Thermonuclear Explosions in Neutron Stars

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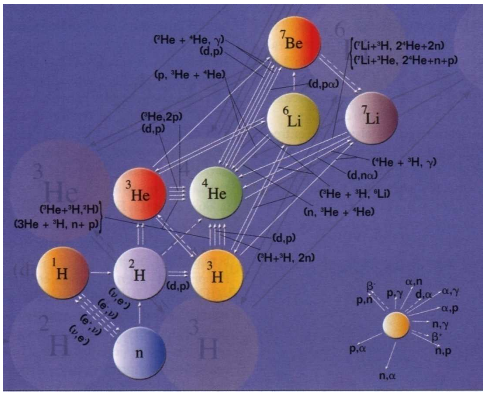
I. Introduction

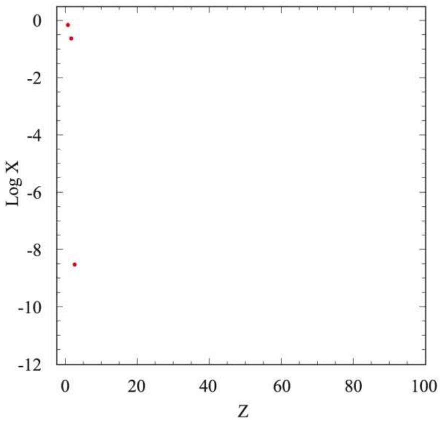


Primordial Nucleosynthesis:
~minutes after the Big Bang

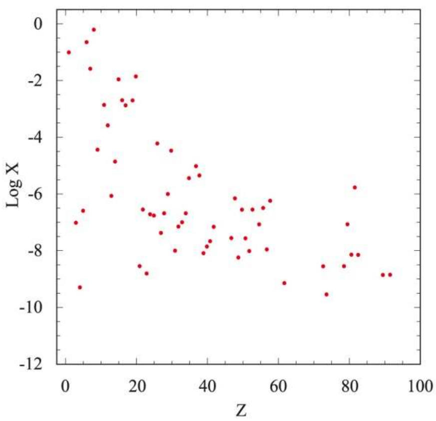
Chemical composition of the early Universe:

75% H
25% ^{4}He
+ traces of D, ^{3}He (10^{-5} %)
and ^{7}Li (10^{-7} %)

Composition of the early universe



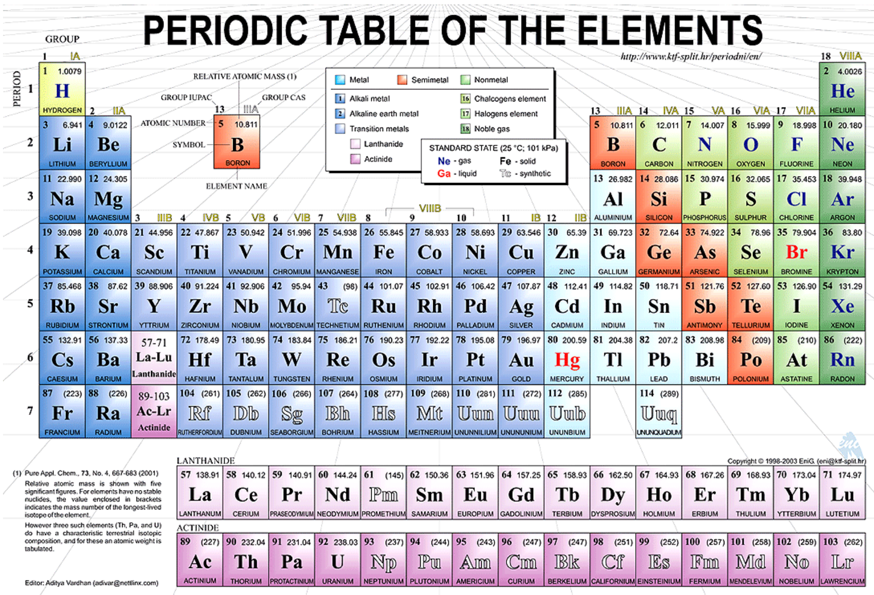
Composition of a human

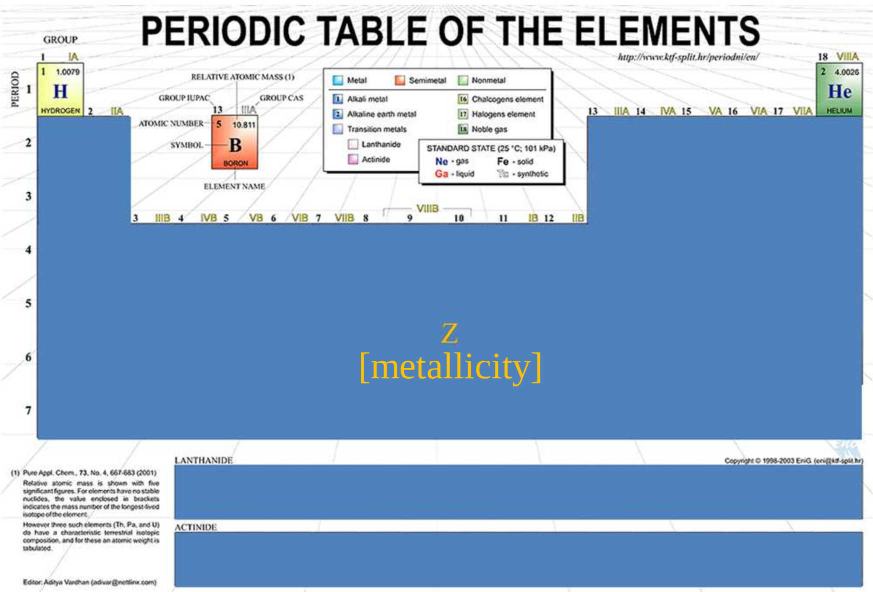


JJ (2016)

The idea that **elements** could be **synthesized in stellar environments** was developed in the mid 1940s by **F. Hoyle** (following early work on 1920/30s by Bethe, Gamow, von Weizsäcker, and others…)

P.W. Merrill detected ***technecium*** (1952) in several giant stars → **Tc** has no stable isotopes (longest lived: τ ~ 4 Myr): **Stellar nucleosynthesis**


PERIODIC TABLE OF THE ELEMENTS
http://www.ktf-split.hr/periodni/en/
Metal
Semimetal
Nonmetal
Alkali metal
Alkaline earth metal
Transition metals
Lanthanide
Actinide
Chalcogens element
Halogens element
Noble gas
STANDARD STATE (25 °C; 101 kPa)
LANTHANIDE
ACTINIDE


PERIODIC TABLE OF THE ELEMENTS
Z
[metallicity]
LANTHANIDE
ACTINIDE

Thermonuclear Supernovae

$v \sim 10^4$ km/s, $L_{Peak} \sim 10^{10}\ L_\odot$, $E \sim 10^{51}$ erg, $M_{ej} = 1.4\ M_\odot$

no remnant left

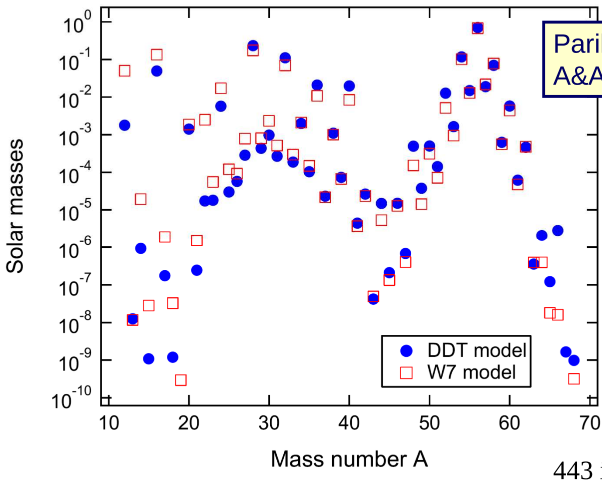
* **homogeneity:** ~70% of all **SN Ia** have similar spectra, light curves and peak absolute magnitudes (Li et al. 2011): **diversity of SNIa progenitors??**

* Scenario: not fully understood
- Single degenerate scenario: **WD + 'Normal' companion**
- Double degenerate scenario: **WD + WD**

* main **Fe factories**

Thermonuclear Supernovae: Nucleosynthesis

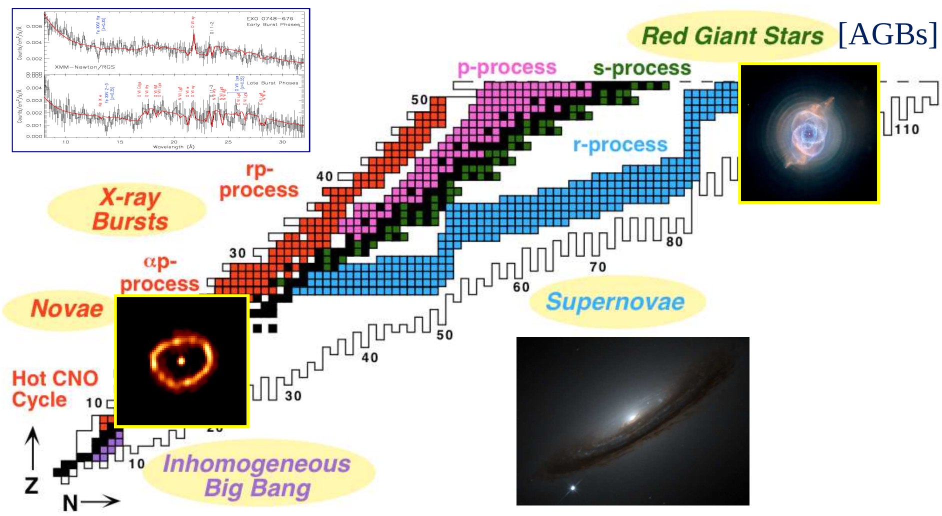
Supernovae are crucial for life... But never get too close!



Parikh, JJ, Seitenzahl & Röpke, A&A (2013)

See also:
Nomoto et al 1984,
Thielemann et al. 1986
Woosley 1986
Bravo, Isern & Canal 1993
Röpke et al. 2006
García-Senz et al. 2007
...

443 isotopes (H – Kr); 5267 links



Nucleosynthesis is produced in both **non-explosive** (i.e., **AGB Stars**) and **explosive sites** (**supernovae Ia & II,** classical novae –X-ray bursts?)

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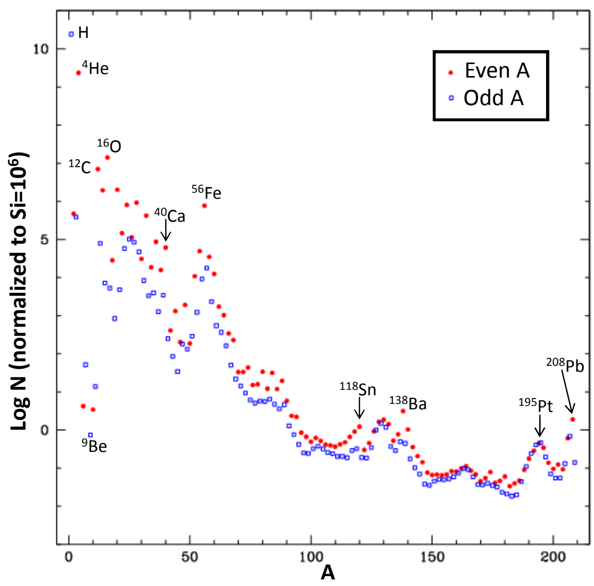
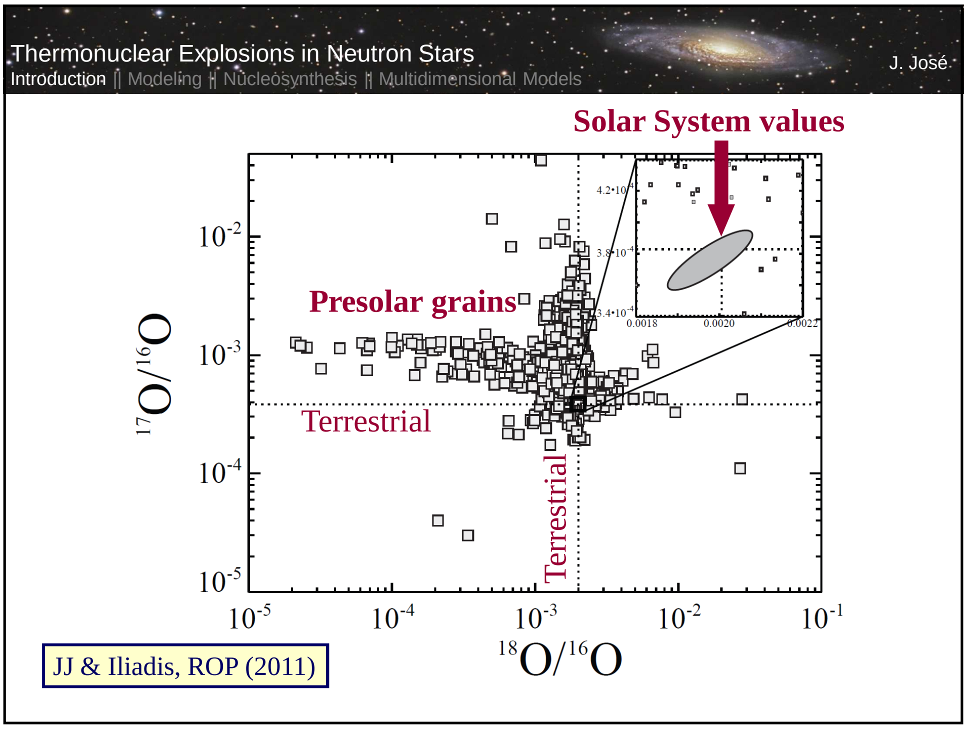


JJ & Iliadis (2011), ROP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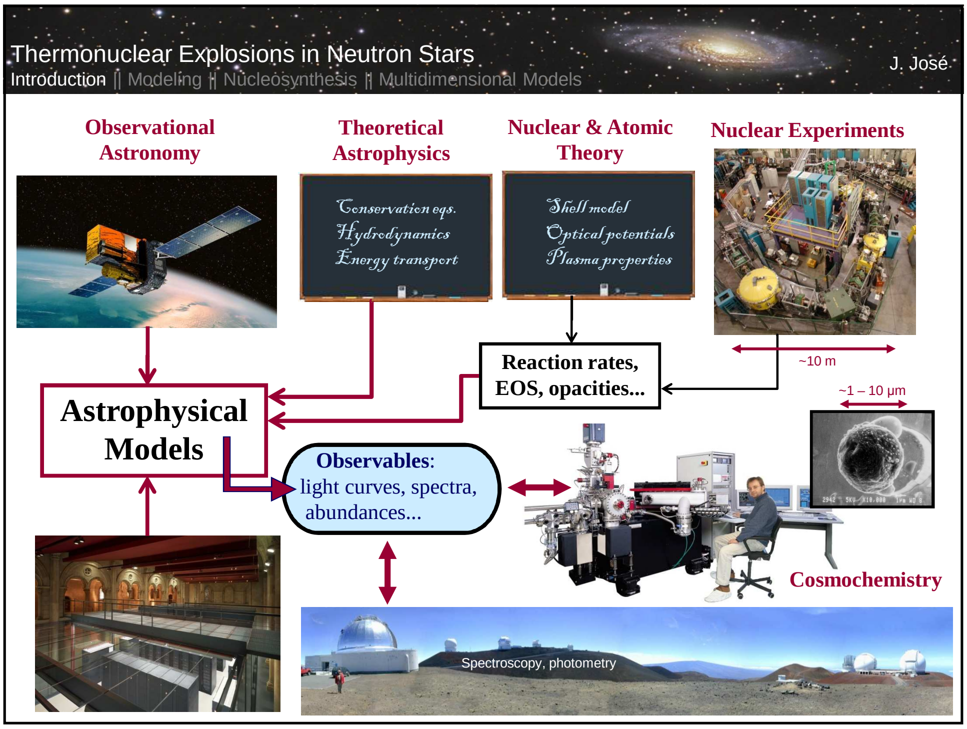
Solar System values
Presolar grains
Terrestrial
Terrestrial
$^{17}O/^{16}O$
$^{18}O/^{16}O$
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
JJ & Iliadis, ROP (2011)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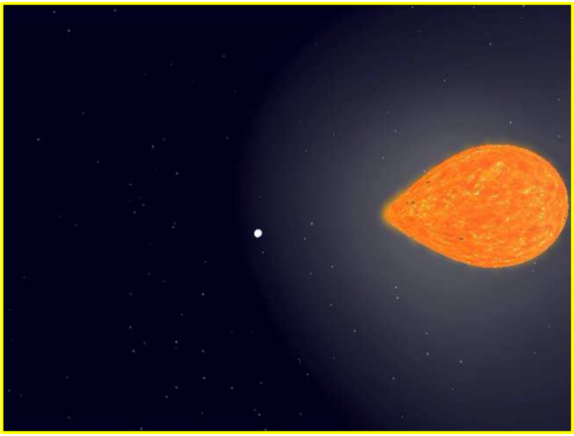
Observational Astronomy
Theoretical Astrophysics
Conservation eqs.
Hydrodynamics
Energy transport
Nuclear & Atomic Theory
Shell model
Optical potentials
Plasma properties
Nuclear Experiments
~10 m
Reaction rates, EOS, opacities...
~1 – 10 μm
Astrophysical Models
Observables: light curves, spectra, abundances...
Cosmochemistry
Spectroscopy, photometry



