Thermonuclear X-ray bursts from neutron stars

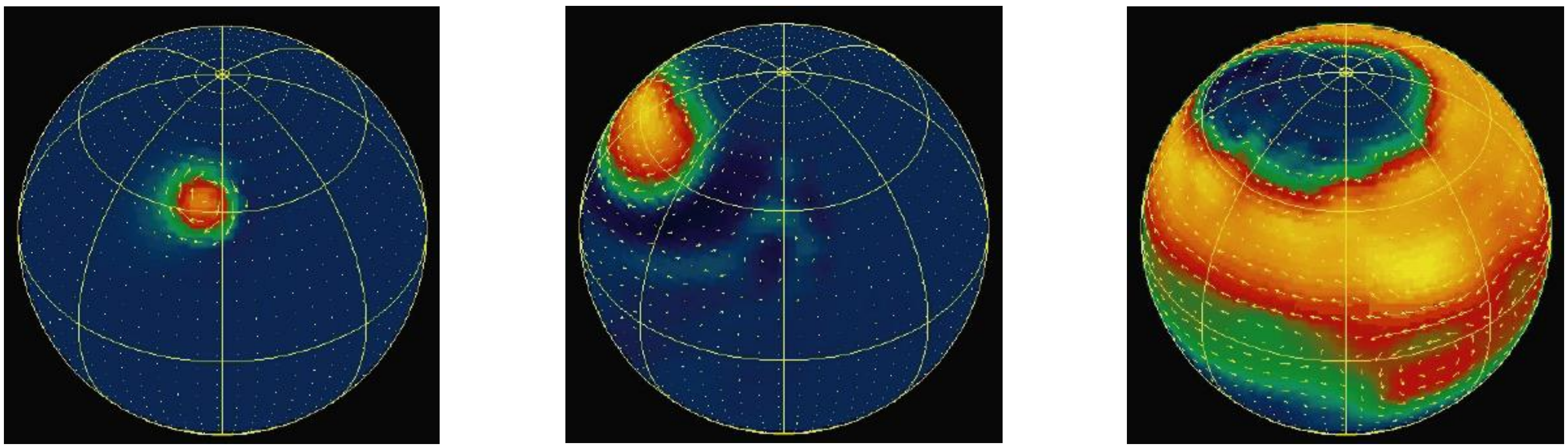


Figure courtesy: Anatoly Spitkovsky

Sudip Bhattacharyya

Department of Astronomy and Astrophysics

Tata Institute of Fundamental Research, India

Outline

- Introduction: neutron star, X-ray astronomy
- Thermonuclear X-ray Bursts
- Various aspects of bursts
- Importance of bursts

Neutron Star

Neutron star vs. a city

Figure courtesy M. Coleman Miller

Radius ~ 10 - 20 km

Mass ~ 1.4 - 2.0 solar mass

Core density ~ 5 -10 times the nuclear density

Magnetic field ~ 10^{7} - 10^{15} G

Spin frequency (in some binary stellar systems) ~ 300 - 600 Hz

Some of the most extreme conditions of the universe exist in neutron stars.

Neutron Star: Surface and Interior

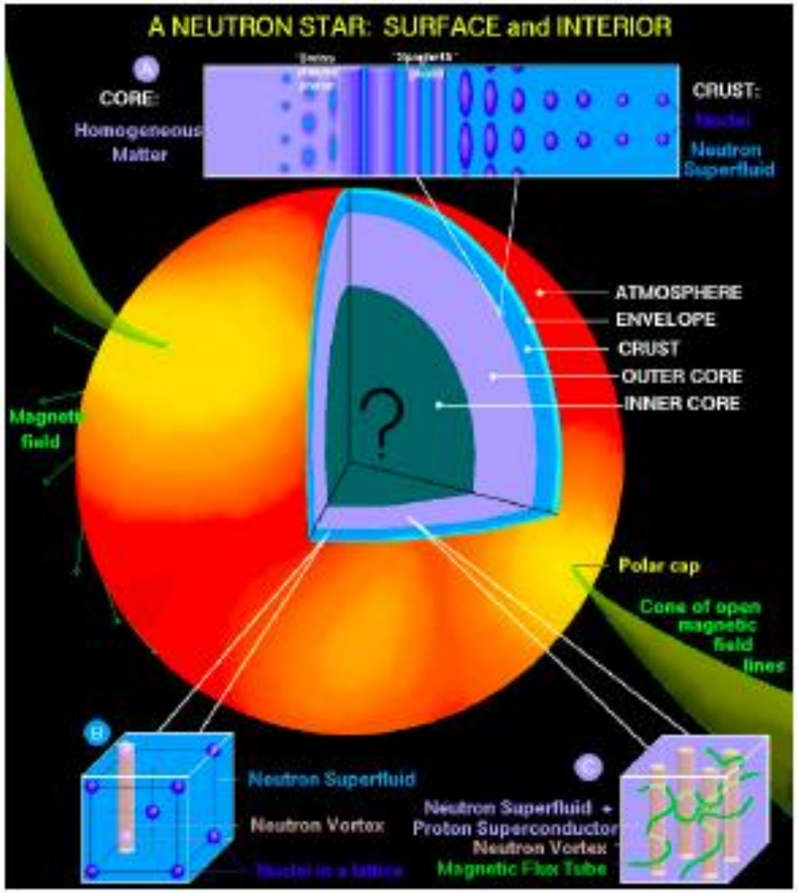


Figure courtesy D. Page

Core density > nuclear density
⇓
Exotic matter???

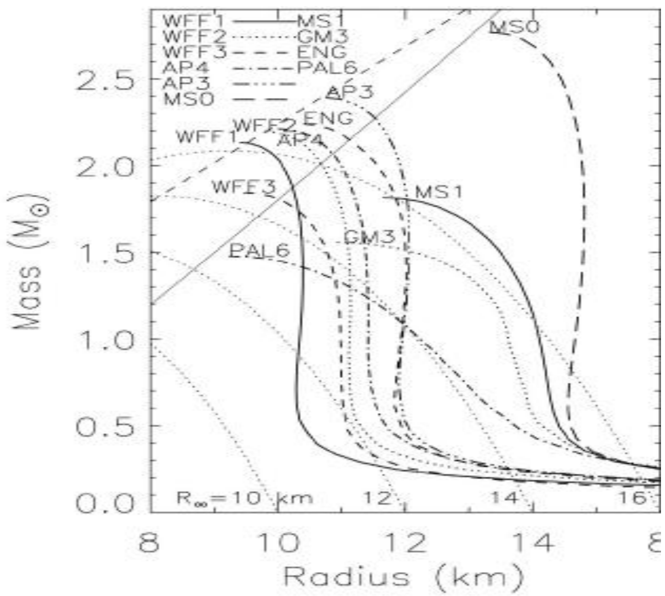
No terrestrial experiments seem possible at such high densities and relatively low temperatures.

Many equation of state (EoS) models for the neutron star core matter are available in the literature. We need to constrain these models by observing neutron stars.

The constituents of neutron star interiors remain a mystery after 40 years.

Neutron Star

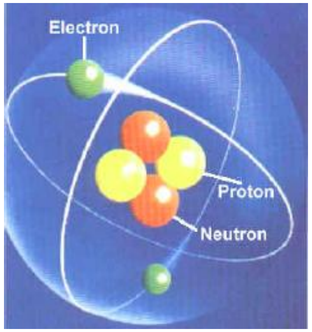
How to constrain EoS models?



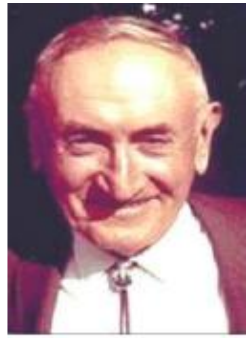
Lattimer & Prakash (2001)

Mass, radius and **spin frequency**, or three independent structural parameters of the *same* neutron star are to be measured in order to constrain **equation of state** models.

Discovery of neutron stars



Neutron was discovered in 1932



Fritz Zwicky

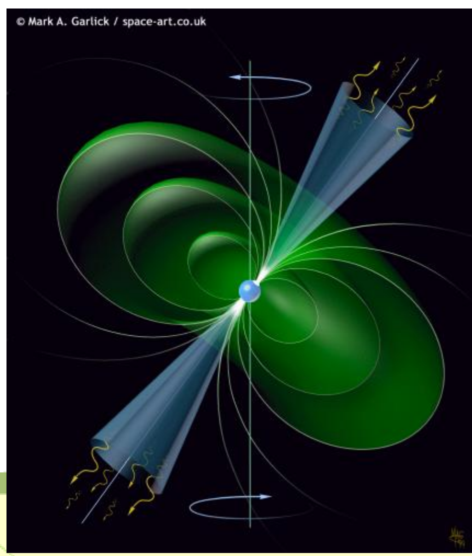
+

Walter Baade

→ In 1933, proposed the existence of neutron stars in order to explain the origin of supernovae.

