Type-I X-ray Burst as a tool to probe the physics of interior neutron stars

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～中性子星の観測と理論～　研究活性化ワークショップ 2021

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    - 1RXS J180408.9–342058 (on-going work with W. B. Iwakiri, N. Nishimura, T. Noda)
5. Conclusion

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Low-Mass X-ray binary (LMXB)

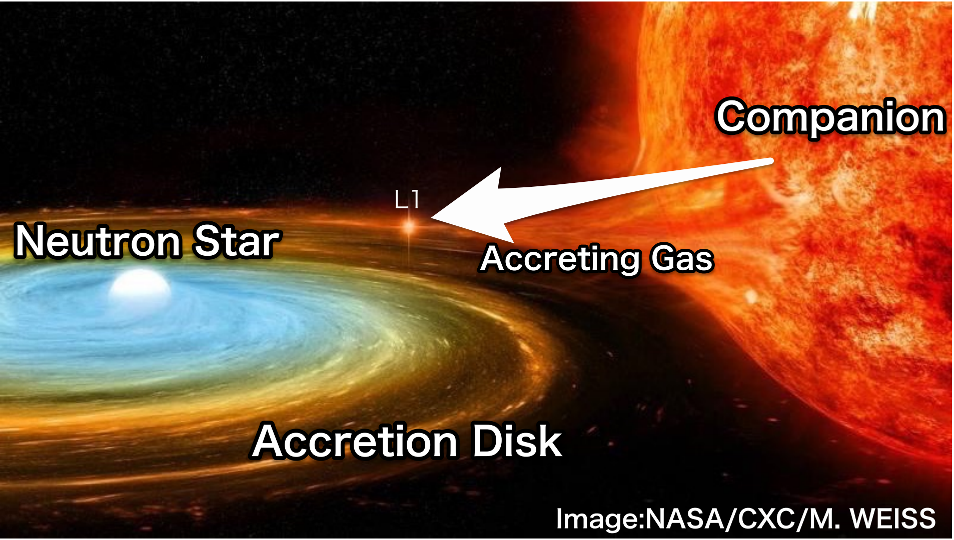
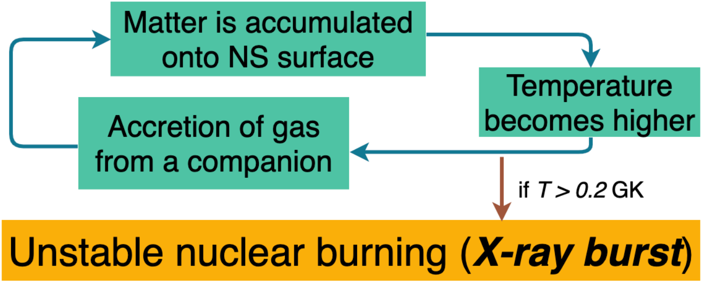


Image:NASA/CXC/M. WEISS

Thermonuclear (Type-I) X-ray burst

Accretion of gas due to Roche-lobe overflow



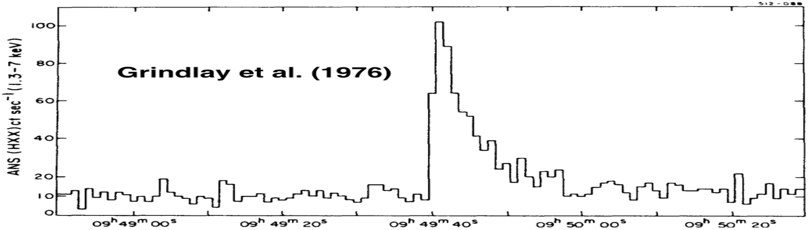
Matter is accumulated onto NS surface

Temperature becomes higher

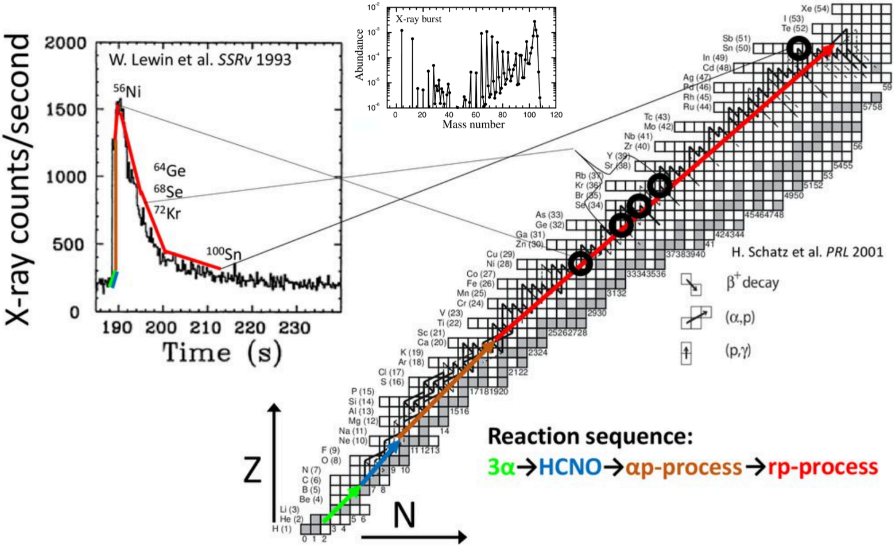
Accretion of gas from a companion

if $T > 0.2$ GK

Unstable nuclear burning (*X-ray burst*)