Type Ia (or thermonuclear) **Supernovae** [SN Ia] } WD
Classical Nova Outbursts [CN]

X-Ray Bursts [XRBs]: NS

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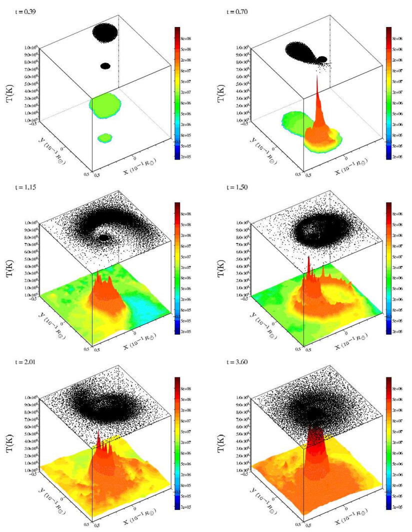
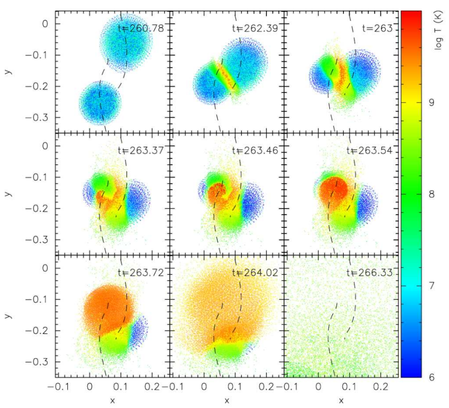
Stellar Mergers and Collisions



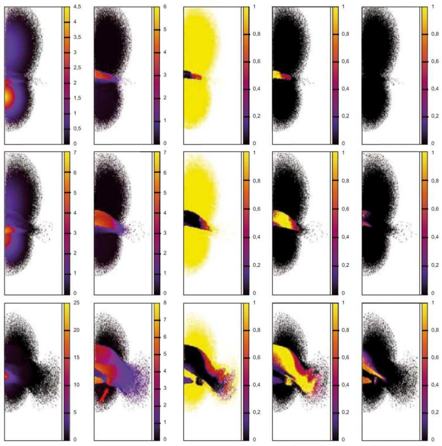


Detonations in white dwarf dynamic interactions
Aznar-Siguán, García-Berro, Lorén-Aguilar, JJ & Isern, MNRAS (2013)

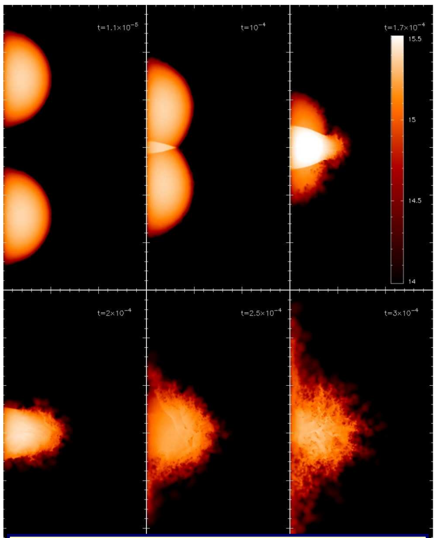
Guerrero, García-Berro & Isern, A&A (2004)

f ~ f(SNIa in spiral galaxies)

Stellar Mergers and Collisions



García-Senz, Cabezón, Arcones, Relaño & Thielemann (2013)



NS+NS, R. Cabezón, PhD Thesis (2010)

II. X-Ray Fireworks: Models vs. Observations

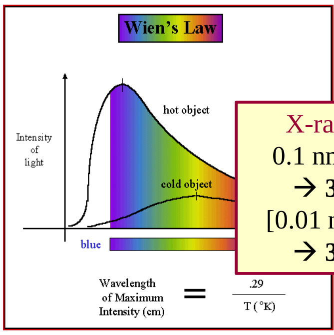
The first, primitive X-ray instruments, launched in the 1940s and 1950s on board balloons and rockets, revealed a modest amount of X-rays emitted by the Sun

↓

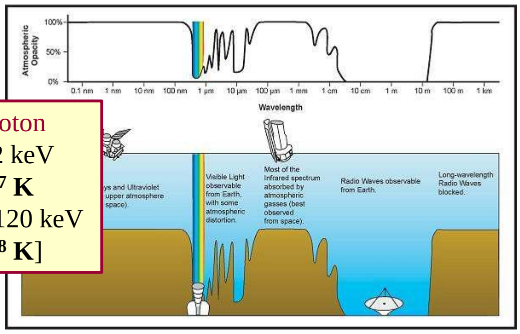
The discovery of extrasolar sources prominent in X-rays came as a real surprise: **Scorpius X-1** (X-ray) power output = 2.3×10^{38} erg s^{-1} [60,000 times the overall L_{Sun} integrated for all λ's] → launch of space probes with X-ray detectors (Solrad 1, Kosmos 215, several Vela, OSO, and OGO satellites; NASA's satellite **Uhuru** in 1970, the first specifically suited for X-ray astronomy).

Blackbody spectrum

- Blackbody source function (spectral radiant exitance; Planck's law):
  $B_\nu(T) = (2h\nu^3/c^2)/[\exp(h\nu/kT)-1]$ → units: J/(s m^2 sr Hz)
- Maximum of intensity: $\lambda_{max}\, T = 0.2897$ cm·K (Wien's law)
- Power output: $B = \int B'_\nu \cdot d\nu = \sigma T^4$ [Stefan-Boltzmann's law;
- Photon flux ∝ T^3 → units: J/(s m^2)]



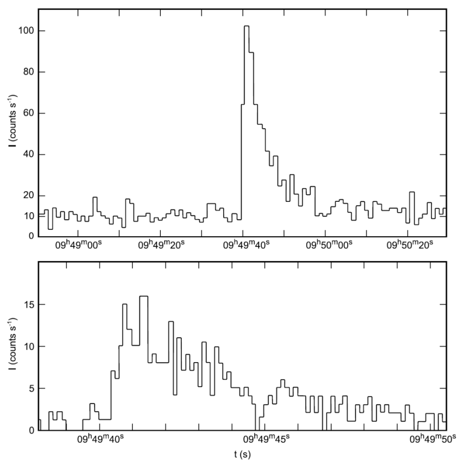
X-ray photon
0.1 nm, 12 keV
→ **3×10^7 K**
[0.01 nm, 120 keV
→ **3×10^8 K**]



A large variety of astrophysical sources have been identified in X-rays

* **Stars:** accreting white dwarfs (CNe)
  accreting neutron stars (XRBs, pulsars)
  accreting black holes (X-ray novae)
  plasma ejected from the Sun and other stars
  early-type stars
  SNe and SNRs
  GRBs
* **Galaxies:** quasars and other AGNs
* **Clusters of galaxies**

Accreting NS (XRBs) have deserved particular attention, becoming unique natural laboratories that serve as probes of the NS structure and of the properties of matter under extreme conditions → valuable info on NS (e.g., **M-R relation, EOS, thermal state**), and on **different burning regimes and flame spreading** (also relevant for other TN-driven explosions, e.g., CNe and SNIa).

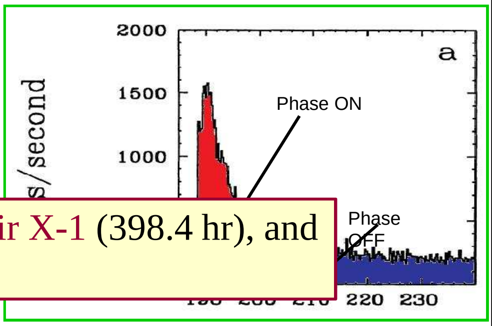


3U 1820-30 (Sgr X-4), Grindlay et al. (1976), ANS satellite

The (Type I) X-Ray Burst ID Card

Prominent emitters in X-rays [discovered in the 1970s; Babushkina et al., Grindlay et al., Belian, Conner & Evans]

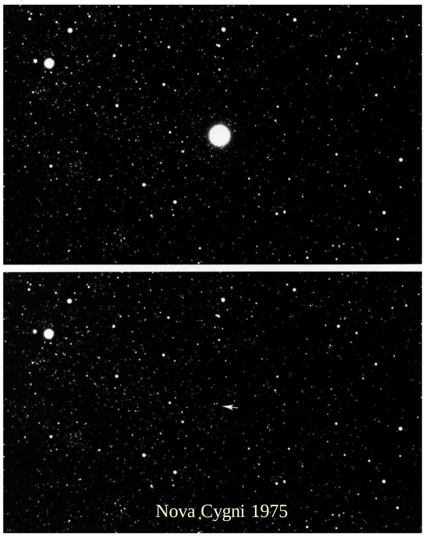
Very fast rise times (1 – 10 s)
$L_{peak} \sim 10^4 – 10^5 L_\odot$
E ~ $10^{39} – 10^{40}$ ergs (in 10 - 100 s)
Recurrence time: ~ hours – days



GX 13+1 (P_{orb} = 592.8 hr), Cir X-1 (398.4 hr), and Cyg X-2 (236.2 hr)

Orbital periods: mostly, 0.2 – 15 hr
Stellar binary systems: NS + MS; Recurrence time: ~ hr – days
Mass ejected? Unlikely (by the explosion)

Novae have been observed in all wavelengths (but detected in γ-rays only at E > 100 MeV)



The Classical Nova ID Card

Moderate rise times (<1 – 2 days):

8 – 18 magnitude increase in brigthness

$L_{Peak} \sim 10^4 – 10^5\ L_\odot$

Stellar binary systems: WD + MS (often, K-M dwarfs)

Recurrence time: ~ 1 - 100 yr (RNe) – 10^5 yr (CNe)

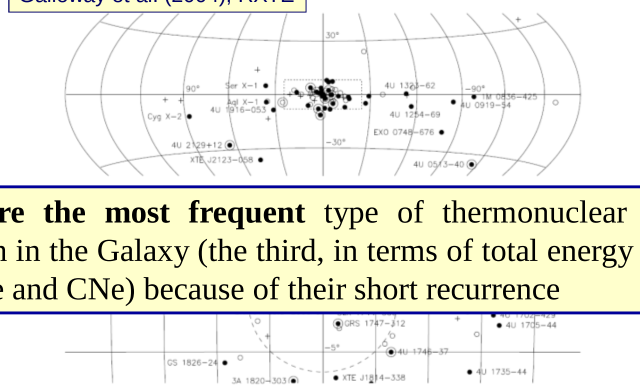
Frequency: $30 \pm 10\ yr^{-1}$

Observed frequency: $\sim 10\ yr^{-1}$

E ~ 10^{45} ergs

Mass ejected: $10^{-3} – 10^{-7}\ M_\odot$ (~10^3 km s^{-1})

Galloway et al. (2004), RXTE



XRBs are the most frequent type of thermonuclear stellar explosion in the Galaxy (the third, in terms of total energy output after SNe and CNe) because of their short recurrence

Fig. 7.— Sky distribution of bursters showing those observed by *RXTE*, as well as those from which bursts were detected. Sources within globular clusters are additionally indicated by a larger concentric circle. The lower panel shows the region around the Galactic center. The four (unlabeled) sources closest to the Galactic origin are (clockwise from lower left) are SAX J1747.0–2853, GRS 1741.9–2853, KS 1741–293 and 2E 1742.9–2929. The dashed line shows the approximate projected radius of the Galactic bulge.

107 Galactic low-mass X-ray binaries exhibiting XRBs (https://presonal.sron.nl/~jeanz/bursterlist.html) discovered to date

Type I XRB sources show a strong concentration around the Galactic center (Galloway et al. 2008), with a spatial distribution matching that of **low-mass X-ray binaries**, that is, stellar binary systems that contain either a **neutron star** or a **black hole**. In such systems, the secondary is less massive than the compact star, frequently a MS star, a RG, or even a WD.

Noticeable fraction of XRBs found in globular clusters → **old population stars** (Lewin, van Paradijs and Taam 1993)

X-Ray Burst: Classification

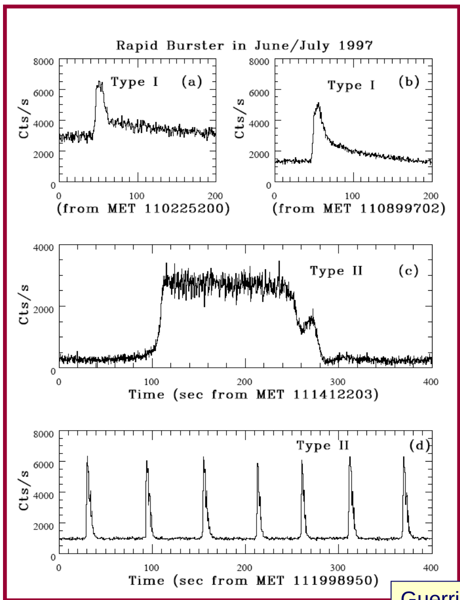
Type I X-ray bursts: TNR of accreted material on the surface of a neutron star

Type II bursts: powered by the release of gravitational potential energy, presumably resulting from an accretion disk instability

Type II bursters:

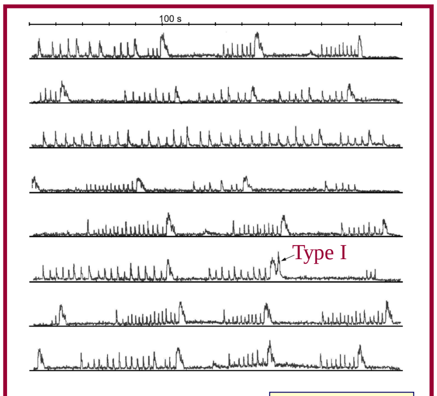
* The ***Rapid Burster*** (**MXB 1730−335**), discovered in 1976, located at a distance of 8 kpc (Ortolani, Bica, & Barbuy 1996) in the globular cluster Liller 1 (Liller 1977)

* **GRO J1744−28** (Kouveliotou et al. 1996; Lewin et al. 1996a; Kommers et al. 1997)



Guerriero et al. (2000)

Duration of type II bursts can range from **4 sec** up to **680 sec** (the longest type II XRB observed to date)



Lewin (1977)

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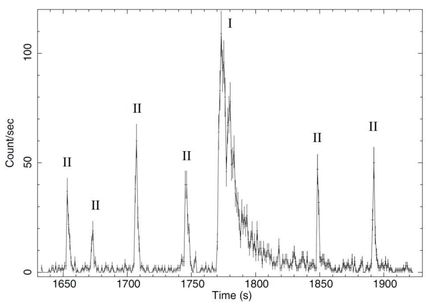

