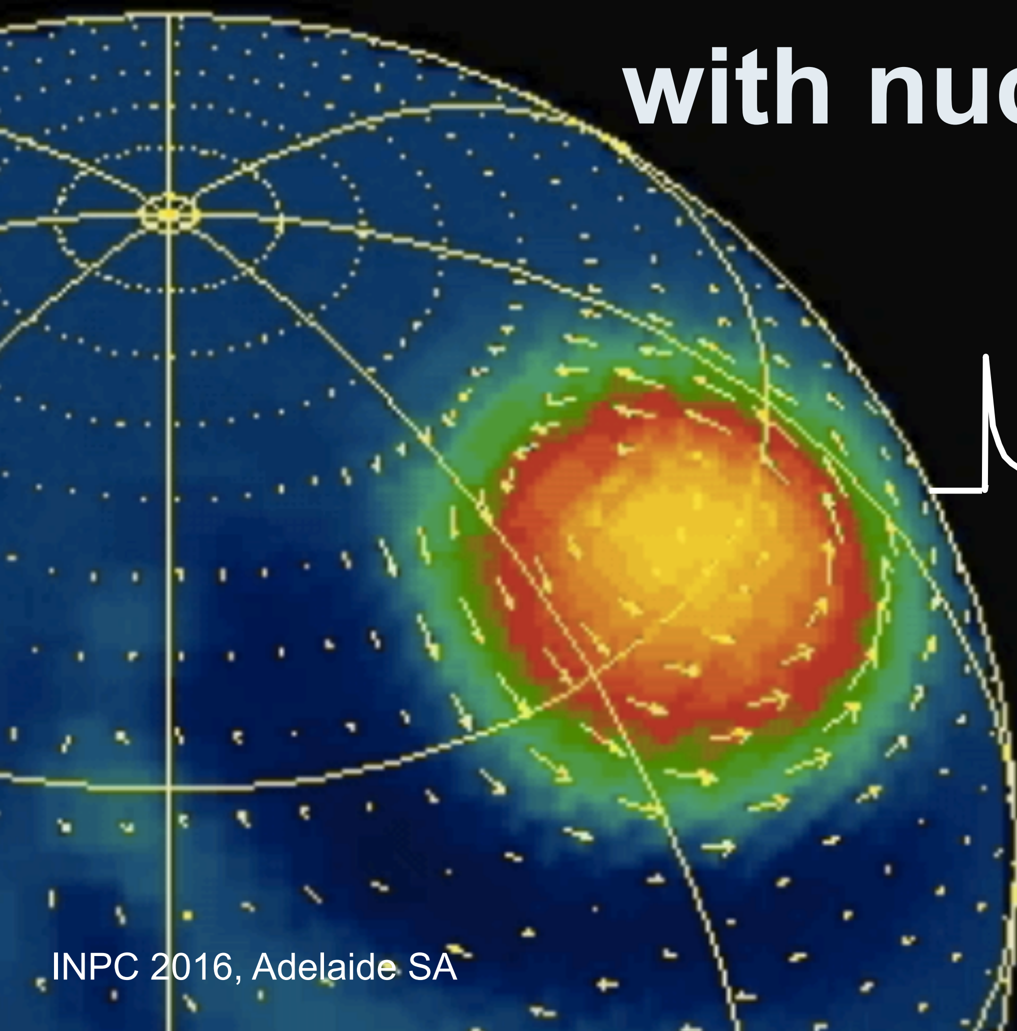
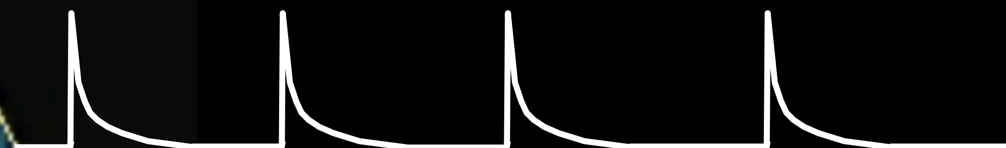
Reconciling observations and models of thermonuclear bursts with nuclear experiments





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INPC 2016, Adelaide SA

JINA–CEE
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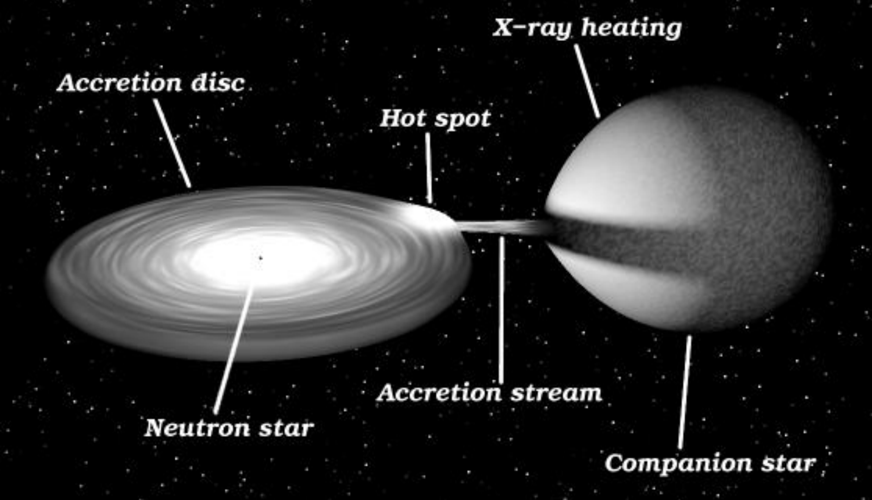
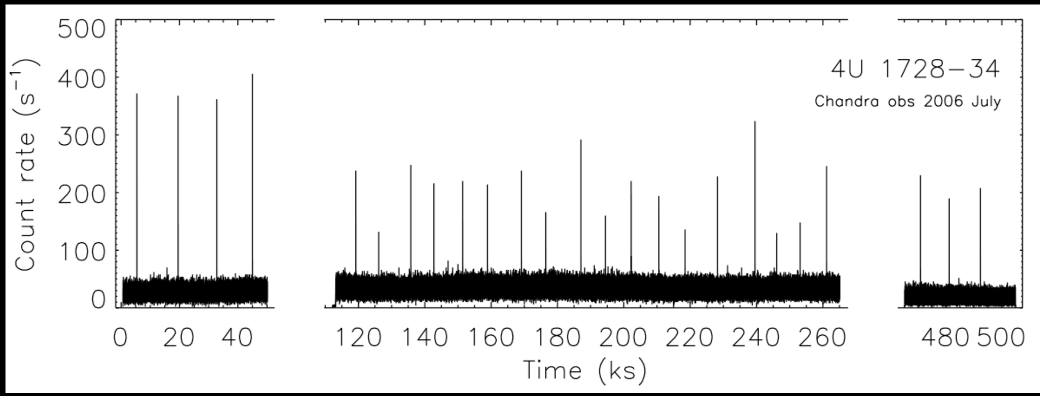
MoCA Monash Centre for Astrophysics

