Mass-loss and composition of wind ejecta from type I X-ray bursts

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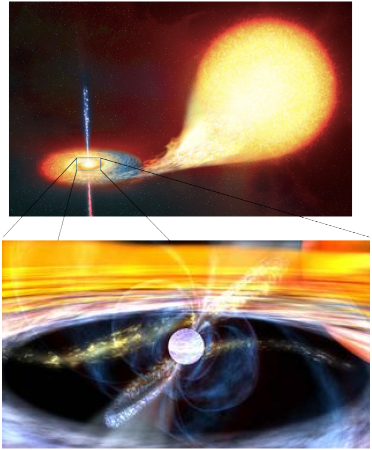
XRB mechanism



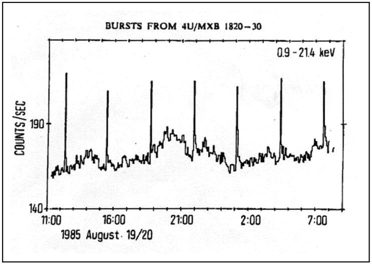
Scenario: Low-mass X-ray Binary (LMXB)

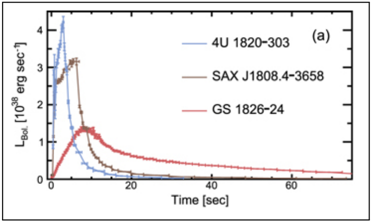
- Accreting NS + main seq./ RG
- Orbital period: 0.2-15 hr
- Accretion disk: hot plasma ($\sim 10^7$K), viscosity: $U_{\text{grav}} \rightarrow$ X-ray (persistent)

Type I XRB

- Accretion → Mildly degenerate envelope
- Temp/density build-up
- Thermonuclear runaway
  → Heavy elem. nucleosynthesis ($A \sim 64$)
  → Massive L increase
  --→ Photospheric radius expansion (PRE)
- Strong NS g → No explosive ejection (unlike novae)
  → Stellar wind mass-loss ?

XRB observational features (Type I normal)



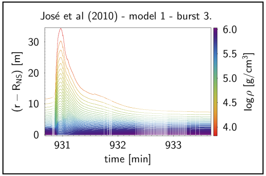


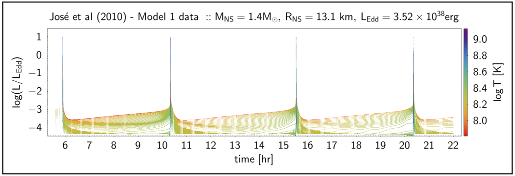
Sudden spike in X-ray band (mostly).

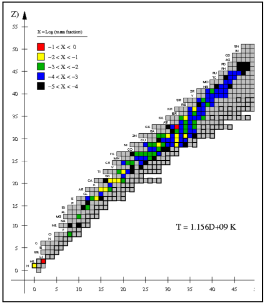
- FRED: Fast Rise ($\sim 1-10$ s) and Exponential Decay ($\sim$ few min).
- Short recurrence time ($\sim$ few hr – days) (Most frequent high energy event!)
- Luminosity peak: $\times 10-1000$ normal luminosity of the source (LMXB)
- Energy output $\sim 10^{39}$ erg. (3rd HE galactic events after SN, novae)
- $\alpha = E_{\text{persist}}/E_{\text{burst}} \sim 40-120$ $\simeq u_{\text{grav}}/u_{\text{nuclear}} \longrightarrow$ Thermonuclear origin.