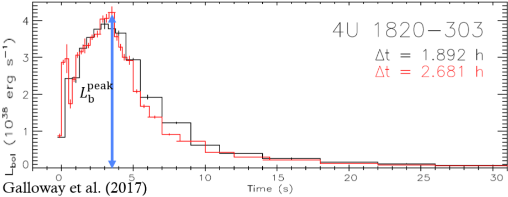
Nucleosynthesis during X-ray Burst



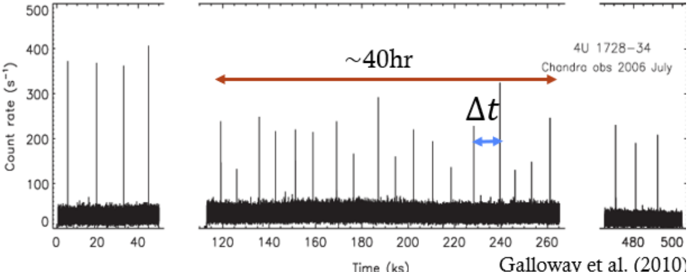
(Meisel+18)

Observation of X-ray bursters

- 115 bursters have been observed (Galloway+20)
- Burst luminosity: exponentially mild decay after rapidly increasing ($L_{\mathrm{b,peak}} \sim 10^{38}$ erg/s)
- Δt: from hr to yr



Galloway et al. (2017)



Galloway et al. (2010)

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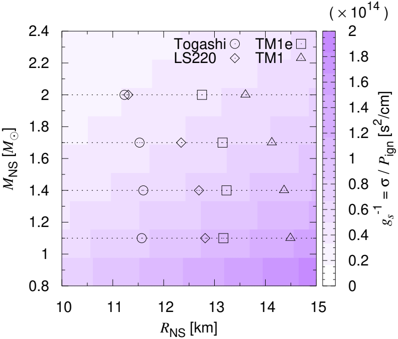
Simplest X-ray Burst Model (Fujimoto+1981)

- *Plane-parallel* model ($P = const.$)
- The ignition condition on the NS shell is given by

$$P_{\rm ign} \equiv P = g_{\rm s}\sigma$$

$$\left.\frac{\partial \epsilon_{\rm tot}}{\partial T}\right|_P - \left.\frac{\partial \epsilon_{\rm rad}}{\partial T}\right|_P = 0$$

where σ is column density, $g_{\rm s}$ surface gravity, $\epsilon_{\rm tot}$ total energy generation, $\epsilon_{\rm rad}$ radiation energy loss.



  - In one-zone model, compacted NS models (higher g_s) tend to have lower σ, that is, lower Δt and $L_b^{\rm peak}$.

⇒ **How does the physics of accreting NSs affect the X-ray burst light curves in multi-zone framework?**

Model parameters to describe X-ray burst

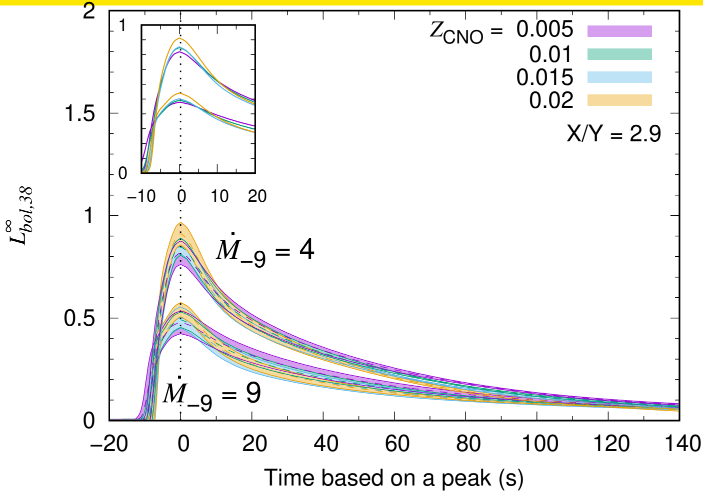
Well studied so far (e.g., Johnston 20, Galloway and Keek 21)

- Mass accretion rate: $\dot{M}$ or $\dot{M}_{-9} = \dot{M}/\left(10^{-9}\ M_\odot\ \mathrm{yr}^{-1}\right)$
  - Amount of fuel (σ)
  - Crustal heating ⇒ Temperature structure (P_ign)
- Composition of accreted matter: X, Y, Z_CNO
  - Amount of fuel (σ)
  - Pure He burst? Mixed H/He burst? Or C burning?
- Nuclear Reaction Rate

Less studied so far: Microphysics of interior NS

- **Structure and Energy loss inside NS**
  - Equation of State ⇒ Mass and radius (g_s)
  - Neutrino Urca cooling ⇒ Temperature structure (P_ign)

