Formation of Mg-rich SNRs by shell merger and its effect on the explodability

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More details are on **KM et al. 2024 (arXiv:2405.20736), accepted to ApJ** and **Sato, KM, et al. 2024 (arXiv:2403.04156)**

1. Scientific motivation: What kind of massive stars can explode?

The "explodability" of a massive star is an open question. Some results conflict with each other.

- All of the progenitors of type-IIP SN events seem to be $\lesssim 20M_\odot$. (e.g., Smartt 2015)
- The theoretical studies suggest that $\lesssim 20M_\odot$ stars will explode. (e.g., Heger+2003, Sukhbold+2016)
- The chemical composition of our galaxy needs explosions of $\gtrsim 20M_\odot$ stars. (e.g., Suzuki & Maeda 2018)
- The Fe/Si abundance ratios in some SNRs indicate the progenitors of $\gtrsim 20M_\odot$ stars. (Katsuda+2016)

Here, we focus on the abundance patterns of inter-mediate mass elements (Ne, Mg, Si) in SNRs, measured with X-ray. They are expected to give us information about the progenitors before exploding.

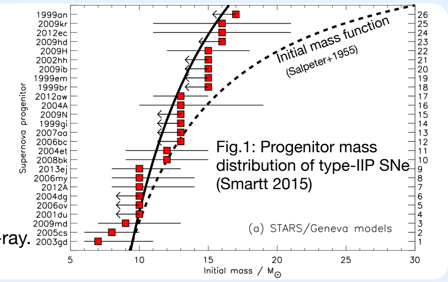


Fig.1: Progenitor mass distribution of type-IIP SNe (Smartt 2015)

2. Mg-rich SNRs

Some X-ray observations report "Mg-rich" SNRs (N49B, Park+2003; G284.3-1.8, Williams+2015), whose Mg/Ne abundance ratiois significantly greater than the solar.

The progenitors and forming mechanisms still need to be clarified.

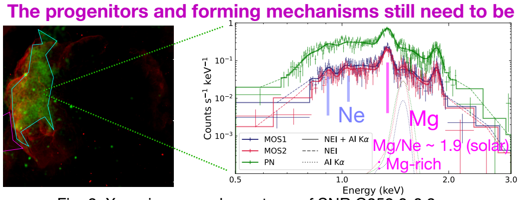


Fig. 2: X-ray image and spectrum of SNR G359.0-0.9, obtained with XMM-Newton EPIC.

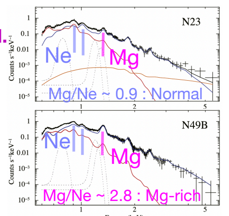
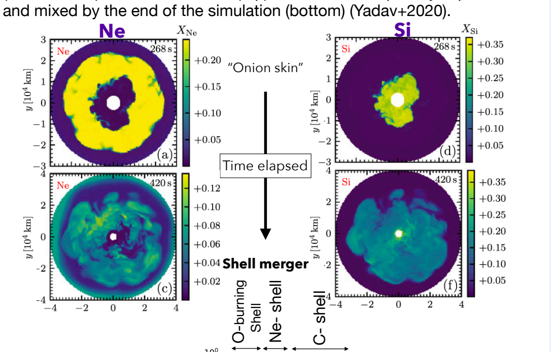


Fig. 3: X-ray spectra of N23 (normal) and N49B (Mg-rich) (Uchida+2015)

Fig. 5: Spatial distribution of Ne and Si at various times in a 3D simulation (Yadav+2020). At the initial state (top), Ne and Si are spatially separated and mixed by the end of the simulation (bottom) (Yadav+2020).



3. Shell mergers can explain Mg-rich

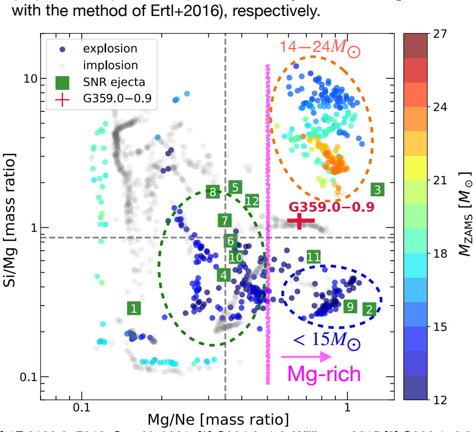
To reveal the origin of the Mg-rich ejecta, we compare the observed Mg/Ne ratios with the stellar models (Fig. 4). The comparison result suggests that the distribution of the Mg/Ne ratios is consistent with that of the models.