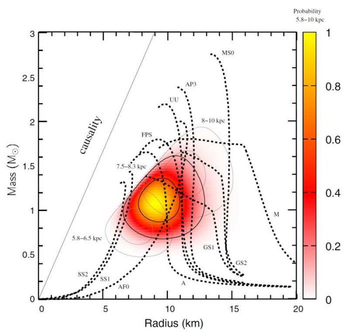

The Astrophysical Journal, 752:158 (7pp), 2012 June 20
doi:10.1088/0004-637X/752/2/158

CONSTRAINTS ON THE MASS AND RADIUS OF THE ACCRETING NEUTRON STAR IN THE RAPID BURSTER

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[2] Institut d'Estudis Espacials de Catalunya, c/Gran Capità 2-4, Ed. Nexus-201, E-08034 Barcelona, Spain
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[4] Grup de Caracterització de Materials, Departament de Física i Enginyeria Nuclear, ETSEIB, Universitat Politècnica de Catalunya, Diagonal 647, E-08028 Barcelona, Catalonia, Spain
[5] Research & Scientific Support Department, European Space Agency, ESTEC, Keplerlaan 1, NL-2200 AG Noordwijk, The Netherlands
Received 2011 September 12; accepted 2012 April 13; published 2012 June 6

Some Observational Constraints [Galloway et al. 2008]

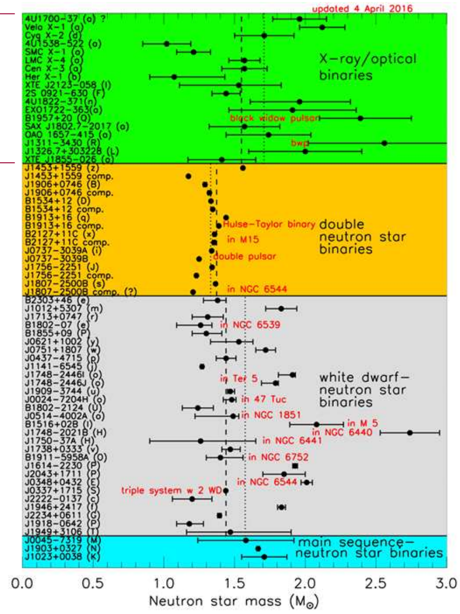
Mass-accretion rates can be inferred from the persistent X-ray flux between bursts, F_{per}:

$$\dot{M}(\mathrm{M_\odot\,yr^{-1}}) = 1.33 \times 10^{-11} \left(\frac{F_{\rm per}\, C_{\rm bol}}{10^{-9}\,\mathrm{erg\,cm^{-2}\,s^{-1}}} \right) \left(\frac{D}{10\,\mathrm{kpc}} \right)^2 \left(\frac{M_{\rm ns}}{1.4\,\mathrm{M_\odot}} \right)^{-1} \left(\frac{1+z}{1.31} \right) \left(\frac{R_{\rm ns}}{10\,\mathrm{km}} \right),$$

Maximum mass-accretion rate is set by the **Eddington limit** ($\dot{M}_{Edd} \sim 2 \times 10^{-8}\,\mathrm{M_\odot\,yr^{-1}}$, for H-rich accretion onto a 1.4 $\mathrm{M_\odot}$ NS).

NS masses in XRBs are quite uncertain

Mean: 1.708 $\mathrm{M_\odot}$



Lattimer (2012)

Clues on the Nature of X-Ray Bursts

Shortly after the discovery of the **neutron** by James Chadwick (1932), Walter Baade and Fritz Zwicky (1934) proposed that during a **SN explosion**, the nucleons of the stellar plasma are transformed into neutrons, forcing the star to adopt the closely packed configuration of a **neutron star**

Discovery of pulsars and other X-ray sources, interpreted soon as **spinning NS accreting mass from a stellar companion**

⬇

* Rosenbluth et al. (1973): **first estimates of the energy released** from accretion and fusion of H–rich material piled up onto a NS
* Van Horn and Hansen (1974, 1975) pointed out that **nuclear burning** on the surface of NS may actually be **unstable**.

The **link** between **TNRs** driven by **unstable nuclear burning and XRBs** was independently suggested by Woosley and Taam (1976) (He– or C–burning driven bursts), and Maraschi and Cavaliere (1977) (H–burning bursts)

These scenarios assumed large amounts of E_{grav} released as X-rays by the matter infalling into a compact star → **Nature of the object hosting the burst?**

Early explanations:

- a giant, supermassive **black hole** (> 100 $M_\odot$; Grindlay & Gursky 1976).
- From observations of bursting sources in **globular clusters** (from which reasonably accurate distance estimates can be obtained) → spectral evolution of one of the longest bursts observed from **4U 1724-30** by the **OSO-8 satellite** (Swank et al. 1977), best fitted with a blackbody with kT ~ 0.87–2.3 keV, suggested a much smaller object (i.e., **NS or stellar BH**) → a blackbody radius of ~ **10 km** was inferred, assuming a distance of ~ 10 kpc to the source

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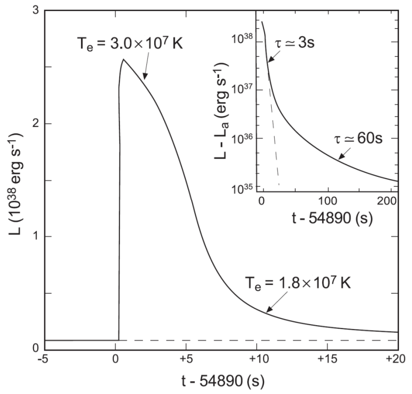
Modeling the Bursts

XRBs driven by accreting NS were first explored by means of semi–analytical models by Joss (1977), and Lamb and Lamb (1978), built on the basis of Hansen and Van Horn's models.

➡ **L_{peak} ~ 10^{37} erg s^{-1}**, light curve **rise times** of ~ 0.1 s, **burst durations** ≥ 10 s, an overall **energy release** of 10^{39} erg per burst, and ratios of persistent over burst luminosities about **α ≥ 100**, in good agreement with observationally-inferred values.

→ Likely **fuel**: **He** (and **C**)

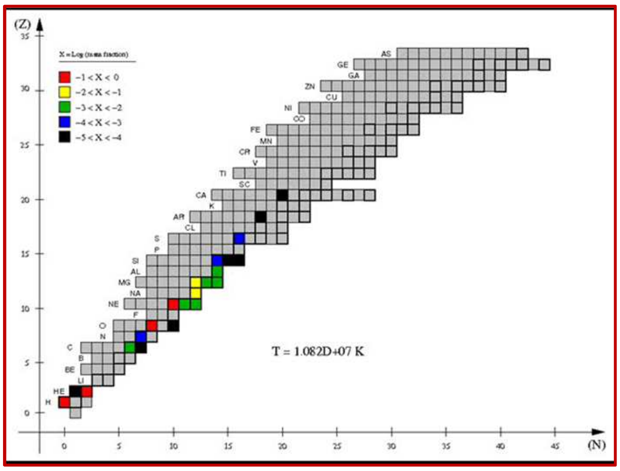
First detailed hydro **simulations** by Joss (1978): for different mass–accretion rates, and NS central temperatures



Joss (1978)

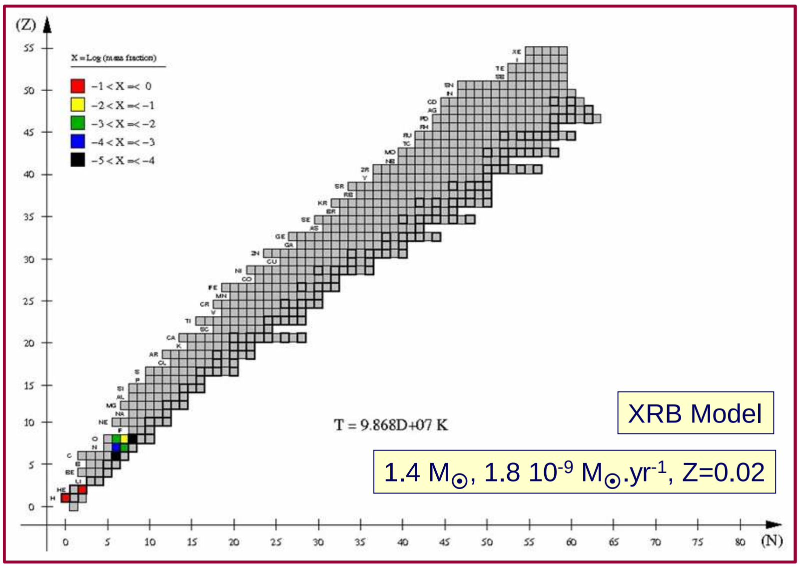
→ unstable He–burning can account for **XRB light curves** (i.e., peak luminosities, rise and decay times, the presence of low–energy tails...), **total energies, spectral features,** and **recurrence times.**

→ first claim that **nuclear fuel gets virtually consumed** (into Fe-peak nuclei); energy preferentially released in **X-rays**



1.35 $M_\odot$, 2 10^{-10} $M_\odot$.yr^{-1}, Z=Solar (+50% pre-enrichment)

Classical nova model: JJ (2016)



JJ, Moreno, Parikh & Iliadis (2010), ApJS

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Degeneracy

At the very early stages of accretion, the envelope is mildly degenerate. As in CNe, a small increase in T is enough **to lift degeneracy** in XRBs.

A simple estimate: for a chemical mixture characterized by Z/A ~ 0.5, and a density of 10^5 g cm^{-3} (close to ρ_{max}), **degeneracy is lifted** (i.e., the thermal energy of the electrons becomes comparable to the Fermi energy) at **$T \geq 1.8\times10^8$ K** (~ 0.1 T_{peak})

NS → $M_{NS} \sim 1.4\ M_{\odot}$, $R_{NS} \sim 10$ km → $v_{esc} = \sqrt{2G\ M_{NS}/R_{NS}} \sim$ **190,000 km s^{-1}**

WD → $M_{WD} \sim 1\ M_{\odot}$, $R_{WD} \sim 6000$ km → $v_{esc} \sim$ **7000 km s^{-1}**

➡ **XRBs are halted by fuel consumption** (due to efficient CNO–breakout reactions) rather than by expansion → nearly **constant pressure** at ignition depth

ρ (g cm^{-3})

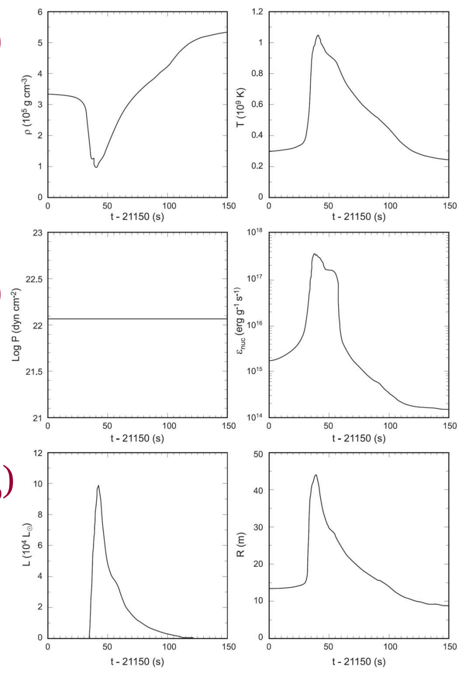
T (K)

Log P (dyn cm^{-2})

ε_{nuc} (erg g^{-1} s^{-1})

L (10^4 L$_o$)

R (m)



JJ, Moreno, Parikh & Iliadis (2010), ApJS

The modeling of TNRs on accreting NS experienced a *burst* during the 1980s:

* **semi-analytical models**: Barranco et al. 1980, Buchler et al. 1980, Czerny & Jaroszynski 1980, Ergma & Tutukov 1980, Fujimoto et al. 1981, Paczynski 1983

* **hydrostatic/hydrodynamic simulations in 1-D**: Taam & Picklum 1979, Taam 1980, Joss & Li 1980, Ayasli & Joss 1982, Taam 1982, Wallace et al. 1982, Paczynski 1983, Woosley & Weaver 1984

⬇

Most **influential parameters**: **mass–accretion rate, NS temperature (luminosity), metallicity of the accreted material** (Ayasli & Joss 1982, who also included GR corrections)

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Dependencies:

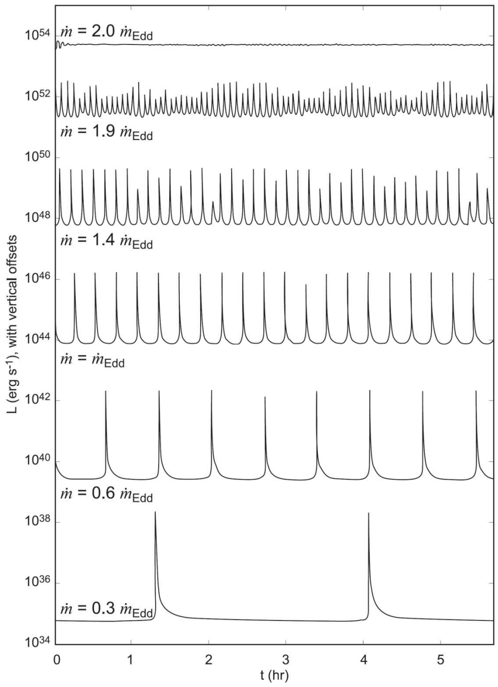
- e.g., an increase in the mass–accretion rate translates into bursts of shorter duration and recurrence (with a **stable burning** regime obtained for high mass–accretion rates)

- a reduction of the overall metallicity of the accreted material delays the burst, increasing the amount of mass piled up on top of the star, and in turn, the strength of the explosion

Major drawbacks: shared by ALL models from 1980s

- use of reduced nuclear reaction networks to limit the computational load

- results exclusively based on a single burst, because of computational constraints → major step forward: modeling of full series of bursts (properties of the first burst may be affected by the initial conditions): **XRBs vs CNe**



Zamfir, Cumming & Niquette (2014), MESA

Simulations predict that the **transition between stable and bursting regimes** (Taam 1981) **occurs at about 2 - 10 times higher mass–accretion rates than observed** (Keek et al. 2014, Zamfir et al. 2014)

Attempts to reconcile theoretical and observed values include **variations of key nuclear reaction rates** (e.g., the 3α reaction, $^{15}O(\alpha, \gamma)^{19}Ne$, and $^{18}Ne(\alpha, p)^{21}Na$ (Keek et al. 2014) or the **inclusion of a base heating flux** in models of accreting neutron stars (Zamfir et al. 2014).

Marginally–stable nuclear burning (close to transition) → **oscillations** in the XRB light curve (Cumming & Bildsten 2000, Heger et al. 2007) identified with the mHz quasi–periodic oscillations discovered in NS accreting H–rich matter at rates in the range 0.05 $\dot{M}_{Edd}$ – 0.5 $\dot{M}_{Edd}$ (Revnivtsev et al. 2001, Altamirano et al. 2008, Linares et al. 2012).

Transition to stable burning has also been invoked to account for the observed **quenching** of type I X–ray bursts following a superburst (Cumming & Bildsten 2001, Cumming & Macbeth 2004, Kuulkers et al. 2002, Keek et al. 2012)

Dependencies:
- e.g., an increase in the mass–accretion rate translates into bursts of shorter duration and recurrence (with a **stable burning** regime obtained for high mass–accretion rates)
- a reduction of the overall metallicity of the accreted material delays the burst, increasing the amount of mass piled up on top of the star, and in turn, the strength of the explosion

Major drawbacks: shared by ALL models from 1980s
- use of reduced nuclear reaction networks to limit the computational load
- results exclusively based on a single burst, because of computational constraints → major step forward: modeling of full series of bursts (properties of the first burst may be affected by the initial conditions): **XRBs vs CNe**

Lagrangian vs. Eulerian Formulation

The simulation of a sequence of **XRBs** is relatively easy in a Lagrangian framework → models suggest that no mass is directly ejected by the explosion (i.e., no numerical shell achieves escape velocity and therefore needs to be removed from the computational domain) → In sharp contrast with other astrophysical scenarios (e.g., CNe), freshly accreted material continuously piles up on top of previously accreted layers.