That is, for most XRB (Type I normal)

Motivation 1: XRB's impact on galactic chemical abundances



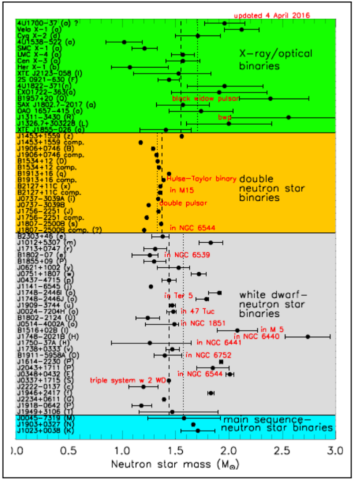




- Recent detailed 1D XRB-HD modeling
  (José & al 2010, Fisker & al 2008, Woosley & al 2004).
  - ○ Higher computing power, spatial/temporal resolution.
  - ○ Multiple bursts ⟶ evolution.
  - ○ 300+ isotopes reaction networks ⟶ proton-rich nuclei production.
- High NS gravity ($v_{esc} \sim 0.6c$) ⟶ no explosive ejection.
- Debated origin of p-nuclei: ^{92,94}Mo, ^{96,98}Ru (Schatz & al 1998,2001) under-produced in canonical scenarios (e.g. SN)
- Produced in XRB-HD simulations (José & al 2010), but... ejected?
- However: PRE ⟶ Outer shells: $T \downarrow$, $\kappa \uparrow$, $L \sim L_{Edd}$

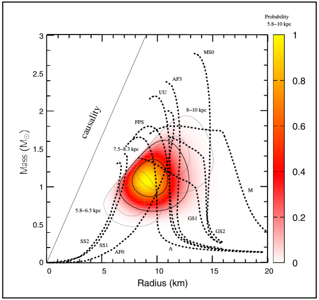
Maybe... "The answer is blowing in the wind"

Motivation 2: NS mass, radius and EoS



Equation of state for neutronic matter

- Theoretical models ⟶ Different mass-radius relations.
- Independent measurements of M,R needed to select.
- Varying error in current techniques.
- Study of NS envelope during XRB-wind may help...



EoS models and M,R observation errors (Sala et al, 2012)

Objectives

Main goals

1. Quantify XRB-wind mass-loss and contribution to galactic abundances.
   ⟶ Possible ejection of p-nuclei: ^{92,94}Mo, ^{96,98}Ru.
2. Characterize observable magnitudes in NS envelope during XRB-wind.
   ⇢ Better R_{NS}, M_{NS} measurement techniques, ⇢ Constrain NS EoS.

Steps

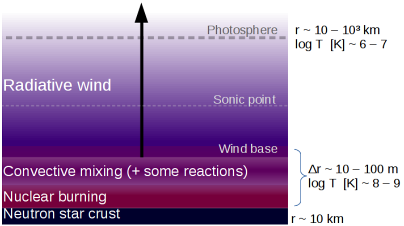
- Study a suitable radiative stellar wind model.
  - Modern numerical techniques and updated micro-physics.
  - Characterize model solutions in a generic NS scenario.
- Apply stellar wind model to realistic XRB conditions.
  - Consistent numerical match with XRB hydrodynamic simulations.
  - Reconstruct time evolution (quasi-stationary approach).
  - Compute mass-loss, composition, study observables.

Stellar wind model

Model hypotheses

- Non-relativistic fluid equations.
- Spherically-symmetric, stationary flow.
- Fully ionized perfect gas + radiation (LTE).
- Diffusive radiative transport.
- Optically thick wind, gray atmosphere.
- Updated opacities tables:
  - OPAL (Rogers & Iglesias, 1996).
  - The Opacity Project (Seaton & al, 1994).

Envelope structure.



Equations

Mass cons. $\dot{M} = 4\pi r^2 \rho v$

Energy cons. $\dot{E} = \dot{M}\left(\frac{v^2}{2} - \frac{GM}{r} + h(X_i)\right) + L_R$

Momentum cons. $0 = v\frac{\mathrm{d}v}{\mathrm{d}r} + \frac{GM}{r^2} + \frac{1}{\rho}\frac{\mathrm{d}P(X_i)}{\mathrm{d}r}$

Energy transport: $\frac{\mathrm{d}P_R}{\mathrm{d}r} = -\frac{\kappa \rho L_R}{4\pi c r^2}$

