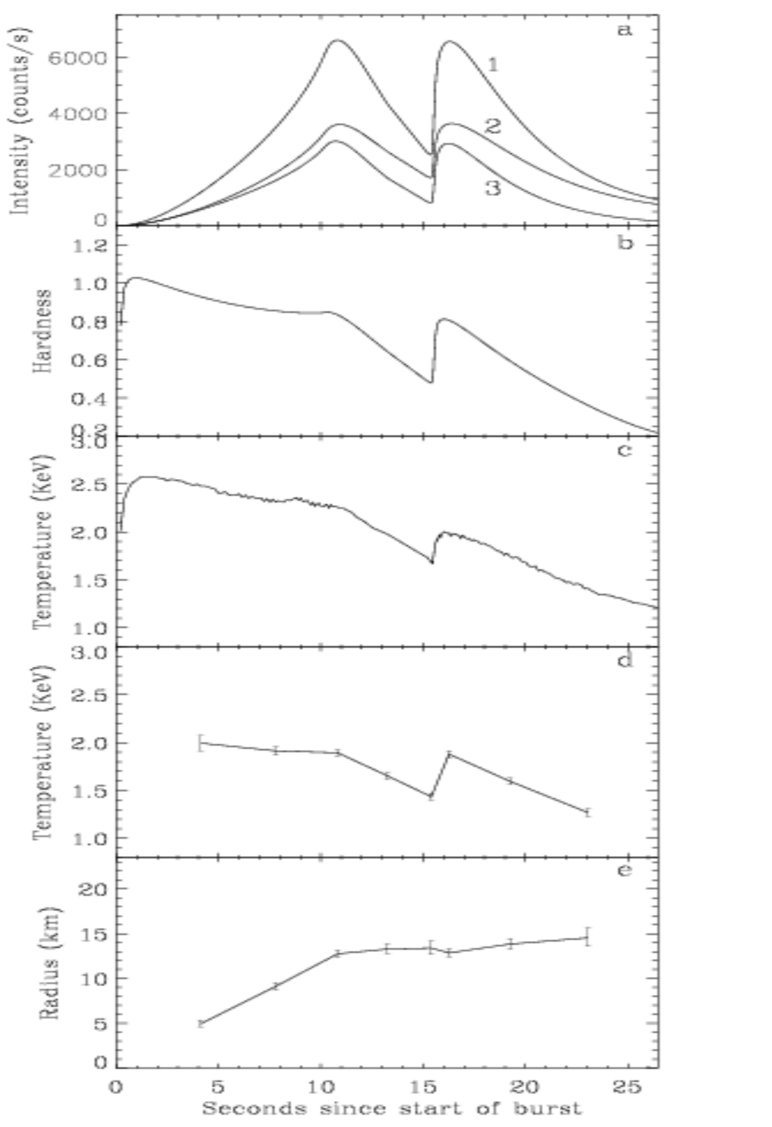
Double-peaked bursts: A Spreading Phenomenon?



- 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)

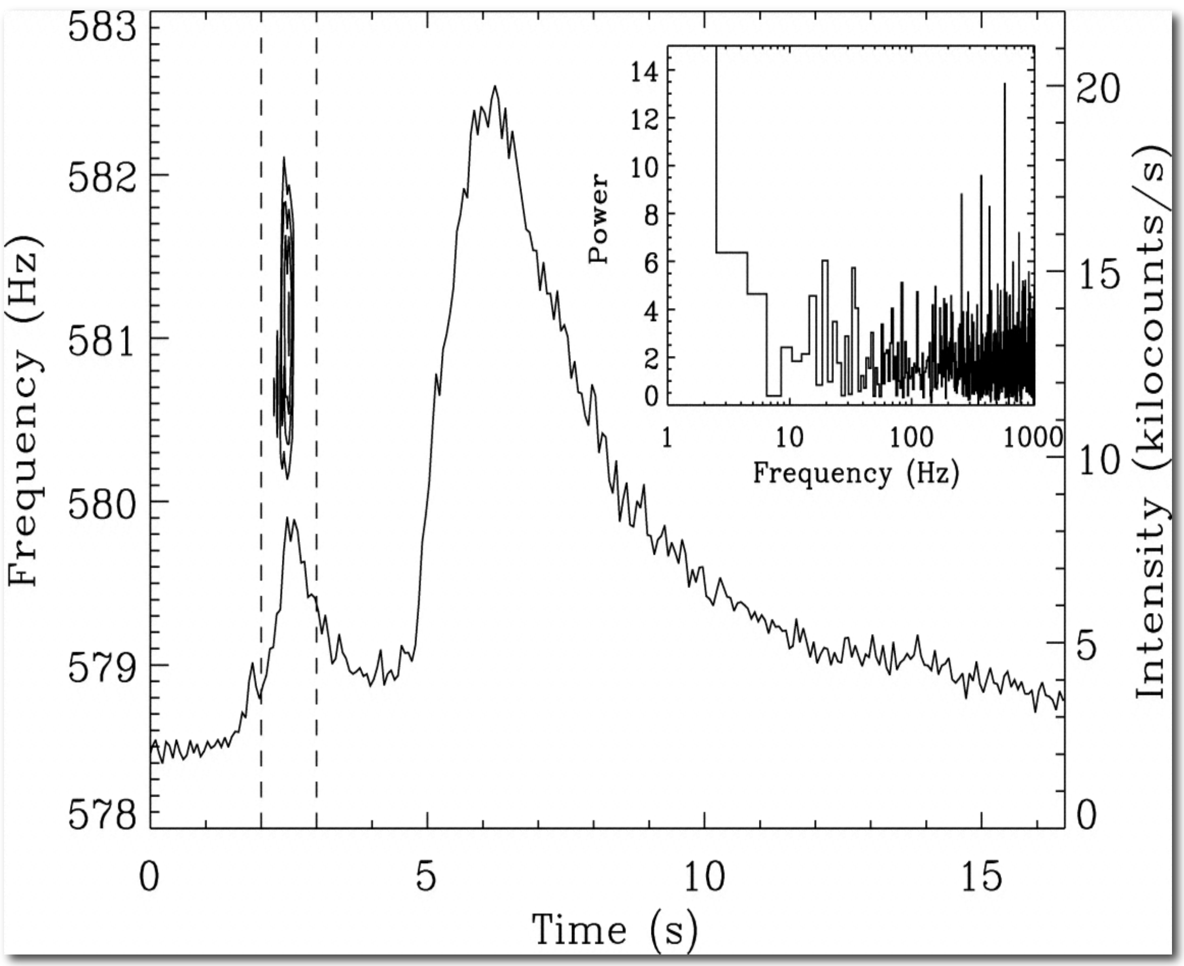
Double-peaked bursts: A Spreading Phenomenon?



- 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)

A Double-peaked Burst with Oscillations: Evidence of Stalling?



Bhattacharyya & Strohmayer (2006)

- An unusual double-peaked burst from 4U 1636-53 shows 582 oscillations during the first (weaker) peak.
- A spreading model can account for double peaks, and oscillations, but ignition must be at high latitude (but not the pole).
- Stalling of the front required again. Some indications for this in the behavior of R.