Thermonuclear X-ray bursts as probes of nuclear physics

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Neutron stars in low mass binaries

- These are “old” (~$10^9$ yr) systems in which the magnetic field has decayed and the accreting material (usually?) directly impacts the surface.
- Orbital periods of typically minutes to hours, compared to as many as hundreds of days for neutron stars with high-mass companions.
- Distinct evolutionary paths to those systems, and are likely the precursors to millisecond (“recycled”) radio pulsars.

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Neutron stars in low mass binaries

- Characteristically exhibit thermonuclear (or type-I) X-ray bursts every few hours or days, first observed in 1975

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Unstable thermonuclear burning

• Material (expected to be mixed H/He) builds up on the surface of the star until a critical temperature/density is reached

• “Thin-shell instability” – energy generation rate is more temperature sensitive than cooling -> “runaway” (Hansen & Van Horn 1975)

• Burning rapidly engulfs the star, exhausting all the available fuel. Predicted efficiency ~5MeV/nucleon, as observed

• Accretion continues, and the fuel buildup begins again

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Burning processes

- $T > 10^{7} K$ (set by the accretion rate) so prior to the burst, H burns via hot CNO cycle:

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

Rate is limited by the mass fraction of CNO nuclei

- Steady burning heats the fuel layer, encouraging earlier ignition, and also affects the H-fraction at ignition -> observational consequences for the burst properties
Burst theory: 3 ignition regimes

3 cases, in order of increasing accretion rate (e.g. Fujimoto et al. 1981):

3) H-burning is unstable, ignition is from H in mixed H/He fuel;

2) H-burning stable, H is exhausted prior to unstable He-ignition, pure He burst;

1) H is not exhausted prior to He-ignition, mixed burst;

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Fuel composition & burst properties

- H-burning is limited by $\beta$-decay lifetimes (relatively slow)
- He-burning occurs via the much more rapid triple-$\alpha$ reaction

$$\frac{4}{2}\text{He} + \frac{4}{2}\text{He} \rightarrow \frac{8}{4}\text{Be} + \frac{4}{2}\text{He} \rightarrow \frac{12}{6}\text{C} + e^+ + e^-$$

Bursts with H have longer durations than bursts burning pure He
- Breakout from the CNO cycle leads to rp-process burning to very heavy ashes
Examples – can you guess the fuel?

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More burning reactions

- When both H & He are present, high temperatures permit “breakout” reactions from the CNO cycle

\[
\begin{align*}
^{15}\text{O}(\alpha, \gamma)^{19}\text{Ne} \\
^{18}\text{Ne}(\alpha, p)^{21}\text{Na}
\end{align*}
\]

- Subsequent burning via the rapid-proton (rp) process, a series of successive proton captures and β-decays

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Endpoint of the rp-process

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Schatz et al. 2001 PRL 86, 3471

X-ray burst

grey=stable
no. of neutrons
Our data

- A unique sample of ~1200 1500 1750 thermonuclear bursts observed by NASA’s *Rossi X-ray Timing Explorer* during its 14-year mission (still going strong!)

- Analysis results consisting of time-resolved X-ray spectral analyses covering each burst, as well as high-time resolution lightcurves for pulsation searches

- Continuing to extend the catalog with additional newly public *RXTE* bursts, *BeppoSAX*/WFC bursts (+2200) and also *INTEGRAL*/JEM-X (+1000?) bursts -> *MINBAR*

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"Conventional" analysis

- For the vast majority of bursts the X-ray spectra throughout are consistent with a Planck (blackbody) spectrum.
- Such spectra are characterised by two parameters: the temperature and the radius of the emitting object.
- We observe a flux at the earth which depends also upon the distance (assuming isotropy).
- The spectrum also is distorted slightly so we must correct based on assumptions about the photosphere.
- Blackbody normalisation is not always constant.

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Nuclear reactions and stability

- Interest has focussed on the CNO cycle “breakout” reaction $^{15}$O($\alpha$,\,$\gamma$)$^{19}$Ne reaction
- Has a significant impact on the stability of burning; (largely) sets the critical accretion rate above which bursts cease
- Prior to measurements of the rate, limits were determined based on observations; existence of bursts at all provided a lower limit Fisker et al. 2006, ApJ 650, 332
- Subsequently, measurements made to reduce uncertainties Tan et al. 2007, 2009, PRC 79, 055805
- Confirmed long-standing identification of Eddington rate as the critical threshold, but more work to be done

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A well-behaved burster: GS 1826-24

- This source, discovered in the late 80s by the Ginga satellite, is unique in that it consistently exhibits highly regular bursts.
- Lightcurves are extremely consistent, and recurrence times exhibit very little scatter within an observation epoch.
- We infer “ideal” burst conditions: steady accretion, complete coverage of fuel, complete burning etc.

$\rightarrow$ unique opportunity to test theoretical models

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... aka the textbook burster

• In RXTE observations spanning several years, the persistent X-ray flux increased by almost a factor of two.

