What Thermonuclear X-ray Bursts can tell us about Neutron Stars

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Outline

- Neutron Stars: why do we care?
- Thermonuclear Bursts: why do we care?
- Neutron Stars: Mass, Radius and Spin:
  a. Continuum Spectroscopy of Bursts
  b. Spectral Lines from Bursts
  c. Timing Properties of Bursts
- Neutron Star Atmosphere: Thermonuclear Flame Spreading
- Future Prospects and Conclusions
Neutron Star

Neutron star vs. a city

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

Figure courtesy M. Coleman Miller

Some of the most extreme conditions of the universe exist in neutron stars.
Neutron Star: Surface and Interior

Core density $\geq$ nuclear density

$\downarrow$

Exotic matter???

No terrestrial experiments seem possible at such high densities and low (comparatively) 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 35 years.
How to constrain EOS models?

Mass, radius and spin frequency of the same neutron star are to be measured in order to constrain equation of state models.

Lattimer & Prakash (2001)
Neutron Star: Spin, Mass and Radius

**Spin frequency measurement:** Observation of spin-induced periodic variation of stellar surface intensity.

**Mass measurement:** Measurements of relativistic orbital effects of binary stellar systems that contain radio pulsars.  
*But radius?*

**Radius measurement:** Hardest! To do it with 5% accuracy, we need to measure the size of the neutron star with less than 1 km error, while the star is $\sim 10^{16}$ km away! Plagued with systematic uncertainties.

We need to study a neutron star surface phenomenon, that will allow us to measure spin, mass and radius of the star.
Low Mass X-ray Binary (LMXB)

**Primary star**: neutron star, or black hole.

**Secondary companion**: mass < 1 solar mass; main sequence star, white dwarf, or red giant star.

**Accretion**: via a disk.

**X-rays**: from inner accretion disk, and from the neutron star surface.

**Age**: ~ $10^9$ years.

**Neutron star magnetic field**: $10^7$-$10^9$ G.

X-rays from neutron star surfaces can give important information about these stars.

Courtesy: http://heasarc.gsfc.nasa.gov/
Some Current X-ray Missions

**Rossi X-ray Timing Explorer (RXTE):** For PCA: Energy range ~ 2 - 60 keV, Effective area (@ 6 keV) ~ 5000 cm$^2$, Energy resolution (@ 2.5 keV) ~ 725 eV, Angular resolution ~ 1°, 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

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

Accretion on neutron star

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

Why is unstable burning needed?
Energy release:
Gravitational ≈ 200 MeV / nucleon
Nuclear ≈ 7 MeV / nucleon

Sun takes more than a week to release this energy.

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

(1) At $T > 8 \times 10^7$ K, hydrogen burns in a stable manner via the hot CNO cycle:

\[ ^{12}\text{C}(p, \gamma)^{13}\text{N}(p, \gamma)^{14}\text{O}(\beta^+)^{14}\text{N}(p, \gamma)^{15}\text{O}(\beta^+)^{15}\text{N}(p, \alpha)^{12}\text{C} \]

(2) Thermal runaway is triggered, that is the burst is ignited, by the temperature sensitivity of helium burning via the $3\alpha$ reaction:

\[ 3\alpha \rightarrow ^{12}\text{C} \]

(3) Helium ignition triggers unstable hydrogen burning via the rapid proton capture process (rp-process).

Parameters that set the ignition condition:

(1) chemical composition of accreted matter,
(2) temperature ($\sim 10^8$ K),
(3) column depth ($\sim 10^8$ gm cm\(^{-2}\)), and
(4) initial conditions set by the previous bursts.
Why are the thermonuclear X-ray bursts important for understanding neutron stars?

(1) They originate from neutron star surfaces.

(2) Their intensities are ~ 10 times higher than the non-burst emission intensity. This gives higher signal-to-noise ratio.

(3) They show timing and spectral features, that can be used to constrain the mass, radius and spin frequency of the same neutron star.