Chandrashekhar and his celebrated limit

In 1930s, Tolman-Oppenheimer-Volkoff equation was developed to calculate the structure of a neutron star.



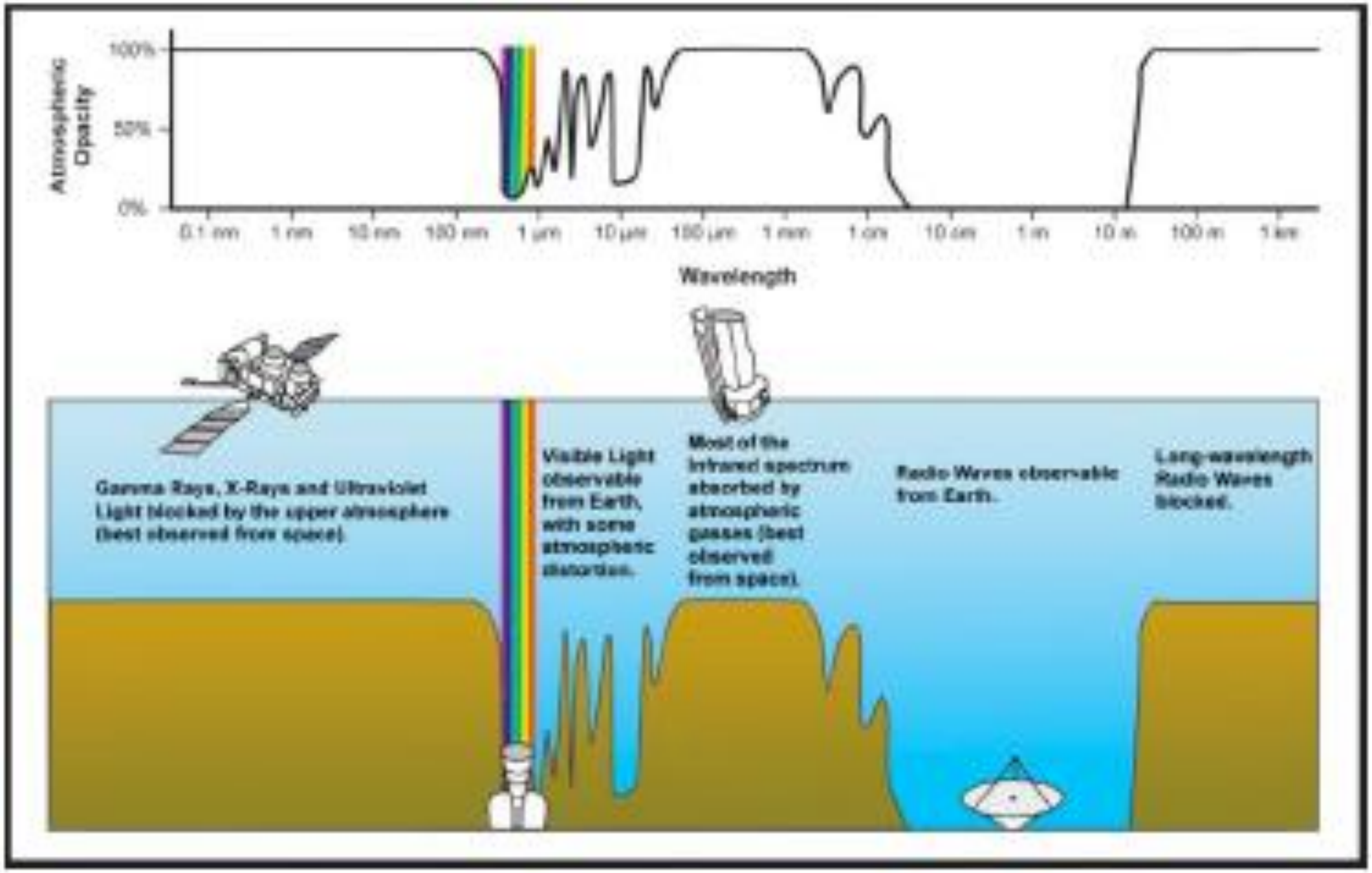
Radio pulsar

But where is the observational evidence?

In 1967, Jocelyn Bell Burnell and Antony Hewish first discovered neutron stars as radio pulsars.

Jocelyn Bell Burnell

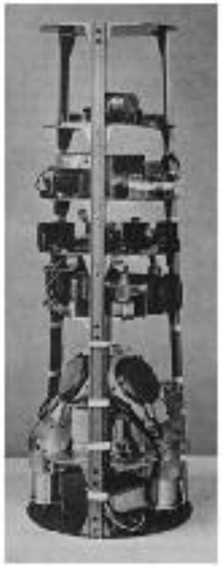
Electromagnetic spectrum



Introduction

X-ray astronomy and LMXBs

Riccardo Giacconi

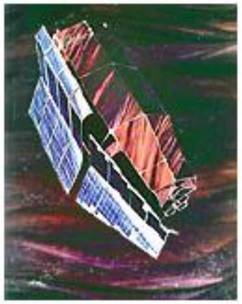


Experiment package that was flown on a rocket and discovered the first extra-solar X-ray source

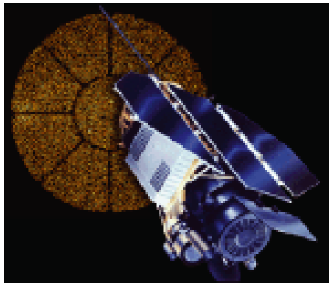
$\Rightarrow$ Bright neutron star LMXB Sco X-1

X-ray instruments on a balloon

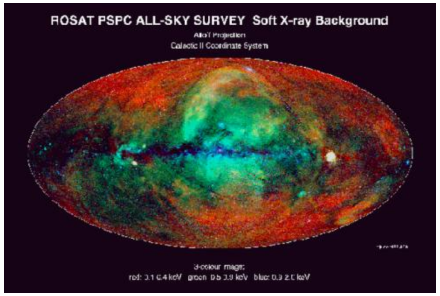
Uhuru: first dedicated X-ray satellite



Einstein: first fully X-ray imaging



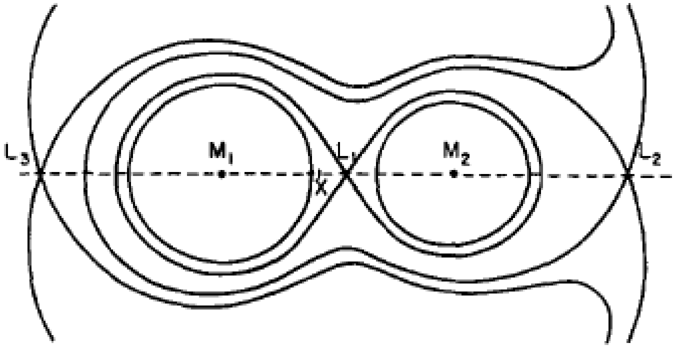
ROSAT: first X-ray all sky survey



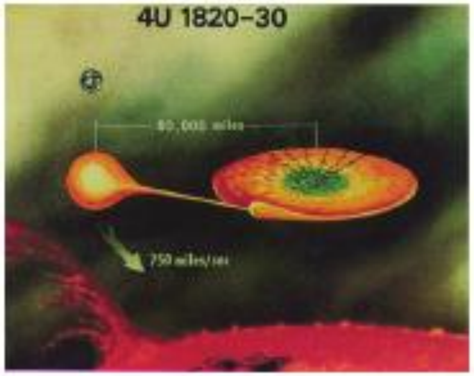
ROSAT all sky survey

Introduction

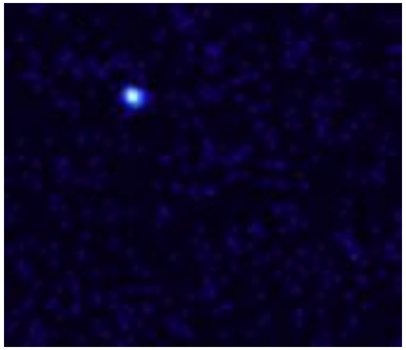
Low-mass X-ray Binary (LMXB)



Equipotential surfaces in a binary system
Courtesy: Bhattacharya & van den Heuvel (1991)



Artist's impression of a low-mass X-ray binary
Courtesy: NASA website



Chandra image of KS 1731-260
Courtesy: NASA website

X-rays from inner accretion disk and neutron star surface.

Orbital period: minutes to days

Age ~ Billion years

Neutron star magnetic field ~ 10^7 to 10^9 G

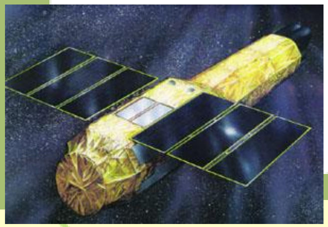
Neutron star spin ~ 300 to 600 Hz

Some Current X-ray Missions

Rossi X-ray Timing Explorer: For PCA: Energy range ~ 2 - 60 keV, Effective area (@ 6 keV) ~ 5000 cm^2, Energy resolution (@ 2.5 keV) ~ 725 eV, Angular resolution ~ 1^o, Time resolution ~ 1 microsecond.