Accretion rate $\dot{M}_{-9}$ and Metallicity $Z_{\rm CNO}$



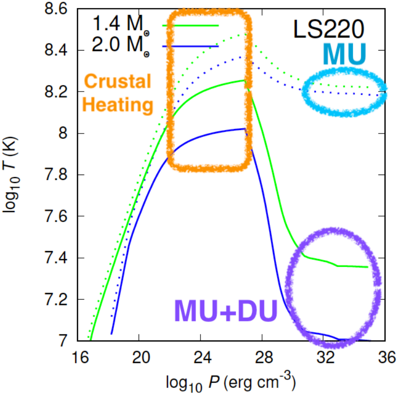
- High $\dot{M}_{-9}$ ⇒ Short bursts of low-peak luminosity due to low σ
- High $Z_{\rm CNO}$ ⇒ High-peak luminosity, but short burst duration

Heating-Cooling effects inside NS

- Crustal Heating ($\propto \dot{M}_{-9}$):
  Accretion matter transforms into the heavy elements via
  * Electron capture
  ** Neutron emission
  *** Pycnonuclear fusion
  (We assume the fixed nuclear model of Haensel & Zdnick 90)

t

- ν Emissions:
  - Fast cooling ($Y_{p,C} > 1/9$): Direct Urca (DU)
    e.g., $n \rightarrow p + e + \nu_e$
  - Slow cooling (always): Modified Urca (MU)
    e.g., $n + n \rightarrow n + p + e + \nu_e$

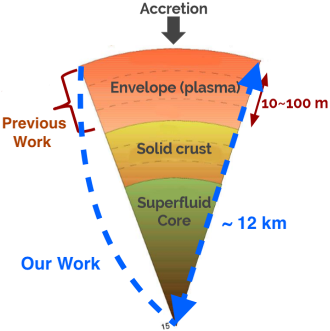


ν cooling processes indirectly decrease the temperature near the surface and increase P_{ign}.

Motivation to consider the NS microphysics

- Previous multi-zone burst models consider only accreted layer, giving the boundary condition on NS crust.
    - KEPLER (Monash Univ. Group, e.g., Johnston, Heger, Galloway 20)
    - MESA (Z. Meisel 18, 19)

  ⇒ various burst models, but there are two following problems:

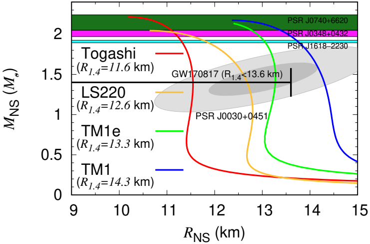


(Chamel & Haensel 08)

- GR effect: Newtonian formulation (but Heger and Keek 11 for the GR correction)
- Energy inside NS: giving the boundary luminosity (Q_b) compatible with crustal heating models (Haensel & Zdnick 08)
  ⇒ To treat the NS microphysics, we cover whole NS regions under quasi-hydrostatic equilibrium condition.

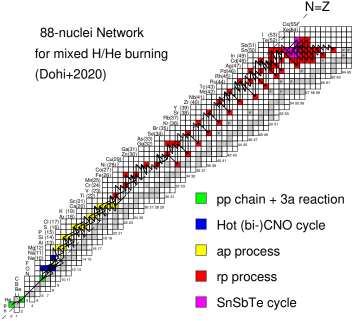
Our models of NS EOS and Reaction Network

- NS Structure



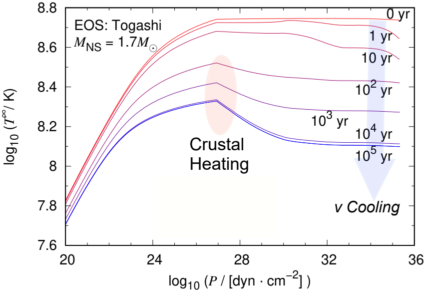
- Different radius EOSs
- 2 $M_\odot$ can be reached
- For ν cooling processes, we mainly assume the slow cooling scenario.

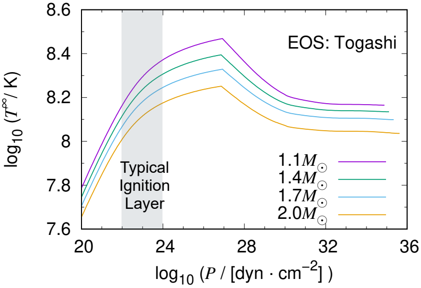
- Reaction Network



- 88 nuclei for mixed H/He burning (AD+20)
- It reproduces the large network within 40% error (Matsuo 17)

Thermal evolution of accreting NSs toward steady state (no nuclear heating)





- Steady state is archived in $t \sim 10^5$ yr after NS formation.
- High-mass models have lower temperature in ignition layer $\Rightarrow$ Slow ν cooling processes prolong $P_{\rm ign}$.
- These steady-state models become our initial models for X-ray burst calculation.