(4) They provide the unique opportunity to understand the thermonuclear flame spreading on neutron star surfaces.

(5) Many bursts are observed from the same neutron star.

(6) Comparatively lower magnetic fields (~ $10^7$-$10^9$ G) of the bursting neutron stars simplify the modeling.
Procedures to constrain neutron star parameters analyzing thermonuclear X-ray bursts:

(1) Spectral studies:
   (a) continuum spectroscopy (RXTE-PCA),
   (b) line spectroscopy (Chandra, XMM-Newton, Suzaku).

(2) Studies of fast (millisecond period) timing properties (RXTE-PCA).
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 ($F_{\text{obs}}$) and blackbody temperature ($T_{\text{obs}}$), and the known source distance ($d$):

$$R_{\text{obs}} = d \left( \frac{F_{\text{obs}}}{\sigma T_{\text{obs}}^4} \right)^{1/2}$$

★ But there are systematic uncertainties:
(1) unknown amount of spectral hardening due to electron scattering;
(2) effect of unknown gravitational redshift.

$$T = T_{\text{obs}} \cdot \frac{1+z}{f} \quad z > 0; \quad f \sim 1.0 - 2.0$$

$$R = R_{\text{obs}} \cdot \frac{f^2}{1+z} \quad 1+z = \left[ 1 - \left( \frac{2GM}{Rc^2} \right) \right]^{-1/2}$$

Chemical composition of neutron star atmosphere $\Rightarrow f$
Neutron star radius-to-mass ratio $\Rightarrow 1+z$
Cottam, Paerels & Mendez (2002)

Observation of surface atomic spectral line at the energy $E_{\text{obs}}$

Identification: original line energy = $E_0$

Gravitational redshift $1+z = E_0/E_{\text{obs}}$

Neutron star “radius to mass” ratio from $1+z = [1-(2GM/Rc^2)]^{-1/2}$

But why LMXBs and X-ray bursts?

XMM-Newton grating observations of surface atomic spectral absorption lines during X-ray bursts from an LMXB (EXO 0748-676): measured gravitational redshift $1+z = 1.35$, and hence $Rc^2/GM = 4.4$.

These Fe absorption lines could be produced in the upper atmosphere of the neutron star, and the continuous accretion might supply the Fe ions.
Line Burst Spectroscopy

Why LMXBs and X-ray bursts?

* Comparatively lower magnetic field ($10^7$-$10^9$ G):
  1. magnetic splitting is negligible: line identification is easier;
  2. magnetic field does not complicate the modeling of neutron star atmosphere and photon emission.

* For isolated neutron stars, heavy elements do not exist in the atmosphere. For LMXBs and during bursts, continuous accretion (at a low rate) and radiative pressure may keep heavy elements in the atmosphere for the time required for spectral line detection.

* During the bursts, high photon flux from the neutron star surface provides good signal-to-noise ratio.
But the neutron stars in LMXBs normally spin very fast due to accretion induced angular momentum transfer.

**Spinning neutron star:** surface speed is ~ 0.1c; Doppler effect will make the spectral line broad and asymmetric.

How do we measure \((1+z)\) from a broad and skewed line?

\[
\begin{align*}
E_{\text{gm}} &= (E_1E_2)^{1/2} \\
1+z &= E_0/E_{\text{gm}} \\
Rc^2/GM &= 2.(1 - (1+z)^{-2})^{-1}
\end{align*}
\]

\[\text{Bhattacharyya, Miller & Lamb (2006)}\]

Modeling of the shapes of the spectral lines will be useful to constrain other neutron star parameters.
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.