Thermonuclear X-ray bursts

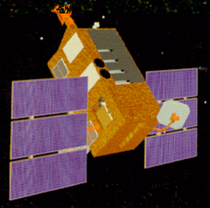
- Occur in neutron stars accreting from low-mass binary companions; ~100 bursters known, ~10^4 bursts observed since early 1970s

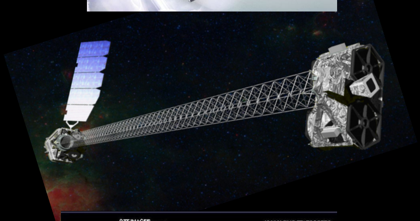


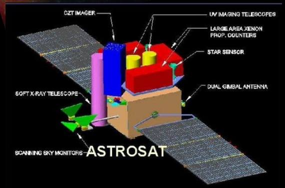


- Understood since the `80s as resulting from unstable ignition of accreted H/He on the NS surface e.g. Fujimoto et al. 1981, ApJ 247, 267

Past & present X-ray missions







- *BeppoSAX*, wide-field Dutch-Italian mission through '90s
- *RXTE* high sensitivity & fast timing, 1995 Dec–2012 Jan
- *INTEGRAL*/JEMX; wide-field, low sensitivity, 2002 onwards

Data from these last three make up the Multi-INstrument Burst ARchive (MINBAR), under assembly at Monash

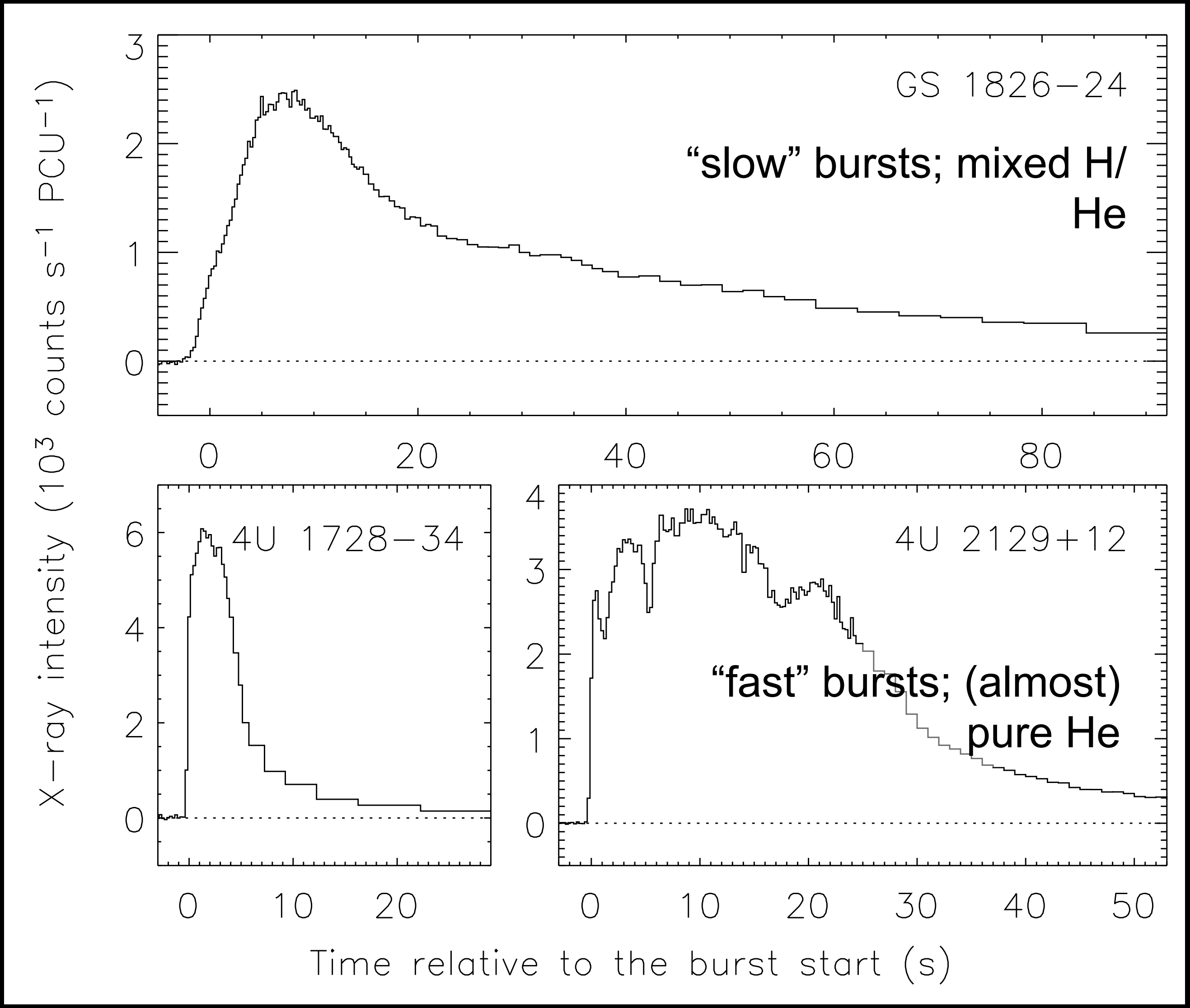
- *Swift*; wide-field, rapid response to transients, new bursts etc.
- *NUSTAR*, hard X-ray sensitivity
- *ASTROSAT*, launched Sep 2015, LAXPC large-area detector + imagers

