Sub-Chandrasekhar Mass Models for Type I Supernovae

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$\dot{M} = 1 \; - \; 10 \text{ x } 10^{-8} \; M_e \; y^{-1}$

Accumulate thick (0.05 - 0.2 M_e) layer of He on CO dwarf

Early work suggested two outcomes

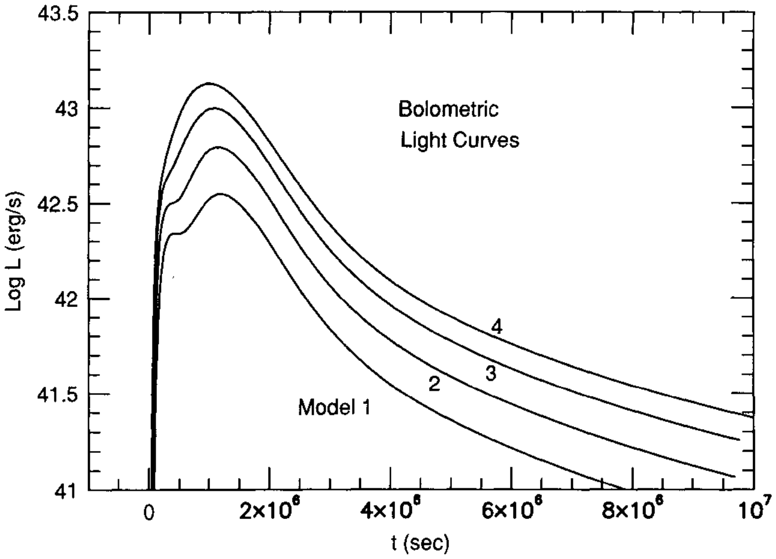
Woosley, Weaver and Taam (1980,1986)
Nomoto (1980, 1982)

1D explorations of double detonation

Livne (1990)
Woosley and Weaver (1994)

Early multi-dimensional studies

Arnett (1997), Livne(1997),
Benz(1997)



But recent interest rekindled by suggestion of Bildsten et al. (ApJL, 662, L95, 2007) of .Ia supernovae,

followed by multi-dimensional sumulations

Fink et al, A&A, 476, 1133 (2007)

Fink et al, arXiv:1002.2173, submitted to A&A, 2010

Sim et al, ApJL, 714, L52 (2010)