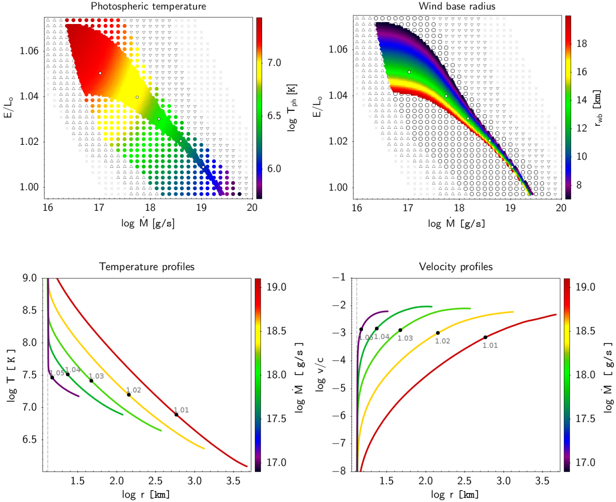
RMO (OPAL/TOP): $\kappa = \kappa(T, \rho, X_i)$

Wind base: extra conditions constrain $\dot{M}$, $\dot{E}$

NS compatible ⟶ Require sensible T_{wb}, ρ_{wb}

$$min\left\{r :: \nabla P_R \gtrsim \nabla P_g\right\} \simeq R_{\mathrm{NS}}$$

Wind profiles and parameter space characterization



Self-consistent (●/○)
· NS compatible (area)
· R_{NS} = 13km (◇)
Non-stationary (▽)
Optically thin (△)
No solution (×)

Parameters:
· $M_{NS} = 1.4\ M_{\odot}$
· $X = 0,\ \ Z = 0.1$ (solar)
· $L_o = \frac{4\pi cGM}{\kappa_o} \simeq 3.52 \times 10^{38}\,\mathrm{erg/s}$

"Generic" NS wind base:
$\nabla P_g = \nabla P_R \leftrightarrow r_{wb} = R_{NS}$

Resulting features:
· $\uparrow \dot{E}, \downarrow \dot{M}, \downarrow r_{ph}, \uparrow T_{ph}$
· $v_{ph}/c \lesssim 10^{-2}$
· $T_{ph}[\mathrm{K}] \sim 10^{6} - 10^{7.5}$
· $\Gamma = \frac{L_R}{L_{Edd}} \simeq 1 \pm$ few %

Correlation in observable variables

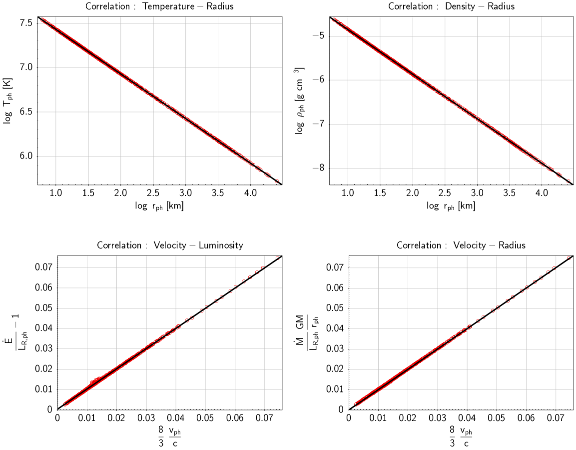
$$\boxed{T_{\rm ph}^2 \sim r_{\rm ph}^{-1} \sim \rho_{\rm ph}}$$

- Derive from:
  $\kappa_{\rm ph} \simeq \kappa_o = 0.2\mathrm{cm}^2/\mathrm{g}$
  $L_{\rm R,ph} \simeq L_o = 4\pi c GM/\kappa_o$
  + Photosphere conditions
- Independent of $(\dot{M}, \dot{E})$.
- All solutions
  (indifferent $R_{\rm NS}$)

$$\boxed{\frac{8}{3}\frac{v_{\rm ph}}{c} = \frac{GM}{r_{\rm ph}}\frac{\dot{M}}{L_{\rm R,ph}} \simeq \frac{\dot{E}}{L_{\rm R,ph}} - 1.}$$

- Derive from:
  $L_{\rm R,ph} \simeq L_{\rm Edd}$
  $v_{\rm ph} \gg c_{\rm s,ph}$
  + Photosphere conditions
  + Energy/mass cons.
- Involve $(\dot{M}, \dot{E})$.
- All solutions
  $(v_{\rm ph} \ll \frac{4L_o}{3\dot{M}c})$.