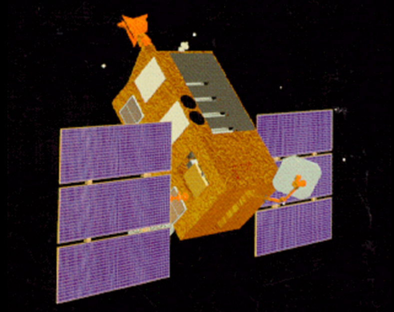
Diversity of X-ray burst behaviour

- *"Intermediate duration" bursts* in low-accretion rate systems, burning of large pure-He reservoirs e.g. Falanga et al. 2009, A&A 496, 333
- *Short recurrence time bursts* occur too promptly to reach critical temperature, density Keek et al. 2010, ApJ 718, 292
- *Multi-peaked bursts* perhaps attributable to nuclear waiting points? e.g. Fisker et al. 2004, ApJ 608, L61
- *Photospheric radius-expansion* bursts reach the (local) Eddington limit; utility as standard candle e.g. Kuulkers et al. 2003, A&A 399, 663
- *"Superbursts"* with durations of hours, likely powered by carbon Cornelisse et al. 2000, A&A 357, L21

Burst profiles and the burst fuel

Different timescales for hot-CNO cycle and triple-α burning result in a diversity of burst profiles for different fuel mixes

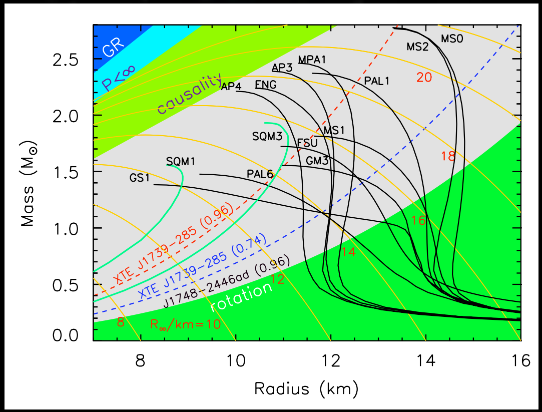


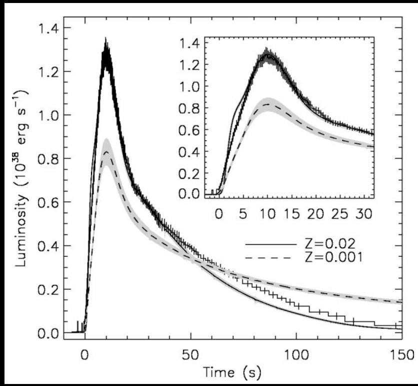


Galloway, "Reconciling observations and models of thermonuclear bursts with nuclear experiments"

Motivation for burst studies

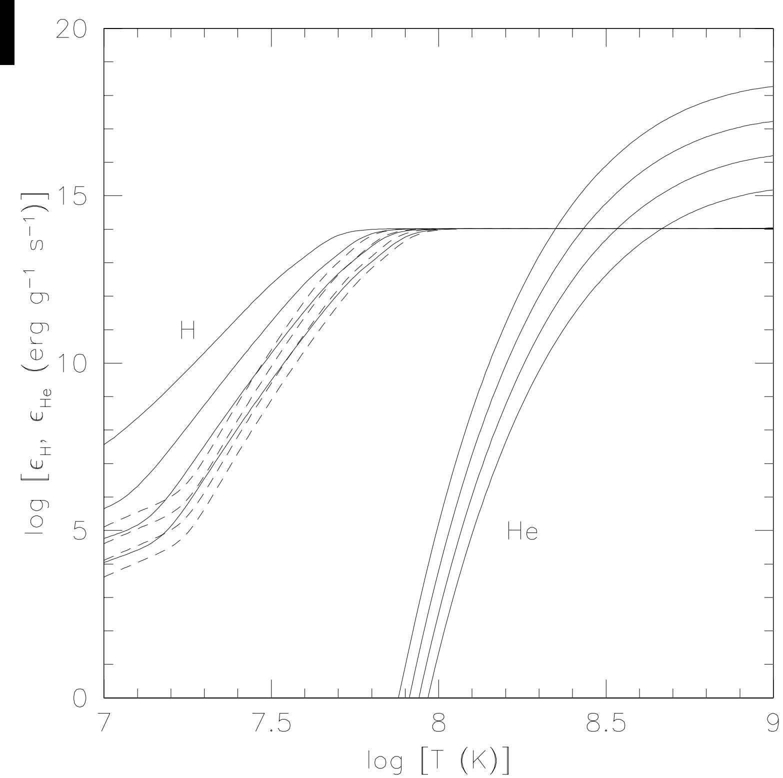
- Thermonuclear bursts offer fundamental astrophysical information about the host sources – confirm neutron star (rather than black hole), determine distance
- Significant efforts over the last decade in measuring neutron star mass and radius from modelling the X-ray spectra, and hence constraining the equation of state e.g. Özel 2013, arXiv:1210.0916
- As-yet poorly exploited utility in probing nuclear reactions which power the bursts, with possible impact on host parameters e.g. Heger et al. 2007, ApJ 671, L141