Fink, Röpke, Hillebrandt et al. A&A, in press

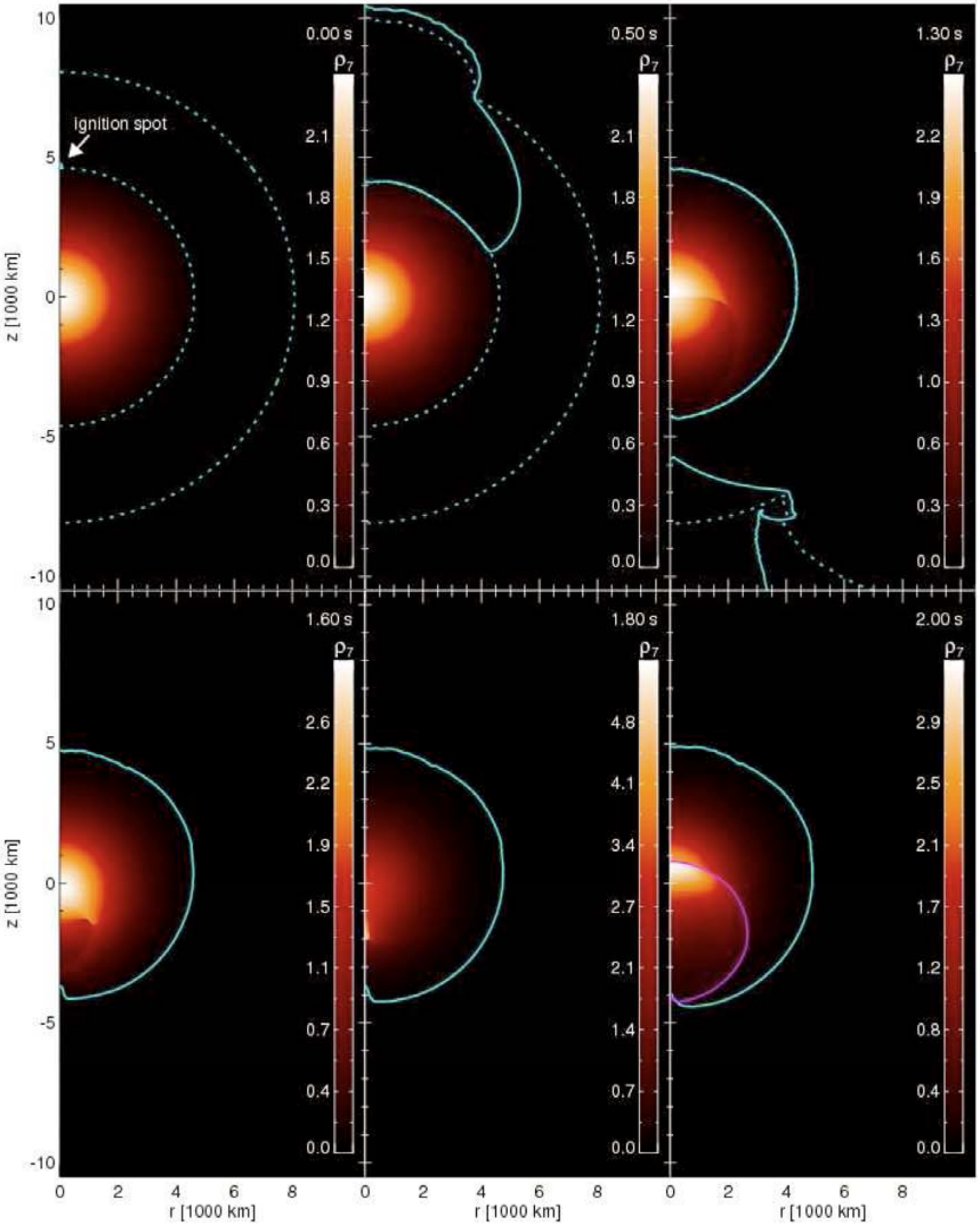


Fig. 1. Explosion evolution for Model 2. The density is color coded, and the solid cyan and magenta lines are the locations of the helium and C/O detonation flames, respectively. Dashed lines in cyan mark the border of the helium shell.

Current claims:

1) Ignition in the helium layer will always lead to helium detonation even for helium masses as small as 0.0035 solar masses (Fink et al 2010)

2) Helium detonation will invariably lead to detonation of the carbon-oxygen core (Fink et al 2010)

3) The explosion of the CO cores will give light curves and spectra that agree with common Type Ia supernovae and may even be the most common mechanism (Sim et al 2007).