Chandra: Energy range ~ 0.1 - 10 keV, Effective area of ACIS front (@ 6 keV) ~ 235 cm^2, Energy resolution of HETG (@ 2.5 keV) ~ 5.2 eV, Angular resolution ~ 0.5’’.

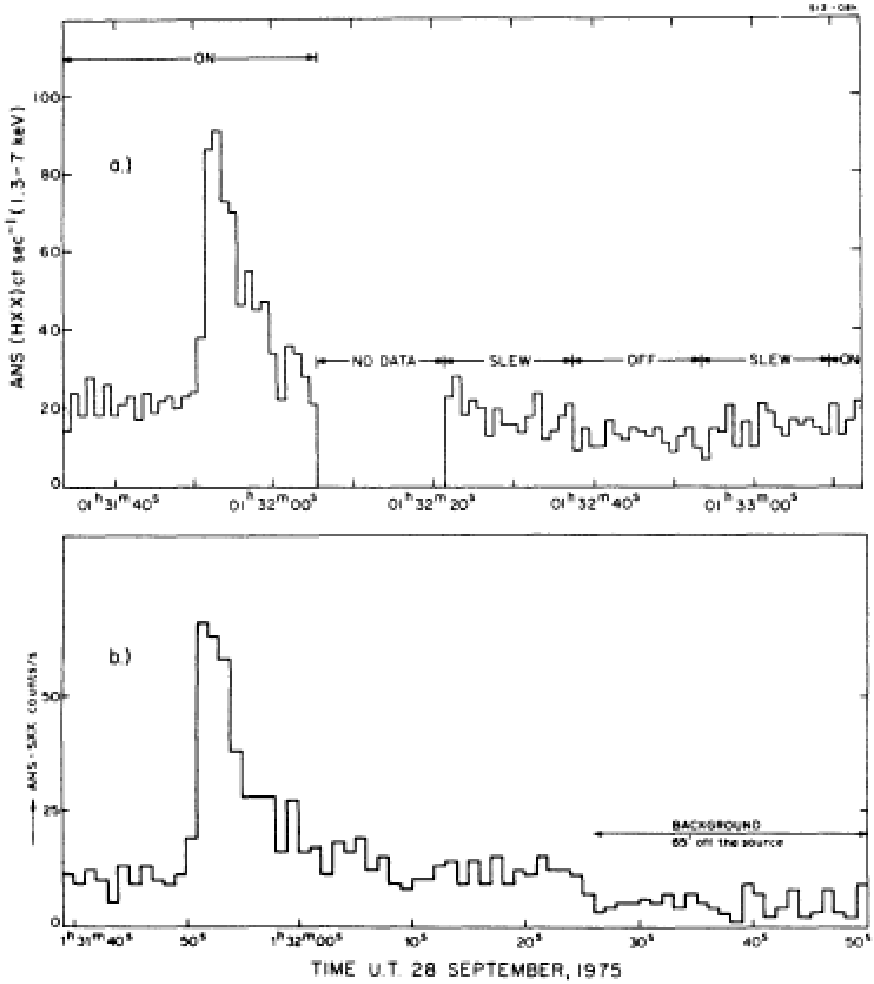
XMM-Newton: Energy range ~ 0.2 - 12 keV, Effective area of EPIC PN (@ 6 keV) ~ 851 cm^2, Energy resolution of RGS (@ 2.5 keV) ~ 17 eV, Angular resolution ~ 6’’.



Suzaku: Energy range ~ 0.4 - 10 keV, Effective area of XIS (@ 6 keV) ~ 1000 cm^2, Energy resolution of XIS (@ 2.5 keV) ~ 80 eV, Angular resolution ~ 1.5’.

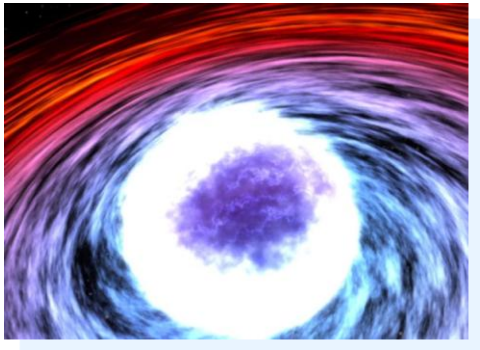
Thermonuclear X-ray Bursts

Discovery: what is the source of energy?



Grindlay et al. (1976)

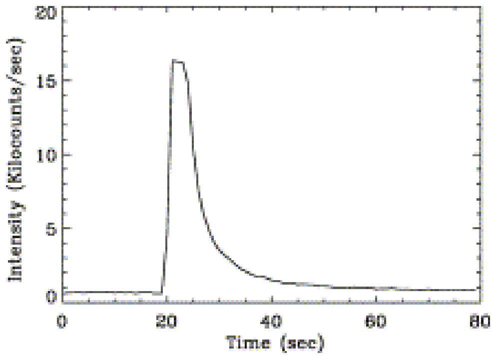
Thermonuclear X-ray Bursts



Accretion on neutron star

Unstable nuclear burning of accreted matter on the neutron star surface causes type I (thermonuclear) X-ray bursts.

Burst light curve



Rise time ≈ 0.5 - 5 seconds
Decay time ≈ 10 - 100 seconds
Recurrence time ≈ hours to day
Energy release in 10 seconds
≈ 10^{39} ergs

↓

Sun takes more than a week to release this energy.

Why is *unstable* burning needed?

Energy release:
Gravitational ≈ 200 MeV / nucleon
Nuclear ≈ 5 MeV / nucleon

Accumulation of accreted matter for hours → Unstable nuclear burning for seconds ⇒ Thermonuclear X-ray burst.

Thermonuclear X-ray Bursts

Parameters which set the ignition condition:

(1) chemical composition of accreted matter,
(2) temperature (~ 10^8 K),
(3) column depth (~ 10^8 gm cm^{-2}), and
(4) initial conditions set by the previous bursts.

Various regimes of burning:

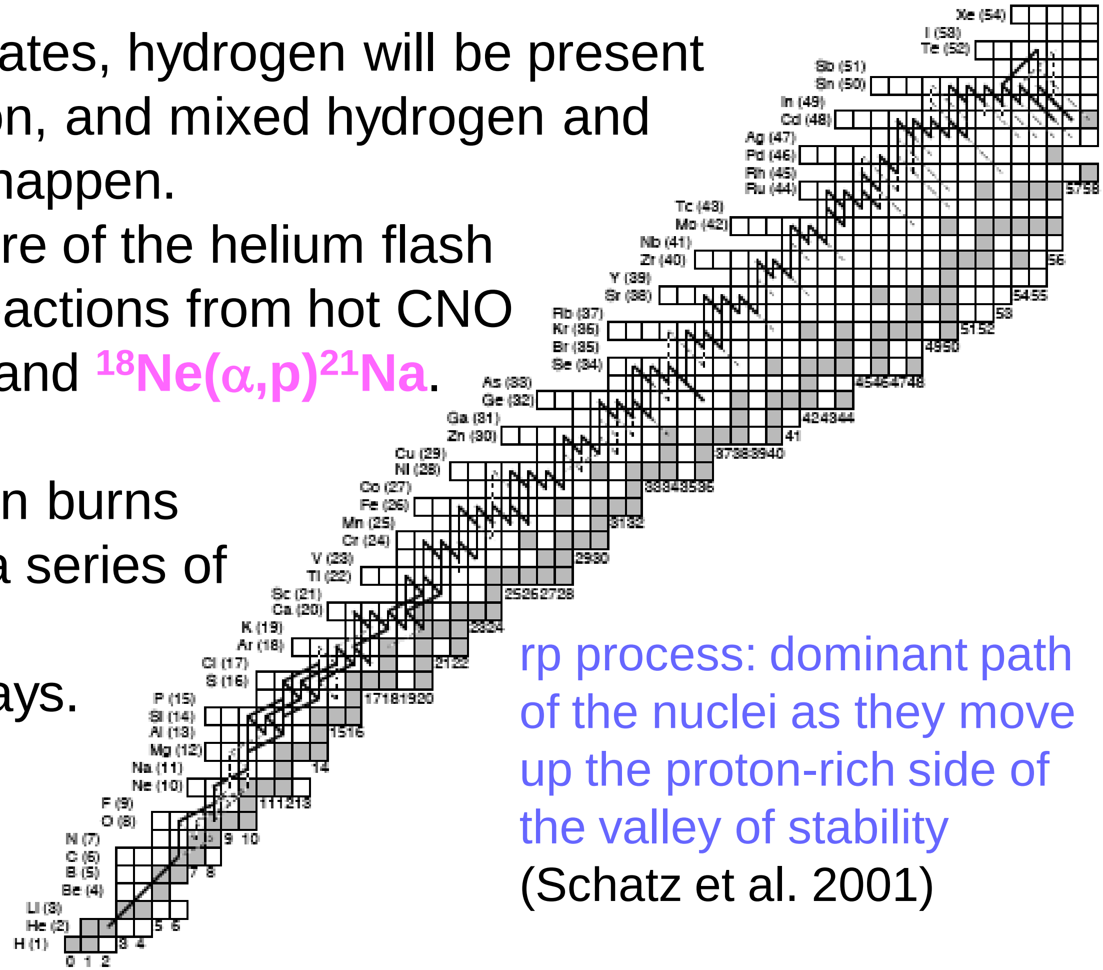
(1) At T > 10^7 K : Mixed hydrogen and helium burning triggered by thermally unstable hydrogen ignition; hydrogen burns via the CNO cycle.
(2) At T > 8 x 10^7 K, hydrogen burns in a stable manner via hot CNO cycle:
$^{12}C(p,\gamma)^{13}N(p,\gamma)^{14}O(\beta^+)^{14}N(p,\gamma)^{15}O(\beta^+)^{15}N(p,\alpha)^{12}C$
(3) When helium ignition condition is met, and hydrogen is depleted, (happens at a small window of accretion rate) pure helium bursts occur (identified by high intensity, short duration and long recurrence time) : $3\alpha \rightarrow {}^{12}C$