→ thermal (Taam 1980) and compositional inertia (Woosley & Weaver 1984)

- **thermal inertia**: role played by the energy released during a burst —and the subsequent heating of the surface layers— on the critical mass required to power the next burst
- **compositional inertia**: burst properties are sensitive to the chemical abundance pattern of the ashes of previous bursts onto which accretion and explosion will occur in the next bursting episode → reduces the influence of metallicity on burst properties.

Different **regimes of unstable burning** on NS have also been identified, including combined H/He bursts and pure He flashes
→ large spread in burst properties (Fujimoto et al. 1981, Taam 1981, Strohmayer & Bildsten 2006)

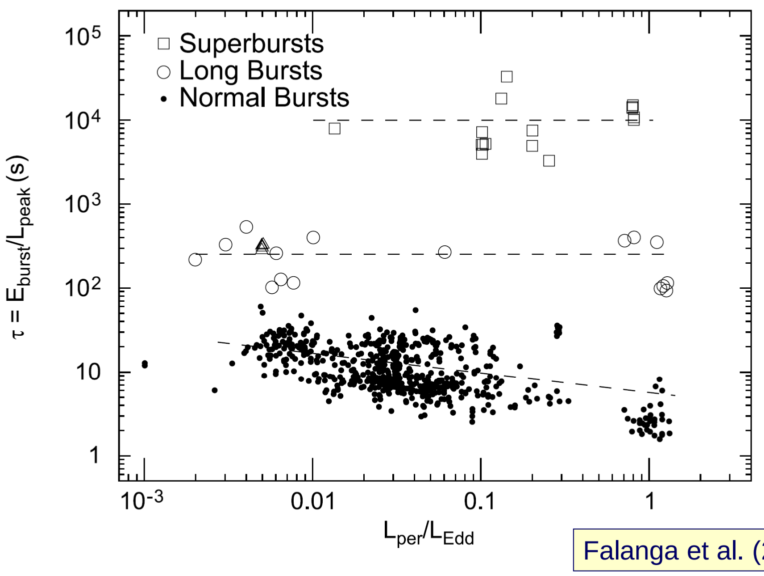
TABLE 6.1
Different burning regimes in accreting neutron stars

$\dot{M}/\dot{M}_{Edd}$	**Burning regime**
≤ 0.005	Mixed H/He flashes (initiated by H–ignition)
$\sim 0.005 - 0.03$	He flashes (with stable H–burning)
$\sim 0.03 - 1$	Mixed H/He flashes (initiated by He–ignition)
≥ 1	Stable H/He burning

Observed spread in burst properties (explained by different fuels and ignition depths)→ **XRB subtypes**: normal and intermediate–duration bursts, and superbursts

TABLE 6.2
Characteristic features in normal and intermediate–duration bursts and superbursts

	Normal bursts	Intermediate bursts	Superbursts
Duration	10 – 100 s	15 – 40 min	1 day
Energy	10^{39} erg	10^{40} – 10^{41} erg	10^{42} erg
Recurrence period	hr – days	tens of days	1 – 2 yr
Observed bursts	~ 12,000 in 104 sources	20 in 8 sources	22 in 13 sources



Falanga et al. (2008)

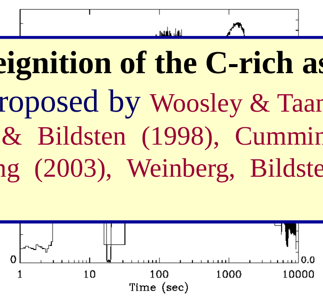
* **Normal bursts**: burst duration is determined by the characteristic cooling timescale of the burning shell (~ 10 s), which is set by the ignition depth. In the presence of H, ignition occurs at similar depths, but rapid proton captures (**rp–process**) during the decay from peak luminosity can extend the duration of a burst up to ~ 100 s.

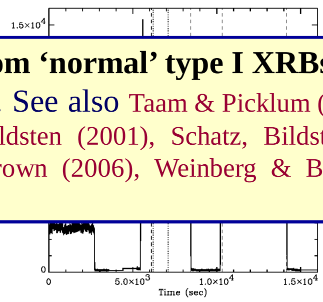
* **Intermediate–duration bursts and superbursts:** ignition at larger depths (higher pressures) →

- Intermediate–duration bursts: ignition in thick He layers on cold NS (direct/indirect He–accretion; Fujimoto et al. 1981, Wallace et al. 1982, Cumming 2003, in't Zand et al. 2005, Cumming et al. 2006, Cooper & Narayan 2007, Peng et al. 2007)

New challenges: Superbursts

* First reported in **4U 1735 –44** (Cornelisse et al. 2000: **BeppoSAX**)
* Superbursts last ~ **1000** times longer (**2 –12 hrs**), and release **~1000** times more energy (**10^{42} ergs**) than 'normal' XRBs [**4U 1636 -53**: **τ_{rec} ~ 4.7 yrs**? (Wijnands 2001)]





Reignition of the C-rich ashes from 'normal' type I XRBs?
First proposed by Woosley & Taam (1976). See also Taam & Picklum (1978), Brown & Bildsten (1998), Cumming & Bildsten (2001), Schatz, Bildsten, & Cumming (2003), Weinberg, Bildsten, & Brown (2006), Weinberg & Bildsten (2007)

Strohmayer & Brown (2002)
4U 1820 –30, RXTE

Strohmayer & Markwardt (2002)
4U 1636 –53, RXTE

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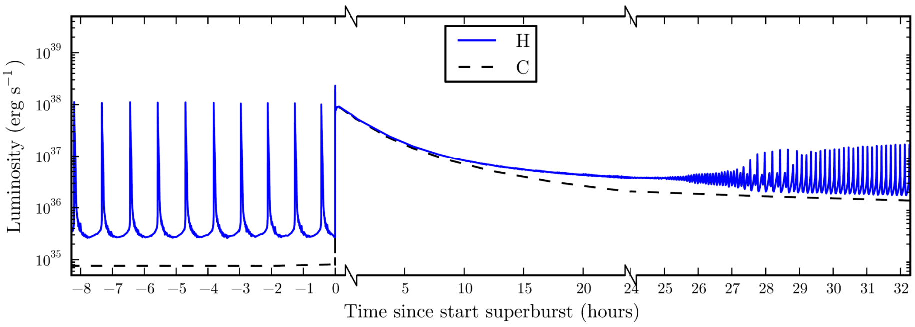

Keek, Heger & Brown (2012)

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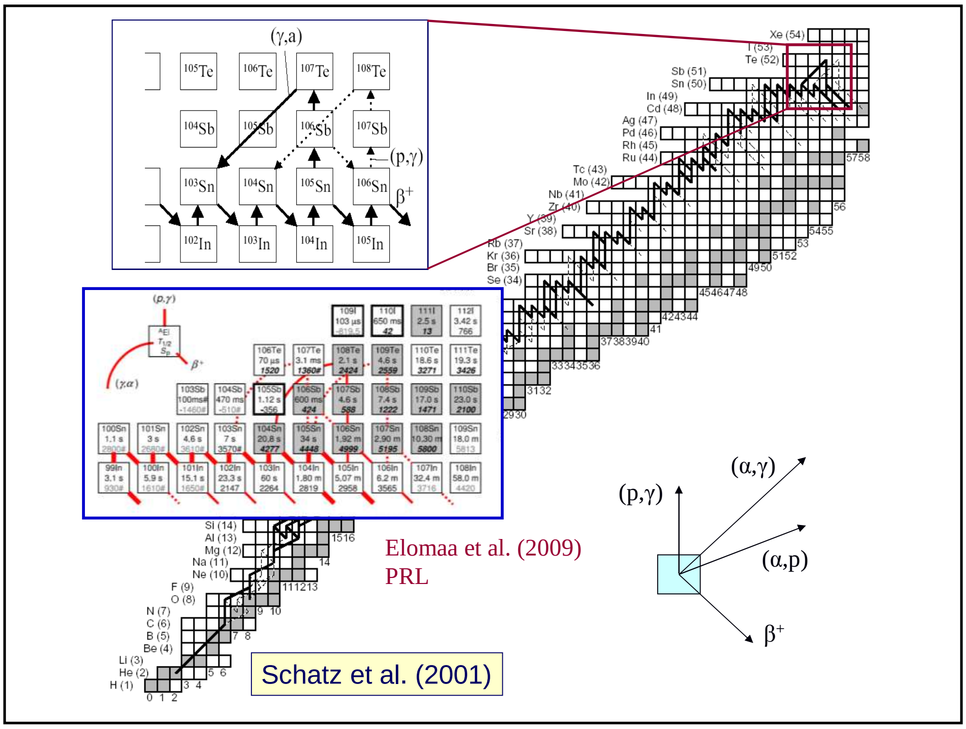
III. Nucleosynthesis in Type I XRBs

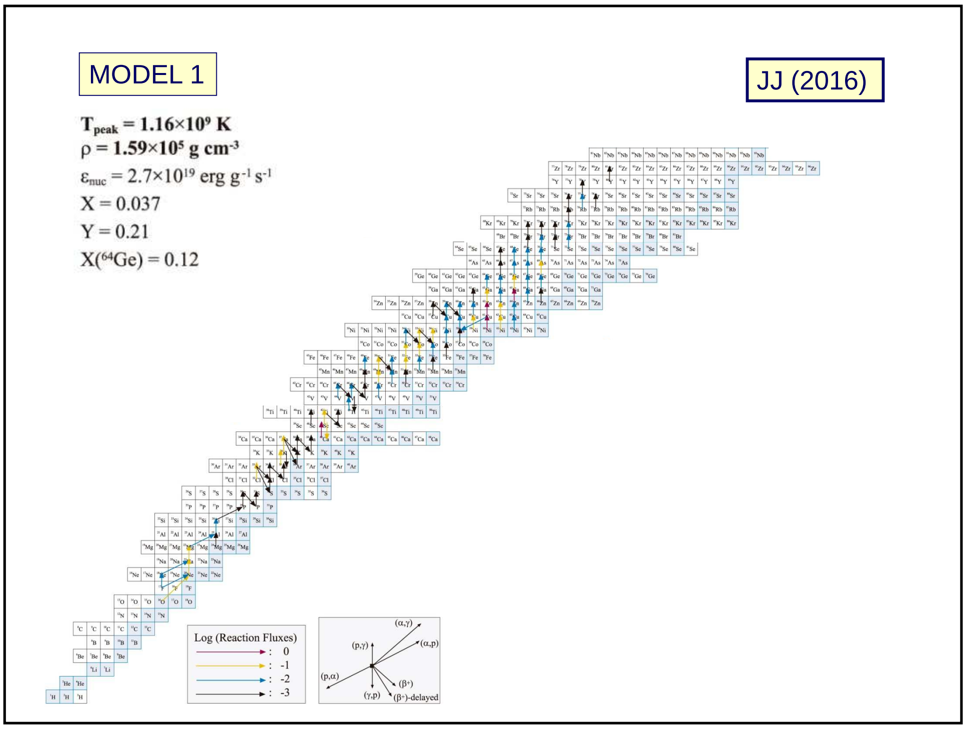
Santa Fe, NM

NS ⟶ $T_{peak} > 10^9$ **K,** $\rho_{max} \sim 10^6$ **g.cm^{-3}**

Detailed nucleosynthesis studies require **hundreds of isotopes**, up to **SnSbTe** mass region (Schatz et al. 2001) or beyond (the flow in Koike et al. 2004 reaches ^{126}Xe), and thousands of nuclear interactions

Main nuclear reaction flow driven by the *rp-process* (rapid p-captures and β^+-decays), the 3α-reaction, and the *αp-process* (a sequence of (α,p) and (p,γ) reactions), and proceeds away from the valley of stability, merging with the proton drip-line beyond **A = 38** (Schatz et al. 1999)


(γ,a)
(p,γ)
β+
Elomaa et al. (2009)
PRL
Schatz et al. (2001)
(p,γ)
(α,γ)
(α,p)
β+


MODEL 1
JJ (2016)
Tpeak = 1.16×10⁹ K
ρ = 1.59×10⁵ g cm⁻³
εnuc = 2.7×10¹⁹ erg g⁻¹ s⁻¹
X = 0.037
Y = 0.21
X(⁶⁴Ge) = 0.12
Log (Reaction Fluxes)
0
-1
-2
-3

The potential impact of XRB nucleosynthesis on **Galactic abundances** is still a matter of debate:

Ejection from a NS **unlikely** because of its large **gravitational potential** (ejection from the surface a NS of mass M and radius R requires $GMm_p/R \sim 200$ MeV/nucleon, whereas only a few MeV/nucleon are released from thermonuclear fusion)

However, it has been suggested that **radiation-driven winds** during photospheric radius expansion may lead to the ejection of a tiny fraction of the envelope (Weinberg et al. 2006a). Indeed, it has been suggested that XRBs might account for the Galactic abundances of the problematic light ***p-nuclei*** (Schatz et al. 1998)

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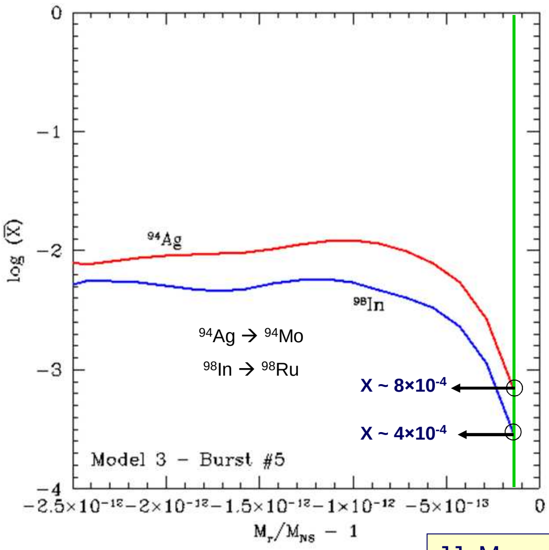

Solar abundances:

^{94}Mo = 5.5×10^{-10}

^{98}Ru = 8.6×10^{-11}

^{94}Mo / (^{94}Mo)$_\odot \approx 10^6$

^{98}Ru / (^{98}Ru)$_\odot \approx 10^6$

Far from the ***f*** required to account for the Galactic values

JJ, Moreno, Parikh & Iliadis (2010), ApJS

Some models achieve high pressures and densities at the envelope base → strong bursts, with short periods of **super–Eddington luminosities**, frequently accompanied by the presence of **precursors** in the X–ray light curve, together with mass–loss episodes through **radiation–driven winds**

Radiation–driven winds: the radiation flux that difusses outwards from the burning regions may exceed the local Eddington limit in the outer, cooler layers of the star → hydrostatic equilibrium is broken. Pioneering models: Kato (1983), Ebisuzaki et al. (1983), and Quinn and Paczynski (1985). GR effects were introduced by Paczynski and Proszynski (1986), and Turolla et al. (1986).

More refined treatments of radiative transfer in quasi–static winds from NS (Joss & Melia 1987, Yahel et al. 1987, Nobili et al. 1994, Weinberg et al. 2006) yield $\dot{M}_{loss} \sim 10^{17} - 10^{20}$ **g s^{-1} ($10^{-9} - 10^{-6}$ $M_\odot$ yr^{-1})**

But ask **Yago Herrera** (UPC) for the latest news on radiation-driven winds!

If XRBs likely do not contribute to the Galactic abundances, what their associated nucleosynthesis is important for?

