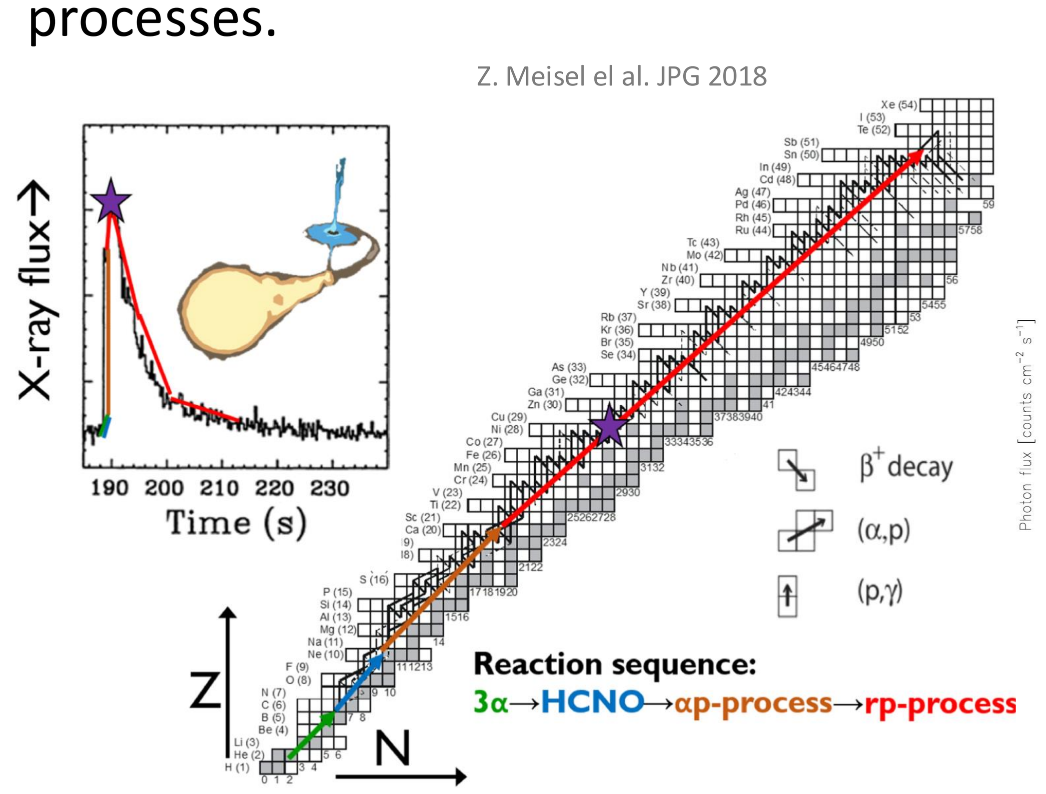
Nuclear Physics Sensitivities in Type-I X-ray Burst

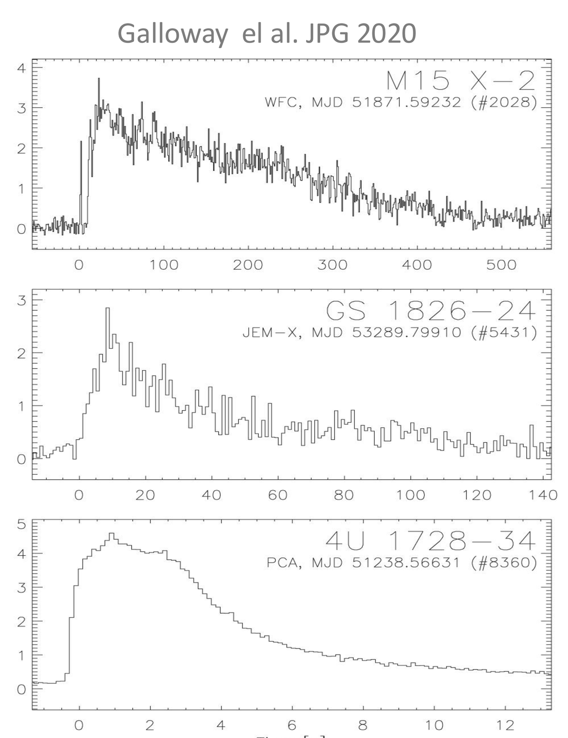
Irin Sultana*, A. Estrade, J. Borowiak, J. Elliot, B. S. Meyer, and H. Schatz
Central Michigan University*