Thermonuclear X-ray Bursts

(4) At higher accretion rates, hydrogen will be present during helium ignition, and mixed hydrogen and helium burning will happen.

High temperature of the helium flash causes break-out reactions from hot CNO cycle: **^{15}O(α,γ)^{19}Ne** and **^{18}Ne(α,p)^{21}Na**.

As a result, hydrogen burns via the rp process: a series of successive proton captures and β decays.



rp process: dominant path of the nuclei as they move up the proton-rich side of the valley of stability (Schatz et al. 2001)

(5) At very high accretion rates, the helium burning temperature sensitivity becomes weaker than cooling rate's sensitivity. So the stable burning sets in.

Thermonuclear X-ray Bursts

Challenges:

(1) Bursts are rare and unpredictable, and satellite time is precious.

(2) No imaging is possible with the current technology. We have to rely on timing and spectral analyses.

(3) Nuclear reactions happen at a depth. So their signatures are indirect, and are affected by radiative transfer, fluid motions and relativistic effects.

Continuum Burst Spectroscopy

- Burst spectra are normally well fitted with a blackbody model.

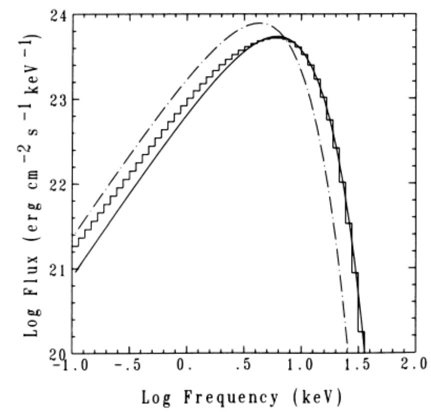
- In principle, neutron star radius can be measured from the observed bolometric flux (F_{obs}) and blackbody temperature (T_{obs}), and the known source distance (d):

$$R_{obs}=d.(F_{obs}/(\sigma T^4_{obs}))^{1/2}$$

- But there are systematic uncertainties:
  (1) unknown amount of spectral hardening;
  (2) effect of unknown gravitational redshift;
  (3) unknown distance;
  (4) if part of the surface emits.

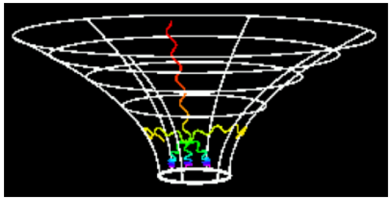
$$T = T_{obs}.(1+z)/f \qquad R = R_{obs}.f^2/(1+z) \qquad \begin{cases} z > 0;\ f \sim 1.0 - 2.0 \\ 1+z = [1 - (2GM/Rc^2)]^{-1/2} \end{cases}$$

Burst spectra



London, Taam & Howard (1986)

Gravitational redshift



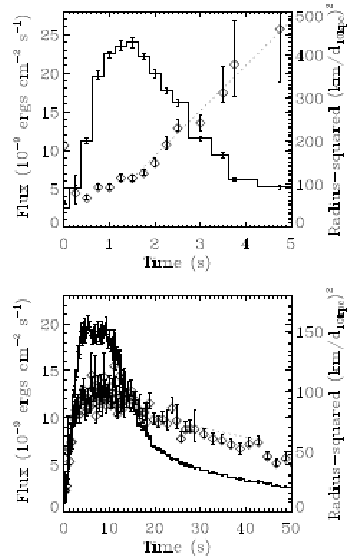
Atmospheric chemical composition, surface gravity, temperature ⇒ f (primary problem)

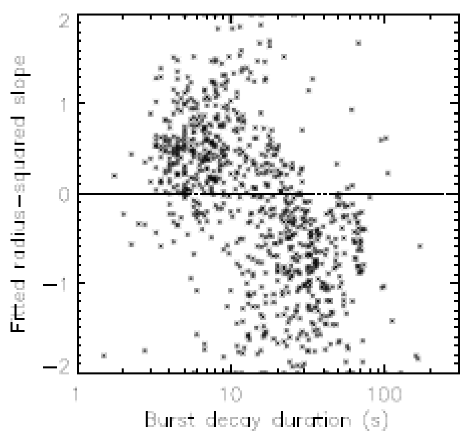
Various aspects of bursts

Continuum Burst Spectroscopy: problem from observation

During burst rise, thermonuclear flame spreading happens, and the entire neutron star surface may not emit. But during burst decay, entire neutron star surface is expected to emit. Therefore, the burning area inferred from the continuum spectroscopy should remain constant during burst decay, and should be useful to measure the neutron star radius. But, observationally we find that the inferred burning area can both increase and decrease apparently erratically. **Without understanding this erratic behavior, we cannot hope to measure the neutron star radius using continuum spectroscopy.**

First discovery of a pattern in the apparently erratic behavior:





The correlation is extremely robust.

Bhattacharyya et al. (2009)

$$R \equiv R_{obs}.f^2$$

The correlation may be because of the systematic variation of the atmospheric chemical composition (and hence the f evolution) between the short and long bursts.

This new pattern will have impact on the nuclear physics and fluid dynamics of bursts.

It can also significantly reduce the systematics due to unknown f.

Various aspects of bursts

Fast Timing Properties of X-ray Bursts (Burst Oscillations)

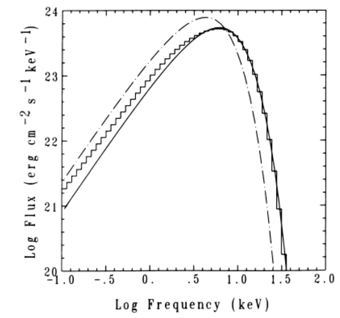
What are burst oscillations?

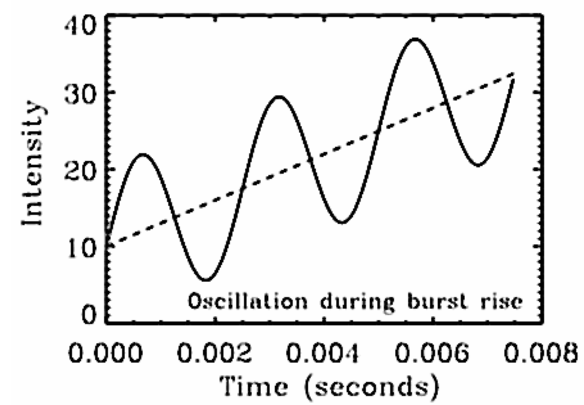
These are millisecond period variations of observed intensity during thermonuclear X-ray bursts.

What is their origin?

Asymmetric brightness pattern on the spinning neutron star surfaces.