Thermonuclear burning

- Accreted fuel is thought to be a mix of H & He, at roughly solar composition (70/28%)
- A subset of sources have *evolved companions* and likely accrete (almost?) pure He
- H and He burning occur ~independently, via the hot CNO cycle & rp-process burning, or triple-alpha
- Burning of both species can be stable or unstable, depending on accretion rate



Narayan & Heyl (2003)

End-point of rp-process burning

- Dominates late-time burning in mixed H/He bursts; terminates in a Sn-Sb-Te cycle

Schatz et al. (2001)

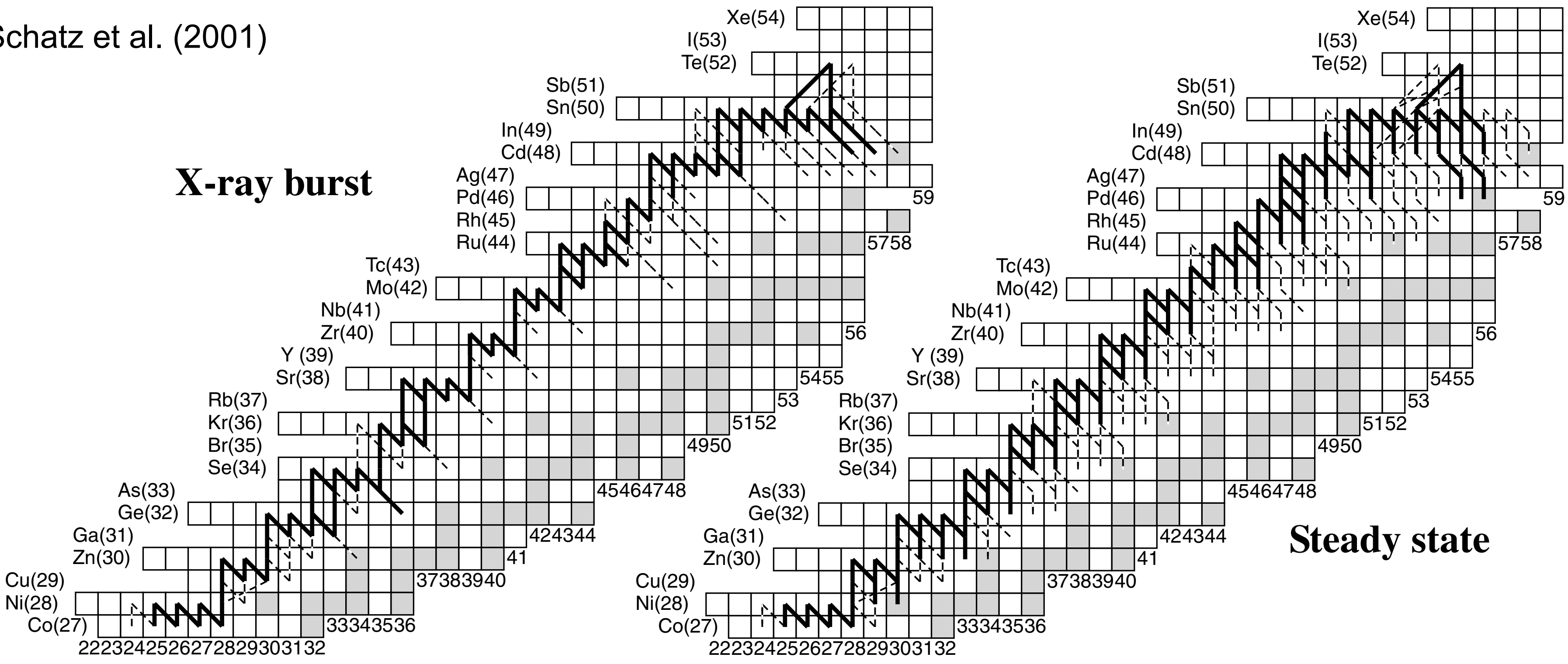


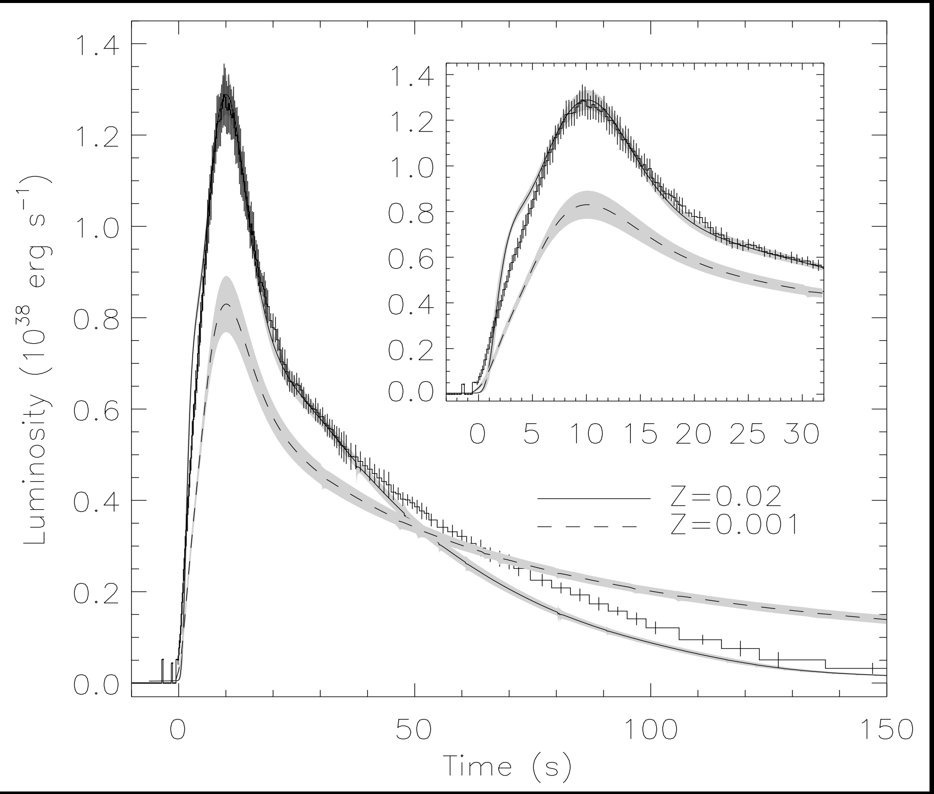
FIG. 1. The time integrated reaction flow above Ga during an x-ray burst and for steady-state burning. Shown are reaction flows of more than 10% (solid line) and of 1%−10% (dashed line) of the reaction flow through the 3α reaction.

GS 1826-24: a case history

- An unusual source in that it consistently* shows regular, consistent bursts
- Early analysis of the variation of the recurrence time with accretion rate suggested metal-poor material Galloway et al. 2004
- Subsequent study showed good agreement with time-dependent 1-D models & *solar composition* Heger et al. 2007