↓

Several **thermal** (Miralda-Escudé, Paczynski, & Haensel 1990; Schatz et al. 1999) and **electrical** properties (Brown & Bildsten 1998; Schatz et al. 1999) of NS depend critically on the specific chemical composition of the envelope

Ashes may provide characteristic **signatures** such as gravitationally redshifted atomic absorption lines from the NS surface that may be identified through **high-resolution X-ray spectra**

→ Cottam, Paerels, & Mendez (2002); Bildsten, Chang, & Paerels (2003); Chang, Bildsten, & Wasserman (2005); Chang et al. (2006); Weinberg, Bildsten, & Schatz (2006)

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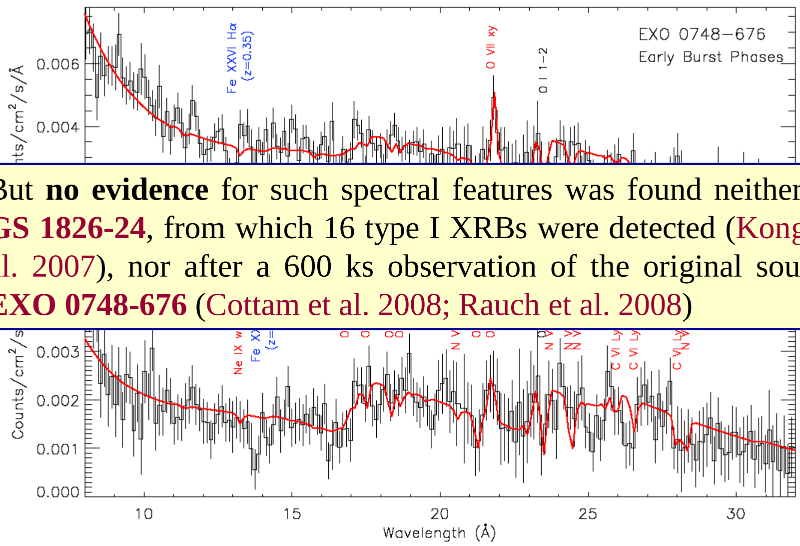
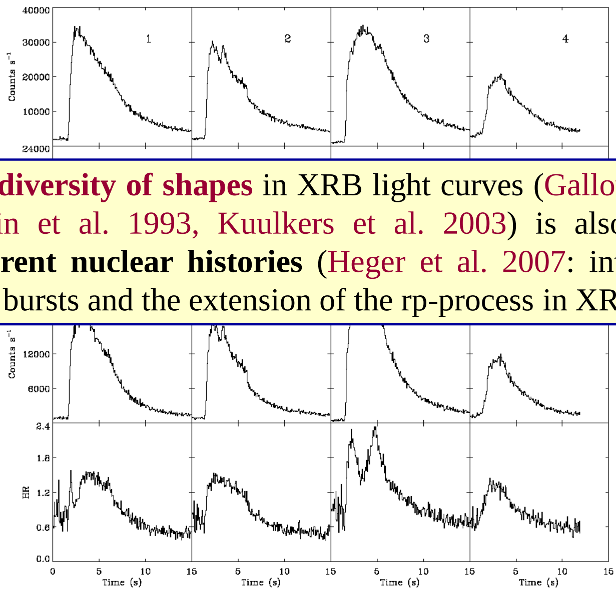


But **no evidence** for such spectral features was found neither in **GS 1826-24**, from which 16 type I XRBs were detected (Kong et al. 2007), nor after a 600 ks observation of the original source **EXO 0748-676** (Cottam et al. 2008; Rauch et al. 2008)

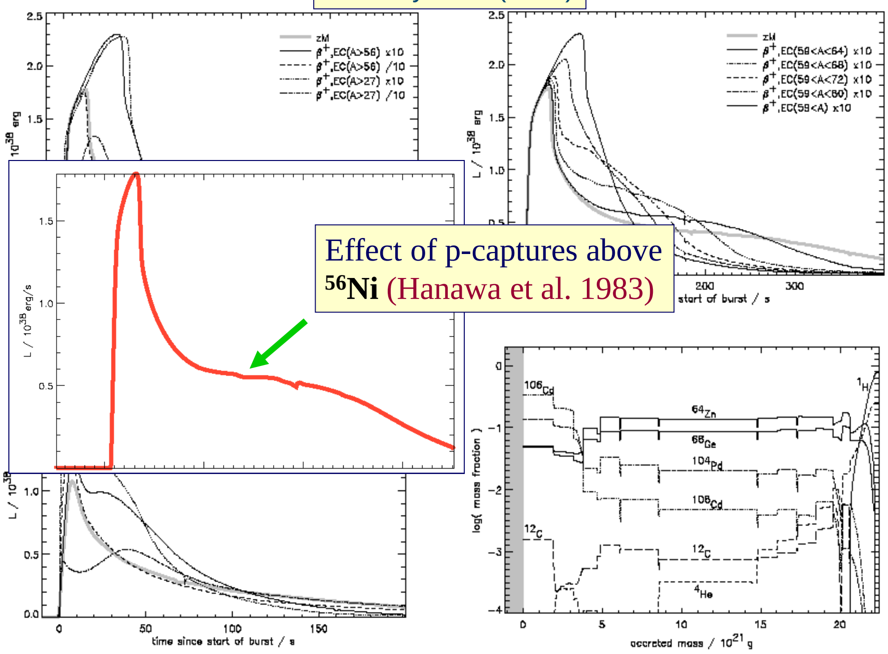
High-resolution spectra (Cottam, Paerels, & Mendez 2002, Nature)



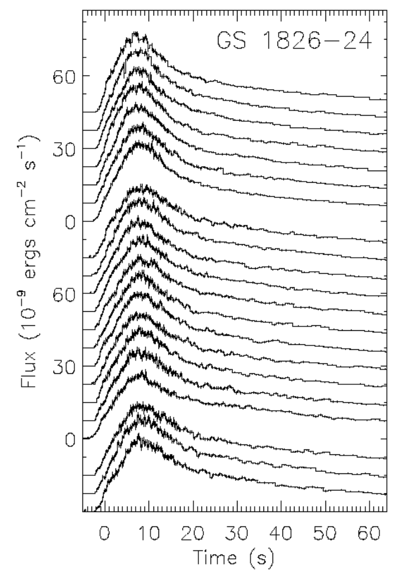
The **diversity of shapes** in XRB light curves (Galloway et al. 2007, Lewin et al. 1993, Kuulkers et al. 2003) is also likely due to **different nuclear histories** (Heger et al. 2007: interplay between long bursts and the extension of the rp-process in XRBs)

Strohmeyer & Bildsten (2002)
4U 1728 –34, RXTE

Woosley et al. (2004)



Effect of p-captures above ^{56}**Ni** (Hanawa et al. 1983)



Galloway et al. (2004), RXTE

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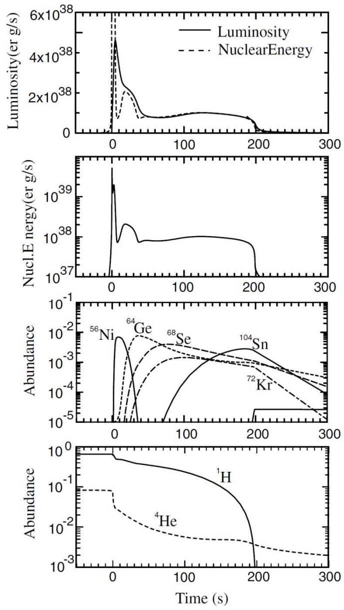
Computational limitations: → studies of XRB nucleosynthesis using **limited** nuclear reaction networks

* Up to **Ni** (Woosley & Weaver 1984; Taam et al. 1993; Taam, Woosley, & Lamb 1996 –all using a **19-isotope network**)
* **Kr** (Hanawa, Sugimoto, & Hashimoto 1983 –**274 isotope-network**; Koike et al. 1999 –**463 nuclides**)
* **Cd** (Wallace & Woosley 1984 –**16-isotope network**)
* **Y** (Wallace & Woosley 1981 –**250-isotope network**)

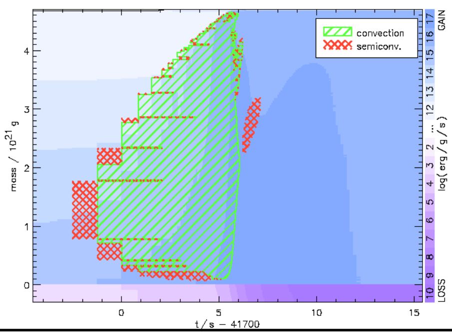
Schatz et al. (1999, 2001) carried out very detailed nucleosynthesis calculations with a network **>600 isotopes** (up to **Xe**), but using a one-zone approach [see Koike et al. (2004) for other one-zone nucleosynthesis calculations, with T-ρ profiles from 1-D calculations, and a **1270-isotope network** up to **Bi**]

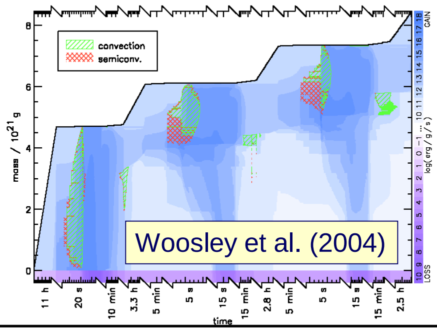
Different numerical approaches and approximations:
Hydrodynamic simulations with limited networks and/or **one-zone calculations** with detailed networks!



Schatz et al., PRL (1999)

Recent attempts to couple **1-D hydrodynamic calculations** [No realistic multi-D simulation performed to date!] and **detailed networks** include Fisker et al. (2004, 2006, 2007, 2008) and Tan et al. (2007) (using networks of **~300 isotopes**, up to **^{107}Te**), JJ et al. (2006, 2010) (using a network of **2640 nuclear reactions**, and **478 isotopes**, up to **Te**) and Woosley et al. (2004), Heger et al. (2007) (using up to **1300 isotopes** with an adaptive network)





Woosley et al. (2004)

Spherically symmetric, **H**ydrodynamic, **I**mplicit no**VA** code

SHIVA Code

JJ & Hernanz (1998), JJ (2016)

The Astrophysical Journal Supplement Series, 189:204–239, 2010 July

HYDRODYNAMIC MODELS OF TYPE I X-RAY BURSTS: METALLICITY EFFECTS

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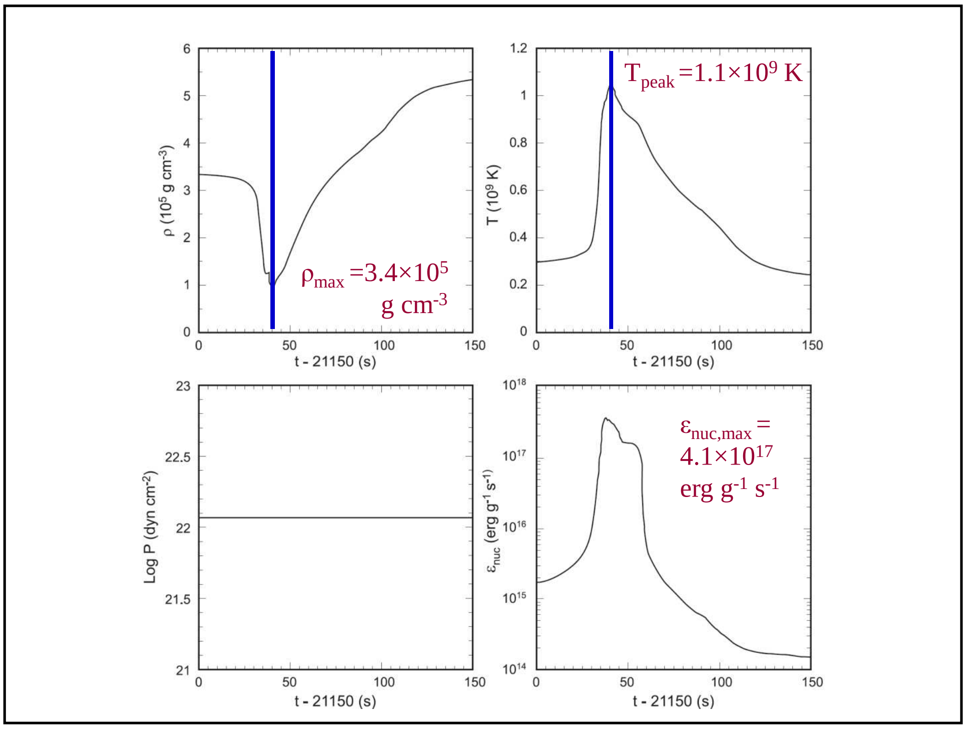
Received 2009 December 16; accepted 2010 May 24; published 2010 June 30

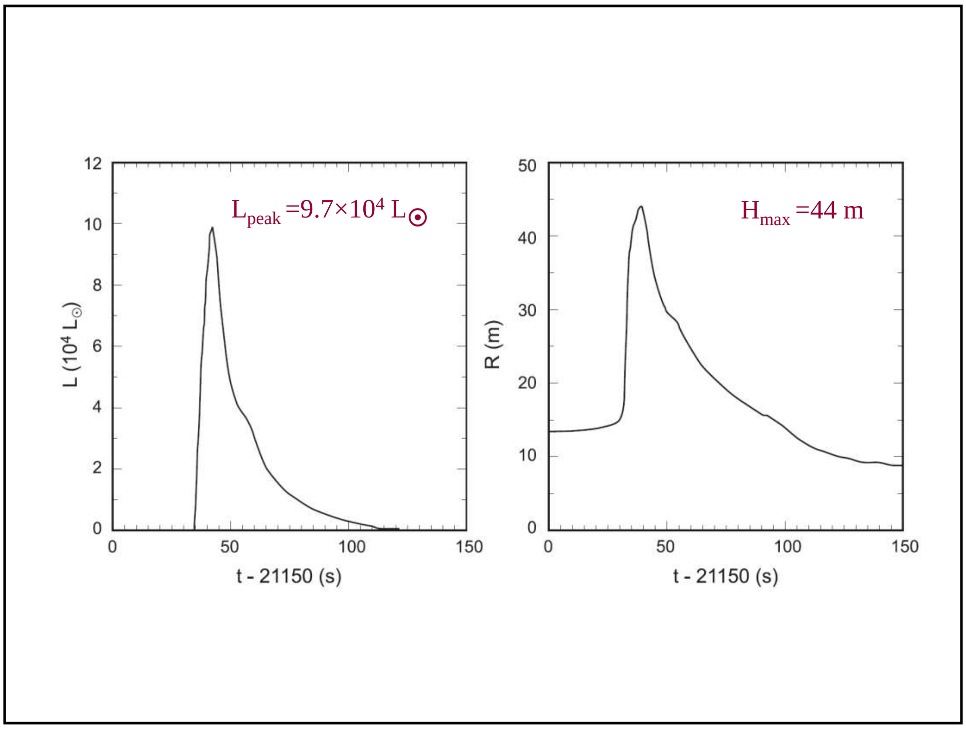
MODEL 1, solar metallicity

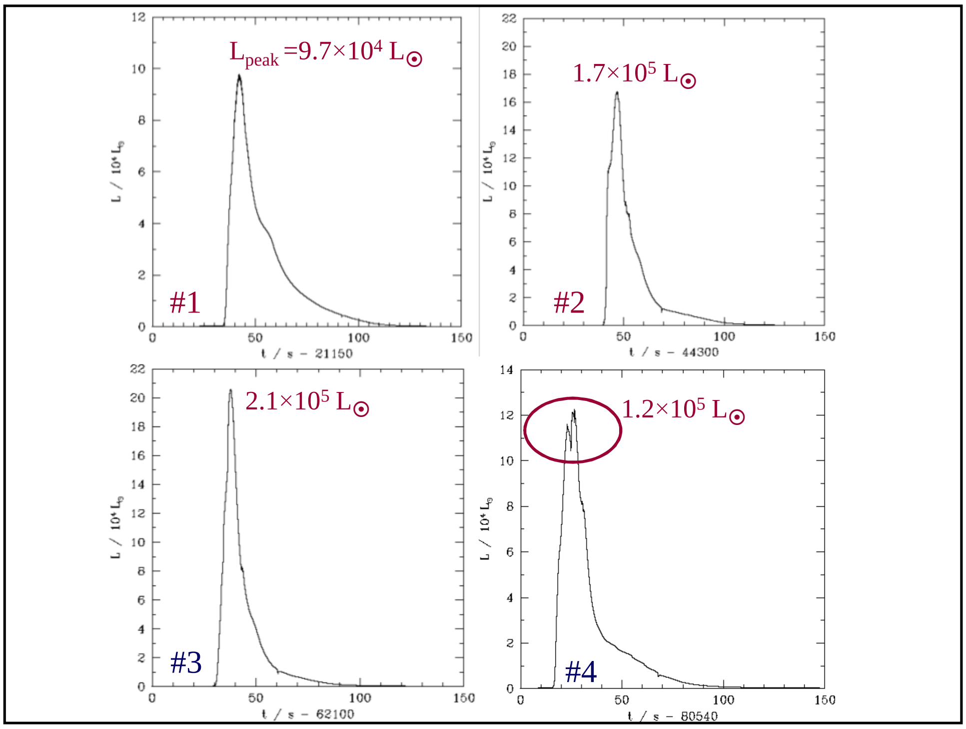
Burst #	T_{peak} (GK)	τ_{rec} (hr)	L_{peak} (10^{38} erg·s^{-1})	$t_{0.01}$ (s)	α
1	1.06	5.9	3.8	75.8	60
2	1.15	6.4	6.6	62.3	40
3	1.26	4.9	8.2	55.4	34
4	1.12	5.1	4.7	75.7	36

