Three-dimensional simulations of double detonations in double-degenerate systems for type Ia supernovae

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Type Ia supernovae

- One of the brightest and most common objects in the universe
- A cosmic distance indicator
- The origin of iron peak elements
- Thermonuclear explosions of white dwarfs (WDs)
- Unknown progenitor
  - Single Degenerate (SD) or Double Degenerate (DD)
  - Near-Chandrasekhar mass (Near-Ch) or sub-Chandrasekhar (sub-Ch) mass

Seitenzahl et al. (2013)  
Fink et al. (2010)
Constraints on the progenitors

- SD or DD
  - Non detection of RG in the pre-explosion image of SN2011fe (e.g. Li et al. 2011)
  - Non detection of MS in LMC SNR 0509-67.5 (e.g. Schaefer, Pagnotta 2012)
  - But see spin-up/down model.
- Near-Ch or sub-Ch
  - Both required (Hitomi Collaboration 2017)
  - Sub-Ch DD can be one of the progenitors

Li et al. (2011)

Hitomi Collaboration (2017)
Hypervelocity WDs

- The discovery of hypervelocity (~1000km/s) WDs (Shen et al. 2018)
- Double detonations in a DD system (Guillochon et al. 2010; Pakmor et al. 2013)
- So-called Dynamically-Driven Double-Degenerate Double-Detonation (D6) explosion
D6 processes

1. Lighter WD

2. He

3. Heavier WD

4. >1000 km/s

5. Converting shock

6. He detonation

7. >1000 km/s

8. Supernova ejecta of the Heavier WD

9. >1000 km/s

10. C detonation
This study

- We perform a SPH simulation of double detonations in a DD system.
- We explore signals of the progenitor model.
- We also investigate various combinations of WDs.
Method

- 3D SPH method
  - Parallelized by FDPS (Iwasawa, AT+ 2016)
  - Vectorized by SIMD (e.g. AT+ 2012; 2013)
- Helmholtz EoS (Timmes, Swesty 2000)
- Aprox13 nuclear reaction networks (Timmes et al. 2000)
Initial condition

- Mass combinations
  - 1.0M\text{sun} + 0.6M\text{sun} COWDs
    - w/o a He shell of the lighter WD
  - 1.0M\text{sun} COWD + 0.45M\text{sun} HeWD
    - Impossibly small separation
  - 1.0 \text{ Msun} + 0.9\text{Msun} COWDs
    - w/ a thick He shell of the lighter WD
- Hot spot in thick He outer shells
Animation

1.0 Msun + 0.6 Msun COWDs
Outcome explosion

- Nuclear energy: 1.35x10^51 erg
- 56Ni: ~0.6Msun
- Stripped mass from the lighter WD: ~0.003Msun
- Captured mass by the lighter WD: ~0.03Msun
SN ejecta

- Almost spherically symmetric shape
- An ejecta shadow formed by the lighter WD
- $^{56}$Ni, Si+S, O, and C from inside to outside
- Companion-origin stream stripped by the SN ejecta
Low-velocity oxygen

- The companion-origin stream consists of carbon and oxygen.
- It contributes to low-velocity components, a few 1000 km/s.
- The D6 explosion has low-velocity oxygen.
Velocity shift

- Radial velocities of O, Si, and $^{56}$Ni are systematically shifted by the orbital motion of the heavier WD.

- The velocity shift is about 1000km/s.

- This is not due to asymmetric explosion of double detonation.

- Double detonation shifts velocities of O+Si and Ni in the opposite directions.
Triple detonations (TD)
1.0 CO + 0.45 He WD
Quadruple detonations (QD)

1.0CO + 0.9CO Msun w/ thick He shell of the lighter WD
Chemical abundance

| Model   | $M_p$  | $M_{p,\text{sh}}$ | $M_{p,\text{He}}$ | $M_c$  | $M_{c,\text{sh}}$ | $r_{\text{sep},i}$ | Exp. | $M_{\text{ej}}$ | $M_{\text{56Ni}}$ | $M_{\text{Si}}$ | $M_{\text{O}}$ | $M_{\text{cos}}$ | $E_{\text{nuc}}$ | $E_{\text{kin}}$ |
|---------|--------|-------------------|--------------------|--------|-------------------|---------------------|------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| He45R09 | 1.0    | 0.05              | 0.03               | 0.45   | –                 | 2.9                 | TD   | 1.45          | 0.81           | 0.15           | 0.08           | –              | 2.3            | 2.0            |
| He45    | 1.0    | 0.05              | 0.03               | 0.45   | –                 | 3.2                 | D$^6$ | 0.98          | 0.56           | 0.15           | 0.07           | 0.0033         | 1.4            | 1.1            |
| CO60He00| 1.0    | 0.05              | 0.03               | 0.60   | 0.000             | 2.5                 | D$^6$ | 0.97          | 0.55           | 0.15           | 0.07           | 0.0028         | 1.4            | 1.1            |
| CO60He06| 1.0    | 0.05              | 0.03               | 0.60   | 0.006             | 2.5                 | D$^6$ | 0.97          | 0.54           | 0.15           | 0.07           | 0.0029         | 1.3            | 1.1            |
| CO90He00| 1.0    | 0.10              | 0.05               | 0.90   | 0.000             | 1.6                 | D$^6$ | 0.93          | 0.51           | 0.14           | 0.06           | 0.0024         | 1.4            | 1.1            |
| CO90He09| 1.0    | 0.10              | 0.05               | 0.90   | 0.009             | 1.6                 | D$^6$ | 0.94          | 0.52           | 0.14           | 0.06           | 0.0033         | 1.4            | 1.1            |
| CO90He54| 1.0    | 0.10              | 0.05               | 0.90   | 0.054             | 1.6                 | QD   | 1.90          | 1.01           | 0.28           | 0.16           | –              | 2.5            | 2.1            |

- Both TD and QD yield a large amount of 56Ni.
- Their feasibilities are unclear.
  - TD requires DD systems whose separation is impossibly small.
  - QD requires the lighter WD with thick He shells, ~0.06 Msun.
Summary

- We have performed a 3D simulation of the D6 model for type Ia supernova.

- CO materials are stripped by the SN ejecta, and compose low-velocity components.

- The SN ejecta have a velocity shift (~1000km/s) due to the binary motion of the progenitor system.

- We have demonstrated triple and quadruple detonations.