Correlation factor $\mathcal{R} \gtrsim 0.9995$



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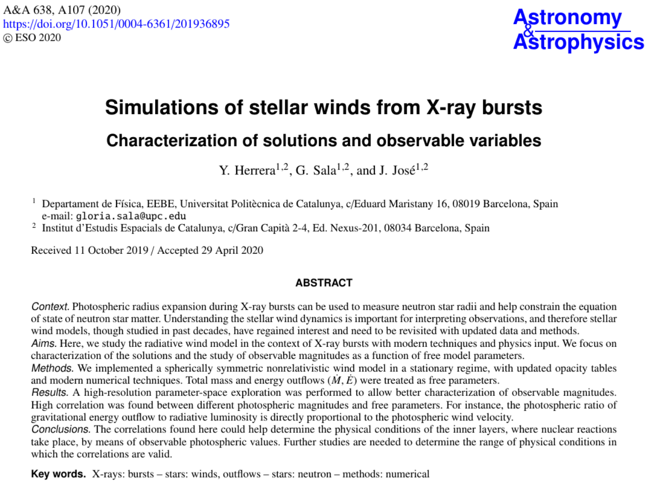

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Astronomy & Astrophysics

Simulations of stellar winds from X-ray bursts

Characterization of solutions and observable variables

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ABSTRACT

Context. Photospheric radius expansion during X-ray bursts can be used to measure neutron star radii and help constrain the equation of state of neutron star matter. Understanding the stellar wind dynamics is important for interpreting observations, and therefore stellar wind models, though studied in past decades, have regained interest and need to be revisited with updated data and methods.

Aims. Here, we study the radiative wind model in the context of X-ray bursts with modern techniques and physics input. We focus on characterization of the solutions and the study of observable magnitudes as a function of free model parameters.

Methods. We implemented a spherically symmetric nonrelativistic wind model in a stationary regime, with updated opacity tables and modern numerical techniques. Total mass and energy outflows $(\dot{M}, \dot{E})$ were treated as free parameters.

Results. A high-resolution parameter-space exploration was performed to allow better characterization of observable magnitudes. High correlation was found between different photospheric magnitudes and free parameters. For instance, the photospheric ratio of gravitational energy outflow to radiative luminosity is directly proportional to the photospheric wind velocity.

Conclusions. The correlations found here could help determine the physical conditions of the inner layers, where nuclear reactions take place, by means of observable photospheric values. Further studies are needed to determine the range of physical conditions in which the correlations are valid.

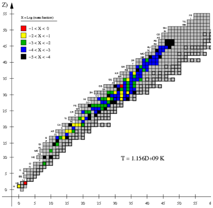
Key words. X-rays: bursts – stars: winds, outflows – stars: neutron – methods: numerical

Link: `https://doi.org/10.1051/0004-6361/201936895`

XRB hydrodynamic models: features

Model Features

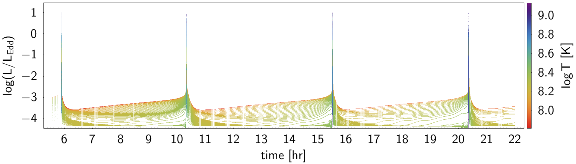
- Hydrodynamic evolution: SHIVA (Jose & Hernanz, 1998).
- 324 isotopes, 1392 nuclear reactions.
- Spherical symmetry, newtonian gravity.
- Convective + radiative energy transfer.
- EoS ← e^- degeneracy.
- Energy ← ν emission.



