Multi-Zone X-Ray Burst Reaction Rate Sensitivities

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Burst Environment, Reactions and Numerical Modelling Workshop 2018 (#BERN18)
June 13, 2018

Today's discussion

1. Previous JINA Sensitivity Study

2. New Study Configuration --
   Better Baselines, Updated ReacLib, and
   Fully Multi-Zone Variations

3. Preliminary Results From 1756
   GS 1826 Variations

In collaboration with:

Zac Johnston, Alexander Heger,
Duncan Galloway (Monash)
Matt Amthor (Bucknell)
Hendrik Schatz, Ed Brown (MSU/NSCL/JINA-CEE)

JINA-CEE themes

+ "Light elements to heavy elements"
+ MA2: Understanding neutron stars, dense matter
+ Productively engage
    + Astrophysical modeling
    + Observation
    + Nuclear experiment
    + Nuclear theory (esp. reaction theory)

Previous JINA Sensitivity Study

Cyburt, Amthor, Heger, et al 2016

Spherical hydrodynamic models with Kepler

- Kepler code employed to carry out multi-zone models
  - See e.g. Woosley et al., ApJS, 2004; Heger et al., ApJ, 2007
- Lagrangian grid with reactive fluid equations
- Realistic microphysics, large adaptive reaction network
- Mixing-length models of convection
- Primary XRB model specification parameters:

X_acc	Z_acc (n14)	m_dot	Q_b	g

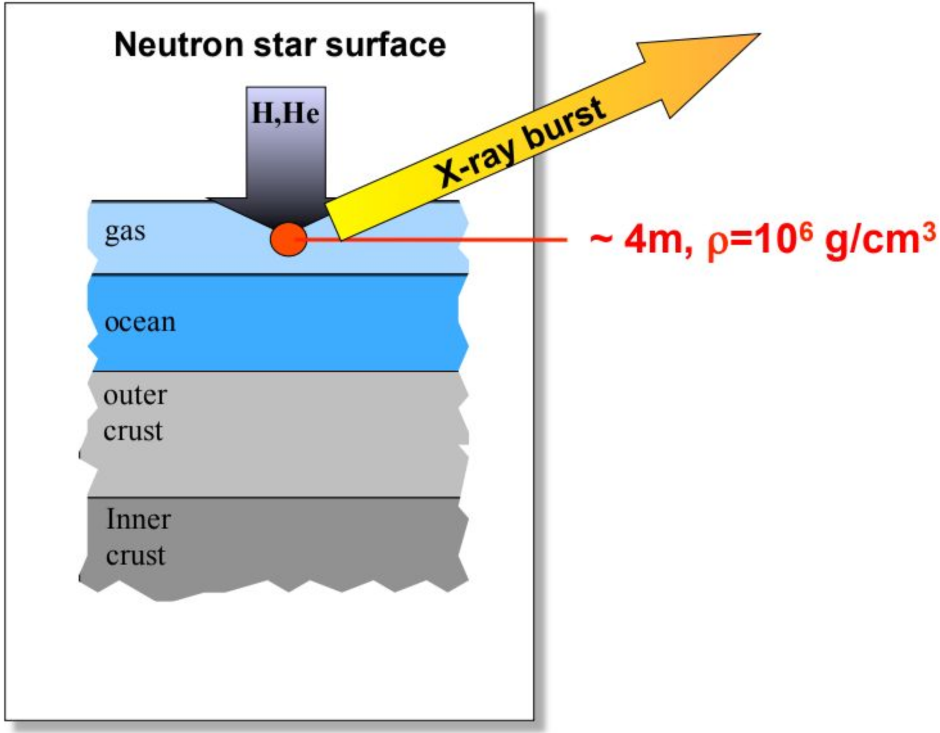


Image courtesy H. Schatz

Summary of previous work, Cyburt et al., 2016

Reactions that Impact the Burst Light Curve in the Multi-zone X-ray Burst Model

Rank	Reaction	Type[a]	Sensitivity[b]	Category
1	$^{15}O(\alpha, \gamma)^{19}Ne$	D	16	1
2	$^{56}Ni(\alpha, p)^{59}Cu$	U	6.4	1
3	$^{59}Cu(p, \gamma)^{60}Zn$	D	5.1	1
4	$^{61}Ga(p, \gamma)^{62}Ge$	D	3.7	1
5	$^{22}Mg(\alpha, p)^{25}Al$	D	2.3	1
6	$^{14}O(\alpha, p)^{17}F$	D	5.8	1
7	$^{23}Al(p, \gamma)^{24}Si$	D	4.6	1
8	$^{18}Ne(\alpha, p)^{21}Na$	U	1.8	1
9	$^{63}Ga(p, \gamma)^{64}Ge$	D	1.4	2
10	$^{19}F(p, \alpha)^{16}O$	U	1.3	2
11	$^{12}C(\alpha, \gamma)^{16}O$	U	2.1	2
12	$^{26}Si(\alpha, p)^{29}P$	U	1.8	2
13	$^{17}F(\alpha, p)^{20}Ne$	U	3.5	2
14	$^{24}Mg(\alpha, \gamma)^{28}Si$	U	1.2	2
15	$^{57}Cu(p, \gamma)^{58}Zn$	D	1.3	2
16	$^{60}Zn(\alpha, p)^{63}Ga$	U	1.1	2
17	$^{17}F(p, \gamma)^{18}Ne$	U	1.7	2
18	$^{40}Sc(p, \gamma)^{41}Ti$	D	1.1	2
19	$^{48}Cr(p, \gamma)^{49}Mn$	D	1.2	2

Notes.
[a] Up (U) or down (D) variation that has the largest impact.
[b] $M_{LC}^{(i)}$ in units of 10^{38} erg s^{-1}.

