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Probing the life and death of massive stars: Unveiling the CSM structure and progenitor mass-loss history of SN 2014C

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1 RATIONALE

❖Remnants of core-collapse supernovae (SNe) encode valuable information about the SN engine and the structure of the inhomogeneous ambient medium through which they expand.

❖Analyzing observations of these remnants can yield crucial insights into the SN event itself and the progenitor stellar system.

❖Particularly intriguing are SNe where the expelled material interacts significantly with their surroundings during the early phases (from a few days to hundreds of days) of evolution.

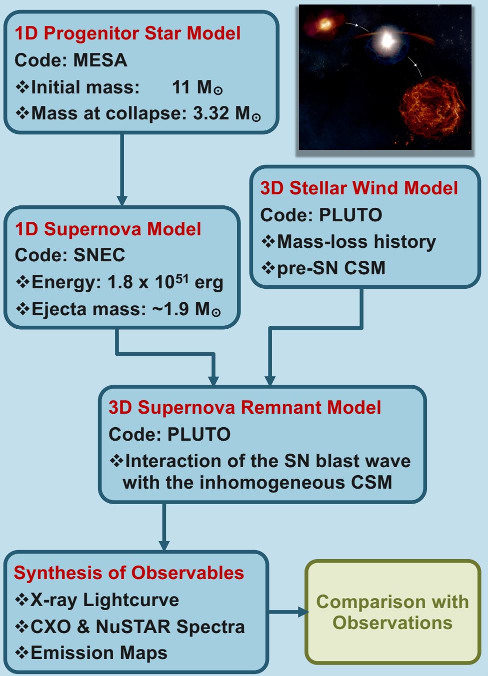
❖Such interactions can provide valuable insights into mass-loss events that occurred centuries to millennia before the SN explosion, thus allowing to shed light on the terminal stages of massive star evolution and the elusive mechanisms driving their mass loss.

We present 3D hydrodynamic modeling describing the evolution of SN 2014C, an interacting SN observed in the X-ray band with Chandra and NuSTAR, covering 15 years of evolution.

AIM: ***Reconstruct the pre-SN CSM structure and constrain the progenitor star's mass-loss history preceding core-collapse***

2 APPROACH AND MODEL SETUP

Modeling SN 2014C from the progenitor star to the SN and to the remnant interacting with the CSM



1D Progenitor Star Model
Code: MESA
❖Initial mass: 11 M$_\odot$
❖Mass at collapse: 3.32 M$_\odot$

1D Supernova Model
Code: SNEC
❖Energy: 1.8 x 10^{51} erg
❖Ejecta mass: ~1.9 M$_\odot$

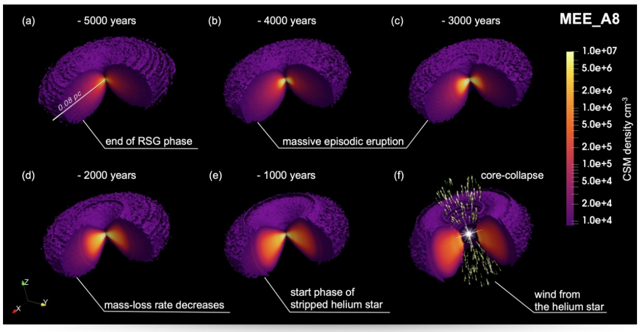
3D Stellar Wind Model
Code: PLUTO
❖Mass-loss history
❖pre-SN CSM

3D Supernova Remnant Model
Code: PLUTO
❖Interaction of the SN blast wave with the inhomogeneous CSM