• The burst recurrence time decreased by a similar factor, exactly as expected for constant accreted mass at ignition.


Fig. 2.— Burst parameters for the $Z = 0.02$ models A1–A4 compared with individual observed bursts. The properties of the observed bursts are plotted as diamonds. The properties of individual model bursts are plotted as crosses, with average values for each model plotted as squares joined by solid lines.

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Data & model comparisons

- We also compared lightcurves with predictions by the time-dependent model of Woosley et al. 2004
- Confirms that the bursts occur via ignition of H/He in fuel with approximately solar metallicity (i.e. CNO mass fraction)
- In addition, we obtained stunning agreement between the observed and predicted lightcurves (this is not a fit!)
- Except for a “bump” during the burst rise, which may be an artifact of the finite time for the burning to spread, or something arising from a particular nuclear reaction

(Heger et al. 2007, ApJL 671, L141)
An admission

- Bursts from other sources are almost without exception, neither regular nor consistent.
- Above about 0.1 of the Eddington accretion rate, the burst rate is observed to decrease, contrary to predictions.
- At the same time, bursts become shorter, indicating less H, and we see mHz QPOs, suggesting quasi-stable burning.
- There are also short wait time bursts, occurring in groups of up to 4, separated by a few minutes e.g. Keek et al. 2010, ApJ 718, 292.

-> there is a lot more going on than we understand.

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New regimes of burning

- Intermediate duration bursts; arising from ignition of a deep He-layer (usually) at low accretion rates
- Work has focussed on understanding the ignition conditions and influence of the crust (Cumming et al. 2006, ApJ 646, 429)
- Also “superbursts” (Falanga et al. 2008, A&A 484, 43)

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Superbursts: carbon burning?

• 1000x more energetic than typical thermonuclear bursts ($10^{42}$ erg)
• 1000x less frequent (recurrence times of months, instead of hours)

• Thought to arise from unstable ignition of carbon produced as a by-product of burning during “normal” thermonuclear bursts...

But models overpredict ignition column & can’t produce the required C fraction

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Ignition is too easy

Whether you look at

• infrequent (intermediate duration) bursts;
• superbursts;

Ignition appears to be taking place earlier than is predicted by theory

This perhaps says something fundamental about the physical conditions and processes in the neutron star crust e.g. Cumming et al. 2006 ApJ 646, 429

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So where’s the nuclear physics?

• At the moment we are effectively limited to using bursts from a single source to probe nuclear reactions in bursts

• Several groups are working on sensitivity analyses of models for various reactions, with a view to
  – identifying the most important reactions
  – assessing the observational consequences of varying reaction rates

• With so very many isotopes and reactions, this is a challenge! But progress is being made


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**Breaking news: Terzan 5 X2**

- A new transient outburst of a previously unknown globular cluster LMXB Atel #2919
- 11 Hz pulsations (<< typical freq); 21-hr orbit Atel #2919
- Frequent bursts occurred closer and closer as the luminosity approached Eddington -> quasi-stable burning
- First time this transition has been observed

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Fig. 1.— Light curves of 1 s resolution of portions of six RXTE PCU-2 continuous data sets from IGR J17480–2446. The date of observation of each data set is mentioned. This figure shows that during the rise of the 2010 outburst, as the non-burst flux increases, the burst peak flux and the burst interval gradually decrease. The initial burst properties return as the source intensity decays (§).

- Motta et al., arXiv:1102.1368;
- Linares et al., arXiv:1102.1455;
- Cavecchi et al., arXiv:1102.1548 etc. etc.
Summary and future work

- There is much about thermonuclear burning on neutron stars that we don’t understand.
- Remarkably however, there is at least one source where this lack of understanding doesn’t seem to matter.
- Observationally, it is a high priority to
  - understand better what is special about 1826-like bursts
  - gather and analyse additional examples.
- This work has begun last year at Monash and hopefully will continue (via the Multi-INstrument Burst ARchive project – see http://users.monash.edu.au/~dgallow/minbar).

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Time dependent burst models

- Ignition by unstable He burning in a mixed H/He environment
- Includes a realistic adaptive reaction network with thousands of individual isotopes
  (simulations from Woosley et al. ‘04)

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Simpler models are sometimes OK

- The time-\textit{independent} models are still OK where steady H-burning is not the dominant heating process.

- For example, at low accretion rates where the recurrence time is long enough to exhaust all the hydrogen prior to ignition.

- For the bursts observed during the 2002 outburst of the millisecond pulsar SAX J1808.4-3658, we obtained excellent agreement between model predictions and observations.

- Can derive the distance of 3.4-3.6 kpc (Galloway et al. 2006, ApJ 652, 559)

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Summary and future work

• A few examples of burst behaviour which show “ideal” behaviour and have been successfully compared to ignition models of various sophistication

• These bursts are particularly high priority for more stringent tests, for example to constrain poorly-known individual reaction rates

• The broader sample of burst sources are more problematic, and there are poorly-understood additional factors which contribute significantly to the burst behaviour

• Potentially a productive area, but little effort right now?

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