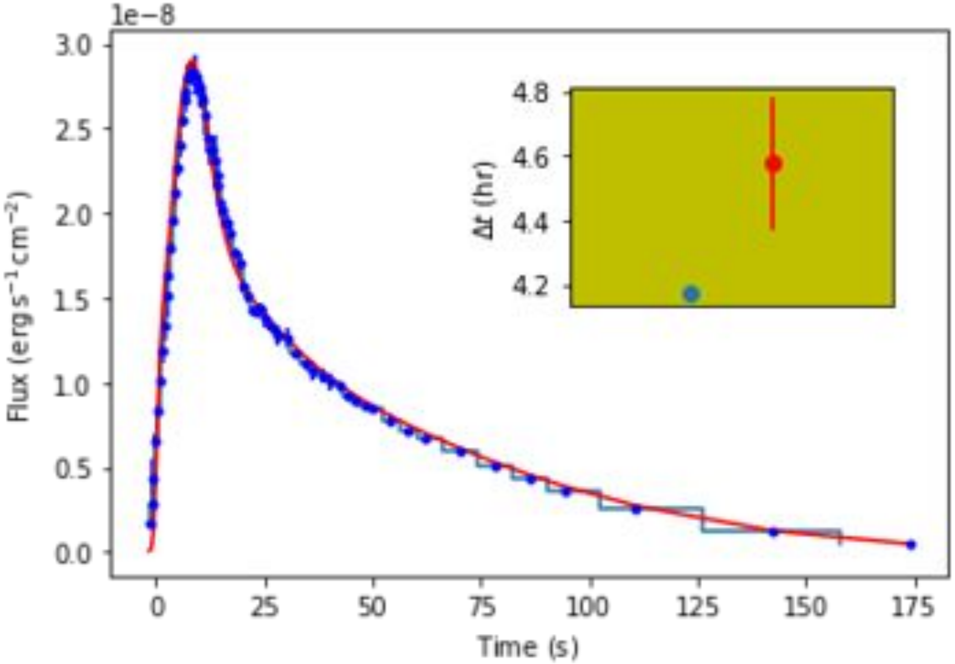
- Uses "generic" GS 1826 fit Woosley et al., 2004
- ReacLib v 1.0 rate library
- Multi-Zone Rxn variation set: 84 rxns (168 models)

X_acc	Z_acc (n14)	m_dot	Q_b	g
0.7048	0.02	0.1 Edd	?	1.9e14 cm / s^2

New Study Configuration

Better Baselines, Updated ReacLib, and
Fully Multi-Zone Variations

My model set:



Example GS 1826 fit to reference set data from Zac Johnston

- GS 1826-24, 4U 1820-303, baselines developed by Zac Johnston (Monash)
- ReacLib v 2.2 rate library
- Rxn variation set (2492): 200 (a,g) ; 130 (a,p) ; 27 (g,a) ; 108 (g,p) ; 233 (p,a) ; 548 (p, g)
- 2 variations, 3 baselines = **7476 models** **~ 120,000 CPU hours**

X_acc	Z_acc (n14)	m_dot Edd	Q_b MeV/u	g cm/s^2
0.7048	0.02	0.1	?	1.9e14
0.7	0.0075	0.19	0.025	2.65e14

Galloway, Goodwin, & Keek, PASA, 2017

New, rich X-ray burst reference dataset

Table 1 Target thermonuclear burst source properties

Source	Dist. (kpc)	Accreted fuel X_0	Accreted fuel Z_{CNO}	$1+z$	g $(10^{14}\,\mathrm{cm\,s^{-2}})$	R (km)	Ref.
GS 1826−24	6.1	0.7	0.02	1.23	*2.34*	12.1	[1,2]
SAX J1808.4−3658	3.4 ± 0.1	$0.48^{+0.12}_{-0.08}$	$0.017^{+0.007}_{-0.005}$	*1.26*	*1.86*	*11.2*	[2]
4U 1820−303	7.6 ± 0.4	$\lesssim 0.1$	*0.02*	1.409	2.96	11.1 ± 1.8	[3,4,5]
4U 1636−536	5.6 ± 0.4	*0.7*	*0.02*	*1.26*	*1.86*	*11.2*	

- Specifically for validating and comparing numerical models
- Source data broken into epochs, publicly available
- https://burst.sci.monash.edu/reference

Preliminary Results

1756 Multi-Zone Reaction Variations on GS 1826 Baseline
~20 000 CPU hours
200 (a,g); 130 (a,p); 548 (p,g);
up and down by 100 unless noted