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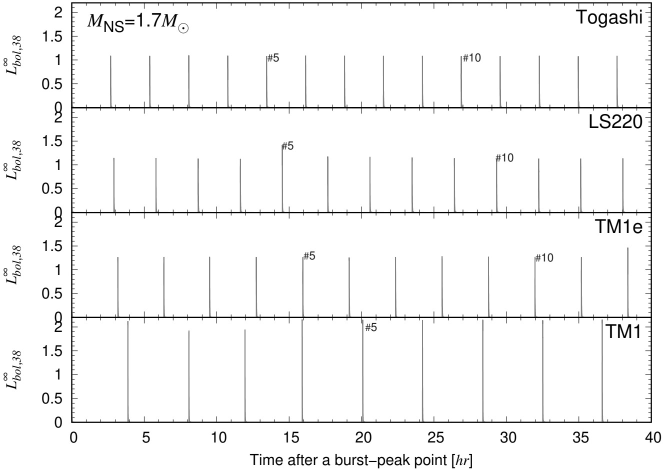
EOS and Light curves ($\dot{M}_{-9} = 2.5$, $Z_{\rm CNO} = 0.01$)

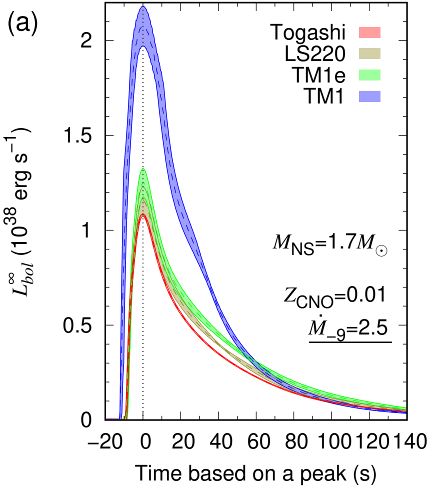


Large-radius EOSs have higher Δt and $L_b^{\rm peak}$.

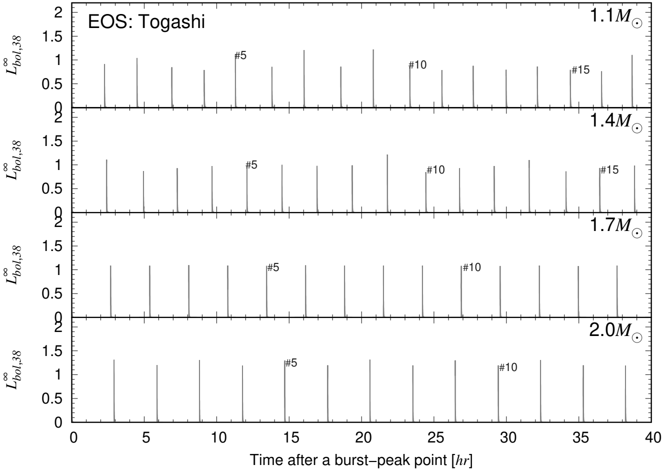
$\Leftarrow$ Due to higher σ with higher g_s^{-1}

EOS and Averaged-light curves over many bursts

- L_b^{peak} tends to be lower with smaller-radius EOS. Above all, the TM1 EOS has much high L_b^{peak} value.
$\Leftarrow$ Due to higher σ with higher g_s^{-1}
- Difference of the decay time (τ) from the peak point is clearly seen among EOSs; shorter τ for smaller-radius EOS.



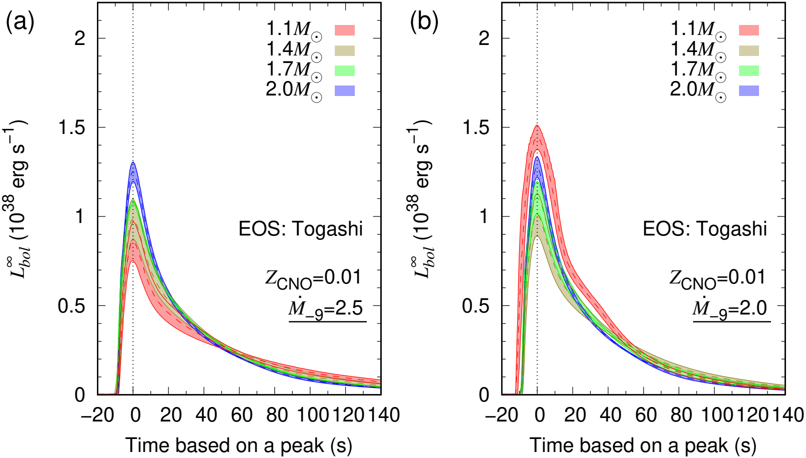
Mass and Light curves ($\dot{M}_{-9} = 2.5$, $Z_{\rm CNO} = 0.01$)



Higher-mass (g_s) models have higher Δt and $L_b^{\rm peak}$ (not always).

