Thermo-nuclear X-ray bursts from ultra-compact binaries

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The Physics of ULTRACOMPACT STELLAR BINARIES

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= UCSB!

<table>
<thead>
<tr>
<th>Source</th>
<th>P orb(min)</th>
<th>T/p</th>
<th>bursts?</th>
<th>N/O excess</th>
<th>Suggested donor</th>
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</thead>
<tbody>
<tr>
<td>4U 1820-30</td>
<td>11</td>
<td>P</td>
<td>Y</td>
<td>?</td>
<td>He</td>
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<td>A1850-08</td>
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<td>C-O</td>
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<td>4U 1626-67</td>
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<td>N</td>
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<td>C-O</td>
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<td>N</td>
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<td>H1825-331</td>
<td>55 or 132?</td>
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<td>XB 1745-25</td>
<td>25-240?</td>
<td>T</td>
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</tbody>
</table>

- $P_{orb} \leq 80$ min $\rightarrow$ H-depleted donors (Nelson et al. 1996)
- N/O excesses - see Juett et al. 2001

$\rightarrow$ X-ray bursts as tracer of donor composition
Observational properties of X-ray bursts

- Fast rise (~1–10 sec), exponential decay (few sec to mins)
- Spectral softening during decay (due to cooling of neutron star surface)
- Burst emission best described by black-body radiation with temperatures of T ~ 1–4 x 10^7 K (kT ~ 1–3 keV) and radius of ~10 km
- Total energy released is typically ~10^39–10^40 erg

⇒ Thermo-nuclear runaway on a neutron star of H/He

- Back-of-the envelope calculation:
  E_{burst} ~ 10^{39} erg;
  E_{nucleon} ~ 1 MeV/nucleon
  (~10^{19} erg/g)

⇒ fuel ΔM ~ 10^{21} g;
for M ~ 10^{-10} to 10^{-9} M_\odot/yr
⇒ t_{ recur} ~ hrs-days

Normal X-ray bursts (continued)

- Left: Typical type I X-ray burst
  - Heating during rise, cooling during decay; radius constant

- Right: If burst luminosity reaches Eddington limit
  ⇒ Radius expansion type I burst
  - L_{burst} = 4πR^2\sigma T^4; when L_{burst} = L_{Edd}
    ⇒ If R increases, T decreases, while L_{burst} ~ constant
  - If R big, radiation shifts to UV (because T very low)
    ⇒ drop in X-ray light curve
Regimes of mass accretion rates

X-ray burst theory predicts 3 different regimes in mass accretion rate ($M$) (e.g. Fujimoto et al. 1981, Fushiki & Lamb 1987).

1) low accretion rates;
   $10^{-14} M_\odot \, yr^{-1} \leq M \leq 2 \times 10^{-10} M_\odot \, yr^{-1}$;
   mixed H/He burning triggered by thermally unstable H ignition

2) intermediate accretion rates;
   $2 \times 10^{-10} M_\odot \, yr^{-1} \leq M \leq 4 - 11 \times 10^{-10} M_\odot \, yr^{-1}$;
   pure He shell ignition after steady H burning

3) high accretion rates;
   $4 - 11 \times 10^{-10} M_\odot \, yr^{-1} \leq M \leq 2 \times 10^{-8} M_\odot \, yr^{-1}$;
   mixed H/He burning triggered by thermally unstable He ignition

- During pure helium flashes the fuel is burned rapidly; they last only $\sim 5 - 30$ s
- Bursts with unstable mixed H/He burning release their energies on a longer, 10 - 100 s, timescale, due to the long series of $\beta$ decays in the rp-process

→ length of X-ray burst = trace of composition!

Low mass accretion rates:
GS 1826–24 (Kong et al. 1999)

- Slow rise ($\sim$10 sec) ⇒ H ignition
- Long decay ⇒ unstable mixed H/He burning through rp-process
Medium mass accretion rates:
4U 1735–44

- Fast rise (∼1 sec) + fast decay (<10 sec) ⇒ pure He flash

High mass accretion rates:
GX 17+2 (Kuulkers et al. 2002)

- Fast rise (∼1 sec) ⇒ He ignition
- Long decay ⇒ unstable mixed H/He burning through rp-process
• X-ray bursts as tracers of donor composition

- radius expansion bursts:
  \[ L_{\text{peak}} = L_{\text{Edd,He}} 	imes 1.7 \times L_{\text{Edd,H}} \]
- duration (or decay time) burst:
  \( t_{\text{burst}} \geq 30 \text{ sec} \Rightarrow \text{H/He} \)
  \( t_{\text{burst}} \leq 30 \text{ sec} \Rightarrow \text{He or H/He} \)
- \( t_{\text{burst}} \leq \text{hr} \Rightarrow \text{He or H/He} \)
  → rule out CO donors?

**Empirical standard candles (2)**

- RE bursts: \( L_x = 3.79 \pm 0.15 \times 10^{38} \text{ erg/s} = L_{\text{Edd}} \) for H-poor material
  (excluding 4U 1746–37)

Kuulkers et al. 2002

X-ray bursters in Globular Clusters
→ distance known independently
Thermonuclear X-Ray Bursts from Ultracompact LMXBs

BerppoSAX/WFC
Cornelisse et al. 2003

$P_{\text{orb}} = 11$ min

$F_{\text{m}} (10^{34} \text{ erg s}^{-1} \text{ cm}^{-2})$

$N_{\text{burst}}$ (burst ccs$^{-1}$)

RXTE/PCA

$4U 1820-30$: $\tau_{\text{exp}} \approx 1 \text{ hr}$

Energy release: $\approx 10^{42}$ erg

Unstable C burning

He burst

C burst

EXOSAT

X-ray observations of X1916−053

Smaie et al. 1988

The normalization of the absorbed component stays roughly constant within the errors, while the normalization of the non-absorbed component decreases by a factor of ~10.

We note that in all of the models fitted the decrease in count rate due to dipping is associated with a steady increase in the measured equivalent hydrogen column density.

3.3 THE BURSTS

A total of five bursts were recorded during the three observations. In Fig. 6 we display the profiles of these bursts in different energy bands. All bursts are Type I (Lewin & Joss 1983), with a rise time of <1 s and e-folding decay time of ~10 s, and are similar to bursts observed previously from this source (Swank et al. 1984). No bursts were observed during dips.

A series of spectra were accumulated through the four bursts observed during the 1985 observations. Background subtraction was performed using sections of data taken immediately before and after the bursts. The burst spectra were found to be well fitted by a simple blackbody.
Conclusions:

- X-ray bursts rule out C-O donor
  (unless spallation of C,N,O $\rightarrow$ H,He)
  see Juett et al. 2001

- $L_{\text{peak}}$ radius expansion bursts NOT
  a good tracer of donor composition:
  - A1850-08, MX 0513-40
    long X-ray burst \& $L_{\text{peak}} = L_{\text{Edd},\text{He}}$
    \rightarrow H
  - Other example: YU 1636-53 ($P_{\text{orb}} = 3.8$ hr)
    optical spectra: H-rich donor
    radius expansion bursts: $L_{\text{peak}} < L_{\text{Edd},\text{He}}$
    \rightarrow H-rich envelope ejected (Sugimoto et al. 1984)

- A1850-08, YU 0614+091, 2S 0918-549, H1825-331:
  long X-ray bursts ($\sim$100-150 s)
  \rightarrow H present
  (consistent with conclusions of Podsiadlowski et al. 2002: small residual H content in UUEBs)

- YU 1820-30, YU 1816-05, XB 1745-25: short