Introduction

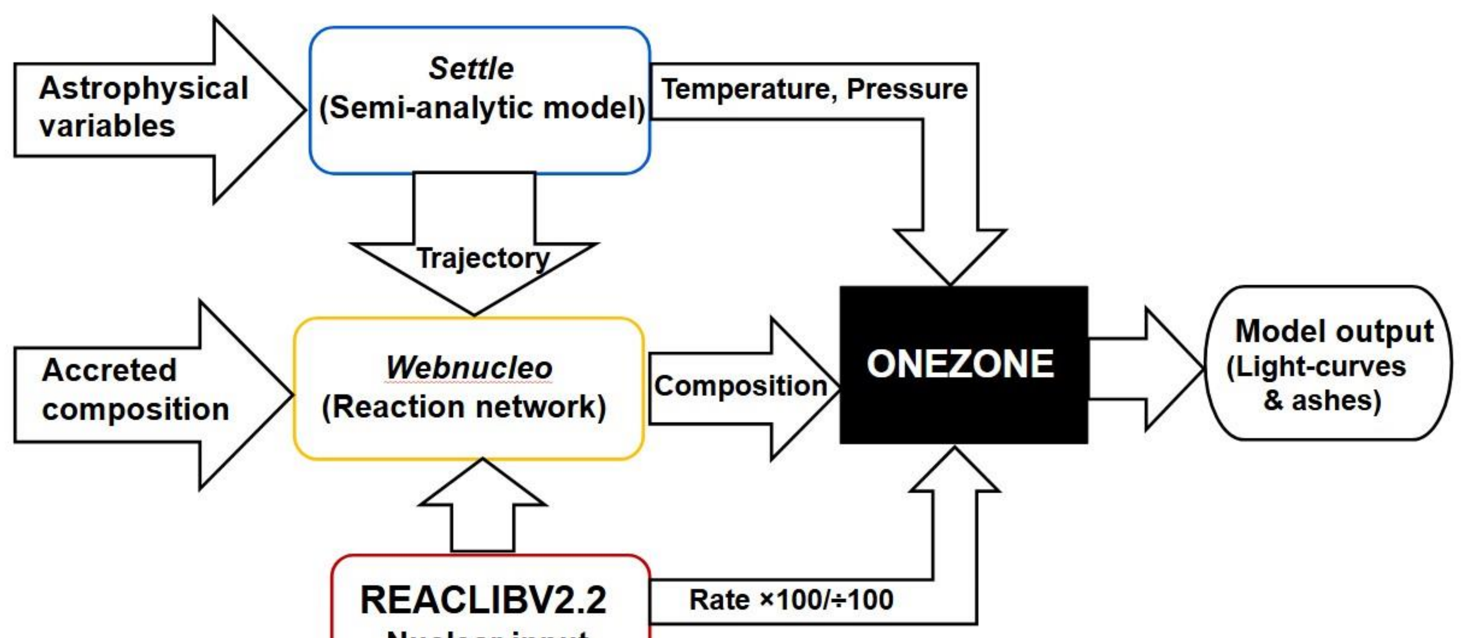
Type-I X-ray bursts (XRB's) are thermonuclear flashes on the surface of accreting neutron stars, powered by the triple-α process, the αp process, and the rapid proton capture process. Uncertainties in nuclear reaction rates significantly impact the accuracy of model predictions and their agreement with observational data.

Observations indicate that the light curve shapes of XRBs vary significantly with binary system parameters, underscoring the necessity for precise modeling and a comprehensive understanding of the underlying nuclear and astrophysical processes.





