Estimation of progenitor of Kepler's SNR with precision X-ray spectroscopic analysis

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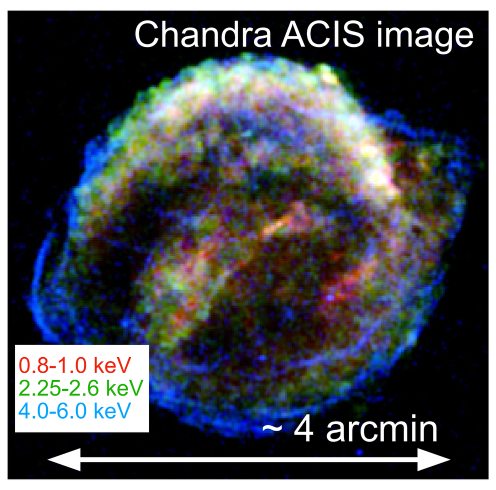
Abstract

Kepler's SNR is the newest Type Ia supernovae (SNe Ia) observed in our galaxy in 1604. There are two main models of the mechanism in which the C-O white dwarf approaches the Chandrasekhar mass to explode as SNe Ia, single-degenerate (SD) model and double-degenerate (DD) model. In the case of the Kepler's SNR, it is believed to have been produced from the an SD model because of the observed radiation from the circumstellar material (CSM) (1). However, no companion star has been found that should have remained (2). We investigated the elemental composition of the CSM using the Reflection Grating Spectrometer on board the XMM- Newton satellite in order to determine the identity of the companion star. As a result, the emission lines of nitrogen and oxygen were detected and the abundance ratio of N to O was obtained to be ~ 2.26. If this reflects the composition of the companion star's stellar wind, this implies a lower limit for the mass of the companion star of ~1.5 M⊙ and that it is likely in asymptotic giant branch (AGB) star phase.

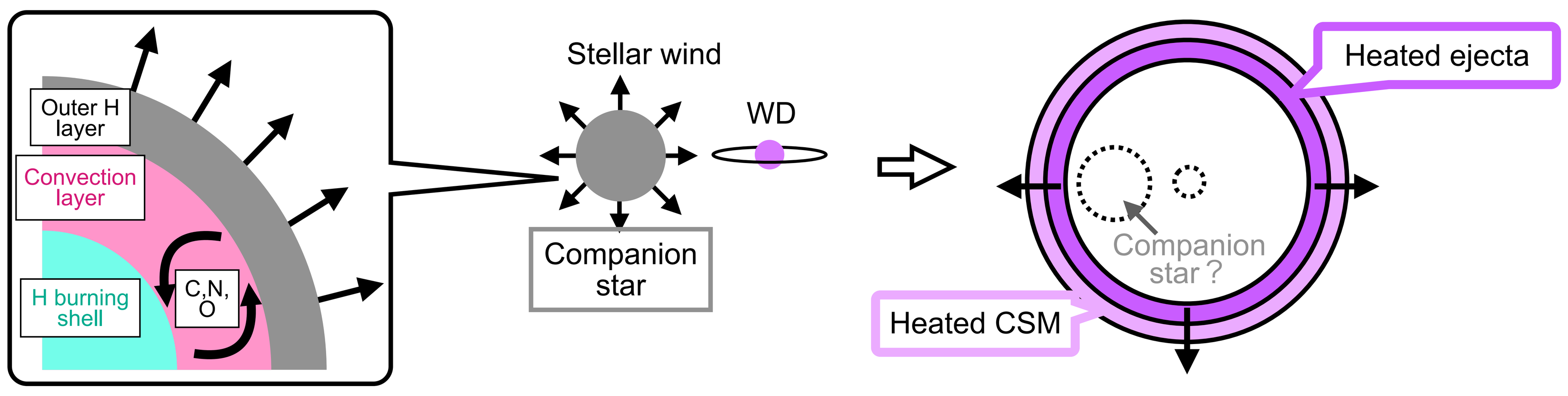
Kepler's SNR



- **Shock-heated CSM** is detected in the X-ray(1). -> SD model?
- No companion star has been found (2).
- Previous studies suggest that the companion star was an AGB star based on mass-loss rate (1).