Preliminary Sensitivities

Reaction	Sensitivity (1e38)
O14 (a, p) * 0.01	21.9
Cu59 (p, g) * 0.01	19.1
Ga63 (p, g) * 0.01	11.7
O15 (a, g) * 0.1	11.1
S30 (a, p) * 100	9.7
Ar34 (a, p) * 100	8.5
Al23 (p, g) * 100	8.1
S29 (a, p) * 100	7.3
Mg22 (a, p) * 0.01	7.2
As65 (p, g) * 100	6.5

Reaction	Sensitivity (1e38)
Al23 (p, g) * 0.01	6.4
Ga61 (p, g) * 0.01	6.3
Si26 (a, p) * 100	6.2
P27 (p, g) * 0.01	5.6
Mg22 (a, p) * 100	5.5
S28 (a, p) * 100	5.0
O14 (a, p) * 100	4.7
S30 (a, p) * 0.01	4.1
Ca37 (a, p) * 100	3.9
Mg22 (p, g) * 0.01	3.7

Significant qualitative difference from previous work

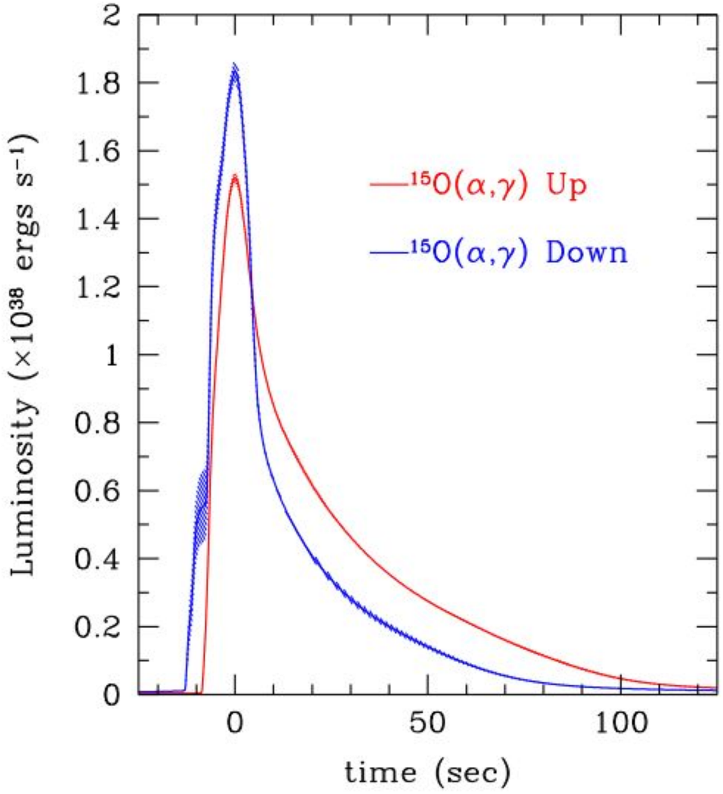
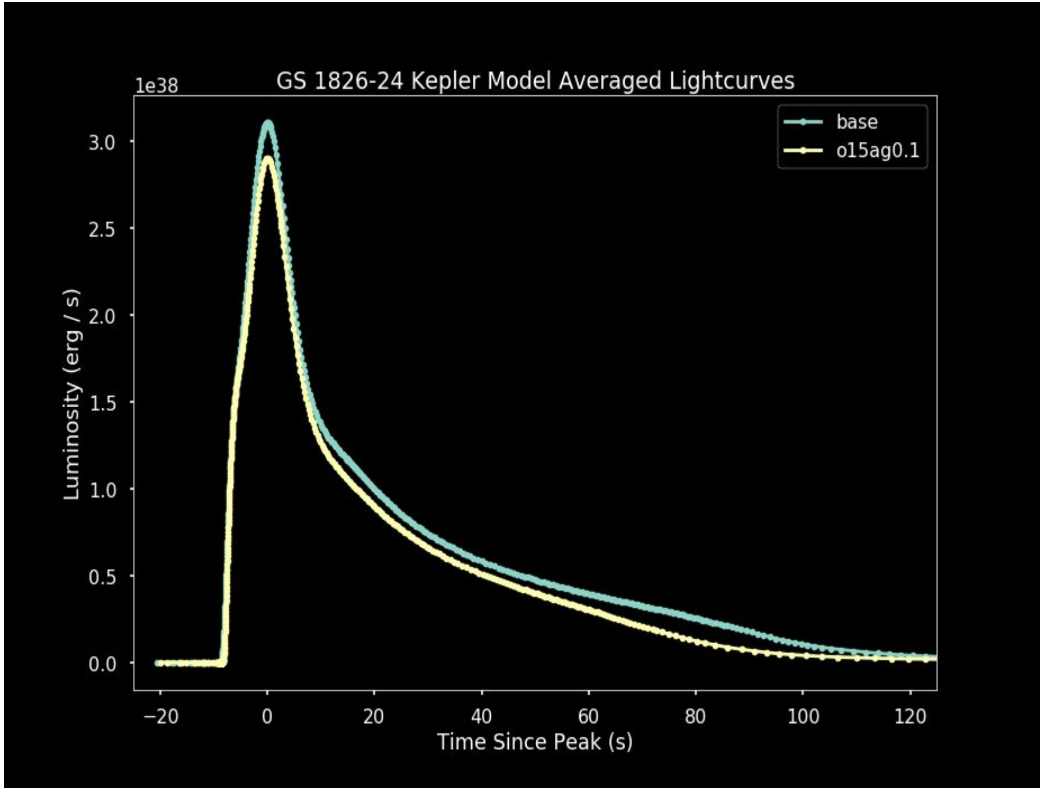
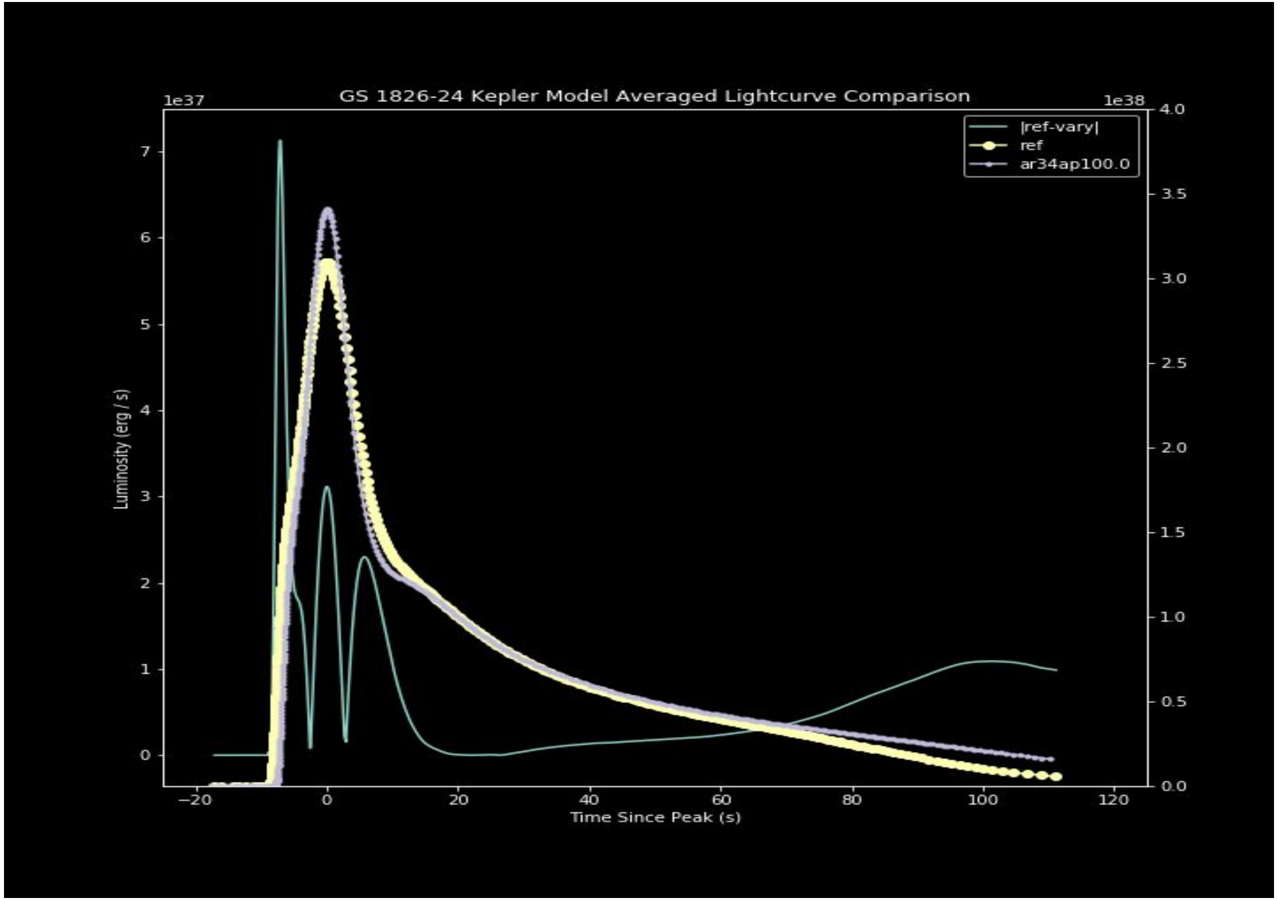