Models analyzed

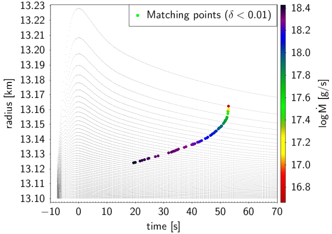
	Model input parameters				Resulting burst features				
#	Shells	M_{NS} ($M_\odot$)	R_{NS} (km)	Z	τ_{rec} (hr)	$\tau_{0.01}$ (s)	T_{pk} (10^9 K)	L_{pk} ($10^5 L_\odot$)	α
1	55	1.4	13.1	0.02	5.9	75.8	1.06	0.97	60
					6.4	62.3	1.15	1.7	40
					4.9	55.4	1.26	2.1	34
					5.1	75.7	1.12	1.2	36
2	200	1.4	13.1	0.02	5.9	59.2	1.05	0.9	62

José et al (2010) - Model 1 data :: $M_{NS} = 1.4 M_\odot$, $R_{NS} = 13.1$ km, $L_{Edd} = 3.52 \times 10^{38}$erg

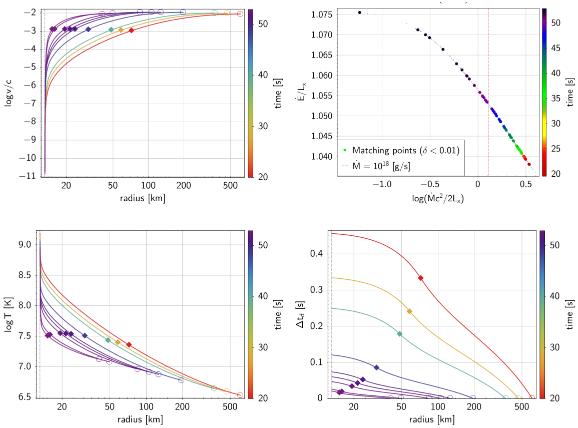


XRB wind matching solutions (200 shells model)