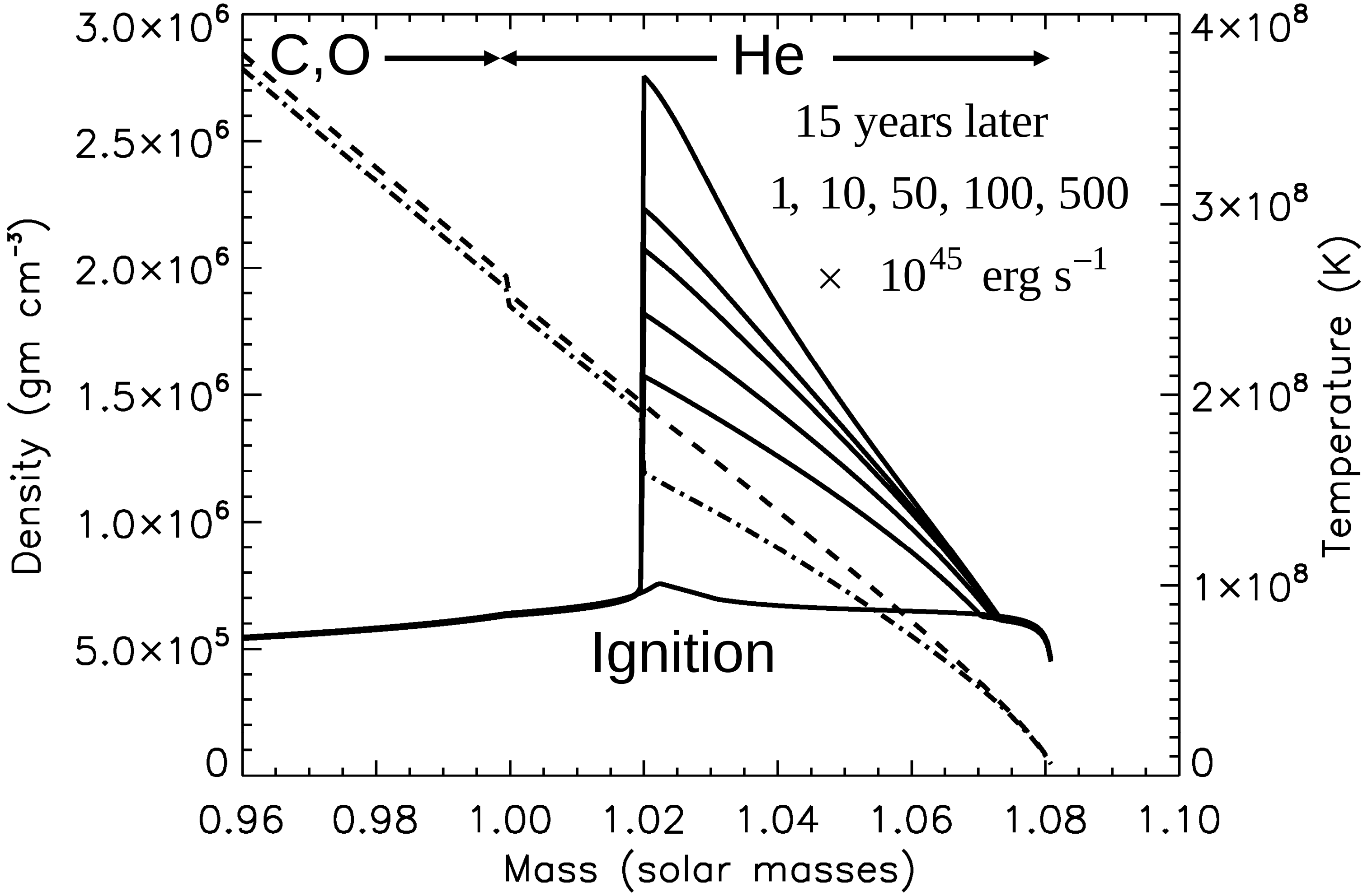
Table 3. Total nucleosynthetic yields of selected species or groups of species. $M_{\mathrm{C/O,fuel}}$ and $M_{\mathrm{He,fuel}}$ are the total masses of initial fuel in the C/O core and the helium shell, respectively. For the helium detonation the values in brackets give the fraction of an isotope mass to the total shell mass $M_{\mathrm{He,fuel}}$. M_L is the total mass of all radioactive species that could power a light curve: ^{56}Ni, ^{52}Fe, and ^{48}Cr. All masses are given in units of $M_\odot$. E_{kin} is the asymptotic total kinetic energy.