Fig 7 of Cyburt et al. 2016



Example Lightcurve Comparison



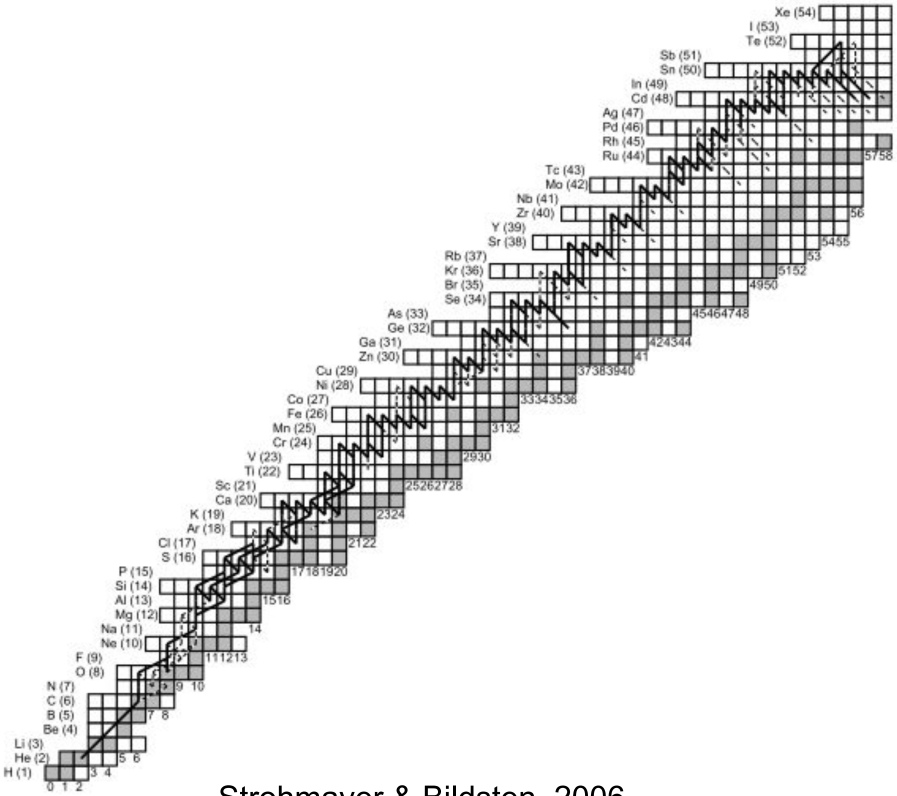
Next Steps and Conclusions

In Summary

- I’m carrying out a fully multi-zone reaction rate sensitivity study (~50x more models than previous work, including new 4U 1820 baseline
  - Uses newer rxn database ReacLib 2.2
  - Uses better-defined baseline models with updated fits to well-defined reference data Enables meaningful comparison with observation *and* other models
- I’ve completed an initial grid of 1756 models varying on GS 1826
- Study confronting detailed reference data with rxn variations is moving forward. **Next**:
  - Complete simulation suites of: GS 1826, 4U 1820 (low and hi X limiting cases)
  - Analyze impact on composition, ashes
  - Adjust scaling as needed
  - Determine most useful sensitivity metric(s)