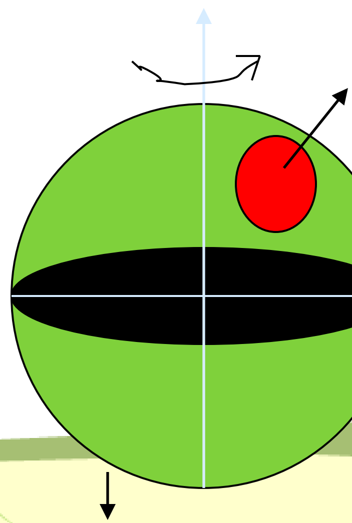
Burst light curve





Neutron star spin frequency

= Burst oscillation frequency

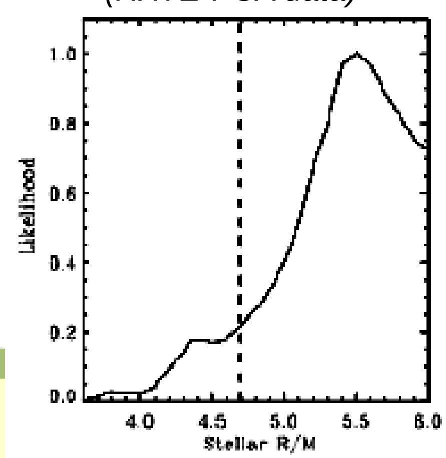


Hot spot

Spinning neutron star

XTE J1814-338

(RXTE-PCA data)

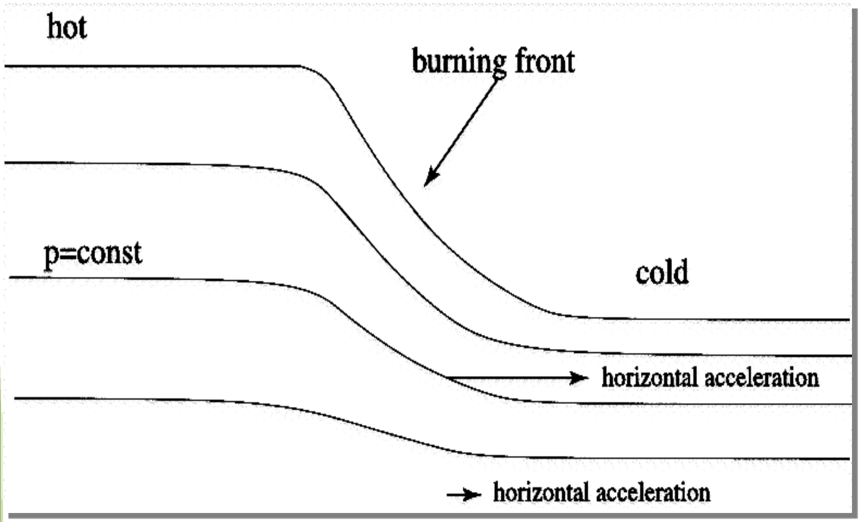


Bhattacharyya et al. (2005)

The vertical dashed line gives the lower limit of the stellar radius-to-mass ratio with 90% confidence.

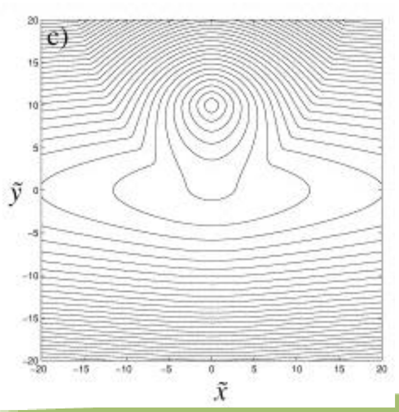
Thermonuclear Flame Spreading

Spitkovsky, Levin & Ushomirsky (2002)

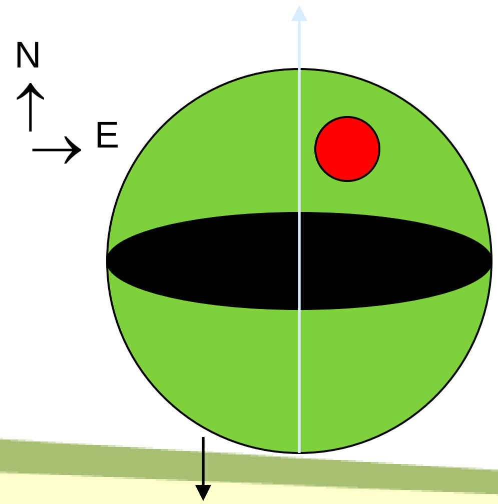


Burning layer on a neutron star surface during flame spreading.

Flame spreading



Contours showing an expanding burning region.



Spinning neutron star

Spin frequency of bursting neutron stars ≈ 300-600 Hz $\Rightarrow$ Coriolis force important.

Burst should be ignited at a certain point on the neutron star surface, and then the thermonuclear flame should spread to ignite the whole stellar surface.

Theoretical expectation:

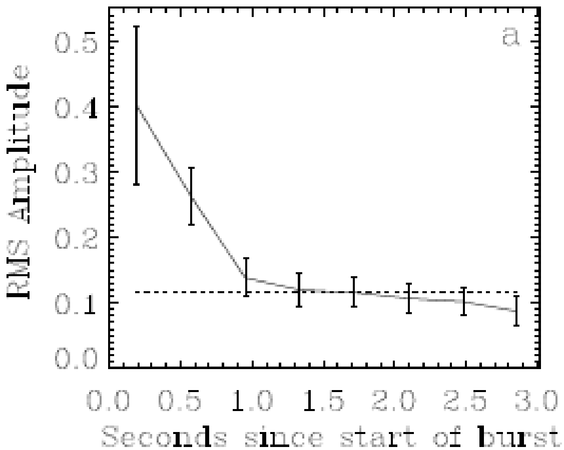
Flame spreads faster near the equator than near the pole (effect of Coriolis force). Hence the burning region should expand asymmetrically, as shown on the left (Spitkovsky, Levin & Ushomirsky 2002).

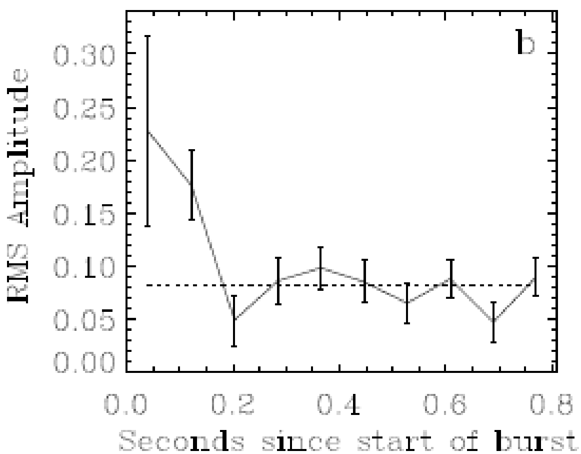
Various aspects of bursts

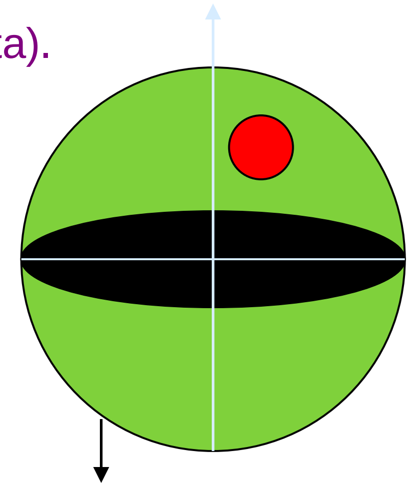
Thermonuclear Flame Spreading

Observed burst oscillation amplitude evolution during burst rise (*RXTE* data).

4U 1636-536 and SAX J1808.4-3658

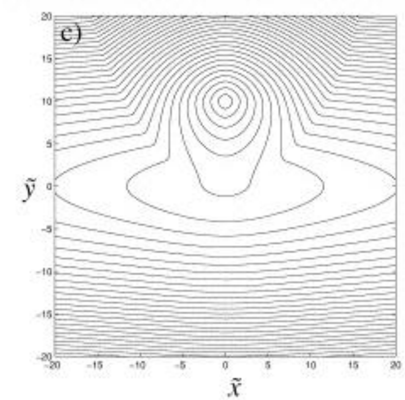






Spinning neutron star

Flame spreading



Spitkovsky, Levin & Ushomirsky (2002)

Plausible theoretical explanation of the observation shown on the left using the expected asymmetric spreading due to Coriolis force:

(1) Initial large amplitude is due to a small hot spot.

(2) As the burning region grows, amplitude decreases quickly.

(3) The persistent low amplitude after some time is due to the residual asymmetry (shown above).

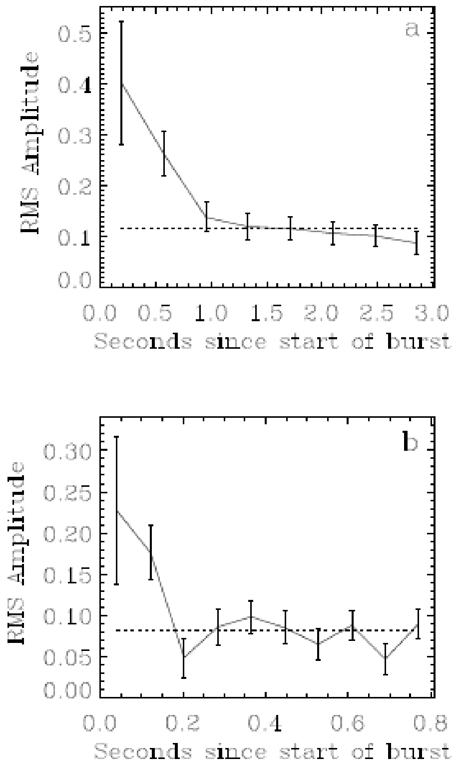
Bhattacharyya & Strohmayer, ApJ, 666, L85, 2007