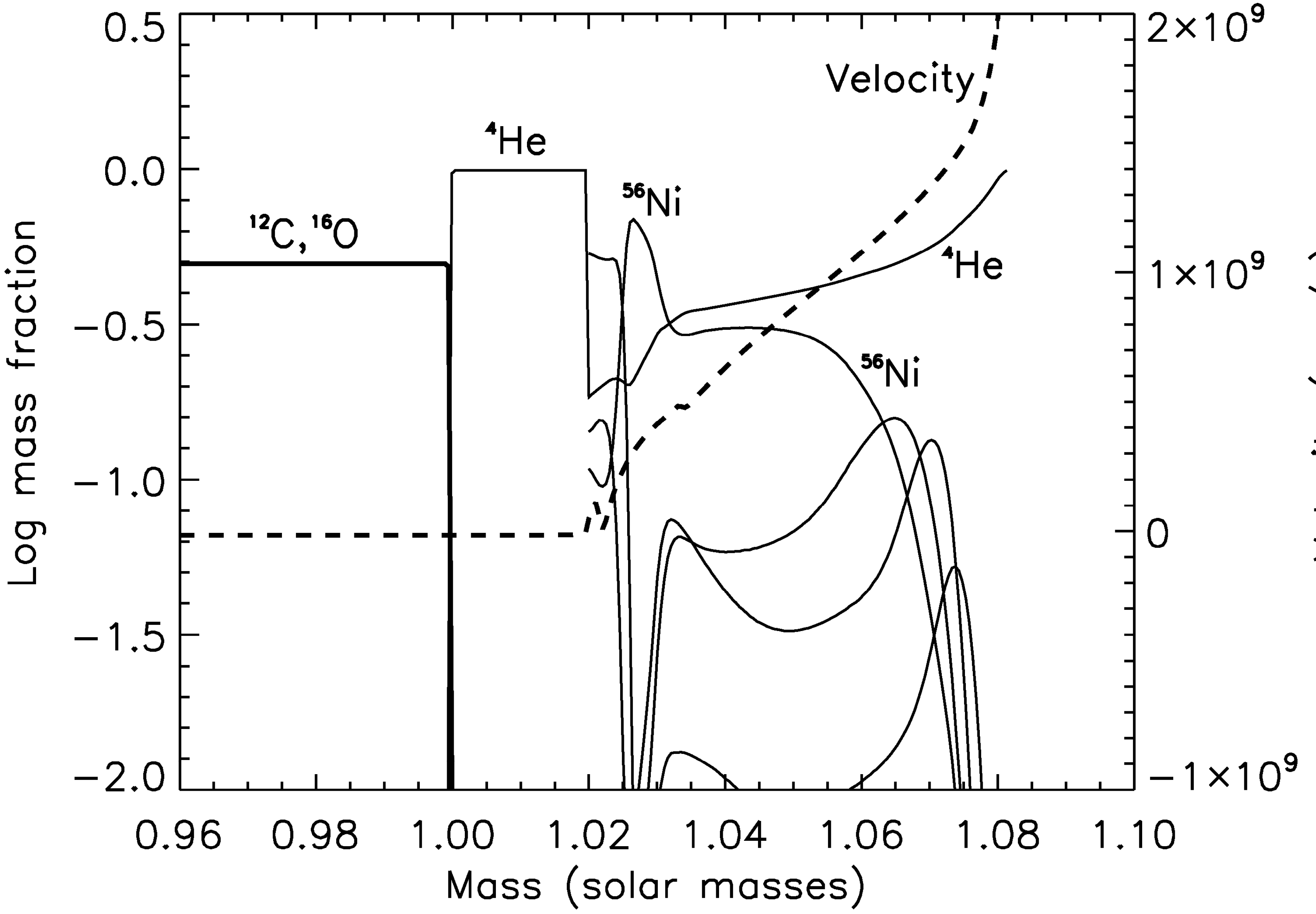
Model	1	2	3	4	5	6
			C/O core detonation			
$M_{\mathrm{C/O,fuel}}$	$8.1 \cdot 10^{-1}$	$9.2 \cdot 10^{-1}$	1.03	1.13	1.28	1.39
M_{IGEs}	$1.8 \cdot 10^{-1}$	$3.6 \cdot 10^{-1}$	$5.7 \cdot 10^{-1}$	$8.2 \cdot 10^{-1}$	1.11	1.33
M_{IMEs}	$4.8 \cdot 10^{-1}$	$4.4 \cdot 10^{-1}$	$3.7 \cdot 10^{-1}$	$2.6 \cdot 10^{-1}$	$1.2 \cdot 10^{-1}$	$3.1 \cdot 10^{-2}$
$M_{^{56}\mathrm{Ni}}$	$1.7 \cdot 10^{-1}$	$3.4 \cdot 10^{-1}$	$5.5 \cdot 10^{-1}$	$7.8 \cdot 10^{-1}$	1.05	1.10
$M_{^{52}\mathrm{Fe}}$	$7.6 \cdot 10^{-3}$	$9.9 \cdot 10^{-3}$	$9.6 \cdot 10^{-3}$	$7.9 \cdot 10^{-3}$	$4.2 \cdot 10^{-3}$	$1.7 \cdot 10^{-3}$
$M_{^{48}\mathrm{Cr}}$	$3.9 \cdot 10^{-4}$	$4.6 \cdot 10^{-4}$	$4.5 \cdot 10^{-4}$	$3.8 \cdot 10^{-4}$	$2.1 \cdot 10^{-4}$	$7.1 \cdot 10^{-5}$
$M_{^{16}\mathrm{O}}$	$1.4 \cdot 10^{-1}$	$1.1 \cdot 10^{-1}$	$8.0 \cdot 10^{-2}$	$4.2 \cdot 10^{-2}$	$3.1 \cdot 10^{-2}$	$1.2 \cdot 10^{-2}$