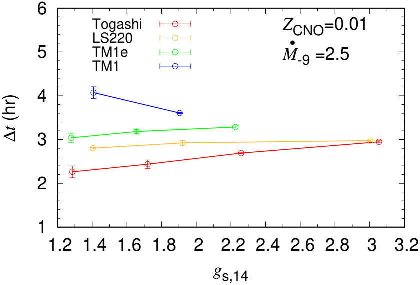
$\Leftarrow$ Not due to the effect of g_s^{-1} but other effects

Mass and Averaged-light curves over many bursts



Higher $L_{\rm b,peak}$ with (a) higher mass / (b) lower mass
$\Rightarrow$ The mass relationship is different with $\dot{M}_{-9}$

EOS dependence of Δt and $L_{\rm peak}$



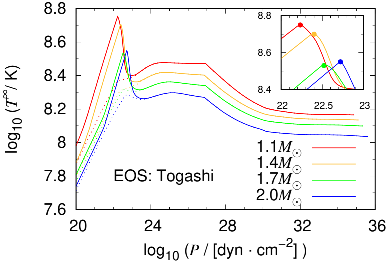
$$(g_{s,14} = g_s / \left(10^{14}\ \mathrm{cm\ s^{-2}}\right))$$

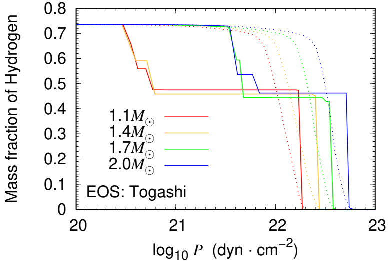
- Smaller-radius EOS tends to have lower Δt and $L_{\rm peak}$.
- Since $\sigma = P_{\rm ign}/g_s$, if we assume that $P_{\rm ign}$ is independent of EOS, Δt and $L_{\rm peak}$ should be higher with low g_s. However, this trend does not match with most of models.

  $\Rightarrow$ $P_{\rm ign}$ seems to be also affected by neutrino cooling !!

ν Cooling Effect and Mass relation

- ν Cooling makes the overall temperature lower with higher-mass (g_s) NS.
- The ignition pressure $P_{\rm ign}$ is also higher. That is, Δt and $L_b^{\rm peak}$ could be also higher due to higher $\sigma (= g_s^{-1} P_{\rm ign})$. $\Leftarrow$ Conflicted with the gravitational effect of g_s^{-1}
- From burst light curves, we may see which effects of gravitation and ν cooling are higher.





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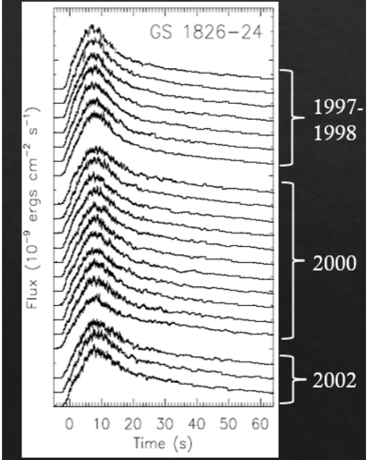
Periodic Bursts from *Clocked Burster*

- Some outburst is periodic ($\Delta t \simeq const.$) $\Rightarrow$ *Clocked Burster*
- In burst sequence, the shape of light curves is almost unchanged. $\Rightarrow$ Useful to examine the validity of burst models (Heger+07a)
- Observed *Clocked bursters* so far:
    - GS1826–24 (Galloway+17)
    - GS 0836–429 (Aranzana+16)
    - EXO 1745–248 (Matranga+17b)
    - 1RXS J180408.9–342058 (Fiocchi+19)

Light curve of GS 1826-24

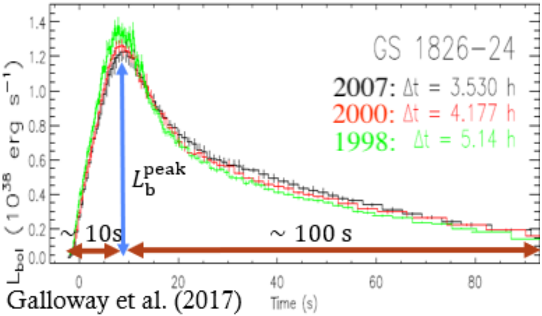


Galloway et al. (2004)

GS1826–24

- First X-ray burst was observed by Ginga (Tanaka 1988)

- 3 series of outbursts
- Photospheric radius expansion (PRE) does not appear in above 3 epochs.
- Long burst duration $\Rightarrow$ *rp*-process is possibly enhanced !?



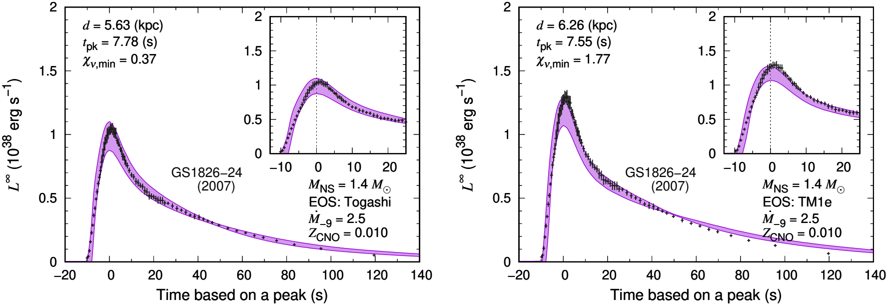
Galloway et al. (2017)

- $\Delta t = 3.530 \pm 0.004$ hr (2007)

- $L_b^{\rm peak} \approx 1.2 \times {\rm d}^2 \xi_b / (6.1\ {\rm kpc})^2 \times 10^{38}$ erg s^{-1}