Want to know the identify of the companion star!

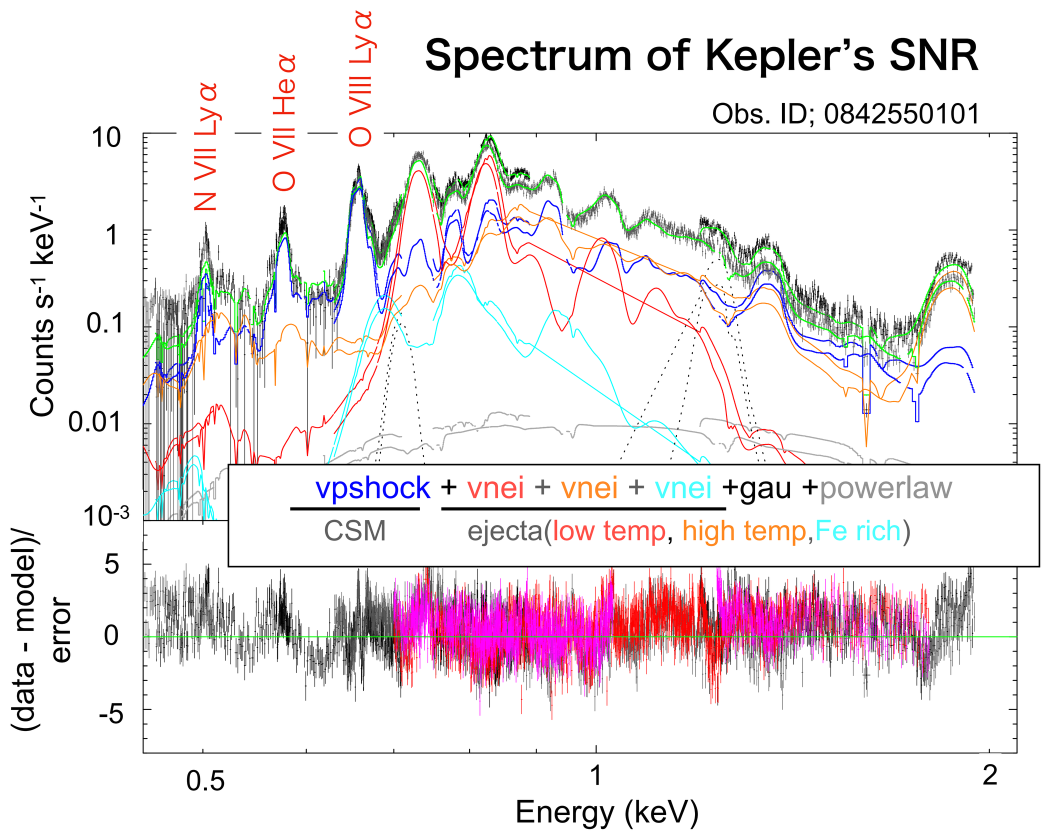
Estimation of companion stars with CSM

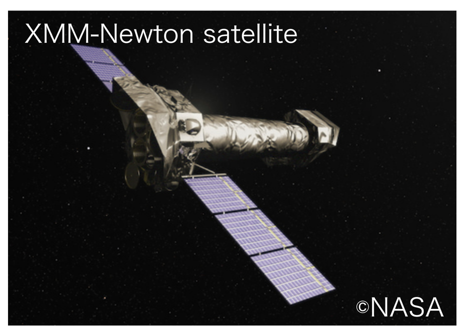


- C, N, O synthesized near the core of the companion star is transported to the surface by the convection layer.
- N/O abundance depends on the degree of evolution of the star.

We can estimate mass-loss history and progenitor properties of companion star with N/O !