- Relied on lightcurve comparison at a *single epoch*

* from ~1986 to 2014 June

Heger et al. 2007, ApJ 671, 141L



our objective:

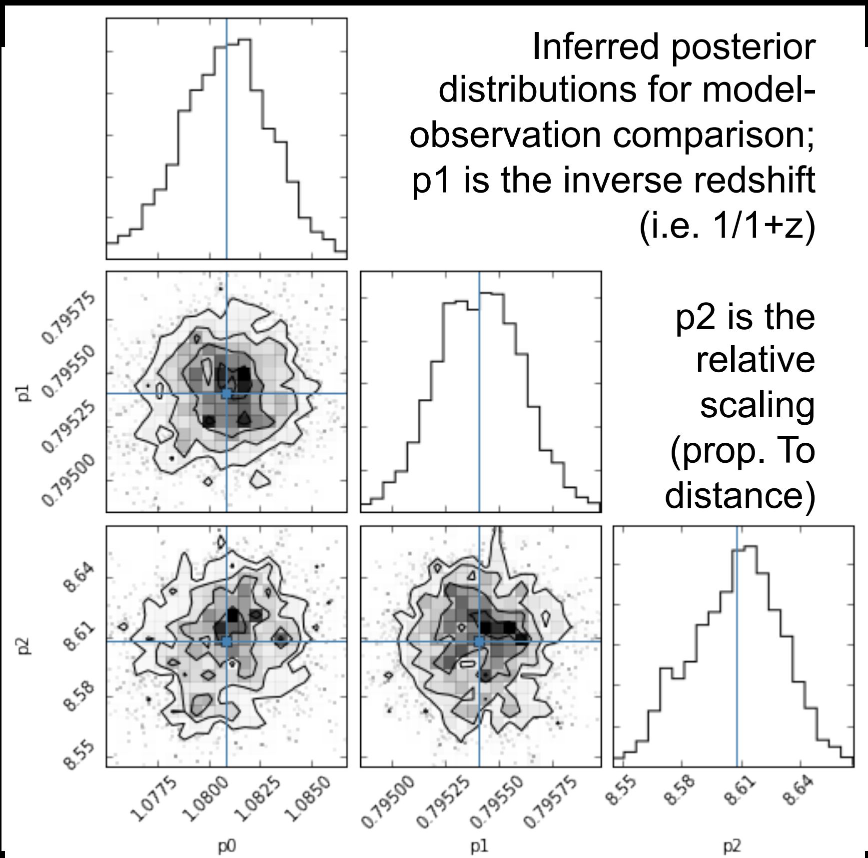
“precision” nuclear astrophysics from thermonuclear bursts

Meaning, we want to reduce the *astrophysical* uncertainties for observations of bursts, to the point where we are sensitive to the nuclear physics

Our approach

- The three main obstacles to this goal are
  - Lack of well-calibrated observational data for modelers
  - Difficulty to observers in obtaining model results suitable for comparisons (run time/lack of large model grids)
  - No tools to formally compare models and observations in response to variations in nuclear data
- We are pursuing this goal via the Joint Intitute for Nuclear Astrophysics (JINA) Centre for the Evolution of the Elements
- Allow us to draw together experimentalists and observers and offer the long-term opportunity of guiding the experiments
- We have assembled a team of observers, theorists, and nuclear physicists who met in December 2015 at ISSI, Bern, &subsequently in Japan in mid-2016 http://www.issibern.ch/teams/labtostars

