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

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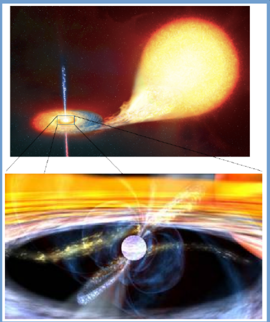
1. Context

- **Scenario.** Low mass X-ray binary (LMXB): accreting neutron star + Main Sequence or Red Giant companion.
- **Event.** Type I X-ray bursts (XRB): High energy (10^{39-40} erg), luminous (10^{5-6} $L_{\odot}$), short lived (~min), short recurrence (~hr-days), thermonuclear runaway of accreted material.
- **Motivation 1.** XRB Simulations show synthesis of heavy elements (A~64), but no explosive ejection due to high surface gravity. [2]
  However: photospheric radius expansion (L ~ L_{Edd}) may lead to ejection through stellar wind.
- **Motivation 2.** EoS for neutronic matter is debated. Available models predict different M-R relations for NS. Independent measuring techniques are needed. [4]

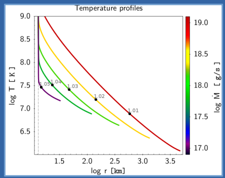


2. Objectives

- Apply a modern stellar wind model to XRB conditions (numerical match with XRB hydrodynamic simulations).
- Quantify wind related mass-loss and composition.
- Characterize observable magnitudes during wind phase that may help constrain M-R relation for neutron stars.

3a. Wind simulation [1]

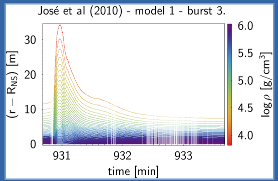
- Non-relativistic, spherically-symmetric, stationary fluid equations.
- Fully ionized perfect gas + radiation in local thermal equilibrium (LTE).
- Diffusive radiative transport.
- Optically thick wind, gray atmosphere.
- Updated opacities tables: OPAL/OP.



Possible wind T-r profiles, with varying input $\dot{M}$ and $\dot{E}/L_{edd}$, result in different physical values at desired wind base [1]

3b. XRB simulation [2]

- Hydrodynamic code: SHIVA.[3]
- Spherical symmetry, newtonian gravity.
- Network: 324 isot. + 1392 reactions.
- Convective + radiative energy transfer.
- Incl. e- degeneracy in EoS and energy losses due to neutrino emission.



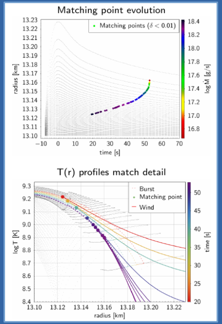
Time evolution of envelope radial expansion and density from a XRB hydrodynamic simulation model data [2]

3c. Matching technique

- Continuous transition of all physical magnitudes.
- Custom non derivative-based root-finding methods and large data grid sweep techniques.
- At each XRB grid point (given ***r, T, ρ, Ė, X$_i$***) find wind profile with matching ***ρ***, by varying ***Ṁ***.
- From previous ***ρ*** matches, filter for grid points with a match in ***T***, within desired residual threshold, given by:

$$\delta = \sqrt{\frac{\delta\rho^2}{\rho^2} + \frac{\delta T^2}{T^2}}$$

- Reconstruct time evolution: quasi-stationary sequence of matching profiles ***Ė(t), Ṁ(t), X$_i$(t)***.