Similar to the observed properties (τ_{rec}, α) of several XRB sources:

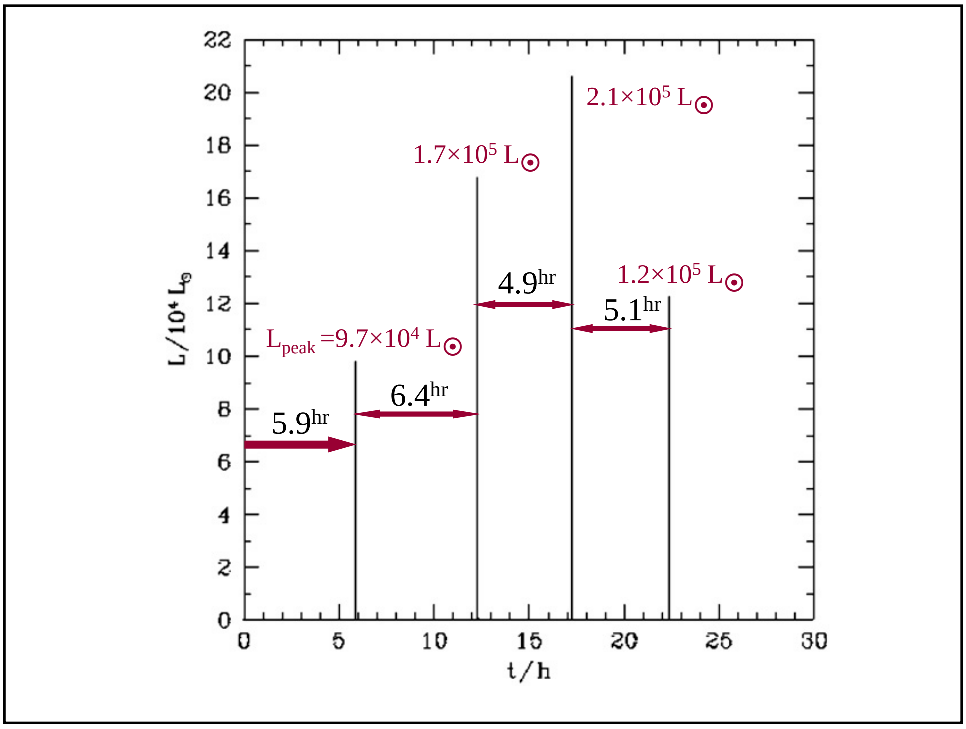
* GS 1826-24 **[τ_{rec} = 5.74 ± 0.13 hr, α = 41.7 ± 1.6]**
* 4U 1323-62 **[τ_{rec} = 5.3 hr, α = 38 ± 4]**
* 4U 1608-52 **[τ_{rec} = 4.14−7.5 hr, α = 41−54]**


ρ (10^5 g cm^-3)
t - 21150 (s)
ρmax =3.4×10^5 g cm^-3
T (10^9 K)
Tpeak =1.1×10^9 K
Log P (dyn cm^-2)
εnuc (erg g^-1 s^-1)
εnuc,max = 4.1×10^17 erg g^-1 s^-1


L (10^4 L⊙)
Lpeak =9.7×10^4 L⊙
t - 21150 (s)
R (m)
Hmax =44 m



L_peak =9.7×10^4 L⊙
1.7×10^5 L⊙
2.1×10^5 L⊙
1.2×10^5 L⊙
#1
#2
#3
#4
L / 10⁴ L⊙
t / s − 21150
t / s − 44300
t / s − 62100
t / s − 80540



L/10⁴ L⊙
t/h
L_peak =9.7×10^4 L⊙
1.7×10^5 L⊙
2.1×10^5 L⊙
1.2×10^5 L⊙
5.9^hr
6.4^hr
4.9^hr
5.1^hr

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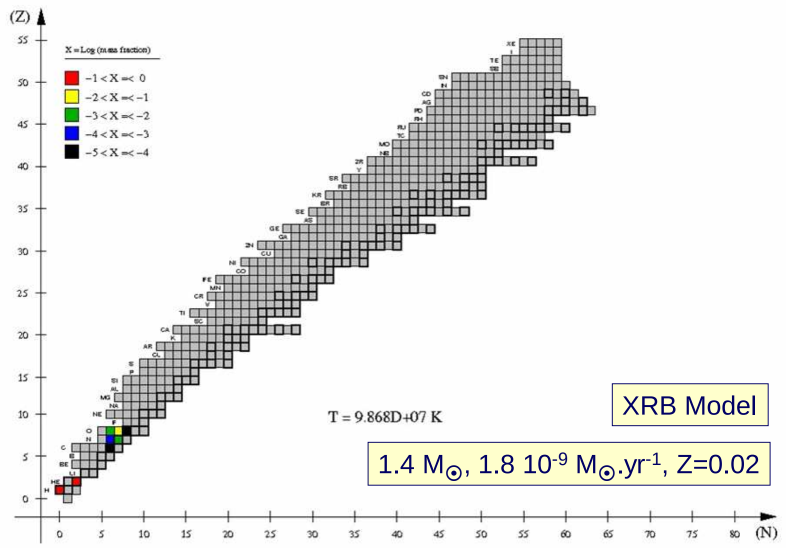

XRB Model

1.4 $M_\odot$, 1.8 10^{-9} $M_\odot.yr^{-1}$, Z=0.02

JJ, Moreno, Parikh & Iliadis (2010), ApJS

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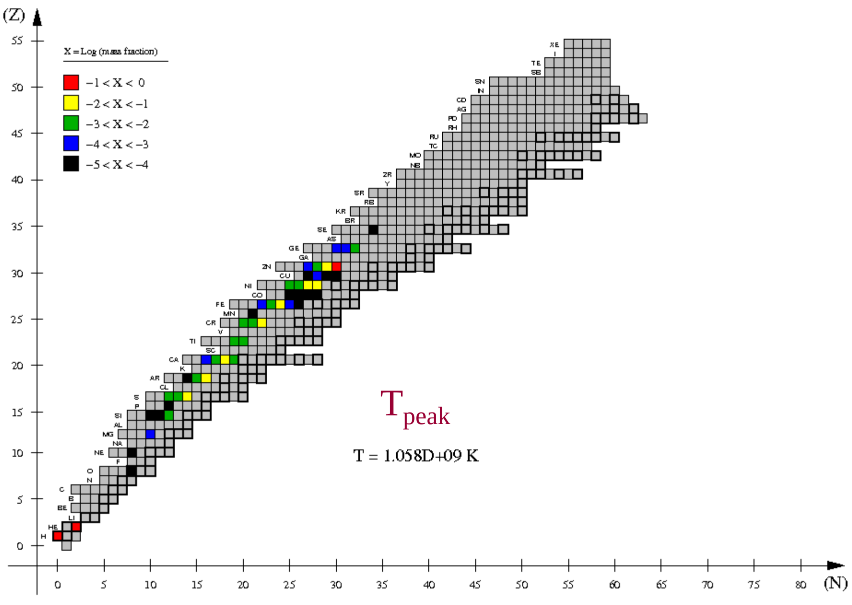
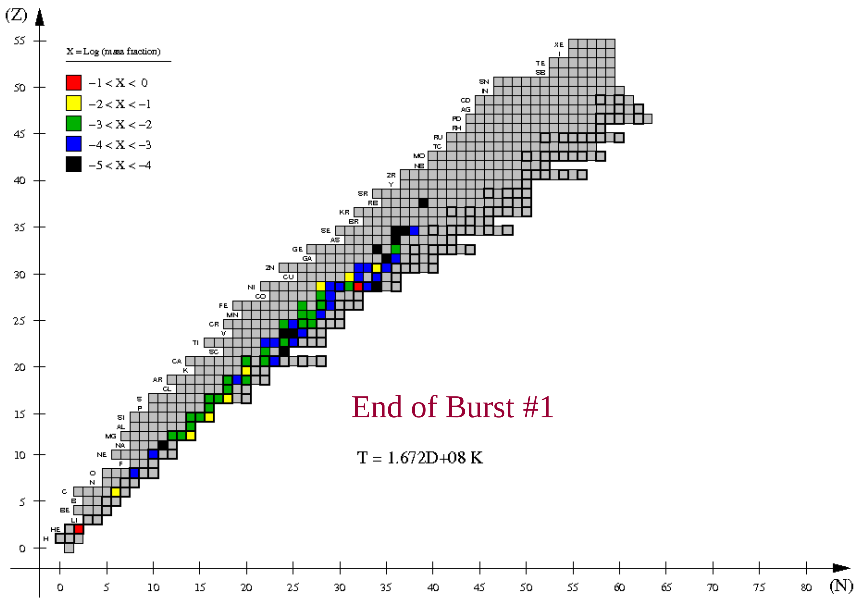
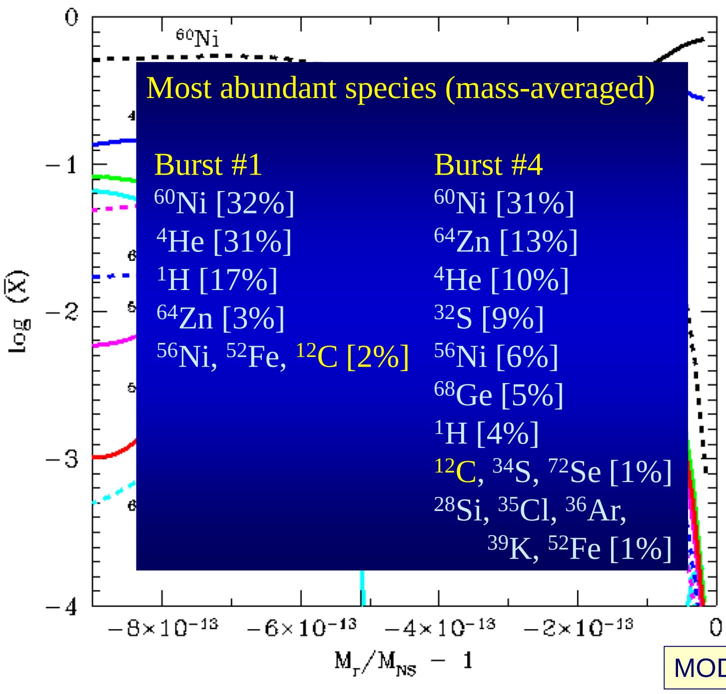






Most abundant species (mass-averaged)

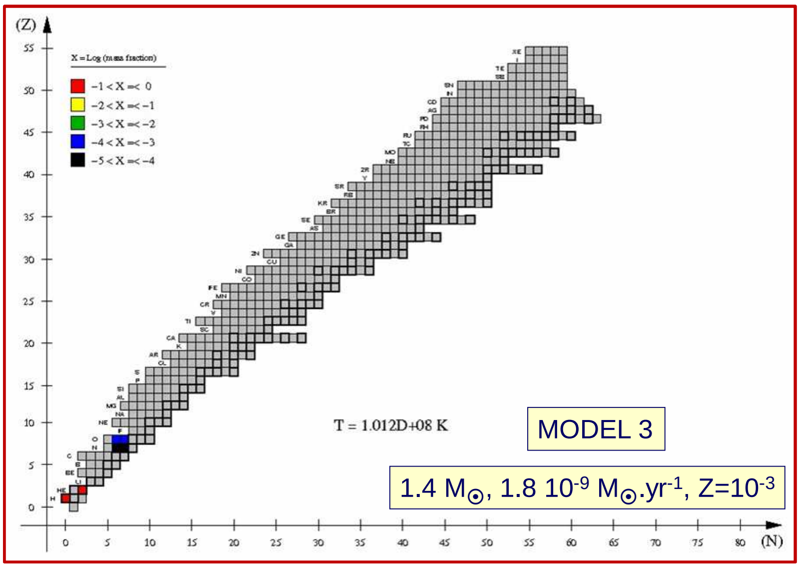
Burst #1	Burst #4
^{60}Ni [32%]	^{60}Ni [31%]
^{4}He [31%]	^{64}Zn [13%]
^{1}H [17%]	^{4}He [10%]
^{64}Zn [3%]	^{32}S [9%]
^{56}Ni, ^{52}Fe, ^{12}C [2%]	^{56}Ni [6%]
	^{68}Ge [5%]
	^{1}H [4%]
	^{12}C, ^{34}S, ^{72}Se [1%]
	^{28}Si, ^{35}Cl, ^{36}Ar, ^{39}K, ^{52}Fe [1%]

MODEL 3, Z=10^{-3}

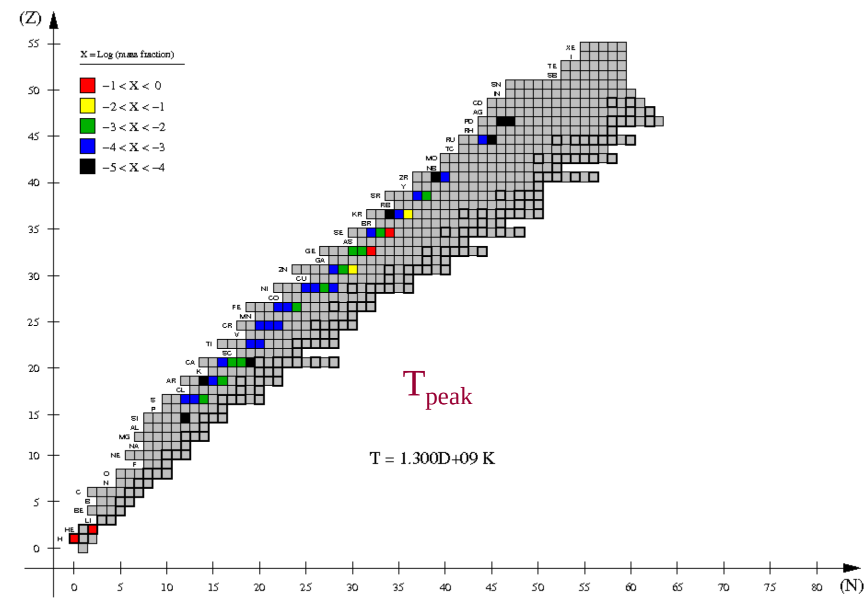
Burst #	T_{peak} (GK)	τ_{rec} (hr)	L_{peak} (10^{38} erg·s^{-1})	$t_{0.01}$ (s)	α
1	1.40	18.1	3.9	423	34
2	1.39	9.4	4.3	296	24
3	1.32	8.9	3.8	281	24
4	1.30	8.9	3.9	252	27
5	1.26	8.9	3.9	250	30

Similar to the observed properties (τ_{rec}, α) of several XRB sources:

* 1A 1905+00 **[τ_{rec} = 8.9 hr]**
* 4U 1254-69 **[τ_{rec} = 9.2 hr]**
* XTE J1710-281 **[τ_{rec} = 8.9 hr, α = 22−100]**