Results of X-ray spectroscopic observations





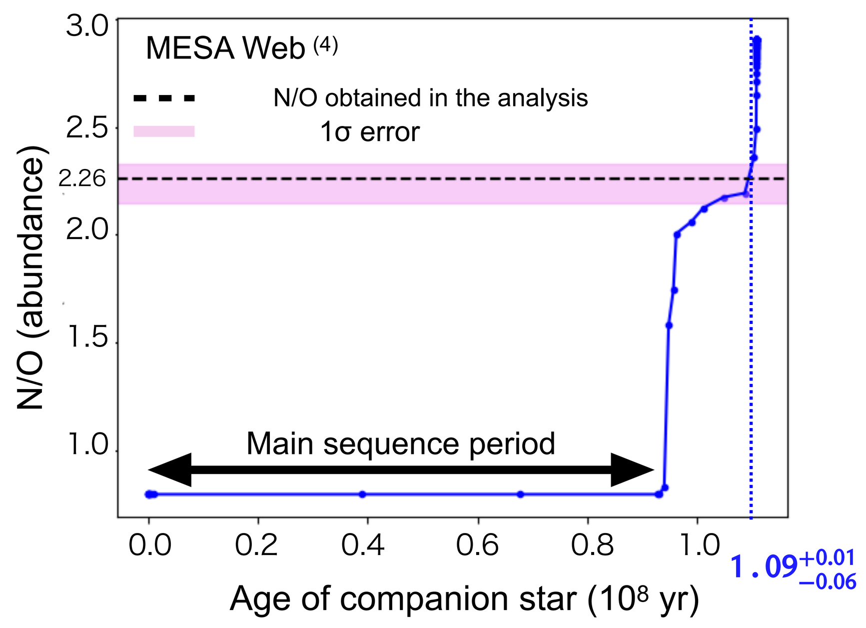
X-ray data used

Obs. ID	Date	Exposure
0084100101	2001 Mar 10	32 ksec
0842550101	2020 Mar 19	132 ksec
0853790101	2020 Mar 11	37 ksec

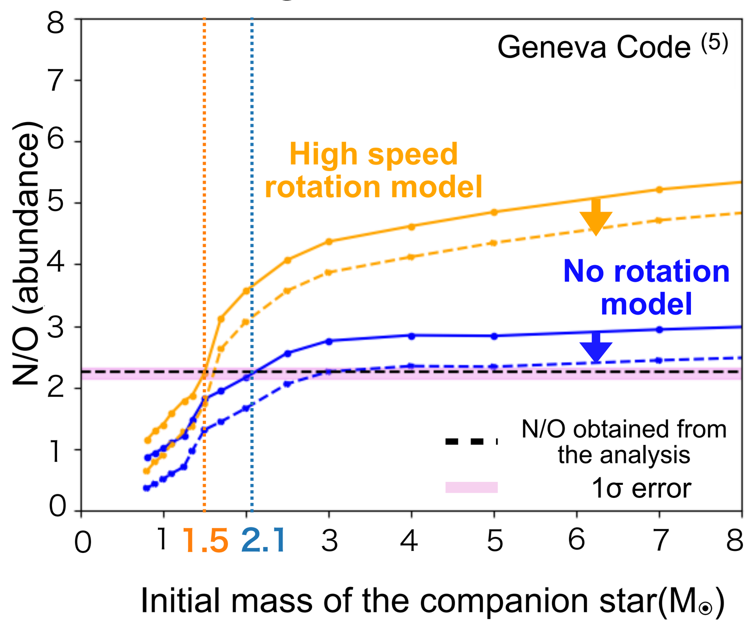
- The analysis uses data from all 3 observations with the Reflection Grating Spectrometer(RGS) on board XMM-Newton.
- emission lines of nitrogen and oxygen, which could not be separated with the energy resolution of the CCD, are detected using the RGS.
- N/O-rich material originates from the CSM
- N/O(abundance) ; $2.26^{+0.07}_{-0.11}$ (1σ error)
- The obtained abundance significantly exceeds that of interstellar matter (ISM) around Kepler's SNR (~1.29) (3).
- **Kepler's N/O abundance is measured accurately !**