Supplemental Slides

Reactions driving the burst: the rp-process



Strohmayer & Bildsten, 2006

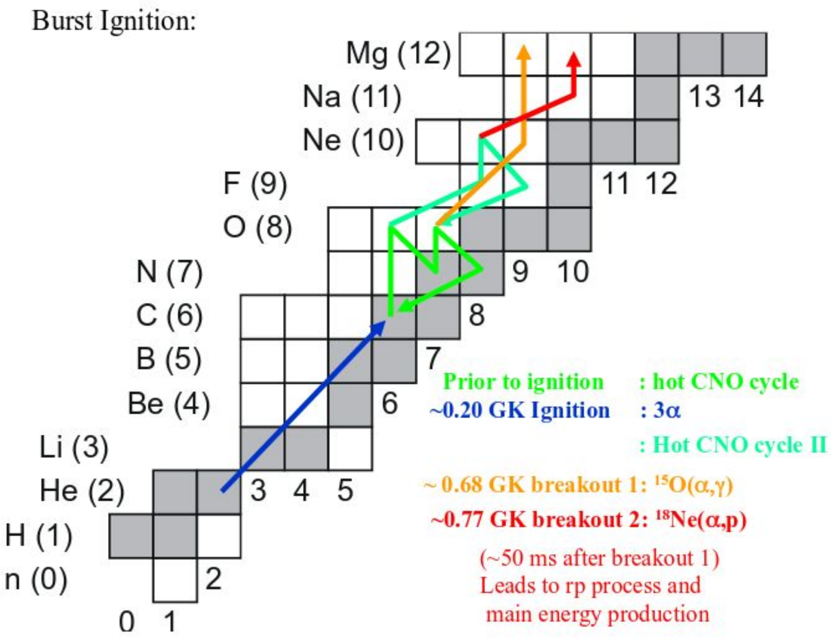
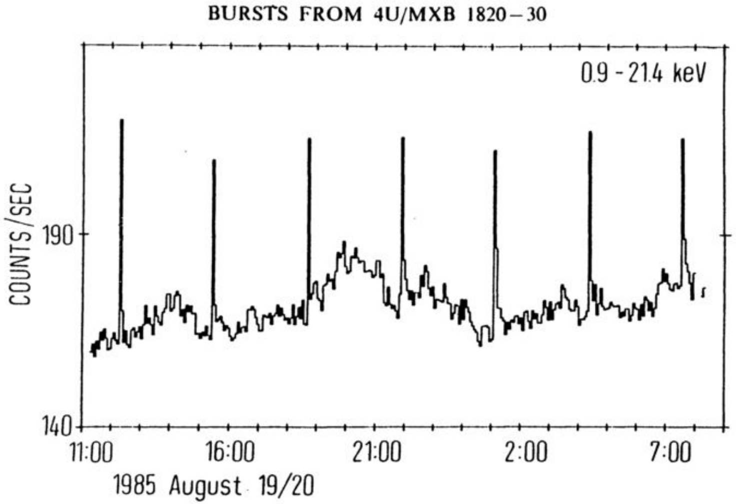
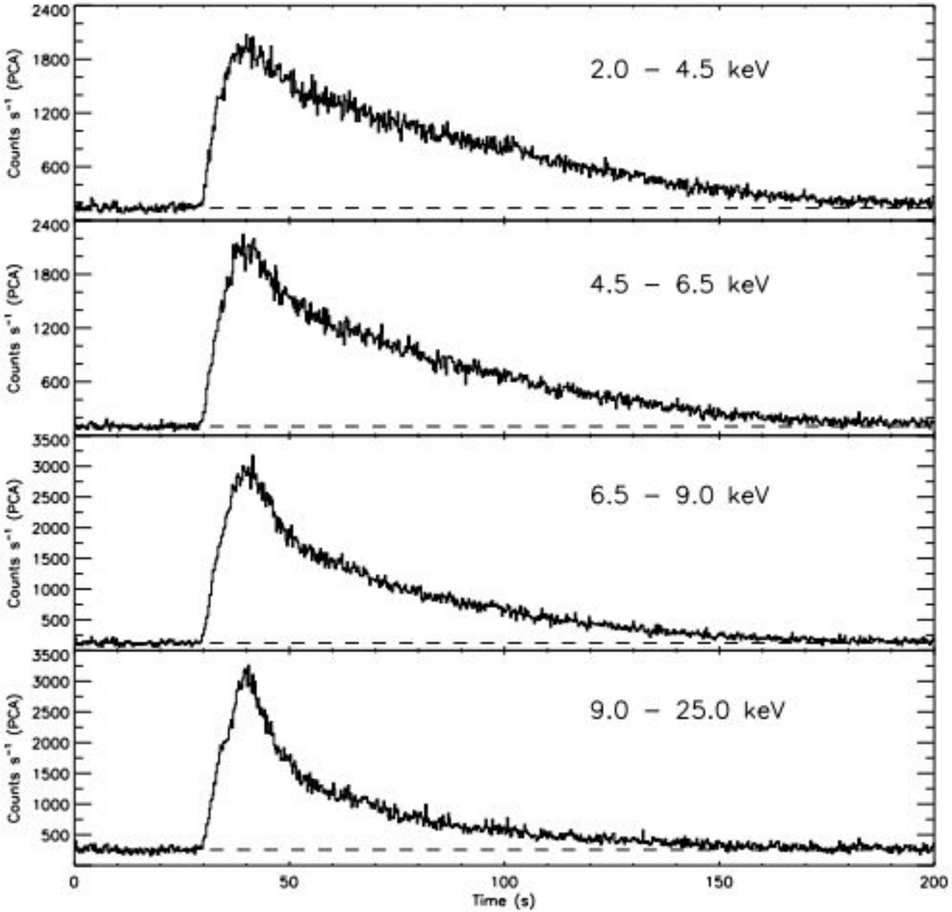