Theory-compliant bursts



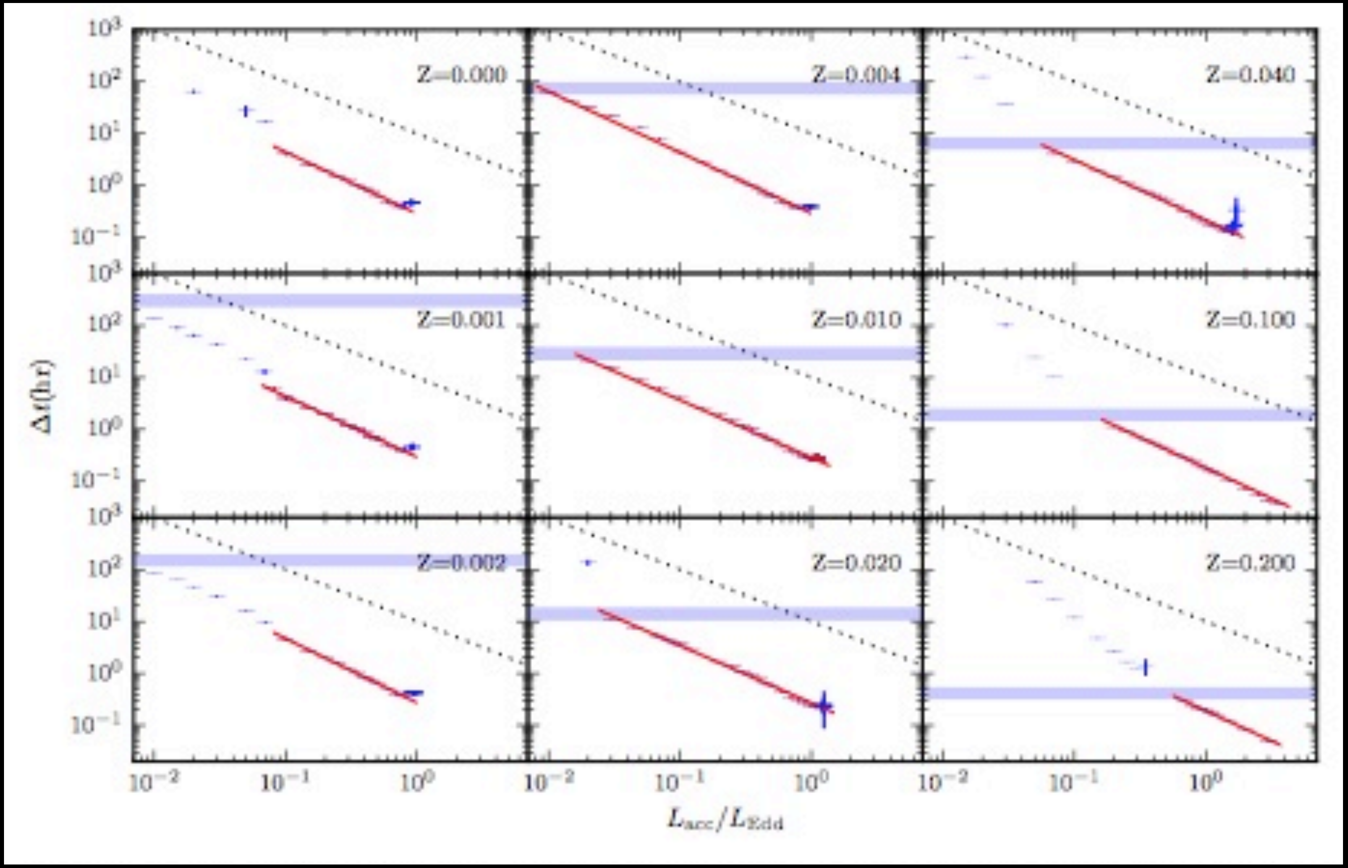
Model-observation comparison for regular, consistent bursts from GS 1826-24, the “clocked” or “textbook” burster; Heger et al. 2007, ApJ 671, 141L

- We will target systems that show trains of regular, consistent bursts amenable to comparisons with models (e.g. KEPLER)
- We seek to improve the comparisons that are possible via sharing of software tools, observed data & burst model results

New databases of model results

- We have assembled, published, a large sample of KEPLER simulations for comparison with observations

Lampe et al. 2016, ApJ 819, 46



Calibrating burst models

- Another important activity is quantifying the uncertainty in our predictions of burst lightcurves (beyond that introduced from nuclear physics)
- To this end we are working on a set of *test cases* for numerical models
- Numericists with different codes will be encouraged to test their codes against our best estimates for the system parameters (accretion rate etc.) of these objects
- Can compare code results directly against each other
- Will be out soon (preliminary results available now)

Reaction rates and bursts

- Some theoretical work on the expected influence of individual reactions on burst rates, lightcurve shape
- Most important reactions identified from 1-D multizone models Fisker et al. 2008; Cyburt et al. 2010 & 2016
- At the same time, extensive experimental efforts to measure the rates of important reactions, e.g. $^{15}O(\alpha,\gamma)^{19}Ne$ Tan et al. 2009