Identify the companion star

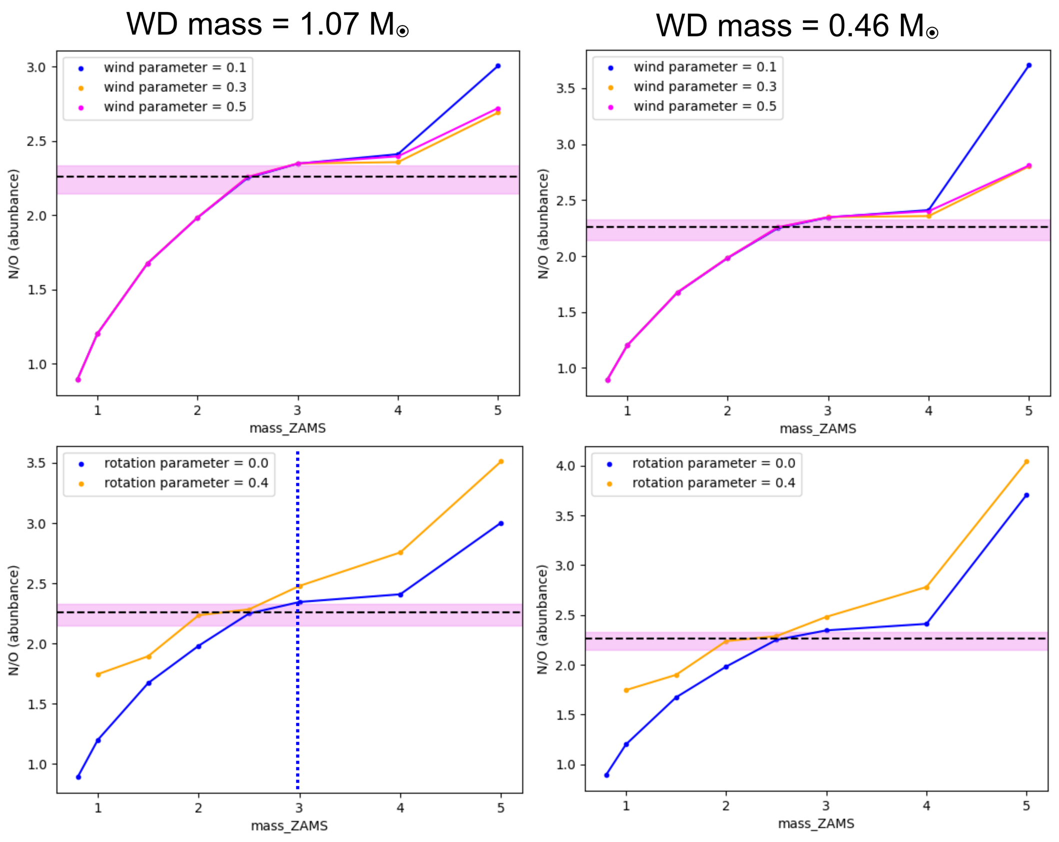
N/O abundance ratio when stellar winds are integrated vs. Time



N/O abundance ratio when stellar winds are integrated vs. Initial mass



- Simulated 1D stellar evolution of the companion star using MESA web and Geneva Code.
- Assuming all stellar winds accrete mass to the WD as CSM.
- Age ; ~10^8 yr, lower limit of initial mass; 1.5$M_\odot$
- If the WD explodes during the evolution of the companion star, expected N/O will decrease (orange and blue dotted lines in the right panel of the above figure).



← **N/O abundance ratio comparing different parameters vs. Initial mass**

Assuming all stellar winds accrete mass to the WD, initial mass of the companion star vs. N/O abundance ratio of CSM when stellar winds are integrated until the mass of the WD approaches the Chandrasekhar mass with MESA web. **Top**: models with mass of WD = 1.07$M_\odot$ and 0.46$M_\odot$,with initial uniform rotation rate(V_{ZAMS}/V_{crit}) = 0(6). Color correspond to different scaling factor for wind mass loss rate on the AGB phase = 0.1(blue), 0.3(orange), and 0.5(magenta). **Bottom**: with scaling factor for wind mass loss rate on the AGB phase = 0.1. Color correspond to different rotation rate(V_{ZAMS}/V_{crit}) = 0(blue), 0.4(orange)

- Wind parameters(6) do not significantly affect the total amount of N and O and hence our estimation of the progenitor mass: **1.5–3$M_\odot$**.