4a. Results: Wind mass-loss

- XRB-wind matches found allow integration of mass ejection curves.
- Several bursts analyzed, resulting in:
  - Avg. envelope mass ejected

$$\frac{\Delta m}{M_{\rm env}} \sim 0.1\%$$

  - Avg. ejection/accretion rate

$$\frac{\Delta m}{\tau_{\rm rec}\ \dot{M}_{\rm acc}} \sim 2\%$$

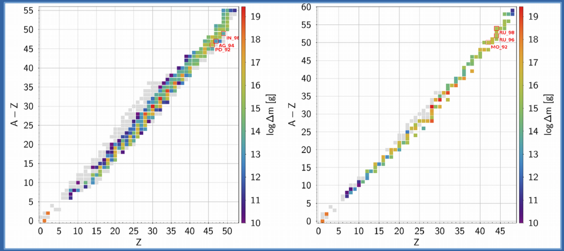
  (recurrence time ~ 5-6 hr).
- Small fractions of rare light p-nuclei (^{92}Mo, ^{96,98}Ru)

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}

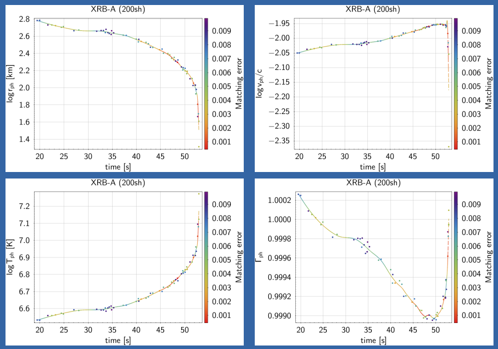
$\Delta M_{\rm env}$(g) :
· XRB-A: 1.5×10^{22}
· XRB-[1-4]: $(1.5 - 5.2) \times 10^{21}$

XRB wind phase duration and ejected mass.



Total mass ejected per isotope during wind phase in XRB-A.
Left: isotopes directly produced in XRB nucleosynthesis. Right: final stable isotopes after radioactive decay.

4b. Results: observables evolution



Reconstructed time evolution (line) from XRB-wind matching profiles data (dots).
Photospheric radius, temperature, wind velocity and radiative luminosity in terms of LEdd.

Correlations from our previous study [1] were found to hold (with factor > 99,94%), now with realistic evolving conditions at the wind base.

$$T_{\rm ph}^2 \sim r_{\rm ph}^{-1} \sim \rho_{\rm ph} \qquad \frac{8}{3}\frac{v_{\rm ph}}{c} = \frac{GM}{r_{\rm ph}}\frac{\dot{M}}{L_{\rm R,ph}} \simeq \frac{\dot{E}}{L_{\rm R,ph}} - 1$$

These provide a direct link between observable features and wind parameters determined by burst physical conditions, close to the NS core surface.

Wind base (≈ r_{NS}) was found to be always where: $\frac{\nabla P_g}{\nabla P_R} \sim 1$

5. Summary

- A new technique was developed to match stellar wind models to modern XRB hydrodynamic simulations.
- A more realistic determination of XRB wind related mass-loss was achieved (~0.1% of the NS envelope, at 2% of accretion rate).
- Detailed composition of the wind ejecta was obtained, with ^{60}Ni, ^{64}Zn, ^{68}Ge, ^{56}Ni and ^{2}He adding up to over 90% mass, no significant amounts of light p-nuclei.
- Predicted observable magnitudes evolve in a direct correlation with physical parameters determined by inner layers of the envelope, close to neutron star core.
- This can help develop new techniques to measure NS radii and constrain their mass-radius relation.

References

[1] **Herrera, Y.; Sala, G.; José, J. (2020)**. Simulations of stellar winds from X-ray bursts: Characterization of solutions and observable variables. A&A, 638, A107.

[2] **José, J.; Moreno, F.; Parikh, A.; Iliadis, C. (2010)**. Hydrodynamic Models of Type I X-ray Bursts: Metallicity Effects. ApJS, 189(1), 204–239.

[3] **José, J.; Hernanz, M. (1998).** Nucleosynthesis in Classical Novae: CO versus ONe White Dwarfs. ApJ, 494(Feb.), 680–690.

[4] **Sala, G.; Haberl, F.; José, J.; Parikh, A.; Longland, R.; Pardo, L. C.; Andersen, M. (2012)**. Constraints on the Mass and Radius of the Accreting Neutron Star in the Rapid Burster. ApJ, 752(2), 158.