Neutron star spin frequency = Burst oscillation frequency
Burst Oscillations

Burst oscillation sources:

<table>
<thead>
<tr>
<th>Number</th>
<th>LMXB</th>
<th>Spin frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>EXO 0748–676</td>
<td>45</td>
</tr>
<tr>
<td>2</td>
<td>4U 1916-05</td>
<td>270</td>
</tr>
<tr>
<td>3</td>
<td>XTE J1814–338P</td>
<td>314</td>
</tr>
<tr>
<td>4</td>
<td>4U 1702–429</td>
<td>330</td>
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<tr>
<td>5</td>
<td>4U 1728–34</td>
<td>363</td>
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<tr>
<td>6</td>
<td>SAX J1808.4–3658P</td>
<td>401</td>
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<td>7</td>
<td>SAX J1748.9–2021</td>
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<td>8</td>
<td>KS 1731–260</td>
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<td>9</td>
<td>1A 1744–361</td>
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<td>Aql X–1</td>
<td>549</td>
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<td>11</td>
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<td>15</td>
<td>4U 1608–52</td>
<td>619</td>
</tr>
</tbody>
</table>

The spin frequencies of neutron stars in 13 LMXBs are known from burst oscillations.

Bhattacharyya et al. 2006

Measured spin rates can be used to constrain neutron star mass and radius.

RXTE-PCA is the only current instrument that can detect burst oscillations. In future, Indian instrument ASTROSAT-LAXPC will be able to do it.
Burst Oscillations: Stellar Mass and Radius

- Modeling of burst oscillation amplitudes and light-curve-shapes:
  - ↓
  - Neutron star mass and radius-to-mass ratio.

- Models should include the following physical effects: Doppler effect, special relativistic beaming, gravitational redshift, gravitational light bending, frame dragging, etc.

- However non-sinusoidal burst oscillation light curves are required to fully utilize this procedure.
Non-sinusoidal light curves from the decay portions of the X-ray bursts from the LMXB XTE J1814-338.

Fitting the observed burst oscillation light curves with our theoretical model (assuming a hot spot on the spinning neutron star surface), we have constrained a few parameters, including stellar radius-to-mass ratio.

The vertical dashed line gives the lower limit of the stellar radius-to-mass ratio with 90% confidence.
But what causes oscillations during the burst decay?

What causes the brightness (and temperature) asymmetry on the neutron star surface?

Possibilities:

(1) Hot spot created by vortex or surface magnetic field.

(2) Surface waves in the burning layer or photosphere in the equatorial region may cause temperature variation on the stellar surface.

However, it is unlikely for surface waves to produce the significantly non-sinusoidal burst oscillation light curves observed from XTE J1814-338.
Burst Oscillations during the Burst Rise

Hot spot ⇒ Oscillations during the burst rise.

Reasons:

(1) The expanding hot spot (burning region) can naturally give rise to oscillations during burst rise.

(2) The observed amplitude of oscillations during the early burst rise is large, which is expected from a small hot spot.

(3) A small hot spot (burning region) expected during early burst rise can give rise to significantly non-sinusoidal burst oscillation light curve. We have recently, for the first time, discovered such a light curve from the early rising phase of the bursts from an LMXB.

Data: solid line
Combined for nine bursts for one-third of the rise time interval.

Bhattacharyya & Strohmayer 2005
(RXTE-PCA data)
Burst rise oscillations are promising for constraining neutron star mass and radius-to-mass ratio.

**Problem:**
Early phase of burst rise exist for less than a second, and the total number of detected photons is comparatively smaller. Hence, for many bursts, signal-to-noise ratio is not high.

Nevertheless, it is worthwhile to study the burst rise oscillations. Such a study will also provide the opportunity to understand the thermonuclear flame spreading on the neutron star surfaces.
Summary of constraining neutron star EOS models

EOS $\leftrightarrow$ spin, mass and radius of the same neutron star.

Thermonuclear X-ray bursts give the opportunity of three types of studies: continuum spectroscopy, line spectroscopy and fast timing study.