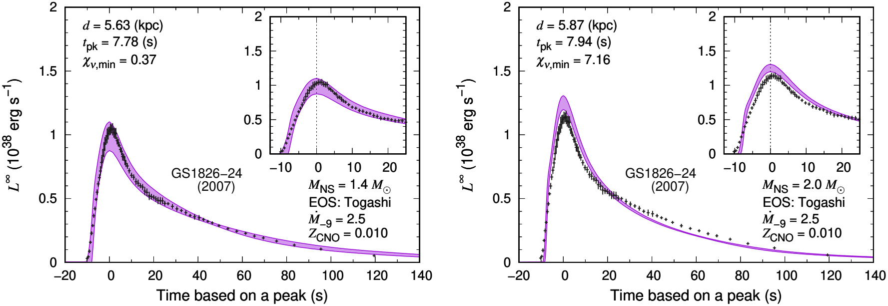
d: distance from NS and companion, ξ_b: burst anisotropy factor

Comparison with GS1826–24: EOS



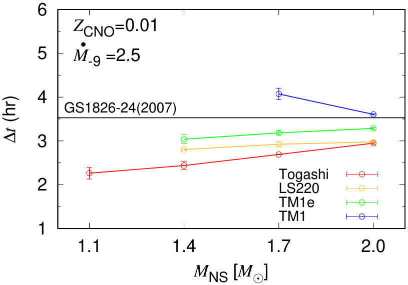
- For TM1e EOS, L_b^{peak} is higher than that with Togashi EOS.
  $\Leftarrow$ Due to gravitational effect
- For observations, If $M = 1.4\ M_\odot$, smaller-radius EOS is better, though it depends on other parameters.

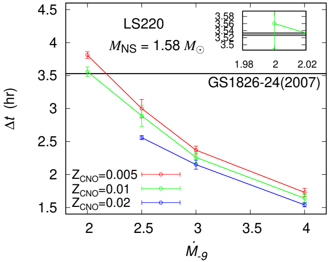
Comparison with GS1826–24: Mass



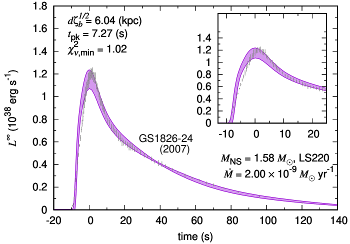
- L_b^{peak} is higher with $M = 2.0\ M_\odot$ compared with $M = 1.4\ M_\odot$
  $\Rightarrow$ ν cooling effect $>$ Gravitational effect
- For $M = 2.0\ M_\odot$, L_b^{peak} is higher than the observations. Then, the shape of light curves does not match with the observations so much.

Comparison of Δt and Best-fit model





- Many models show short Δt compared with the observation, though it depends on $\dot{M}, Z_{\mathrm{CNO}}$.
- In our models, LS220 with $M = 1.58 M_\odot$ is consistent with the observations.



The effect of Direct Urca(DU) process

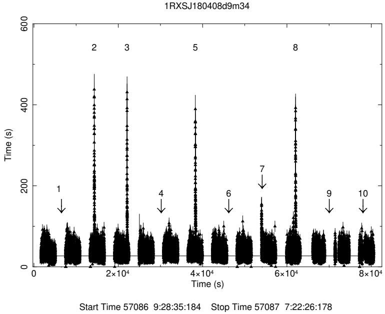
The results are preliminary. A figure in this slide is removed.

- If the DU process works, $\log_{10} P_{\rm ign}$ is higher by $0.05 - 0.06$.
  $\Rightarrow \Delta t$ should be also higher in the same order.
- Δt is longer by 20%, which matches with the one from $P_{\rm ign}$.

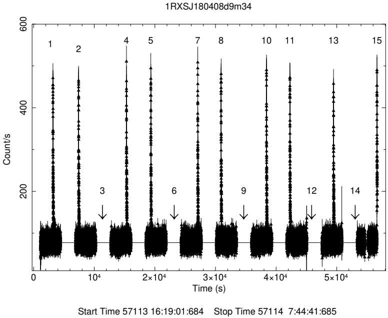
1RXS J180408.9–342058 (Fiocchi+19)

- First X-ray burst observed by INTEGRAL (Chenevez+12)

** 1st epoch **

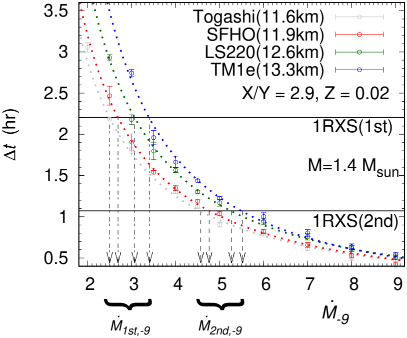


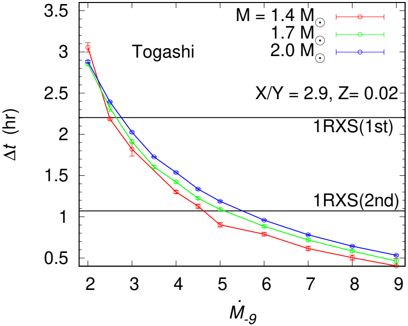
** 2nd epoch **



- 2 successful bursts with mixed H/He burning, observed by *NuStar* ($E = 3.5 - 30$ keV)
- Δt: 2.20 hr → 1.08 hr ⇒ *Clocked burster*
- Persistent flux: 77 cps → 34 cps ⇒ $\dot{M}_{\rm 1st} : \dot{M}_{\rm 2nd} \simeq 1 : 2$