Synthesis of Observables
❖X-ray Lightcurve
❖CXO & NuSTAR Spectra
❖Emission Maps

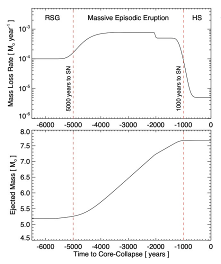
Comparison with Observations

3 CSM EVOLUTION DUE TO THE WINDS OF THE PROGENITOR STAR

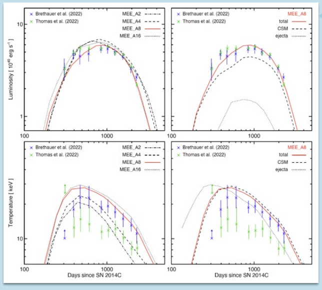


Evolution of the CSM in our favourite model **MEE_A8**. The frames in the figure show the geometry and distribution of density of the CSM at the labeled times before the SN event. Isosurface delineates material with particle number density $n > 10^4$ cm^{-3}; the color indicates the density value (color legend on the right). Arrows in frames (f) denote the wind velocity during the helium star phase.

4 EXPANSION OF THE SNR THROUGH THE INHOMOGENEOUS CSM

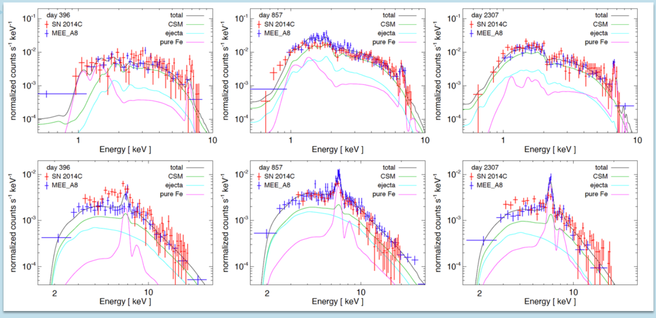


Upper panel: Mass-loss history used in our wind models, leading to X-ray lightcurve and temperature evolution of the SNR consistent with those inferred from the analysis of X-ray observations of SN 2014C (e.g., *Thomas et al. 2022, ApJ 930, 57*; *Brethauer et al. 2022, ApJ 939, 105*).
Lower panel: Corresponding amount of mass released by the progenitor star in the millennia leading up to its core-collapse.



Upper panels: X-ray lightcurve in the [0.5, 100] keV band synthesized from a subsample of our models (on the left) compared with the observed lightcurve of SN 2014C. Model **MEE_A8** is shown on the right together with the contributions to emission from the shocked gas from the nebula and the shocked ejecta.
Lower panels: Corresponding evolution of average X-ray emission-weighted electron temperature.

Comparison of spectra synthesized from model MEE_A8 (blue crosses) and true spectra of SN 2014C (red) collected with CXO (upper panels) and NuSTAR (lower panels) at the labeled times since the SN.
The synthetic ideal spectra (black lines) and the contributions from plasma components are also reported: shocked CSM (green), shocked ejecta (without the contribution of iron; light blue), and shocked pure-Fe ejecta (magenta).



5 Summary

Our analysis revealed that:

❖the remnant interacted with a dense toroidal nebula extending from 4.3 x 10^{16} cm to 1.5 x 10^{17} cm in the equatorial plane, with a thickness of approximately 1.2 x 10^{17} cm;

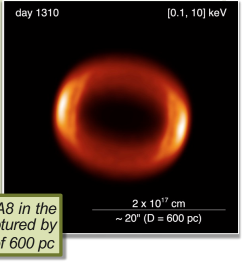
❖the nebula exhibits a peak density of ~ 3 x 10^6 cm^{-3} at the inner boundary, gradually decreasing as ~ r^{-2} at greater distances;

❖the nebula formed as a result of intense mass-loss from the progenitor star between 5500 and 1200 years before its collapse;

❖the maximum mass-loss rate reached ~ 8 x 10^{-4} M$_\odot$ yr^{-1}, leading to the release of ~ 2.5 M$_\odot$ of stellar material into the CSM;

❖Our model reproduces Chandra and NuSTAR spectra, across the entire SNR evolution, highlighting the contribution of shocked CSM and ejecta;

❖We found that ~ 0.05 M$_{sun}$ of pure-Fe ejecta were shocked during the remnant-nebula interaction.



Synthetic X-ray emission map from model MEE_A8 in the [0.1,10] keV band at day 1310 as it would be captured by Chandra if SN 2014C were located at a distance of 600 pc