Multidimensional simulations of thermonuclear supernovae

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Consistent multi-D modeling pipeline





t = 0.0025 s



t = 0.200 s



t = 0.600 s



t = 1.000 s

t = 1.600 s

 outcome sensitive to ignition geometry (Fink+ 2014)





Seitenzahl+, 2012; Fink+, 2014

A model for SNe lax?-20

- Do models cover the entire brightness range? \rightarrow faint end??
- previous studies covered bright end (SN 2002cx-likes Phillips+ 2007, Jordan+ 2012, Kromer+ 2013, Kromer+ 2015, Leung+ 2020)
- Do models reproduce spectra and light curves?



A model for SNe lax?

 Lach+ (2022): systematic study of single-spark ignition scenarios to explore faint end of models

roff

200 km

- 30 models with different
 - ignition radii
 - central densities
 - metallicities
 - rates of (rigid) rotation
 - carbon mass fractions





 $t = 0.6 \, \mathrm{s}$

 $t = 1.55 \,\mathrm{s}$

 $t = 1.55 \,\mathrm{s}$

A model for SN lax?

- ► Lach+ 2022a
- ▶ lowest ⁵⁶Ni mass in ejecta: 0.006 M_☉
- kick velocities of bound remnants 0 to ~350 km/s



 $t = 0.6 \, \mathrm{s}$

A model for SN lax?

- ▶ peak bolometric brightness: -14.91 mag to -17.35 mag
- brighter models agree reasonably well with observations
- ▶ strong correlation between $M(^{56}Ni)$ and $M_{ej} \rightarrow light$ curves of faint models evolve too fast





A model for SNe lax?

- overall still reasonable agreement
- but: problems with reproducing faint events
 - difficult to break strong M(⁵⁶Ni) to M_{ej} correlation, but seems to be necessary to capture faint objects
 - shortcomings in explosion modeling? \rightarrow ignition configuration
 - ▶ shortcomings in RT modeling? \rightarrow non-LTE effects (Shingles+ 2020)
 - contributions of bound remnant to emission? (Kromer+ 2013, 2015, Foley+ 2014, 2016, Shen & Schwab 2017)
 - ▶ shortcomings of the explosion scenario? → stratified ejecta composition in outer layers (Stritzinger+ 2015, Barna+ 2017, 2018, 2020)
- Can SNe lax be explained in single explosion scenario? → core collapse SN scenario for faintest objects (Valenti+ 2009)





Pulsationally-assisted GCD models



- wide range of brightnesses: 0.257 to 1.057 M_{\odot} of ⁵⁶Ni
- spectra and lightcurves: some similarities with SN 1991T-like objects, but not with normal SNe Ia



Detonations in sub-M_{Ch} WDs

promising scenario (Sim+ 2010)



- primary parameter driving trends: mass of exploding WD (Pinto & Eastman 2000)
- How to trigger detonation?

Double detonation model



A model for normal SNe la?

- Do models cover the entire brightness range? → YES
- ▶ Do models follow correlations? → PROBABLY (Sim+ 2010, Shen+ 2021)
- Do models reproduce spectra and light curves? (Townsley+ 2019, Shen+ 2021)
- How robust is the ignition mechanism?
- ▶ He shell detonation critical → improve modeling approach: use AREPO code (Gronow+ 2020, 2021, sub.)





Gronow+ 2020

A model for normal SNe Ia?

- ► 13 model parameter study of different core (0.8 – 1.1 M_☉) and He shell masses (0.02 – 0.1 M_☉); Gronow+ (2021) → 3 different C-detonation ignition mechanisms
- too red because of He shell detonation
 products (Gronow+ 2020)
- ▶ shortcomings in RT modeling? → non-LTE effects (Shingles+ 2020, Shen+ 2021)
- too strong variation with viewing angle (Gronow+ 2021)







- production of ⁵⁵Mn \rightarrow Lach+ (2020)
- production ⁵⁵Mn → normal freeze-out from NSE needed to reach solar [Mn/Fe] Seitenzahl+ (2014)





- production of ${}^{55}Mn$ \rightarrow Lach+ (2020)
- He shell detonation contributes significantly (Lach+ 2020, Gronow+ 2021)



Are M_{Ch} explosions required?

 GCE calculation Gronow+ (2021); with B. Côté in a ChETEC-funded visit to Heidelberg

- models with He-shell detonations can produce supersolar Zn/Fe and Cu/Fe ratios (Lach+ 2020)
- GCE studies should include a variety of SN la models!



Conclusions

- ► explosion modeling pipeline → valuable tool to test progenitor scenarios
- predictive power due to consistent multi-D modeling
- allows for comparison of observables with data (nucleosynthesis yields, optical observables, SNR structures...)

Seitenzahl+ 2013, Lach+, 2020





- ► sub-M_{Ch} model looks promising for normal SNe Ia
- Type lax supernovae from M_{Ch} explosions?
- use a variety of models for GCE calculations!