$\dot{M}_{\rm 1st}$ and $\dot{M}_{\rm 2nd}$ matching with observed Δt

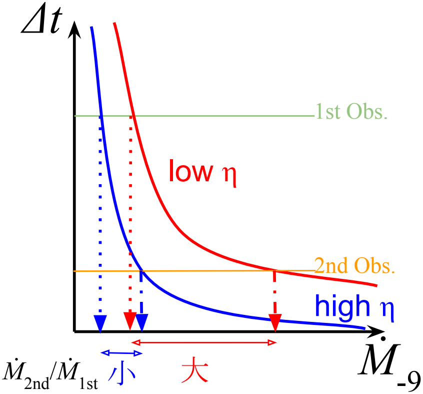




- $\dot{M}_{\rm 1st}$ and $\dot{M}_{\rm 2nd}$ are obtained for each model.
- By checking $\dot{M}_{\rm 1st} : \dot{M}_{\rm 2nd} \sim 1 : 2$ (rigidly $\dot{M}_{\rm 2nd}/\dot{M}_{\rm 1st} > 2.07$), we might probe the NS structure (in particular the mass).

How to probe the NS structure via $\dot{M}_{\rm 2nd}/\dot{M}_{\rm 1st}$

- Empirically, $\Delta t \propto \dot{M}_{-9}^{-\eta}$ with $\eta > 1$ (Lampe+16)
- If η is lower, $\dot{M}_{\rm 2nd}/\dot{M}_{\rm 1st}$ should become higher.
- For Togashi EOS, fitted η is lower with higher mass because ν cooling effect is higher than gravitational one.



Fitted η	$Z_{\rm CNO} = 0.01$	0.015	0.02
1.4 $M_\odot$	1.19(0.03)	1.28(0.03)	1.27(0.03)
1.7 $M_\odot$	1.11(0.03)	1.10(0.03)	1.09(0.03)
2.0 $M_\odot$	1.06(0.04)	1.04(0.03)	1.02(0.03)

On the possibility of high-mass *Clocked burster* 1RXS J180408.9–342058 (but not enough)

The results are preliminary. A figure in this slide is removed.

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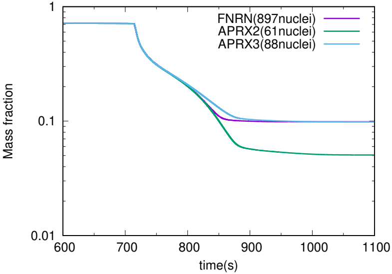
Summary of My Talk

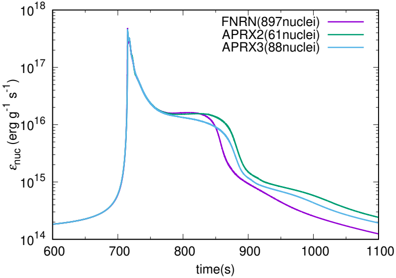
- We examine the influence of NS structure on X-ray burst
    - EOS (g_s): Large radius → Higher Δt and $L_{\rm peak}$
    - ν cooling ($P_{\rm ign}$): Higher mass → Higher Δt and $L_{\rm peak}$

      $\Rightarrow$ Q_b should not be treated as an artificial parameters !!
- These microphysical effects are conflicted for Δt and $L_{\rm peak}$.
- Comparison with *Clocked bursters*
    - GS1826–24: Large-radius EOSs seem to be unpreferred.
    - 1RXS J180408.9–342058: Possibly high-mass NS ($\gtrsim 2\ M_\odot$)
- Thus, *Clocked bursters* can probe the NS structure. Hence, long-term observation of X-ray burst by good X-ray detector is desired for more constraints on NS models.

Approximate Networks (Matsuo 17, AD+20)

- By solving from the center of NS, the numerical cost becomes very high
- To reduce the numerical cost, we constructed the approximate network with 88 nuclei (APRX3).
- Compared to full reaction network (FNRN), APRX3 reproduces the X and the generation energy $\epsilon_{\rm nuc}$. (Results of <u>One-zone</u> X-ray burst calculation at H ignition pressure $P_{\rm ign} = 10^{22.8}$ $\nearrow\nearrow\nearrow$)





Base Heat: $Q_{b+\nu}$ and $Q_b(\sim 0.3 - 0.4\ \mathrm{MeV/u})$

- Q_b is the base heat excluding ν cooling:

$$Q_b = \frac{L_{\mathrm{crust}} - L_\nu}{6\dot{M}_{-9} \times 10^{34}}\ (\mathrm{MeV/u})$$