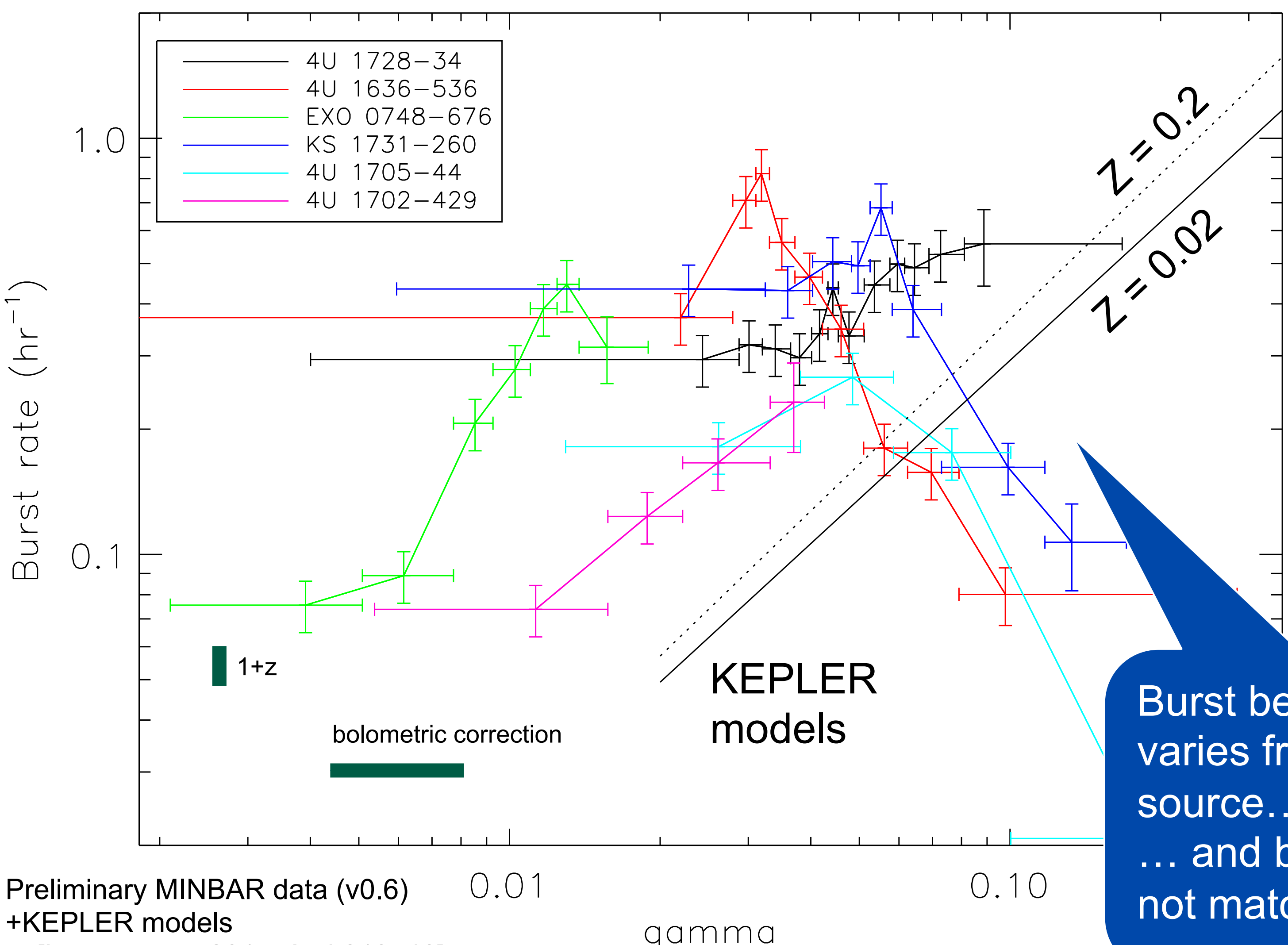
TABLE 1
REACTIONS THAT IMPACT THE BURST LIGHT CURVE IN THE SINGLE-ZONE X-RAY BURST MODEL.

Rank	Reaction	Type[a]	Sensitivity[b]	Category
1	$^{56}Ni(\alpha,p)^{59}Cu$	U	12.5	1
2	$^{59}Cu(p,\gamma)^{60}Zn$	D	12.1	1
3	$^{15}O(\alpha,\gamma)^{19}Ne$	D	7.9	1
4	$^{30}S(\alpha,p)^{33}Cl$	U	7.8	1
5	$^{26}Si(\alpha,p)^{29}P$	U	5.3	1
6	$^{61}Ga(p,\gamma)^{62}Ge$	D	5.0	1
7	$^{23}Al(p,\gamma)^{24}Si$	U	4.8	1
8	$^{27}P(p,\gamma)^{28}S$	D	4.4	1
9	$^{63}Ga(p,\gamma)^{64}Ge$	D	3.8	1
10	$^{60}Zn(\alpha,p)^{63}Ga$	U	3.6	1
11	$^{22}Mg(\alpha,p)^{25}Al$	D	3.5	1
12	$^{56}Ni(p,\gamma)^{57}Cu$	D	3.4	1
13	$^{29}S(\alpha,p)^{32}Cl$	U	2.8	1
14	$^{28}S(\alpha,p)^{31}Cl$	U	2.7	1
15	$^{31}Cl(p,\gamma)^{32}Ar$	U	2.7	1
16	$^{35}K(p,\gamma)^{36}Ca$	U	2.5	2
17	$^{18}Ne(\alpha,p)^{21}Na$	D	2.3	2
18	$^{25}Si(\alpha,p)^{28}P$	U	1.9	2
19	$^{57}Cu(p,\gamma)^{58}Zn$	D	1.7	2
20	$^{34}Ar(\alpha,p)^{37}K$	U	1.6	3
21	$^{24}Si(\alpha,p)^{27}P$	U	1.4	3
22	$^{22}Mg(p,\gamma)^{23}Al$	D	1.1	3
23	$^{65}As(p,\gamma)^{66}Se$	U	1.0	3
24	$^{14}O(\alpha,p)^{17}F$	U	1.0	3
25	$^{40}Sc(p,\gamma)^{41}Ti$	D	0.9	3
26	$^{34}Ar(p,\gamma)^{35}K$	D	0.8	3
27	$^{47}Mn(p,\gamma)^{48}Fe$	D	0.8	3
28	$^{39}Ca(p,\gamma)^{40}Sc$	D	0.8	3