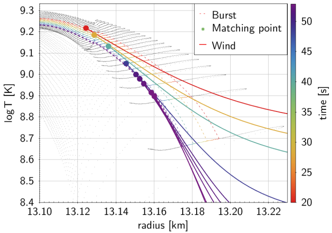
Matching point evolution



Matching wind profiles and parameter space evolution

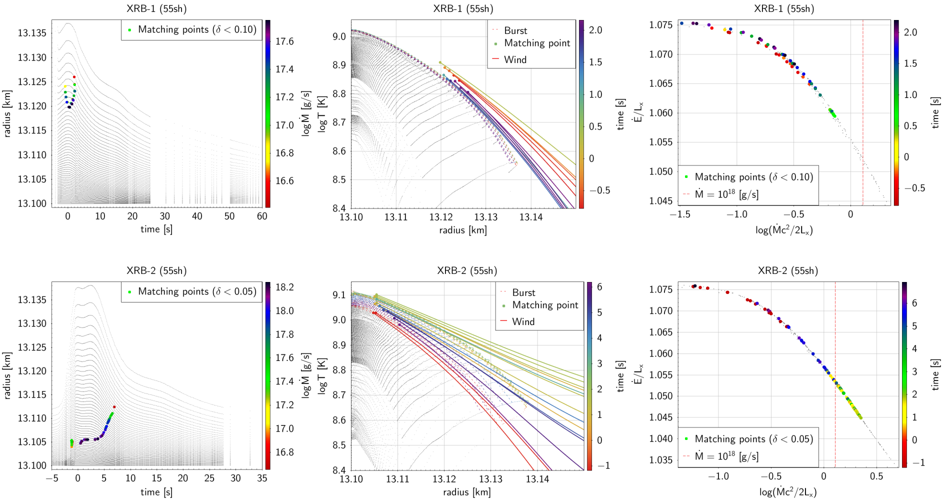


T(r) profiles match detail

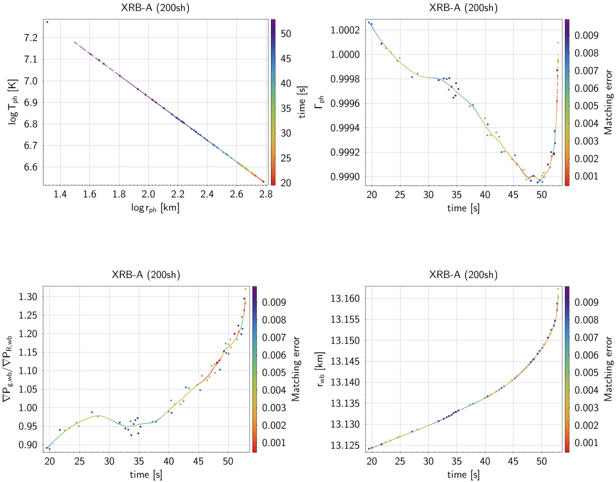


$$\Delta t_d = \int_{\mathrm{wb}}^{\mathrm{cr}} c_s^{-1} dr + \int_{\mathrm{cr}}^{\mathrm{ph}} v^{-1} dr << \Delta t_{\mathrm{XRB}}$$

XRB wind matching solutions (55 shells models)



XRB wind variables correlations and NS radius



Photospheric correlations

– Even with evolving X_i, $\rho_{\rm wb}$, $T_{\rm wb}$:

$$T_{\rm ph}^2 \sim r_{\rm ph}^{-1} \sim \rho_{\rm ph}$$

– Since $\Gamma_{\rm ph} \simeq 1$, then also:

$$\frac{8}{3}\,\frac{v_{\rm ph}}{c} = \frac{GM}{r_{\rm ph}}\,\frac{\dot{M}}{L_{\rm R,ph}} \simeq \frac{\dot{E}}{L_{\rm R,ph}} - 1.$$

$\longrightarrow$ evolution in $(\dot{M}, \dot{E})$ space.

Add approx. X_i $\left(\frac{\Delta\mu}{\mu} \sim 2\%\right)$, run the wind sims, and get estimates for...

Wind base location

– Matching point approximately at:

$$\nabla P_g \sim \nabla P_R$$

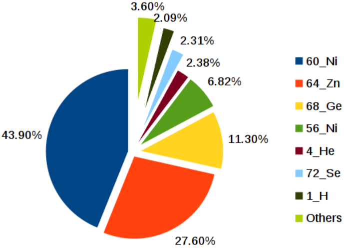
with $r \simeq R_{\rm NS} + (40 \pm 30)$m.

XRB wind mass loss (200-shell)

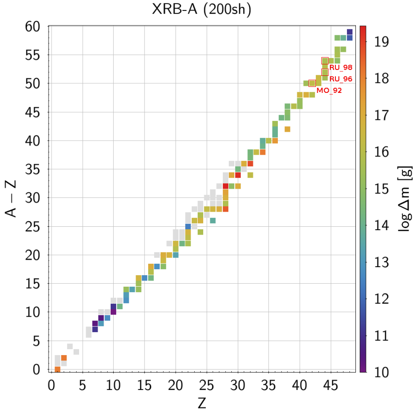
- Mass ejected by XRB wind for each isotope:

$$\Delta m_i = \int_{t_o}^{t_f} \dot{M}(t) X_i(t)\, dt$$

- $\dot{M}X_i$ at matching points, varying matching error δ, and irregular time distribution.
- Reconstruct time evolution.
  → Smooth (LOWESS) + interpolate.