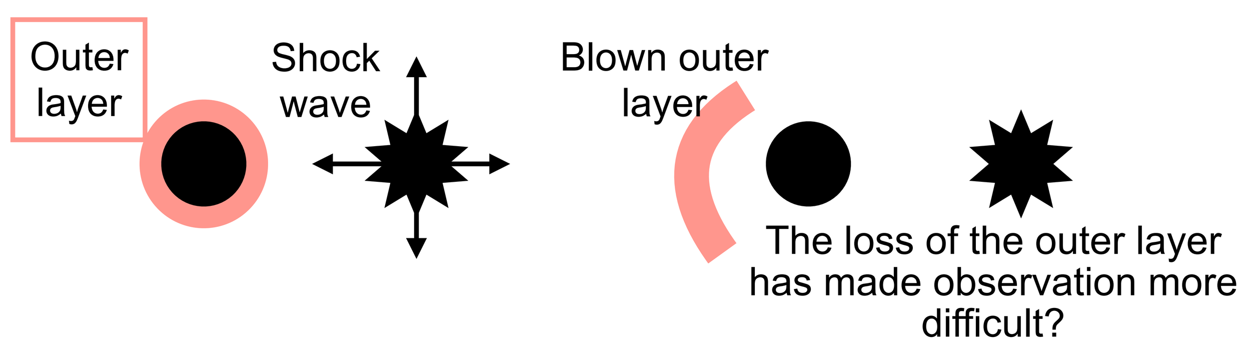
The companion star of Kepler's SN was most likely in the AGB star phase.

What is Progenitor of Kepler's SNR ?

Why has no companion star(AGB star ?) been found?

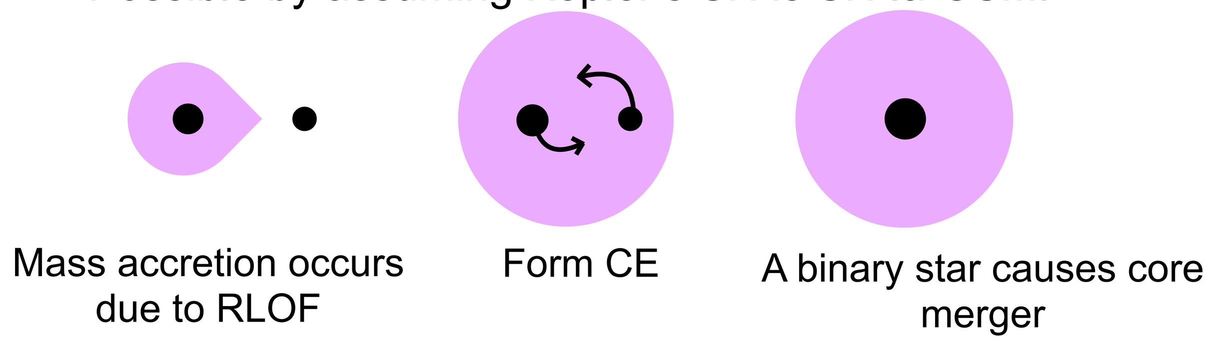
✓ Outer layer of the AGB companion star was stripped by the SN shock wave(7)?

- No robust evidence has been found so far.



✓ The AGB star was in a close binary system and was merged with the WD before the explosion in common envelope (CE)(8)?

- Possible by assuming Kepler's SN is SN Ia-CSM.



Summary and conclusion

✓ Kepler's SNR is one of the SNe Ia in which CSM was observed.

✓ N/O abundance could be measured in detail using the 3 data by XMM-Newton.

✓ The age and initial mass of the companion star can be estimated, and the rotation velocity is found to have an effect.

(1) Katsuda et al., 2015, ApJ, 808, 49, 14
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