Various aspects of bursts

Thermonuclear Flame Spreading

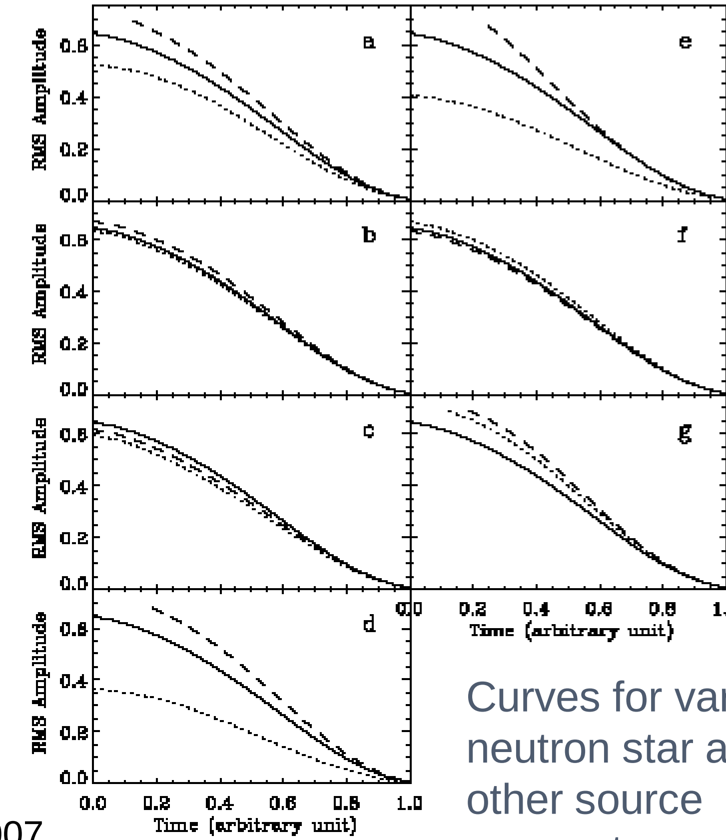
Burst oscillation amplitude evolution:
RXTE observation

4U 1636-536 and SAX J1808.4-3658



Bhattacharyya & Strohmayer, ApJ, 666, L85, 2007

Burst oscillation amplitude evolution:
Model: uniform expansion of a circular burning region (effect of Coriolis force is not included).



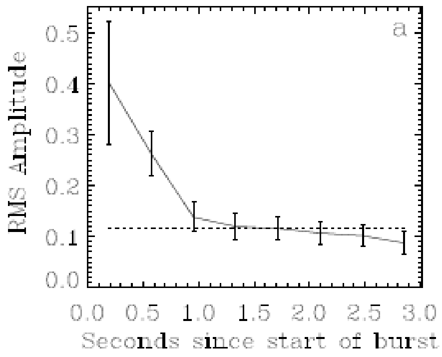
Curves for various neutron star and other source parameters.

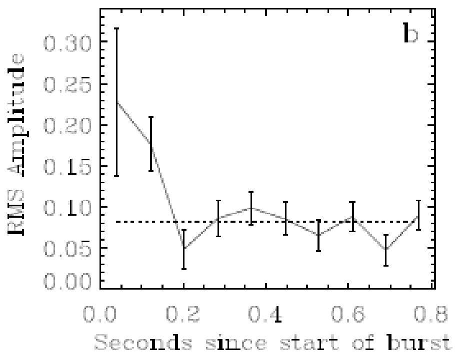
Model without the Coriolis force effect on flame spreading cannot explain the observations.

Thermonuclear Flame Spreading

Burst oscillation amplitude evolution:
RXTE observation

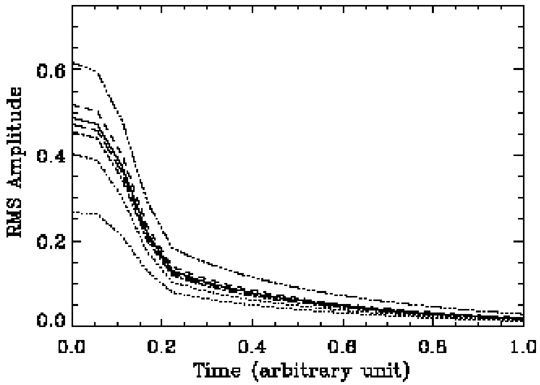
4U 1636-536 and SAX J1808.4-3658





Bhattacharyya & Strohmayer, ApJ, 666, L85, 2007

Burst oscillation amplitude evolution:
Model: expansion of burning region considering some salient features of the effects of Coriolis force.

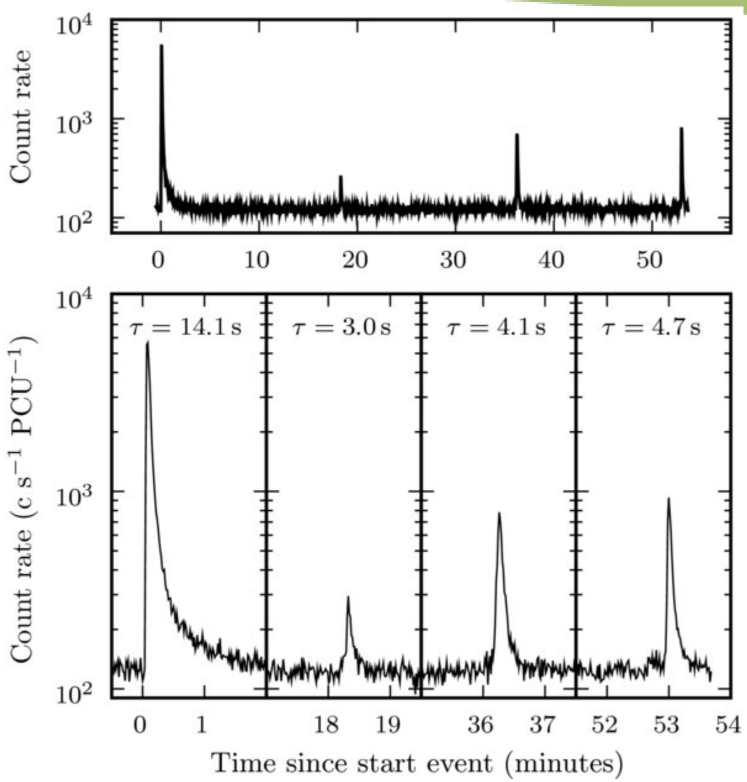


Curves for various neutron star and other source parameters.

Model with the salient features of the Coriolis force effects on flame spreading can qualitatively explain the observations.

Various aspects of bursts

Unusually frequent bursts



Keek et al. (2010)

Plausible explanations:

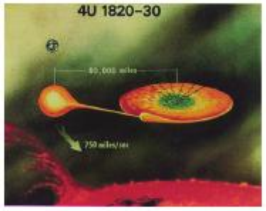
(1) Successive bursts from layers of accumulated accreted matter?

(2) Burning temporarily stalled by waiting points in the chain of nuclear reactions?

Either of them will be important for nuclear physics.

These frequent bursts are not observed from short period binaries. This implies that hydrogen burning processes play a crucial role for these bursts. How do we know?

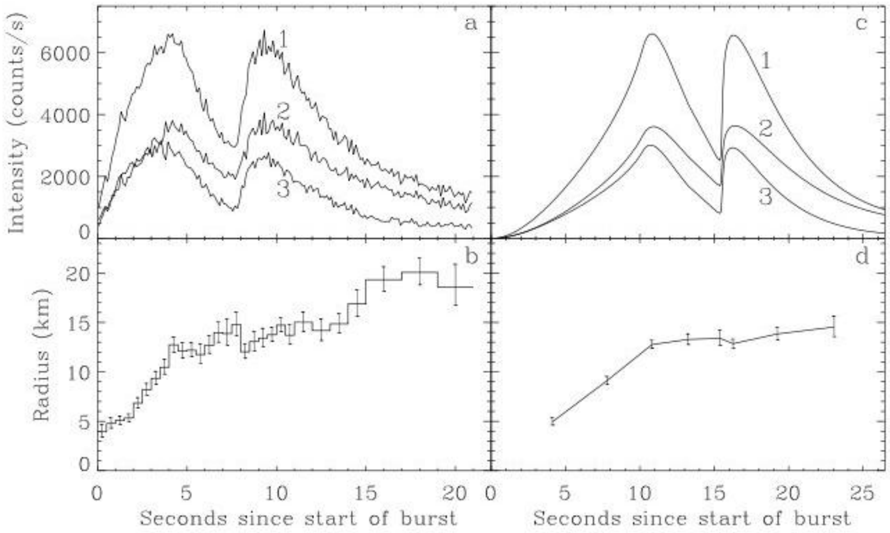
This is an example of how astrophysics can give input to nuclear physics.