[a] Up (U) or down (D) variation that has the largest impact
[b] $M_{LC}^{(i)}$ in units of 10^{17}ergs/g/s

https://arxiv.org/abs/1607.03416

A caveat: burst physics is far from complete



Preliminary MINBAR data (v0.6)
+KEPLER models
[Lampe et al. 2015, ApJ 819, 46]

Burst behaviour varies from source to source…
… and broadly does not match models

Summary and future prospects

- There remain some fundamental shortcomings in our understanding of the various burst phenomena
- At the same time we have access to a substantial accumulated dataset to analyse, as well as detailed models
- Prospects for future model-observation comparisons are excellent, and incorporating nuclear physics may allow us to constrain reaction rates etc.
- Longer term we have the prospect of exciting new data coming in from ASTROSAT and NICER

Observational milestones

- *Photospheric radius-expansion* bursts reach the (local) Eddington limit; utility as standard candle Basinska et al. 1984; Kuulkers et al. 2003
- *Burst oscillations* measure the neutron star spin; exhibit 1–2 Hz drifts Strohmayer et al. 1996; Chakrabarty et al. 2003; Watts 2012
- *“Superbursts”* with durations of hours likely arising from carbon burning Cornelisse et al. 2000
- *“Intermediate duration” bursts* arising in low-accretion rate systems, burning of large pure-He fuel reservoirs Falanga et al. 2009
- *Burst spectra* exploited to measure neutron star *M, R* Özel et al. 2006, 2009, 2012 etc; Steiner et al. 2010

… see also in ‘t Zand, arXiv:1102.3345, Strohmayer & Bildsten 2003

Cases of thermonuclear burning

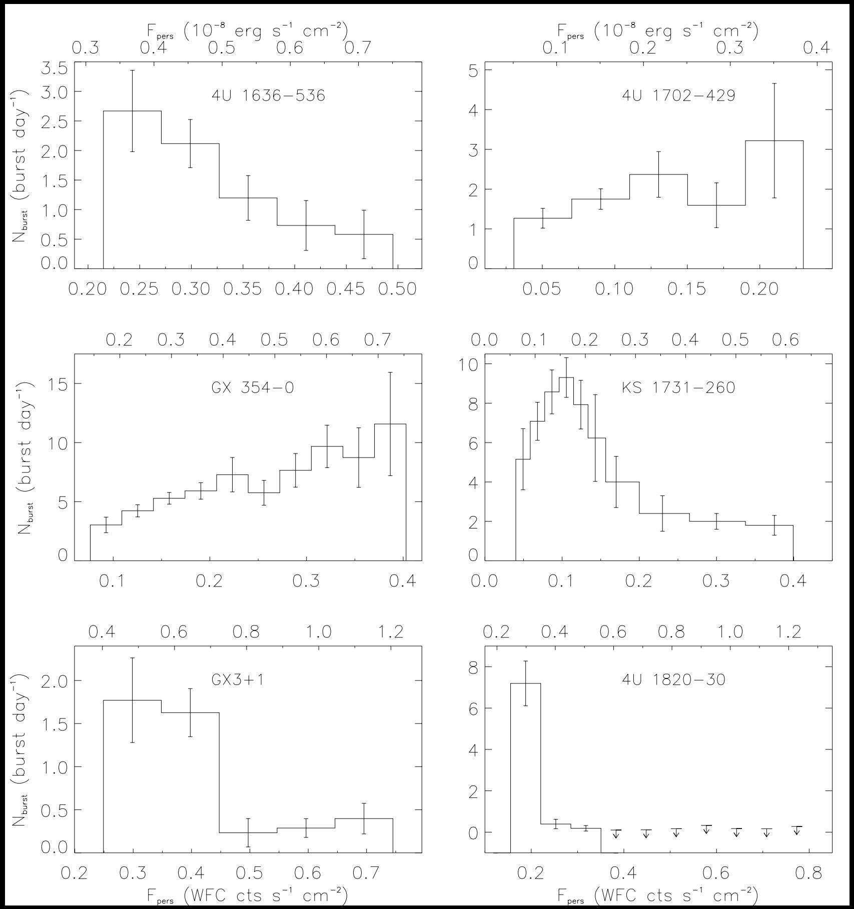
Label	Accretion rate	H-burning	He-burning	Notes
I	> 0.25	stable	stable	no bursts
II	0.15–0.25	stable?	overstable	not observed?
III	0.04–0.15	stable	unstable	mixed H/He bursts+ short recurrence times
III*	?	*none present*	unstable	“fast” pure-He bursts in ultracompacts
IV	0.004–0.04	stable	unstable	pure He bursts
V	< 0.004	unstable	unstable	mixed H/He triggered by H; not observed

Accretion rate given as a fraction of the Eddington rate, $1.75\times10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$
From global linear stability analysis of Narayan & Heyl (2003)

Outstanding questions

- What causes burst oscillations?
- What causes the decrease in burst rate, observed for most sources at accretion rates above ~5% Eddington?
- Can we use bursts to unambiguously measure neutron star mass and radius?
- What ignites in superbursts?
- Why do all types of bursts – short, intermediate-duration, and super – seem to ignite at columns well below theoretical predictions?
- Can we use bursts to constrain (or measure) nuclear reactions?

Global burst behaviour



- Burst ignition models predict increasing burst rate with increasing accretion rate, up to the stable burning threshold
- Observations instead show a peak burst rate achieved at much lower accretion rate, and then *decreasing* burst rate at higher accretion rates

Analysis of 6 years of *BeppoSAX* data; Cornelisse et al. 2003