Type I XRB: JJ, Moreno, Parikh & Iliadis (2010), ApJS



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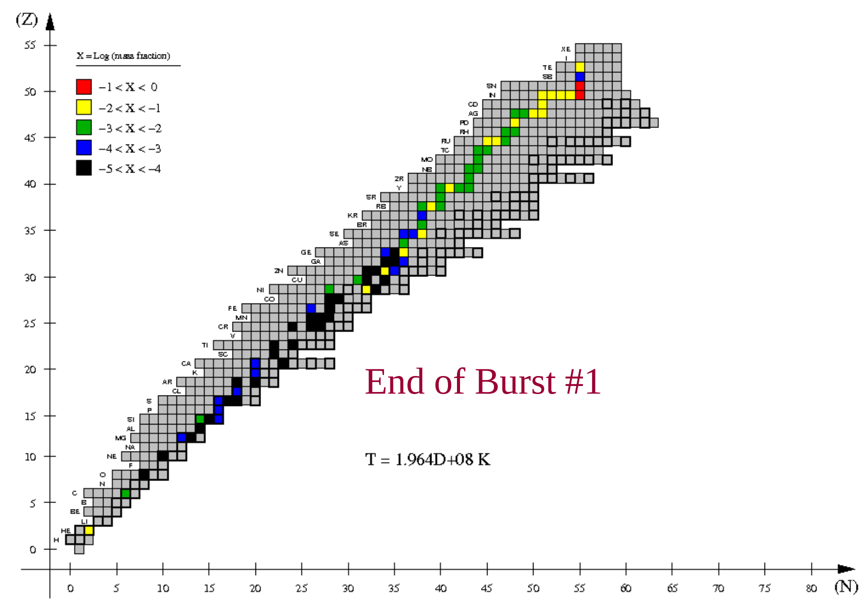

Most abundant species (mass-averaged)

Burst #1	Burst #3
^{1}H [18%]	^{105}Ag [14%]
^{4}He, ^{105}Ag [8%]	^{64}Zn, ^{104}Pd [7%]
^{104}Pd [5%]	^{1}H, ^{68}Ge [6%]
^{64}Zn [4%]	^{60}Ni, ^{94}Tc [5%]
^{68}Ge, ^{94}Tc, ^{95}Ru, ^{103}Ag [3%]	^{4}He [4%]
^{60}Ni, ^{72}Se, ^{82}Sr, ^{86,87}Zr, ^{89}Nb, ^{100,101,102}Pd [2%]	^{72}Se, ^{103}Ag [3%]
	^{76}Kr, ^{86}Zr, ^{89}Nb, ^{99}Rh, ^{101,102}Pd [2%]
	^{65}Zn, ^{69}Ge, ^{80,82,83}Sr, ^{91}Nb, ^{95,97,98}Ru [1%]
^{12}C ~ 0.08%	^{12}C ~ 0.1%

MODEL 3

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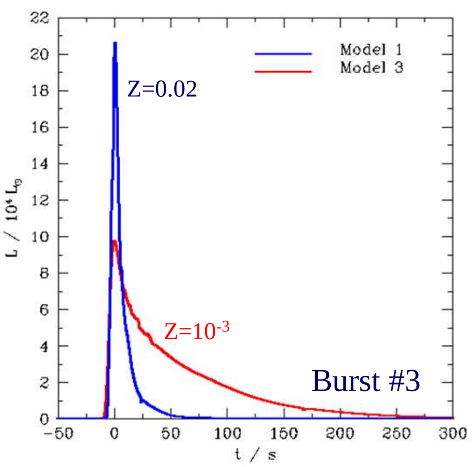
* **Low Z** models yield **less energetic (luminous)**, but **longer bursts** (τ_{rec} & τ_{decay}) [Heger et al. 2007], and **lower α**

* **Low Z** models are also characterized by an extension of the nuclear activity to heavier species (they also exhibit larger overproduction factors)



JJ, Moreno, Parikh & Iliadis (2010), ApJS

Nuclear Cross Sections

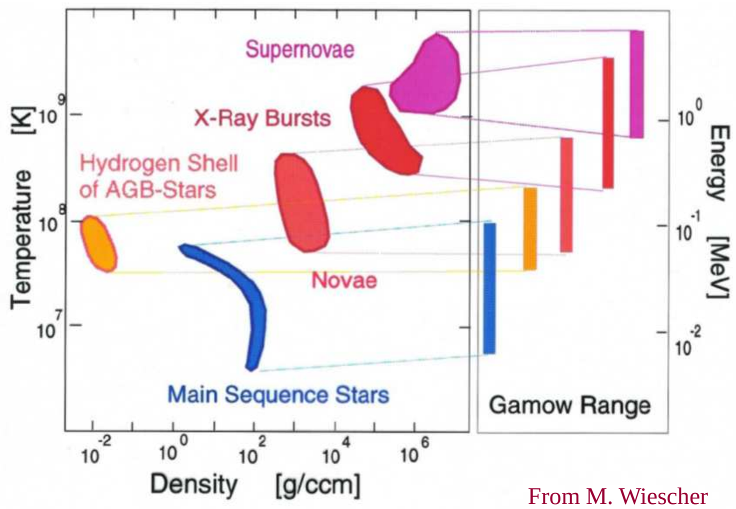
The **cross section, σ**, of a nuclear reaction characterizes the probability that a specific nuclear reaction can occur, quantified in terms of "characteristic area" (a larger area means a larger probability of interaction). It is defined as the number of interactions per time, divided by the number of incident particles per area and time, and divided by the number of target nuclei within the beam (unit: 1 barn = 10^{-24} cm^2).

$$\sigma = \frac{N_{int}/t}{N_i/(t\,S_i)N_j}$$

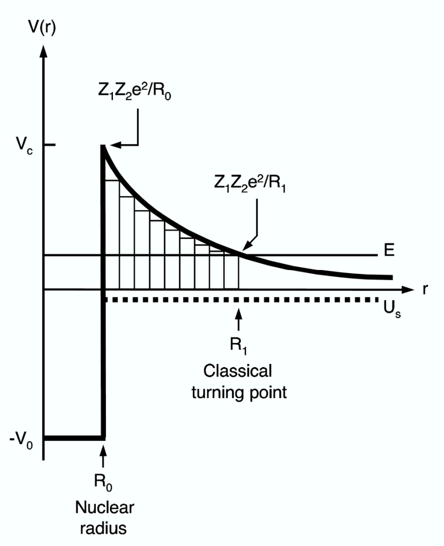
If products are the same as incident particles this is an elastic/inelastic scattering; if they are different, we refer to reactions.
The cross section can be expressed in terms of a particle density flux, $J_i = (N_i/t)/S_i$, and the ratio of the number of emitted interaction products over the number of target nuclei, $N_{rat} = N_e/N_j$, as

$$\sigma = \frac{N_{rat}/t}{J_i}$$

Gamow peak energies



From M. Wiescher



Attractive nuclear square well (r < Ro) plus repulsive Coulomb potential (r > Ro)

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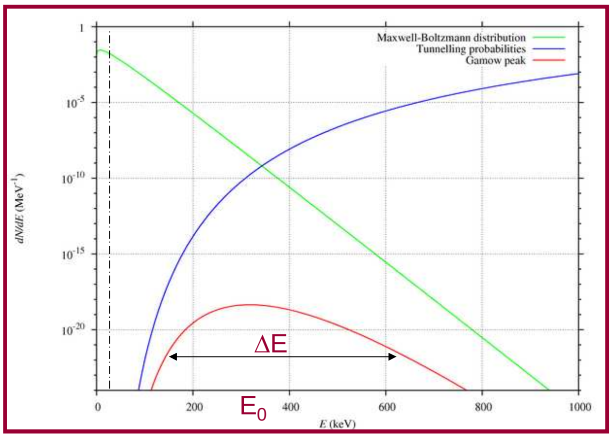
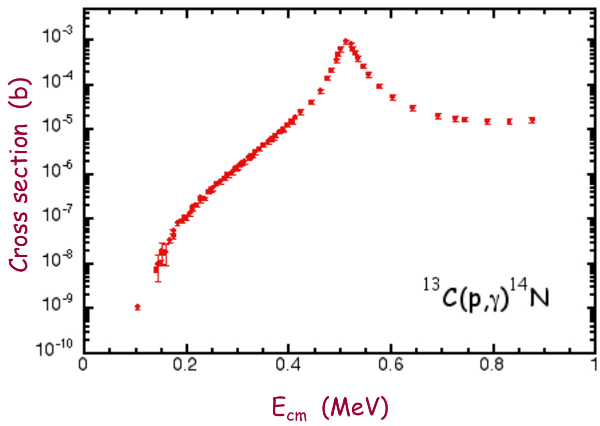


The **Gamow peak** is the product of the Maxwell-Boltzmann distribution with the tunnelling probability of the nuclei through their Coulomb barrier. This is the energy region where the reaction is more likely to take place.

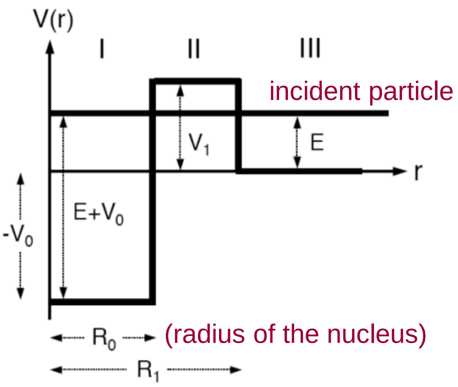
For example, the estimated cross section for the reaction **p + p → d + e⁺ + ν**, which represents the first step in the pp chains, amounts to **$\sigma = 8\times10^{-48}$ cm²** at a laboratory bombarding energy of **1 MeV**. Suppose a measurement of this reaction would be performed using an intense 1 mA beam of protons, incident on a dense hydrogen target (10^{20} protons cm^{-2}), then one obtains only **1 interaction in 6000 years**! Clearly, such a measurement is beyond present experimental capabilities and hence this cross section needs to be estimated theoretically.

But **^{15}N + p → ^{12}C + α** has **$\sigma = 0.5\times10^{-24}$ cm²** at a laboratory bombarding energy of **2 MeV!** → Large count rates expected…

Ex. $^{13}C(p,\gamma)^{14}N$



Difficult measurements at low E → **EXTRAPOLATION**



The solution to the Schrödinger equation for each of the three regions is well know. In regions I and III, the solutions are in the form of complex exponentials. In region II, however, the solutions are given in terms of real exponentials.

Continuity condition: the wave function solutions and their derivatives must be continuous at the two boundaries R_0 and R_1

Most of the nuclear reaction rates required for XRB nucleosynthesis studies (several thousand nuclear processes) rely on **theoretical estimates**

Nuclear uncertainties — Impact on XRB yields?

Only **partial efforts** have been made so far (Wallace & Woosley 1981; Schatz et al. 1998; Iliadis et al. 1999; Koike et al. 1999, 2004; Thielemann et al. 2001; Fisker et al. 2004, 2006, 2008; Amthor et al. 2006)

Comprehensive study of the **effects of thermonuclear reaction-rate variations on type I XRB nucleosynthesis**, sampling the overall parameter space.

Computationally prohibitive for hydro codes

→ **Post-processing calculations**

Two different, complementary approaches, based on post-processing calculations with T-ρ profiles from literature:

* Individual variation of all rates within uncertainty limits so as to check the impact of each nuclear process on the final yields. This technique has been previously applied to a large number of astrophysical sites, including nucleosynthesis in the **Sun** (Bahcall et al. 1982), **SN II** (The et al. 1998; Hoffman, Woosley, & Weaver 2001, Jordan, Gupta, & Meyer 2003), **CN** (Iliadis et al. 2002), **BBN** (Coc et al. 2002, 2004), intermediate-mass **AGB stars** (Izzard et al. 2007), and **XRBs** (Amthor et al. 2006).

* Monte Carlo techniques: random variation factors applied to **each nuclear process** of the network **simultaneously**. This approach has been already applied to **BBN** (Krauss & Romanelli 1990; Smith et al. 1993), **CN** (Smith et al. 2002; Hix et al. 2002, 2003) and **XRB** (Roberts et al. 2006).

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Roberts et al. (2006) questined the **feasibility of the first method**, as compared with the Monte Carlo approach, to properly address the **higher-order correlations** between input rates and XRB model predictions because of the large number of reactions simultaneously involved in the production and destruction of each element:

10 different T-ρ profiles that cover the overall parameter space have been analyzed

Only 28 + 17 (out of 3,551) nuclear reactions (including **β-decays** and **Q-value variations**) show an impact on XRB yields when varied up/down by a factor of **10** (or within uncertainty limits)!

Nuclear Uncertainties

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 178:110–136, 2008 September

THE EFFECTS OF VARIATIONS IN NUCLEAR PROCESSES
ON TYPE I X-RAY BURST NUCLEOSYNTHESIS

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~ **50,000** post-processing calculations [21 CPU months!]

606 isotopes (**^{1}H** to **^{113}Xe**) and **3551** nuclear processes

TABLE 19

SUMMARY OF THE MOST INFLUENTIAL NUCLEAR PROCESSES, AS COLLECTED FROM TABLES 1–10

Reaction	Models Affected
$^{12}C(\alpha, \gamma)^{16}O$[a]	F08, K04-B2, K04-B4, K04-B5
$^{18}Ne(\alpha, p)^{21}Na$[a]	K04-B1[b]
$^{25}Si(\alpha, p)^{28}P$	K04-B5
$^{26g}Al(\alpha, p)^{29}Si$	F08
$^{29}S(\alpha, p)^{32}Cl$	K04-B5
$^{30}P(\alpha, p)^{33}S$	K04-B4
$^{30}S(\alpha, p)^{33}Cl$	K04-B4,[b] K04-B5[b]
$^{31}Cl(p, \gamma)^{32}Ar$	K04-B1
$^{32}S(\alpha, \gamma)^{36}Ar$	K04-B2
$^{56}Ni(\alpha, p)^{59}Cu$	S01,[b] K04-B5
$^{57}Cu(p, \gamma)^{58}Zn$	F08
$^{59}Cu(p, \gamma)^{60}Zn$	S01,[b] K04-B5
$^{61}Ga(p, \gamma)^{62}Ge$	F08, K04-B1, K04-B2, K04-B5, K04-B6
$^{65}As(p, \gamma)^{66}Se$	K04,[b] K04-B1, K04-B2,[b] K04-B3,[b] K04-B4, K04-B5, K04-B6
$^{69}Br(p, \gamma)^{70}Kr$	K04-B7
$^{75}Rb(p, \gamma)^{76}Sr$	K04-B2
$^{82}Zr(p, \gamma)^{83}Nb$	K04-B6
$^{84}Zr(p, \gamma)^{85}Nb$	K04-B2
$^{84}Nb(p, \gamma)^{85}Mo$	K04-B6
$^{85}Mo(p, \gamma)^{86}Tc$	F08
$^{86}Mo(p, \gamma)^{87}Tc$	F08, K04-B6
$^{87}Mo(p, \gamma)^{88}Tc$	K04-B6
$^{92}Ru(p, \gamma)^{93}Rh$	K04-B2, K04-B6
$^{93}Rh(p, \gamma)^{94}Pd$	K04-B2
$^{96}Ag(p, \gamma)^{97}Cd$	K04, K04-B2, K04-B3, K04-B7
$^{102}In(p, \gamma)^{103}Sn$	K04, K04-B3
$^{103}In(p, \gamma)^{104}Sn$	K04-B3, K04-B7
$^{103}Sn(\alpha, p)^{106}Sb$	S01[b]