Image courtesy H. Schatz

What it really looks like

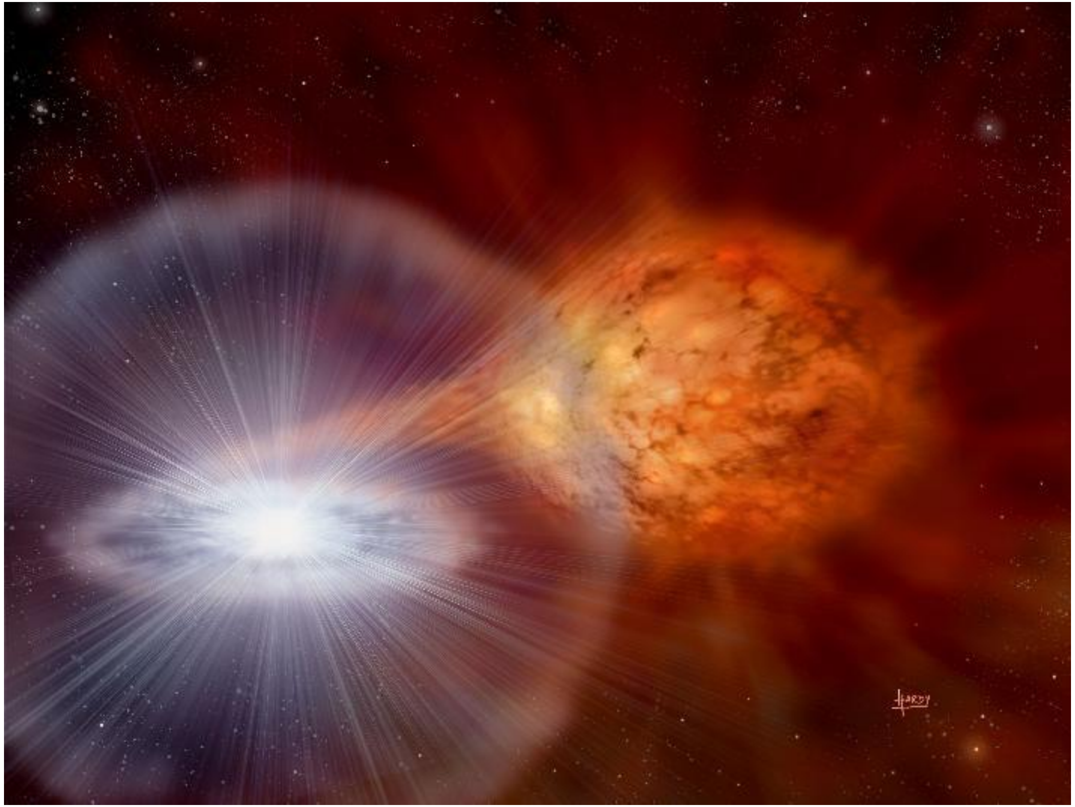


Lewin, van Paradijs, & Taam, 1993



Strohmayer & Bildsten, 2006

The ubiquitous X-ray burst picture



http://www.astro.uva.nl/research/cosmics/thermonuclear-x-ray-bursts/

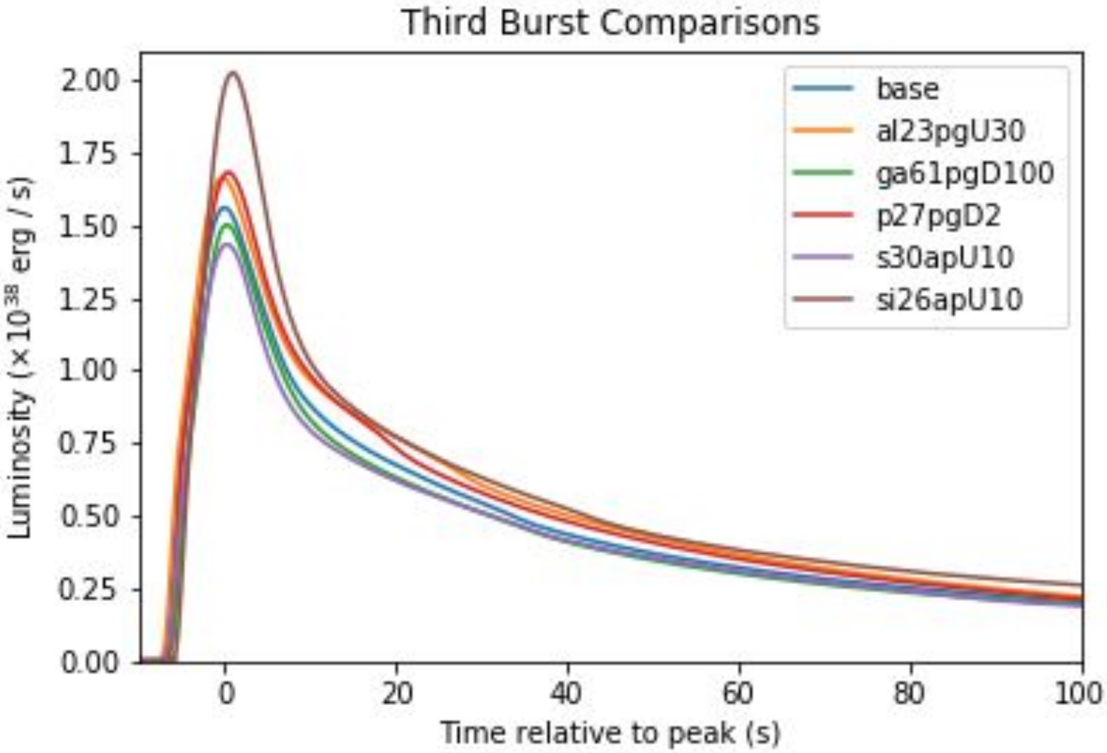
Bursts as probes of dense matter EoS

- Cooling curves probe crust properties
- Photospheric radius expansion can probe neutron star mass-radius relation:

$$L_{Edd} = (4\pi c GM/\kappa)\left(1 - 2GM/c^2R\right)^{-1/2} = 4\pi R^2 \sigma T_{eff}^4$$