Methods



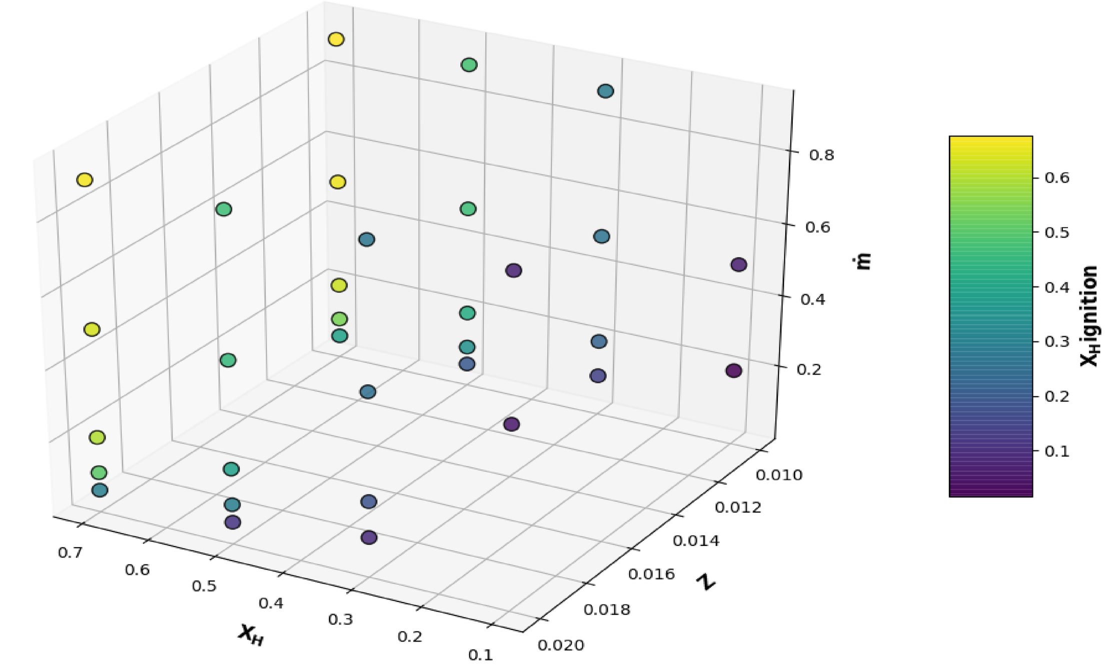
We investigate the impact of nuclear reaction uncertainties on XRB's using the ONEZONE model [1], considering different accreted compositions and accretion rates for the binary systems. The study is conducted in two stages. First, we determine the burst ignition conditions by simulating the settling of the accreted material with a full reaction network code, Webnucleo [2], and a semi-analytical model, Settle [3]. Second, we perform a sensitivity analysis by varying proton- and alpha-induced reaction rates in JINA REACLIBV2.2 within a factor representative of typical uncertainties. We explore the influence of these reactions on the XRBs light curve and the final abundances produced.

Results

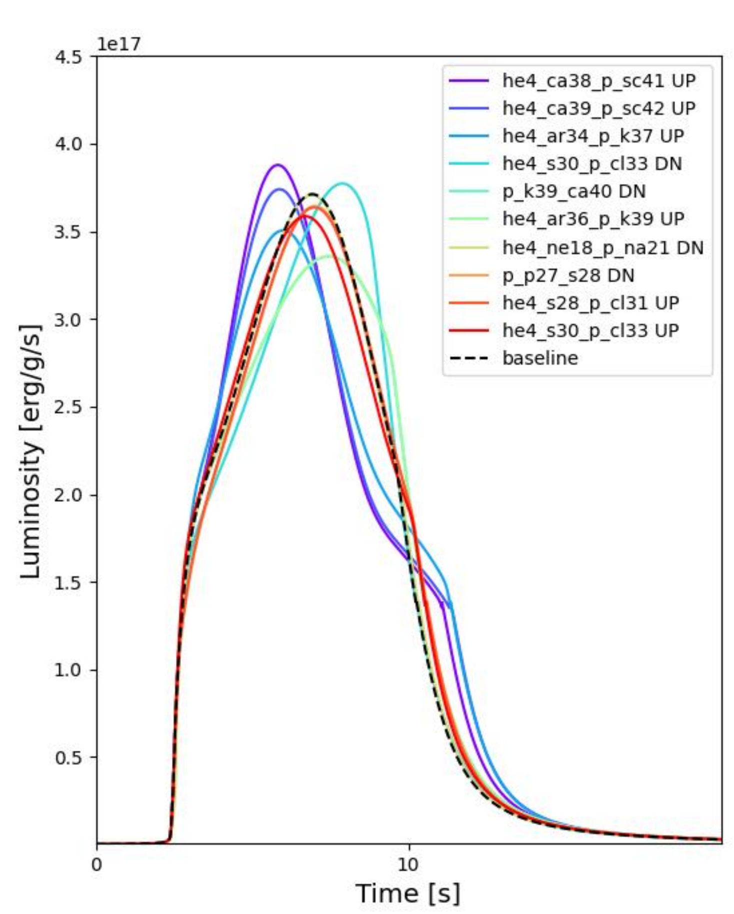
We analyzed 32 astrophysical cases. The grid space for our study is shown in the figure below. For this study, hydrogen mass fraction (X_H) was varied at values 0.7, 0.5, 0.3, 0.1, while the metallicity (Z) was set at 0.02 and 0.01. The accretion rate ($\dot{m}$) was varied at 0.05, 0.1, 0.2, 0,5, and 0.9 (in units of Eddington accretion rate). Sensitivity to individual reaction rates was quantified by evaluating the changes in the model light curve and final abundances, using the following equations:

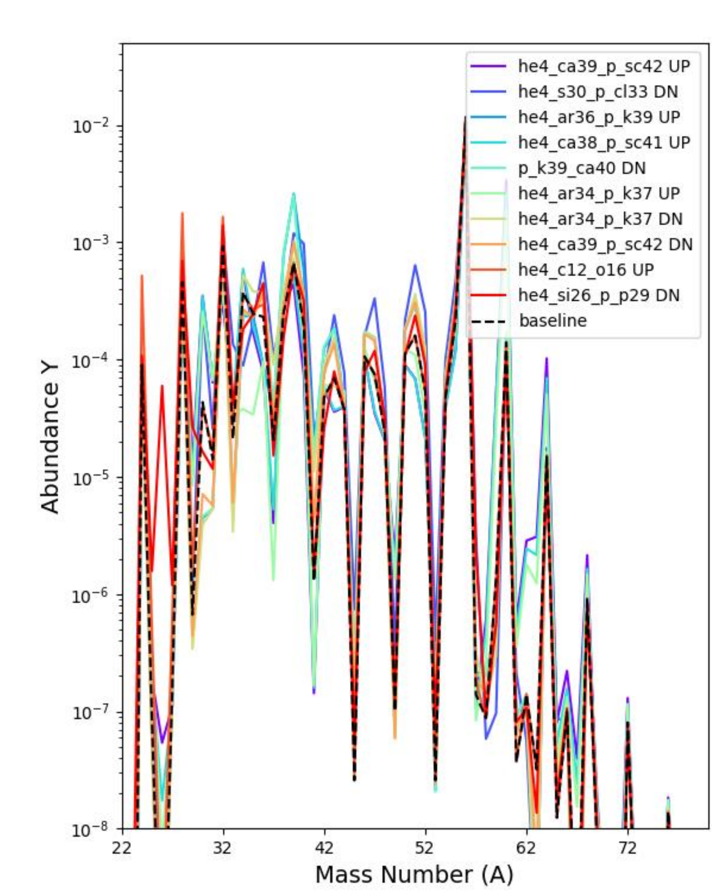
For light-curve, $F_{\mathrm{lc}} = \max |L_{\mathrm{baseline}}(ti) - L_{\mathrm{rate}}(ti)|$

For abundance, $F_{\mathrm{ash}} = \sum_{i=A_0}^{i=A_f} |Y_{i,\mathrm{baseline}} - Y_{i,\mathrm{rate}}|$