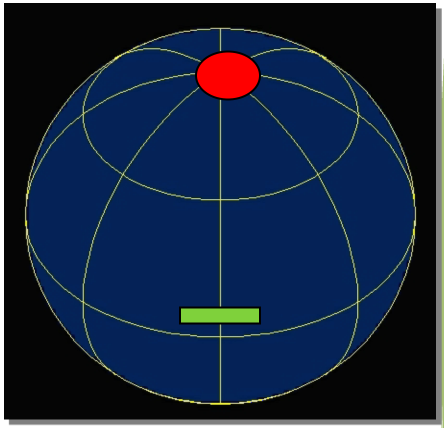


Various aspects of bursts

Rare Weak Double-peaked X-ray Bursts

Data 4U 1636-536 Model





Neutron star with polar ignition

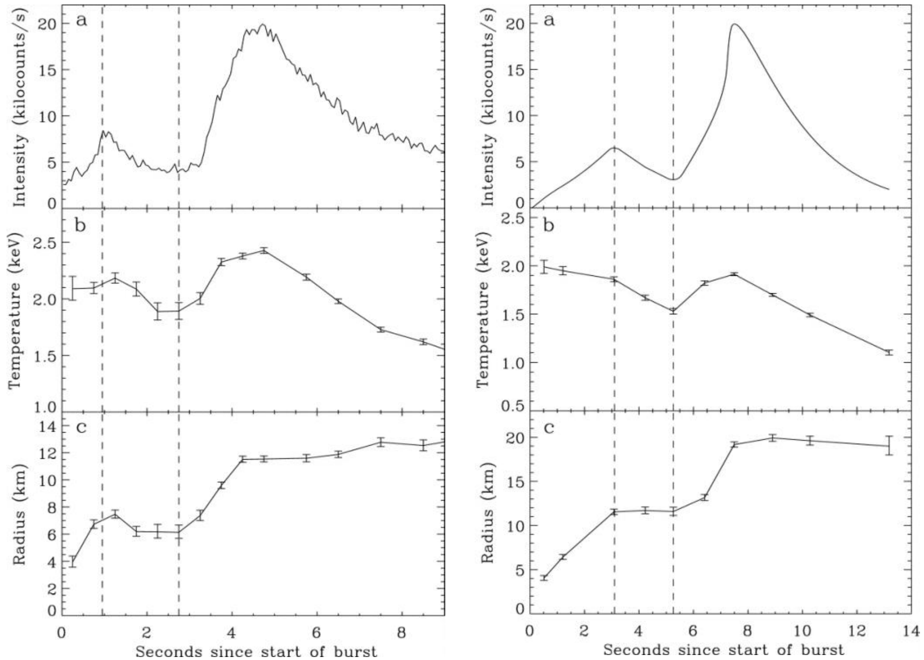
Bhattacharyya & Strohmayer, ApJ, 636, L121, 2006; *RXTE data*

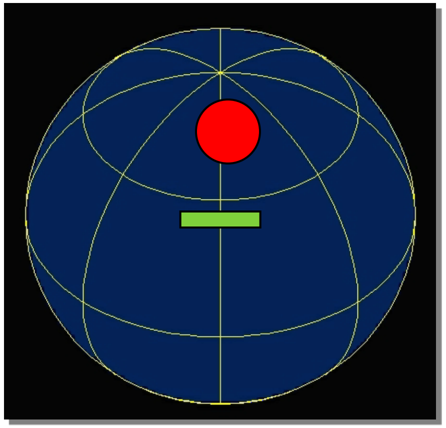
(1) Burst ignition at a pole, which explains the lack of oscillations and the rarity of the burst.
(2) Azimuthally symmetric temporary burning front stalling cools the burning region for a few seconds, while keeping the burning area unchanged. This can explain the intensity and temperature drop during the dip.
(3) The subsequent expansion of burning region explains the second intensity peak.

Various aspects of bursts

Rare Weak Double-peaked X-ray Bursts

Data — 4U 1636-536 — Model





Neutron star with high latitude ignition

Bhattacharyya & Strohmayer, ApJ, 641, L53, 2006; *RXTE data*

Vertical dashed lines give the time interval in which the radius (and hence the burning region area) does not change much and the temporary burning front stalling occurs.

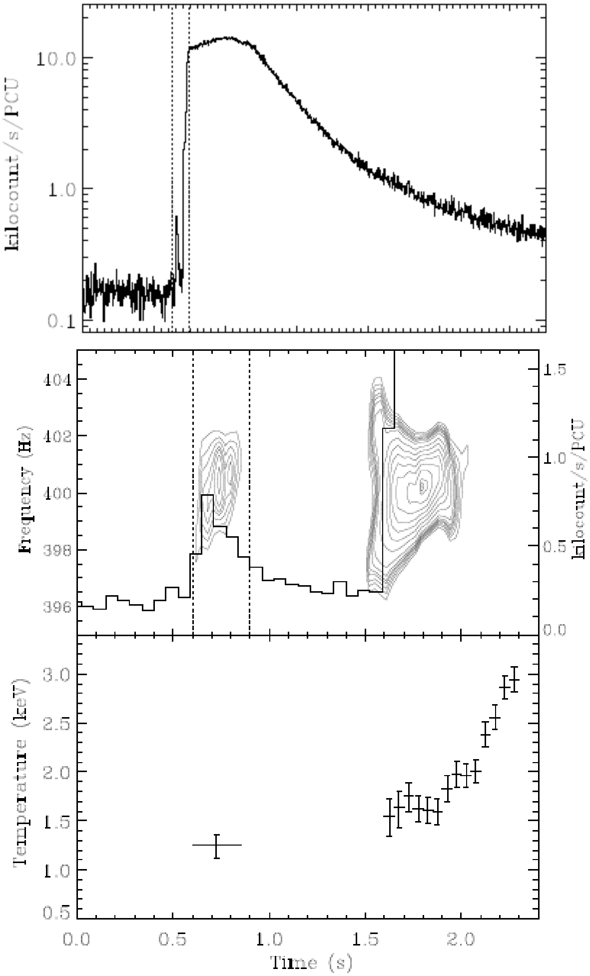
Various aspects of bursts

SAX J1808.4-3658
(RXTE-PCA data)

An unusual precursor with the main burst.

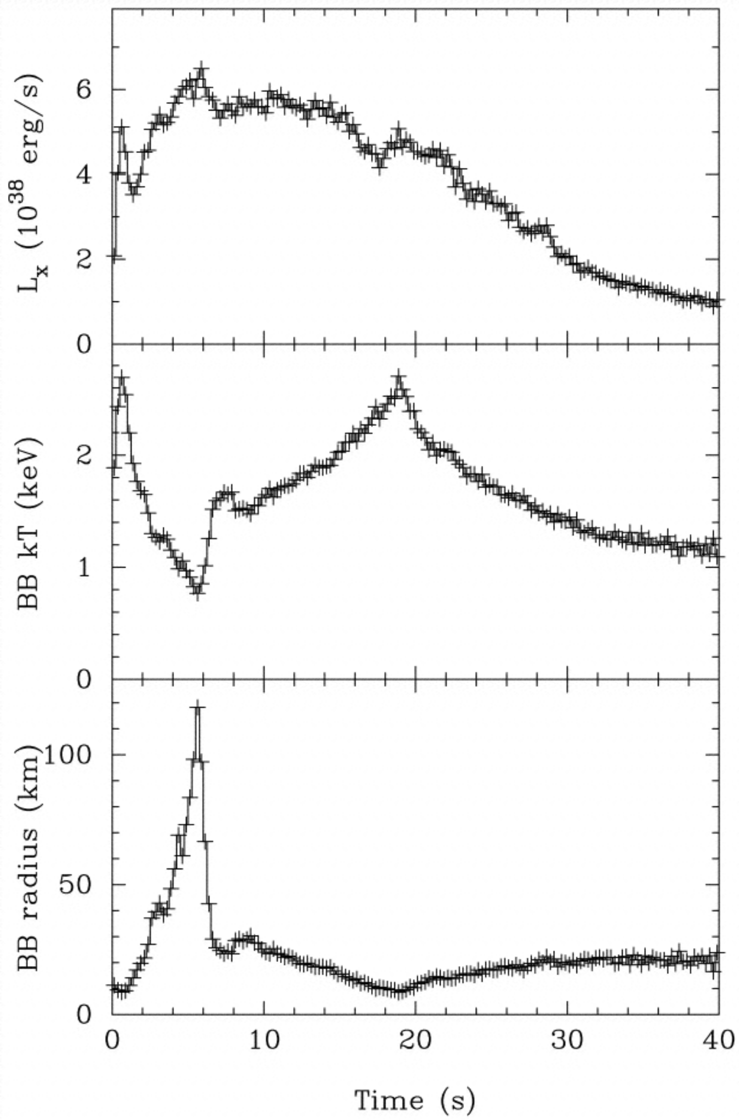
Zoomed precursor and the rising part of the main burst. Burst oscillation power contours and the spectral blackbody temperatures are shown.

Burning in different layers?
Joint burst oscillation and spectral study for the precursor and the main burst indicates flame spreading.