Final stable isotopes



XRB wind mass loss totals (all bursts)

Total masses ejected

$$\Delta m = \int_{t_o}^{t_f} \dot{M} dt$$

Burst	Wind Δt (s)	Δm (g)
XRB-A	32	6.2×10^{19}
XRB-1	3	2.2×10^{17}
XRB-2	8	7.6×10^{18}
XRB-3	5	2.2×10^{18}
XRB-4	4	1.0×10^{18}

Accretion rate (g/s): 1.1×10^{17}

Avg $\Delta m_{\rm wind} / (\tau_{\rm rec} \dot{M}_{\rm acc})$ $\sim 2\%$

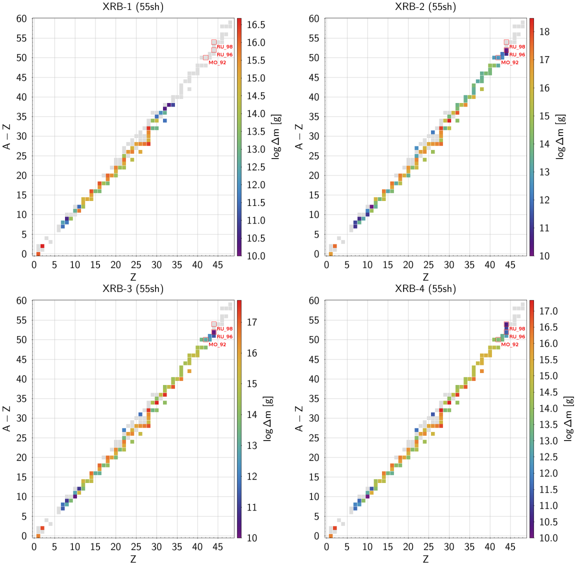
$M_{\rm env}$(g) :

- · XRB-A: 1.5×10^{22}
- · XRB-[1-4]: $(1.5 - 5.2) \times 10^{21}$

Avg $\Delta m_{\rm wind} / M_{\rm env}$: $\sim 10^{-3}$

Weinberg et al. (2006) assumed 1% expelled...

This is the most realistic estimation of XRB wind mass-loss so far!



XRB wind p-nuclei contribution

What about our p-nuclei: ^{92,94}Mo, ^{96,98}Ru?
Are XRBs like this enough to explain observed abundances?

Schatz & al, (2001) predicted ejection with a single-shell XRB model

Isotope	^{92}Mo	^{96}Ru	^{98}Ru
XRB-A wind mass yield per burst (g)	1.57×10^{16}	5.75×10^{15}	4.73×10^{15}
XRB-A annual yield ($M_\odot$/yr) [1]	1.18×10^{-14}	4.29×10^{-15}	3.53×10^{-15}
XRB-A life-time contribution ($M_\odot$) [2]	5.88×10^{-05}	2.15×10^{-05}	1.76×10^{-05}
Solar system X_i (Lodders, 2009) [3]	9.27×10^{-10}	2.59×10^{-10}	8.80×10^{-11}
Isotope mass presence in MW ($M_\odot$) [4]	1.85×10^{02}	5.17×10^{01}	1.76×10^{01}
Sources like XRB-A required to match	3.15×10^{06}	2.41×10^{06}	9.98×10^{05}

More than a millon sources are needed...

And we know around 100 only, with highest estimates of 2000 LMXB(NS) in galactic history!

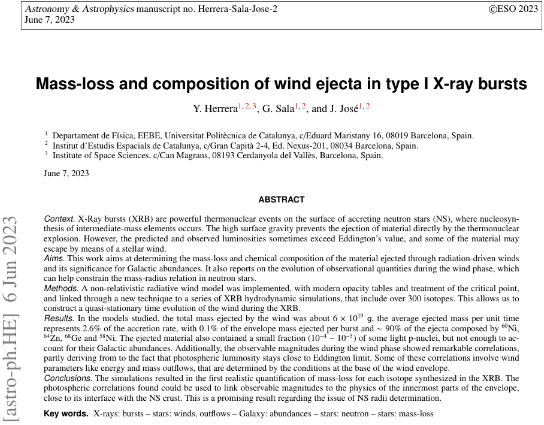
(van Haaften et al, 2015)

Even assuming...

1. XRB recurrence time $\sim$ 5.9`hr` (no inactivity periods)
2. 5 Gyr LMXB lifetime (high estimate)
3. Solar system is representative of galactic abundances
4. Galactic mass $\sim 200 \times 10^9 M_\odot$
   (medium estimate, baryonic matter)

These are not the p-nuclei sources
you are looking for...