- Need correct models to properly extract M-R

Early test, no ReacLib rates



Cyburt et al., 2016 Multi-Zone Reaction Variations

Table 3
Rate Variations in the Multi-zone Model Calculations

Reaction	Variation[a]	Reaction	Variation[a]	Reaction	Variation[a]
3α	x1.2 (2)	$^{12}C(\alpha,\gamma)^{16}O$	2.0 (3)	$^{12}C(p,\gamma)^{13}N$	1.1 (1)
$^{13}N(p,\gamma)^{14}O$	10	$^{14}O(\alpha,p)^{17}F$	10	$^{15}O(\alpha,\gamma)^{19}Ne$	10
$^{16}O(\alpha,\gamma)^{20}Ne$	1.80 (1)	$^{16}O(\alpha,p)^{19}F$	10	$^{17}F(\alpha,p)^{20}Ne$	10
$^{17}F(p,\gamma)^{18}Ne$	6.33[b]	$^{18}F(\alpha,p)^{21}Ne$	100	$^{19}F(\alpha,p)^{22}Ne$	10
$^{18}Ne(\alpha,p)^{21}Na$	30 (4)	$^{19}Ne(\alpha,p)^{22}Na$	10	$^{19}Ne(p,\gamma)^{20}Na$	100
$^{20}Ne(\alpha,\gamma)^{24}Mg$	1.40 (1)	$^{22}Na(\alpha,p)^{25}Mg$	10	$^{22}Na(p,\gamma)^{23}Mg$	2 (1)
$^{22}Mg(\alpha,p)^{25}Al$	10	$^{23}Mg(\alpha,p)^{26}Al$	10	$^{24}Mg(\alpha,\gamma)^{28}Si$	10
$^{23}Al(p,\gamma)^{24}Si$	30–100[c]	$^{26}Al(\alpha,p)^{29}Si$	10	$^{26}Al(p,\gamma)^{27}Si$	2[b]
$^{24}Si(\alpha,p)^{27}P$	10	$^{25}Si(\alpha,p)^{28}P$	10	$^{26}Si(\alpha,p)^{29}P$	10
$^{27}Si(p,\gamma)^{28}P$	3[b]	$^{27}P(p,\gamma)^{28}S$	2–3[c]	$^{29}P(p,\gamma)^{30}S$	10
$^{28}S(\alpha,p)^{31}Cl$	10	$^{29}S(\alpha,p)^{32}Cl$	10	$^{30}S(\alpha,p)^{33}Cl$	10
$^{31}S(p,\gamma)^{32}Cl$	6[b]	$^{31}Cl(p,\gamma)^{32}Ar$	2–3[c]	$^{34}Ar(\alpha,p)^{37}K$	10
$^{35}Ar(p,\gamma)^{36}K$	100	$^{35}K(p,\gamma)^{36}Ca$	3–10[c]	$^{36}K(p,\gamma)^{37}Ca$	10
$^{39}Ca(p,\gamma)^{40}Sc$	3[b]	$^{40}Ca(p,\gamma)^{41}Sc$	1.40[b]	$^{40}Sc(p,\gamma)^{41}Ti$	100
$^{45}V(p,\gamma)^{46}Cr$	100	$^{47}Cr(p,\gamma)^{48}Mn$	10	$^{48}Cr(p,\gamma)^{49}Mn$	100
$^{49}Cr(p,\gamma)^{50}Mn$	10	$^{47}Mn(p,\gamma)^{48}Fe$	100	$^{51}Mn(p,\gamma)^{52}Fe$	100
$^{52}Fe(p,\gamma)^{53}Co$	100	$^{53}Fe(p,\gamma)^{54}Co$	100	$^{54}Fe(p,\gamma)^{55}Co$	10
$^{54}Co(p,\gamma)^{55}Ni$	10	$^{56}Ni(\alpha,p)^{59}Cu$	100	$^{56}Ni(p,\gamma)^{57}Cu$	5[c]
$^{57}Cu(p,\gamma)^{58}Zn$	100[d]	$^{59}Cu(p,\gamma)^{60}Zn$	100	$^{60}Cu(p,\gamma)^{61}Zn$	10
$^{60}Zn(\alpha,p)^{63}Ga$	100	$^{61}Zn(p,\gamma)^{62}Ga$	100	$^{62}Zn(p,\gamma)^{63}Ga$	10
$^{61}Ga(p,\gamma)^{62}Ge$	100	$^{63}Ga(p,\gamma)^{64}Ge$	10	$^{61}Ge(p,\gamma)^{62}As$	100
$^{65}Ge(p,\gamma)^{66}As$	100	$^{66}Ge(p,\gamma)^{67}As$	100	$^{65}As(p,\gamma)^{66}Se$	100
$^{67}As(p,\gamma)^{68}Se$	100	$^{69}Se(p,\gamma)^{70}Br$	100	$^{70}Br(p,\gamma)^{71}Kr$	100
$^{71}Br(p,\gamma)^{72}Kr$	100	$^{72}Br(p,\gamma)^{73}Kr$	10	$^{73}Kr(p,\gamma)^{74}Rb$	10
$^{74}Rb(p,\gamma)^{75}Sr$	10	$^{75}Rb(p,\gamma)^{76}Sr$	100	$^{76}Rb(p,\gamma)^{77}Sr$	10
$^{79}Y(p,\gamma)^{80}Zr$	10	$^{83}Zr(p,\gamma)^{84}Nb$	10	$^{83}Nb(p,\gamma)^{84}Mo$	10
$^{84}Nb(p,\gamma)^{85}Mo$	10	$^{85}Mo(p,\gamma)^{86}Tc$	100	$^{86}Mo(p,\gamma)^{87}Tc$	100
$^{89}Tc(p,\gamma)^{90}Ru$	10	$^{92}Rh(p,\gamma)^{93}Pd$	10	$^{93}Pd(p,\gamma)^{94}Ag$	10