M_{NS}	Togashi	LS220	TM1e	TM1
$1.1M_\odot$	0.39	0.39	0.39	0.40
$1.4M_\odot$	0.35	0.37	0.37	0.37
$1.7M_\odot$	0.34	0.34	0.36	0.36
$2.0M_\odot$	0.30	0.31	0.33	0.34

- $Q_{b+\nu}$ is the *real* base heat where ν cooling is included:

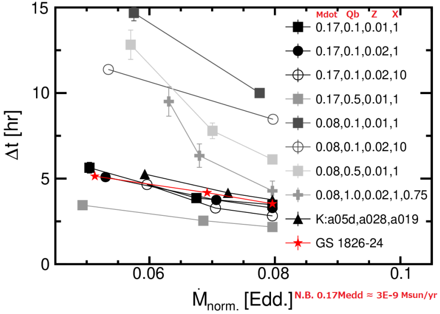
$$Q_{b+\nu} = \frac{L_{\mathrm{crust}}}{6\dot{M}_{-9} \times 10^{34}}\ (\mathrm{MeV/u})$$

M_{NS}	Togashi	LS220	TM1e	TM1
$1.1M_\odot$	0.70	0.71	0.71	0.73
$1.4M_\odot$	0.64	0.67	0.68	0.68
$1.7M_\odot$	0.61	0.62	0.65	0.66
$2.0M_\odot$	0.54	0.57	0.59	0.62

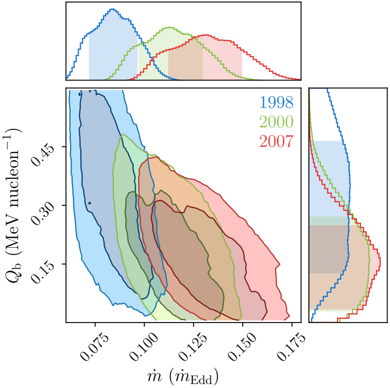
- Slow ν cooling is valid by $\lesssim 40\%$ even on the crust surface.
- Higher-mass models have a little lower $Q_{b+\nu}$ values.
- Our $Q_{b+\nu}$ and Q_b are almost independent of $\dot{M}_{-9}$

Comparison with Recent Work using GS1826–24

- Meisel 2018



- Johnston+20

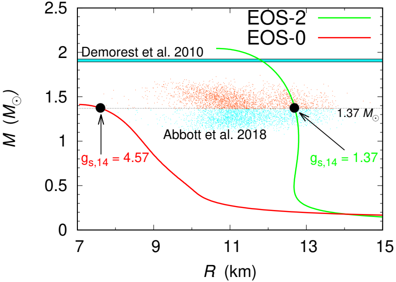


$\Rightarrow Q_b \lesssim 0.5$ MeV/u

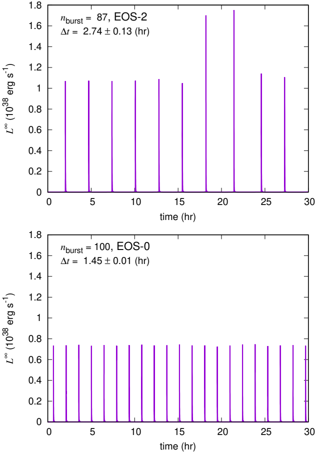
- Our Q_b value is consistent with previous work.

$\Rightarrow Q_b \sim 0.1 - 0.45$ MeV/u

EOS dependence on Long-term Light Curves



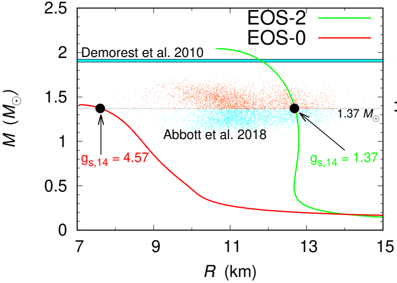
$\Longrightarrow$



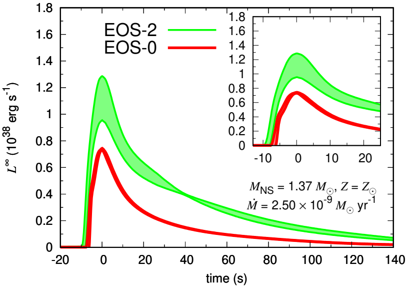
$g_{s,14}$: surface gravity [10^{14} cm s^{-2}]

- Δt is higher with EOS$-$2 compared with EOS$-$0. $\Leftarrow$ Assuming $P_{\rm ign} = const$, column density $\sigma \approx P_{\rm ign}/g_s$ is higher in EOS$-$2 and more fuel is needed for outburst.

EOS dependence on Light Curves in Burst Phase



$\Longrightarrow$



(1σ regions over 30 bursts)

- In the tail part, the luminosity is lower in EOS−0.
  $\Leftarrow$ Due to $L_{\rm per} = \dot{M}c^2\left(1 - \frac{1}{1+z_{\rm g}}\right)$.
- $L_b^{\rm peak}$ is higher in EOS−2
  (Assuming $P_{\rm ign} = const$, column density $\sigma \approx P_{\rm ign}/g_{\rm s}$ is higher in EOS−2 and therefore burst energy per a burst is higher.)