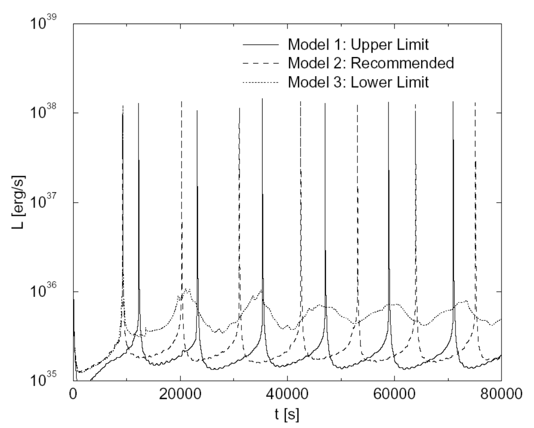
TABLE 20

NUCLEAR PROCESSES AFFECTING THE TOTAL ENERGY OUTPUT BY MORE THAN 5% AND AT LEAST ONE ISOTOPE

Reaction	Models Affected
$^{15}O(\alpha, \gamma)^{19}Ne$[a]	K04, K04-B1, K04-B6
$^{18}Ne(\alpha, p)^{21}Na$[a]	K04-B1, K04-B6
$^{22}Mg(\alpha, p)^{25}Al$	F08
$^{23}Al(p, \gamma)^{24}Si$	K04-B1
$^{24}Mg(\alpha, p)^{27}Al$[a]	K04-B2
$^{26g}Al(p, \gamma)^{27}Si$[a]	F08
$^{28}Si(\alpha, p)^{31}P$[a]	K04-B4
$^{30}S(\alpha, p)^{33}Cl$	K04-B4, K04-B5
$^{31}Cl(p, \gamma)^{32}Ar$	K04-B3
$^{32}S(\alpha, p)^{35}Cl$	K04-B2
$^{35}Cl(p, \gamma)^{36}Ar$[a]	K04-B2
$^{56}Ni(\alpha, p)^{59}Cu$	S01
$^{59}Cu(p, \gamma)^{60}Zn$	S01
$^{65}As(p, \gamma)^{66}Se$	K04, K04-B2, K04-B3
$^{69}Br(p, \gamma)^{70}Kr$	S01
$^{71}Br(p, \gamma)^{72}Kr$	K04-B7
$^{103}Sn(\alpha, p)^{106}Sb$	S01

Parikh et al. (2008, 2009)

Few attempts to analyze the impact of a single nuclear reaction rate (& uncertainty) into the overall nucleosynthesis
* **$^{21}Na(p,\gamma)^{22}Mg$:** D'Auria et al (2004)



Role of $^{15}O(\alpha,\gamma)^{19}Ne$ on type I XRB light curves (Fisker et al. 2006). But see Davids, Cyburt, JJ & Mythili (2011)

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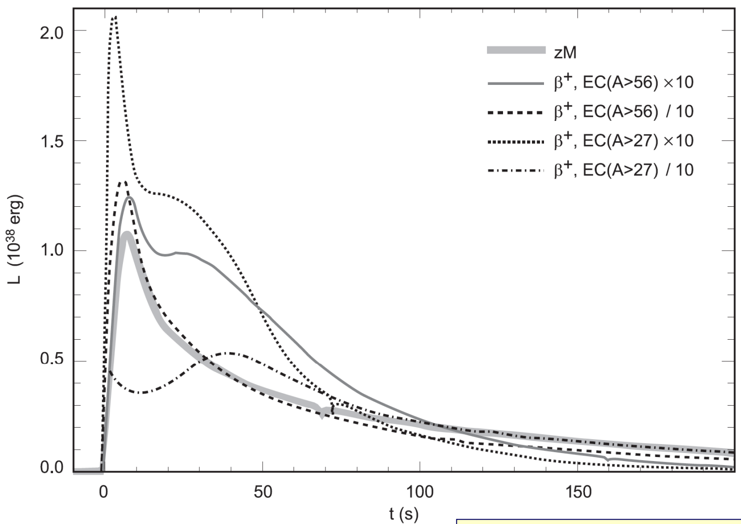


Woosley et al. (2004) ApJS

IV. Multidimensional Models

No self–consistent multidimensional full simulation of an XRB, for realistic conditions, has been performed, neither in 2–D nor in 3–D.

Efforts have focused:
- analysis of **flame propagation** on the envelopes accreted onto neutron stars
- **convection–in–a–box** studies aimed at characterizing convective transport during the stages prior to ignition

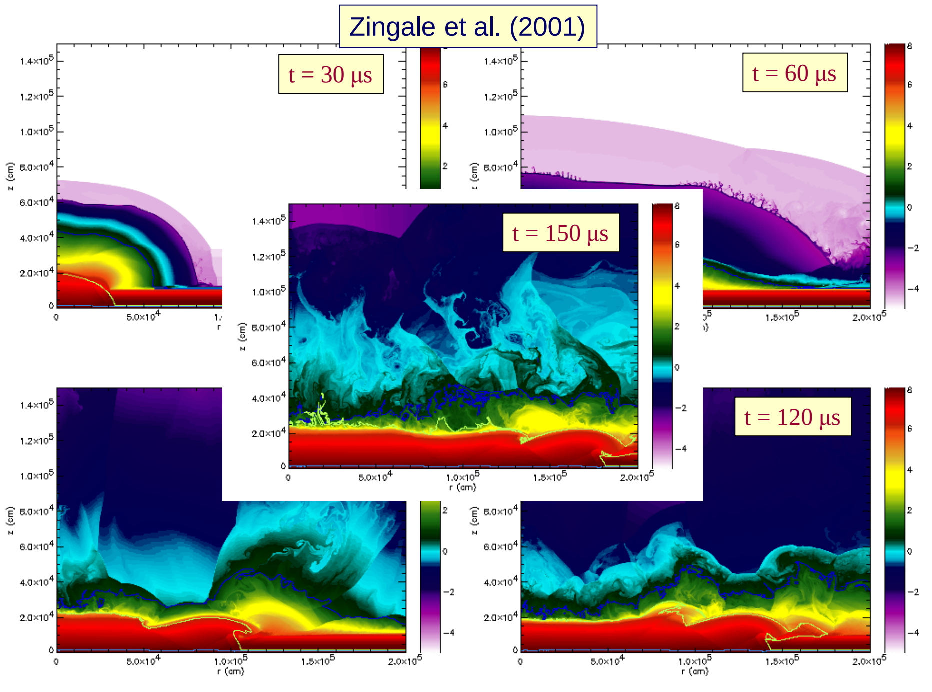
Pioneering studies of thermonuclear flame propagation on neutron stars, in the framework of XRBs, were performed by Shara (1982) → while localized runaways on WD yield volcanic–like eruptions rather than deflagrative spreads, a localized ignition on a NS would likely propagate as a deflagration front, incinerating the whole envelope in a timescale of ~ 100 s.

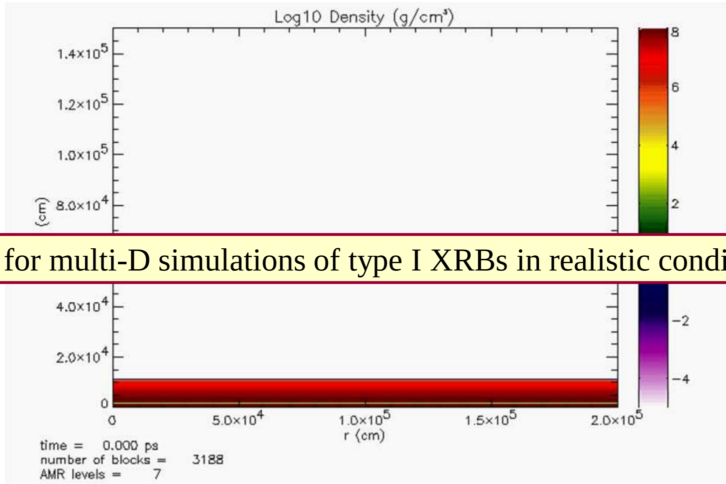
Fryxell and Woosley (1982a): two different propagation regimes are actually possible.
- ignition deep inside the envelope, at **$\rho \sim 10^8$ g cm^{-3}**: a detonation front propagating at v ~ 9000 km s^{-1} will likely occur.
- if the density is **$\rho < 10^7$ g cm^{-3}** a subsonic front (i.e., a deflagration) will ensue (v ~ 5 km s^{-1}) → the front would horizontally spread, with a characteristic timescale for a halfway propagation across the envelope of about 8 s.

* Fryxell & Woosley (1980b): pioneering 2–D hydro simulations of the propagation of a detonation front in a thick envelope on top of a neutron star, during ~ 50 ms. **Unrealistic** XRB conditions (GRBs)

* Zingale et al. (2001): 2–D simulation of the propagation of a Chapman–Jouguet detonation (v ~ 10^9 cm s^{-1}). Again, **unrealistic** XRB conditions.

The dicotomy between detonations and deflagrations was subsequently explored, for different ignition densities, in 2–D by Simonenko et al. (2012a, b).





Need for multi-D simulations of type I XRBs in realistic conditions

Zingale et al. (2001)

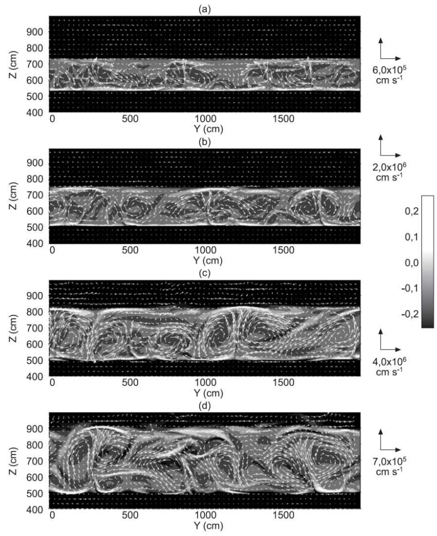
Inclusion of rotational effects in flame propagation has been considered by Cavecchi et al. (2013, 2015), through the analysis of the role of a constant and a latitude–dependent Coriolis force in meridional flame propagation → flame propagation strongly depends on the angular velocity and heat conductivity of the fluid.

The early development of the **convective stages preceding thermonuclear ignition** in XRBs:

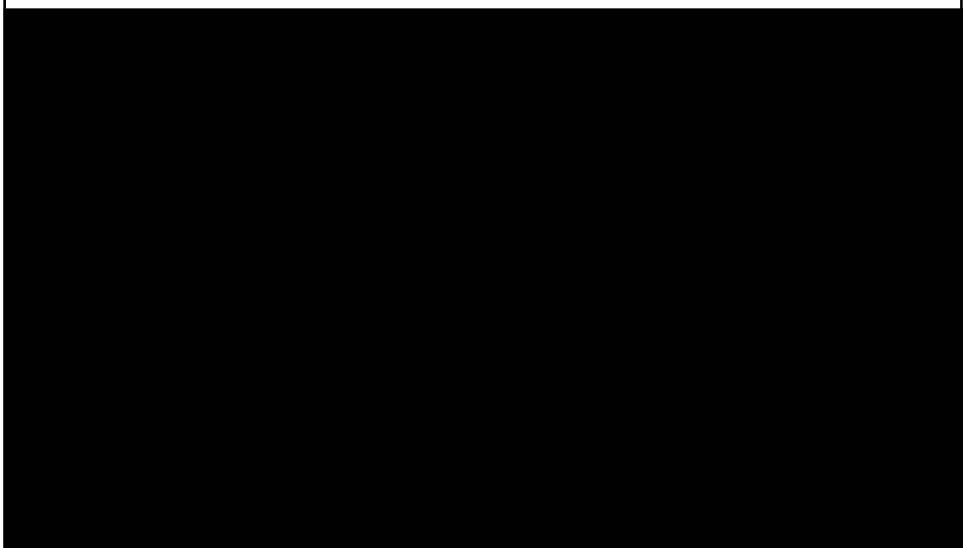
- can a fully–turbulent convection actually modify the expected nucleosynthesis?
- can convection dredge-up ashes enriched in heavy elements to the neutron star photosphere? (Bhattacharyya et al. 2010, in’t Zand & Weinberg 2010)

Pioneering efforts in 2–D by Lin et al. (2006).

2– and 3–D turbulent convection studies by Malone et al. (2011, 2014) and Zingale et al. (2015): similar peak temperatures and Mach numbers, but different convective velocity patterns, with evidence of the **energy cascade** that characterizes 3–D convection.



Lin, Bayliss & Taam (2006)



Casanova, JJ, García-Berro, Shore, & Calder (2011), Nature

Box I. The X-Ray Burst "Hall of Fame"

A selection of facts on normal type I X-ray bursts, intermediate-duration bursts, and superbursts

1. Type I X-ray bursts take place on the neutron star component of a close stellar binary system and represent the most frequent type of thermonuclear explosions in the Galaxy.
2. Different types of X-ray bursts (normal, intermediate-duration, and superbursts) can be distinguised in terms of duration, energetics, and recurrence period, reflecting ignition of different fuels (H/He, He, C) at different depths.
3. X-ray burst light curves are characterized by a fast rise to peak followed by a power law-like decay, occassionally with double or triple peaks. Deviations from the general pattern are produced by a suite of different phenomena, including disturbances driven by the accretion flow, nonspherical emission, or the extent of the rp-process.
4. Oscillations with frequencies ranging between 11 and 600 Hz have been identified in the X-ray burst light curves, in about 25% of all bursting sources. While oscillations during the rising phase to peak luminosity have been linked to the spreading of a hot spot on a rotating neutron star, those observed during decline from peak have yet a controversial origin.
5. Quasi-periodic oscillations at 3–9 mHz have also been observed prior to a burst. They may result from marginally stable nuclear burning on the neutron star surface.

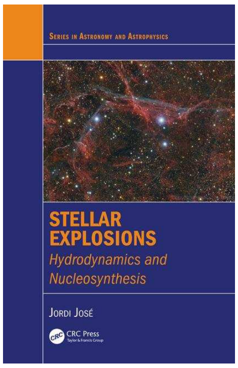
6. Observations suggest that a tiny fraction of the accreted envelope (1%, at most) is ejected from the neutron star by radiation-driven winds.
7. One-dimensional simulations have proved successful in reproducing the main observational features of type I X-ray bursts (i.e., light curve shapes, recurrence periods).
8. The burning front likely propagates subsonically (i.e., a deflagration). The outburst is likely quenched by fuel consumption (rather than by envelope expansion), and is driven by a suite of different nuclear processes. The most complex nuclear path is achieved for mixed H/He bursts, which are driven by the 3α-reaction, the αp-process (a sequence of (α, p) and (p, γ) reactions), and the rp-process (a series of rapid proton-captures and β^+-decays that play a key role in powering the light curve tail).

Box II. Mysteries, Unsolved Problems, and Challenges

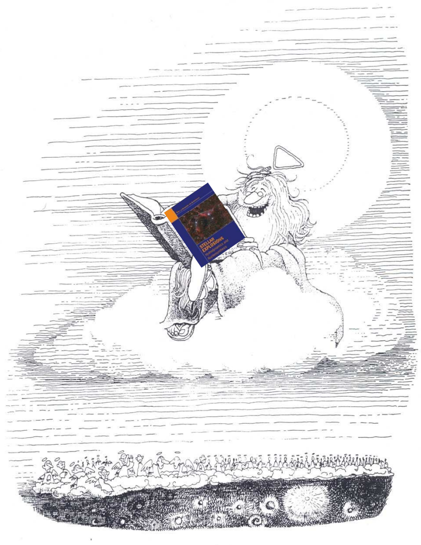
- What causes the appearance of double and triple peaks in the X-ray burst light curves?
- Attempts to resolve gravitationally-redshifted atomic absorption lines from X-ray burst spectra through high-resolution spectroscopy have proved unsuccessful to date (mostly hampered by rotational broadening). To this end, efforts aimed at improving sensitivity in X-ray spectroscopy are highly advisible.
- What is the maximum extent of the rp-process in X-ray burst nucleosynthesis?
- From a nuclear physics viewpoint, efforts should be made to better constrain the rates of key reactions affected by nuclear uncertainties. Since most of the reactions of interest involve short-lived species, direct measurements will be extremely challenging (if not impossible!), and, therefore, improvements should mostly rely on indirect measurements and theoretical approaches.
- Do X-ray bursts contribute to the Galactic abundances?
- Further efforts are needed to clarify the existing controversy between theoretical and observationally inferred values of the mass-accretion rate at the transition between stable burning and bursting regimes.
- Multidimensional simulations of X-ray bursts are limited to date to models of flame propagation on the envelopes accreted onto neutron stars, as well as convection-in-a-box studies aimed at characterizing convective transport during the stages prior to ignition. Such efforts must be extended to 3D simulations of a full burst (and in a longer term, to series of bursts), taking advantage of state-of-the-art parallel computers.

- How localized is ignition in the different X-ray burst types?
- Is carbon the real fuel that powers superbursts? If so, how is it produced, and what heats the ignition layer to explain the shorter than predicted recurrence times?

Bibliography



Chapter 6, JJ (2016)



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1st Institute of Space Sciences Summer School: "Neutron Stars And Their Environments", Bellaterra (Barcelona), July 3 – 7, 2017