Published article



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Mass-loss and composition of wind ejecta in type I X-ray bursts

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June 7, 2023

ABSTRACT

Context. X-Ray bursts (XRB) are powerful thermonuclear events on the surface of accreting neutron stars (NS), where nucleosynthesis of intermediate-mass elements occurs. The high surface gravity prevents the ejection of material directly by the thermonuclear explosion. However, the predicted and observed luminosities sometimes exceed Eddington's value, and some of the material may escape by means of a stellar wind.
Aims. This work aims at determining the mass-loss and chemical composition of the material ejected through radiation-driven winds and its significance for Galactic abundances. It also reports on the evolution of observational quantities during the wind phase, which can help constrain the mass-radius relation in neutron stars.
Methods. A non-relativistic radiative wind model was implemented, with modern opacity tables and treatment of the critical point, and linked through a new technique to a series of XRB hydrodynamic simulations, that include over 300 isotopes. This allows us to construct a quasi-stationary time evolution of the wind during the XRB.
Results. In the models studied, the total mass ejected by the wind was about 6×10^{19} g, the average ejected mass per unit time represents 2.6% of the accretion rate, with 0.1% of the envelope mass ejected per burst and $\sim$ 90% of the ejecta composed by ^{60}Ni, ^{64}Zn, ^{68}Ge and ^{58}Ni. The ejected material also contained a small fraction ($10^{-4} - 10^{-5}$) of some light p-nuclei, but not enough to account for their Galactic abundances. Additionally, the observable magnitudes during the wind phase showed remarkable correlations, partly deriving from to the fact that photospheric luminosity stays close to Eddington limit. Some of these correlations involve wind parameters like energy and mass outflows, that are determined by the conditions at the base of the wind envelope.
Conclusions. The simulations resulted in the first realistic quantification of mass-loss for each isotope synthesized in the XRB. The photospheric correlations found could be used to link observable magnitudes to the physics of the innermost parts of the envelope, close to its interface with the NS crust. This is a promising result regarding the issue of NS radii determination.

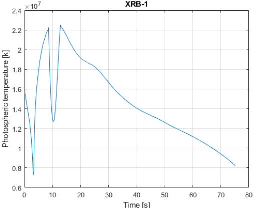
Key words. X-rays: bursts – stars: winds, outflows – Galaxy: abundances – stars: neutron – stars: mass-loss

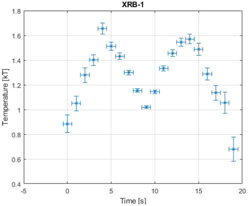
Link: `https://doi.org/10.1051/0004-6361/202346190`

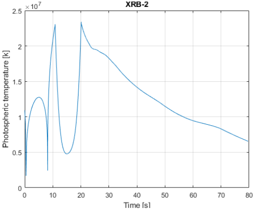
Bonus track

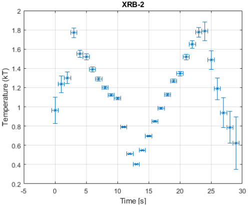
XSPEC observation simulations for NICER

Daniel Muñoz Vela's bachelor thesis (work in progress)









Conclusions

Summary and conclusions:

- Application of modern stellar wind model to realistic XRB hydrodynamic simulations, linked through novel techniques.
- Realistic determination of mass loss and ejecta composition.
  – Ejected mass: $\sim 0.1\%$ of envelope.
  – Average mass ejection rates: $\sim 2\%$ of accretion rate
- Contribution of light p-nuclei to galactic abundance: poor.
  – Several orders of magnitude below observed abundances.
- Notable correlations in observable magnitudes (found in our previous work) upheld.
  – Can be used to estimate wind parameters evolution: $\dot{M}$, $\dot{E}$.
  – Wind base ($\nabla P_g \sim \nabla P_R$) $\leftrightarrow$ R_{NS} + few tens of meters.
  → Possible application to R_{NS} measurement.

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`arXiv:2306.03701`

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Thank you.