Burst oscillations $\Rightarrow$ Neutron star spin frequency

Surface atomic spectral line or burst oscillations $\Rightarrow$ stellar $Rc^2/GM$
Study of bursts and accretion flow $\Rightarrow$ chemical composition of stellar atmosphere

$\downarrow$
Continuum spectroscopy $\Rightarrow$ Stellar radius

Example: LMXB EXO 0748-676:
Spin frequency = 45 Hz (burst oscillations)
$Rc^2/GM = 4.4$ (line spectroscopy)
R or M = ?
Thermonuclear Flame Spreading on Neutron Stars

When does it happen?
During the thermonuclear X-ray bursts (mostly during burst rise).

Why should we care?
(1) It is an interesting research field on its own. It is basically atmospheric physics under extreme conditions: extreme gravity, high density \((10^5-10^6 \text{ gm/cc})\), high magnetic field, huge energy generation and radiation pressure, large stellar spin (and hence Coriolis force), etc.

(2) It can be useful to understand the neutron star atmosphere, and to constrain surface magnetic field, chemical composition of matter, etc. It is also useful to model burst rise oscillations.

Theoretical study:
Not yet done taking all the main physical effects into account. Until recently, observations could not provide enough motivation. Our recent observational findings may provide this motivation.
Thermonuclear Flame Spreading on Neutron Stars

A simulation considering Coriolis force, but ignoring several other physical effects (such as surface magnetic field).

Thanks to Anatoly Spitkovsky!
Theoretical modeling of thermonuclear flame spreading

Neutron star spin frequency 300-600 Hz ⇒ Coriolis force important.

Thin burning layer ⇒ Geostrophic approximation.

Flame speed ~ Ageostrophic speed.

For weak turbulent viscosity, flame speed $\vartheta \sim 5 - 20$ km/s.

For strong turbulent viscosity, flame speed $\vartheta \leq 300$ km/s.

$\vartheta_{\text{pole}} < \vartheta_{\text{equator}}$

Spitkovsky et al. (2002)
Thermonuclear Flame Spreading on Neutron Stars

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

Flame spreading

Spitkovsky et al. (2002)

Spinning neutron star

(1) Initial large amplitude is due to small hot spot.
(2) As the burning region grows, amplitude decreases and radius increases quickly.
(3) The low amplitude after 0.2 second is due to the residual asymmetry.
(4) The complex frequency evolution may be due to the slow eastward or westward acceleration of the center of the burning region. Magnetic field may become dynamically important.

Bhattacharyya & Strohmayer (2006c)
Thermonuclear Flame Spreading on Neutron Stars: Weak Double-peak X-ray Bursts

Bhattacharyya & Strohmayer (2006a); RXTE-PCA 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.
Thermonuclear Flame Spreading on Neutron Stars: Weak Double-peaked X-ray Bursts

Data 4U 1636-536 Model

Bhattacharyya & Strohmayer (2006b); RXTE-PCA 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.
Some Future X-ray Missions

Constellation-X
(\textit{NASA})

The X-ray Evolving Universe Spectrometer (XEUS)
(\textit{ESA})
ASTROSAT
(India’s proposed multiwavelength astronomy mission)

Instruments:

**LAXPC**: Continuum burst spectroscopy, burst oscillations and thermonuclear flame spreading. *This instrument will directly measure neutron star spin frequencies.*

**SSM**: Detection of transient LMXBs during outbursts. Many transient LMXBs exhibit thermonuclear X-ray bursts.

**SXT, CZTI, UVIT**: Accretion flow: continuum and line spectroscopy, and simultaneous X-ray, UV and optical observations ⇒ chemical composition of accreted matter, accretion rate, etc.
Conclusions

- Studies of thermonuclear X-ray bursts can be very useful to constrain the spin rate, mass and radius of the same neutron star ⇒ EOS model of high density cold matter in the neutron star cores.

- Extensive observation and analysis of the data from the rising portions of the bursts ⇒ modeling of burst oscillations and thermonuclear flame spreading.

- Theoretical study of thermonuclear flame spreading on the rapidly spinning neutron stars should be done considering all the main physical effects (including magnetic field, nuclear energy generation, Coriolis effect, strong gravity, etc.).

*** Thank you! ***