Bhattacharyya & Strohmayer, ApJ, 656, 414, 2007

Various aspects of bursts



Smale (2001)

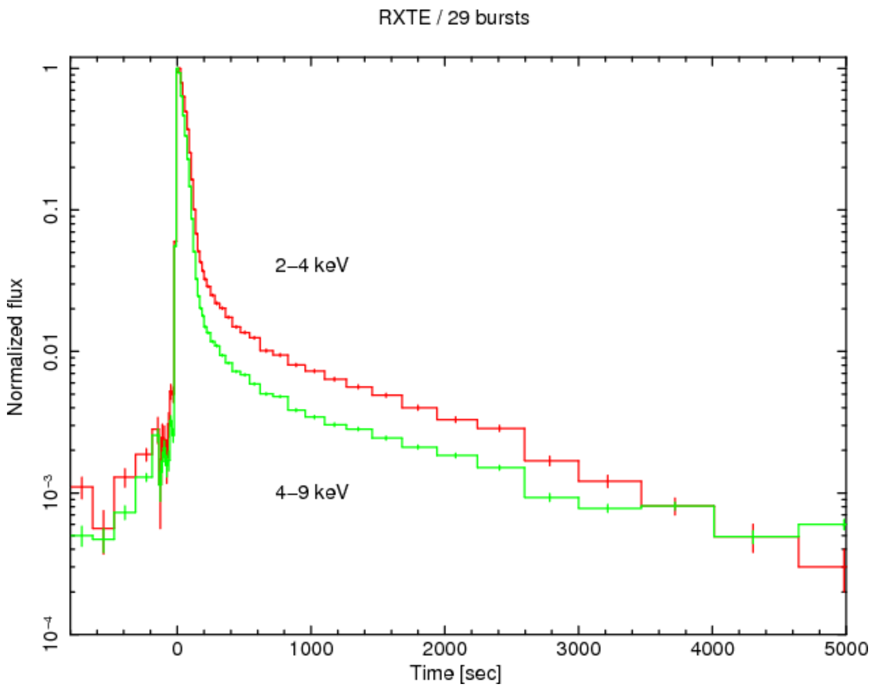
Photospheric Radius Expansion (PRE) bursts

The burst is so strong that the radiative pressure pushes the photosphere or the neutron star atmosphere away from the stellar surface temporarily.

Can some amount of heavy elements generated by the burst escape from the neutron star?

Various aspects of bursts

Long bursts

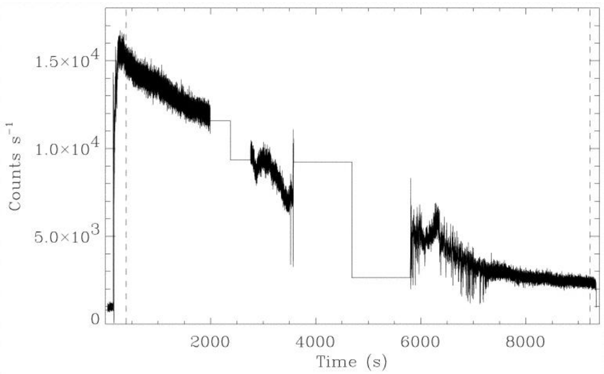


The long tail might be due to the cooling of deeper neutron star layers, which were heated up through inward conduction of heat produced by the burst.

In't Zand et al. (2009)

Various aspects of bursts

Superbursts: a challenge for nuclear physicists!



Strohmayer and Brown (2001)

Released energy ~ 10^{42} ergs
Recurrence time ~ years
Decay time ~ 1-3 hours

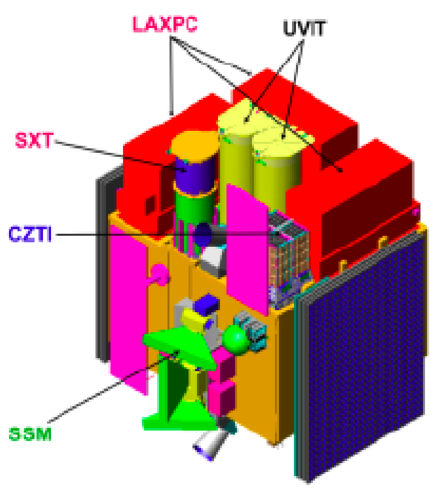
Believed to be caused by ^{12}C fusion at a column depth of ~10^{12} g cm^{-2}

Problem: ^{12}C **cannot survive, and should be destroyed by rp process.**
^{12}C will be converted to ^{15}O by a part of the hot CNO cycle, and then will permanently come out of it by the breakout reaction and proton capture: $^{15}O(\alpha,\gamma)^{19}Ne(p,\gamma)^{20}Na$ destroying the carbon.
Some suggested solutions: (1) CNO abundance in the burning layer is at least four times the solar abundance.
(2) Resonance may exist at the astrophysically relevant energy, where the reaction cross section seem to experimentally unknown (entry of nuclear experimentalists!).

Various aspects of bursts

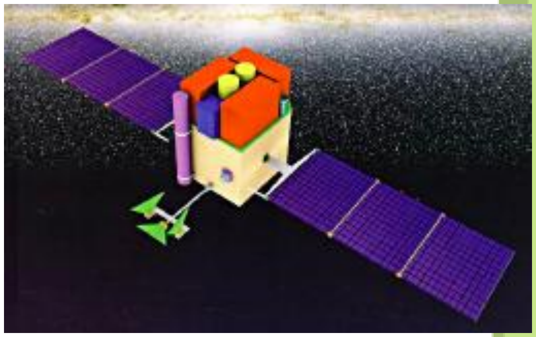
ASTROSAT

(India's proposed multiwavelength astronomy space mission)



ASTROSAT will carry five astronomy payloads for simultaneous multi-band observations:

- Twin 40-cm Ultraviolet Imaging Telescopes (UVIT) covering Far-UV to optical bands
- Three units of Large Area Xenon Proportional Counters (LAXPC) covering medium energy X-rays from 3 to 80 keV with an effective area of 6000 sq.cm. at 10 keV
- A Soft X-ray Telescope (SXT) with conical foil mirrors and X-ray CCD detector, covering the energy range 0.3-8 keV. The effective area will be about 200 sq.cm. at 1 keV
- A Cadmium-Zinc-Telluride coded-mask imager (CZTI), covering hard X-rays from 10 to 150 keV, with about 10 deg field of view and 1000 sq.cm. effective area
- A Scanning Sky Monitor (SSM) consisting of three one-dimensional position-sensitive proportional counters with coded masks. The assembly will be placed on a rotating platform to scan the available sky once every six hours in order to locate transient X-ray sources.



In its time, only *astrosat* will have the capability to study burst oscillations. It will also be the best instrument to study continuum burst spectra.

Importance of bursts

(1) Measurement of neutron star parameters (and hence probing supranuclear stellar core matter) from the spectral and timing analyses of bursts.

(2) The outer crust (~ 10^{-4} solar mass) is entirely replaced in about 10^6 years (the lifetime of these sources is about 10^9 years). Therefore, the crust contains the ashes of bursts, and the crust temperature distribution might depend on bursts. Therefore, the crust (nuclear) physics of these neutron stars crucially depends on bursts.

(3) The accretion of many of these sources occur in phases. In between two such phases, the neutron star cools. The observation of such crust cooling could lead to constraints on neutrino cooling, and hence on the stellar interior structure. However, the crust cooling depends on the crust composition, which in turn depends on the bursts.

Importance of bursts

(4) Bursts can be useful for astrophysical measurements, and to probe the strong gravity regime.

(5) While convection (fluid dynamics) affects nuclear reactions by redistributing temperature and elements, convection can itself depend on composition, and hence on nuclear reactions. Bursts provide unique opportunity to study such interaction in extreme conditions.

(6) Detailed modelling of bursts critically requires nuclear data and theoretical calculations, especially those for very unstable proton and neutron rich nuclei. For burst rp process modelling, masses, half –lives, reaction rates, thermal population of excited states for the relevant elements and energies should be available. For example, because of the mass related lifetime uncertainties, the combined effective lifetime of the waiting points ^{64}Ge, ^{68}Se and ^{72}Kr can vary between 29-108 sec for 1.4 GK.

Waiting points may introduce observable dips in burst intensity profiles.

Importance of bursts

Nuclear physics : ignition condition, nuclei produced, energy generated, duration of burning,..

⇓

Fluid dynamics : spreading of burning all over the surface, bringing heavy nuclei to the photosphere,…

⇓

Astrophysics : spectral and timing properties of the photosphere, effect of radiative transfer, Doppler and relativistic effects, light bending,…

Extreme environments: very strong magnetic field, radiative pressure, gravity

A unique multidisciplinary field!

Importance of bursts

Nuclear physics : ignition condition, nuclei produced, energy generated, duration of burning,..

⇓

Fluid dynamics : spreading of burning all over the surface, bringing heavy nuclei to the photosphere,…

⇓

Astrophysics : spectral and timing properties of the photosphere, effects of radiative transfer, Doppler and relativistic effects, light bending,…

Extreme environments: very strong magnetic field, radiative pressure, gravity

Thank you!

A unique multidisciplinary field!