The Important points are below:

- Mg-rich ejecta can be explained by "shell mergers" (Fig. 5, 6).
- There are two groups in Mg-rich models; $14M_\odot < M_{\rm ZAMS} < 24M_\odot$ progenitors with high Si/Mg ratios and $M_{\rm ZAMS} < 15M_\odot$ progenitors with low Si/Mg ratios (Fig. 5) The difference comes from the internal structures (Fig. 6).
- All massive progenitors with $M_{\rm ZAMS} > 20M_\odot$ have Mg-rich compositions with high Si/Mg ratios (Fig. 4).

In particular, the last point suggests that only a Mg-rich SNR with a high Si/Mg ratio would be a candidate for a massive star's remnant ($M_{\rm ZAMS} > 20M_\odot$).

Fig. 4: Parameter distribution of Mg/Ne and Si/Mg expected from stellar models (circles; Sukhbold et al. 2018) and obtained from previous observations of SNRs (green squares). The colored and gray circles represent explosion and implosion cases (predicted with the method of Ertl+2016), respectively.



[1] 1E 0102.2–7219; Sasaki+2001, [2] G284.3–1.8; Williams+2015 [3] G290.1–0.8; Kamitsukasa+2015 [4] MSH 15–52; Yatsu+2005 [5] MSH 15–56; Yatsu+2013 [6] N132D; Hughes+1998 [7] N23; Uchida+2015 [8] N49; Uchida+2015 [9] N49B; Uchida+2015, [10] N63A; Hughes+1998, [11] RX J1713.7–3946; Katsuda+2015, [12] W44; Uchida+2012.

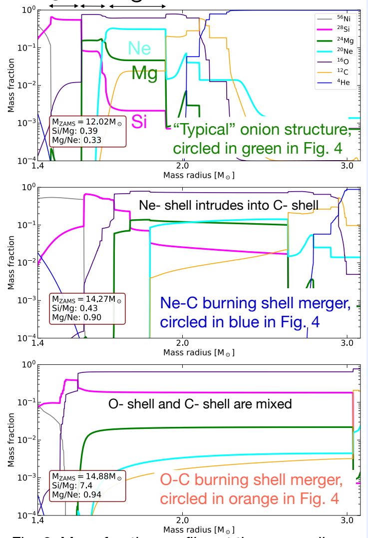


Fig. 6: Mass fraction profiles at the core-collapse. The models are provided by Sukhbold et al. 2018

4. Effects of Shell Mergers on Explodability

In Ertl+2016, they suggest that the explodability of a 1D progenitor can be predicted (in accuracy of $> 97\%$) using two parameters;

- $M_4 \equiv M_r(s = 4)/M_\odot$
- $\mu_4 \equiv \left.\dfrac{\Delta M/M_\odot}{\Delta r/1000\ {\rm km}}\right|_{s=4}$

, where s is the dimensionless entropy per nucleon, and M_r is the mass-radius.

As shown in Fig. 7, we found that Mg-rich (shell merger) progenitors tend to be more explodable than normal progenitors. **Together with Fig.4, shell mergers may lead a massive star ($M_{\rm ZAMS} > 20M_\odot$) to explode.**

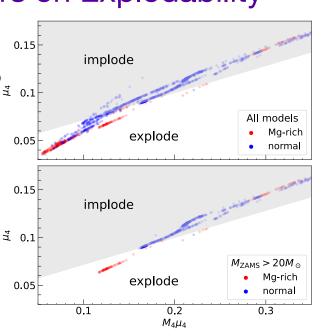


Fig. 7: μ_4 versus $M_4\mu_4$ plot for all models (top) and relatively massive models (bottom). The white/grey areas indicate the explode/implode ranges in W18, respectively. The models are provided by Skukhbold+2018.

5. Effects on odd-Z elements (work with XRISM)

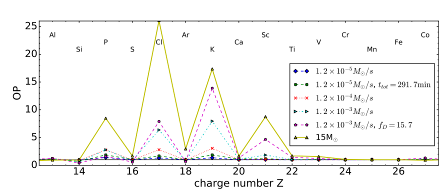


Fig. 8: Overproduction factor versus Z plot for some shell merger models (Ritter+2018a). OP=1 is the case of a model without a shell merger.

Ritter+2018a suggest that O-C shell mergers promote to synthesize the odd-Z elements. Together with our result, that may give us some guidelines to detect those elements with XRISM satellite.

6. Summary and Conclusion

- A few Mg-rich SNRs ($({\rm Mg/Ne})/({\rm Mg/Ne})_\odot > 1$) have been found by X-ray spectroscopy.
- The abundance patterns can be explained by "shell mergers", which seem to affect the explodability and nucleosynthesis of massive stars.