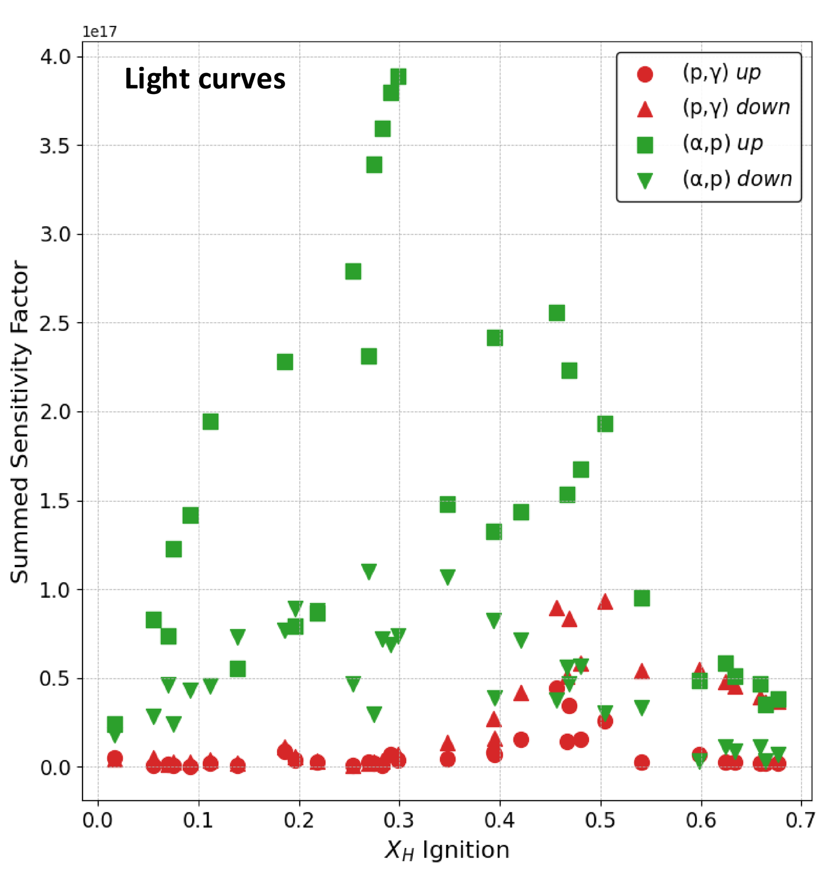


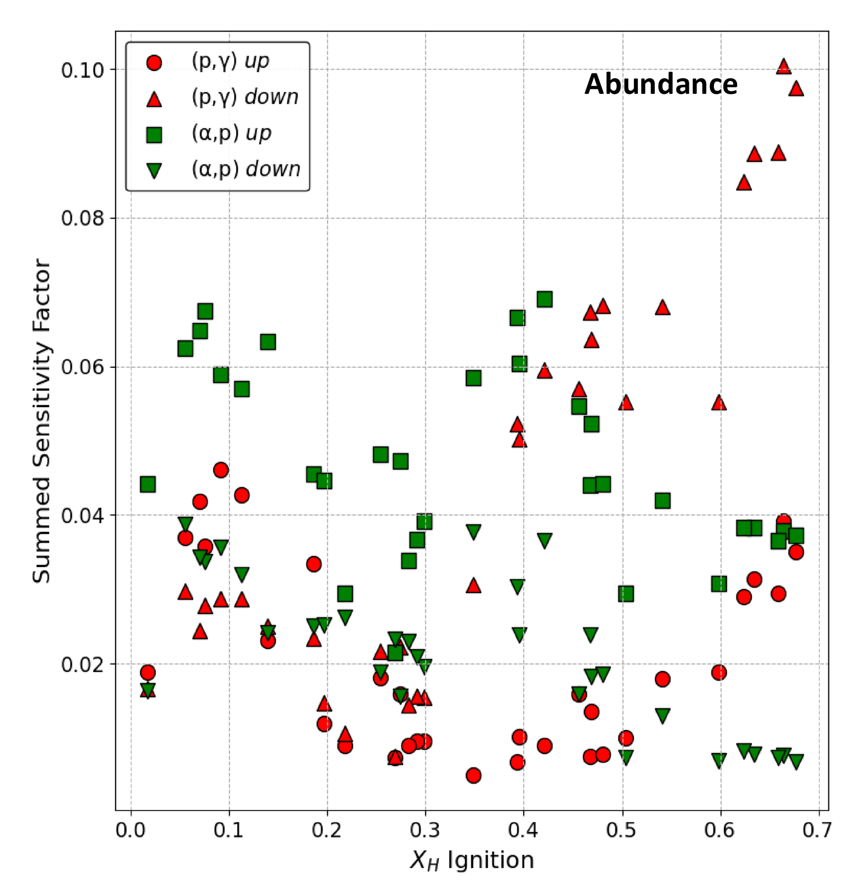
As an example, the figures show the high-impact reactions for an astrophysical conditions with a hydrogen mass fraction of 0.7 and an accretion rate of $0.05\dot{m}_{Edd}$ and a metallicity of 0.02. At ignition, H mass fraction was 0.3 and He mass fraction was 0.68.





The comparison of the sensitivity factor for the (p,γ) and (α,p) reactions as a function of X_H at ignition for all 32 cases is shown in the two figures for light curve and final abundance change. For each astrophysical scenario, the total sensitivity for each reaction type was calculated by summing the individual sensitivities obtained using the given equations. This approach allows us to identify which reaction type exhibits dominant sensitivity as a function of X_H at ignition.





Discussion

- Our study integrates a semi-analytic model with two single-zone reaction network codes, enabling a detailed calculations of nucleosynthesis during the settling process and its impact on burst properties.
- We conducted a sensitivity study across a range of accretion rates and compositions of accreted material.
- The types of impactful reactions vary with astrophysical parameters, as demonstrated by the dependence of reaction rate sensitivities on composition at burst ignition.
- This work underscores the importance of experimental efforts at rare isotope beam facilities to reduce reaction rate uncertainties.

References

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