$M_{^{12}\mathrm{C}}$	$6.6 \cdot 10^{-3}$	$4.4 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$	$8.8 \cdot 10^{-4}$	$5.9 \cdot 10^{-3}$	$7.4 \cdot 10^{-4}$
			Helium shell detonation			
$M_{\mathrm{He,fuel}}$	$1.3 \cdot 10^{-1}$	$8.4 \cdot 10^{-2}$	$5.5 \cdot 10^{-2}$	$3.9 \cdot 10^{-2}$	$1.3 \cdot 10^{-2}$	$3.5 \cdot 10^{-3}$
M_{IGEs}	$2.9 \cdot 10^{-2}$ (23%)	$2.2 \cdot 10^{-2}$ (26%)	$1.7 \cdot 10^{-2}$ (30%)	$1.3 \cdot 10^{-2}$ (33%)	$4.2 \cdot 10^{-3}$ (32%)	$1.1 \cdot 10^{-3}$ (31%)
M_{IMEs}	$1.3 \cdot 10^{-2}$ (10%)	$8.2 \cdot 10^{-3}$ (10%)	$5.3 \cdot 10^{-3}$ (10%)	$5.7 \cdot 10^{-3}$ (15%)	$1.9 \cdot 10^{-3}$ (14%)	$7.3 \cdot 10^{-4}$ (21%)
$M_{^{56}\mathrm{Ni}}$	$8.4 \cdot 10^{-4}$ (1%)	$1.1 \cdot 10^{-3}$ (1%)	$1.7 \cdot 10^{-3}$ (3%)	$4.4 \cdot 10^{-3}$ (11%)	$1.5 \cdot 10^{-3}$ (11%)	$5.7 \cdot 10^{-4}$ (16%)
$M_{^{52}\mathrm{Fe}}$	$7.6 \cdot 10^{-3}$ (6%)	$7.0 \cdot 10^{-3}$ (8%)	$6.2 \cdot 10^{-3}$ (11%)	$3.5 \cdot 10^{-3}$ (9%)	$1.2 \cdot 10^{-3}$ (10%)	$2.0 \cdot 10^{-4}$ (6%)
$M_{^{48}\mathrm{Cr}}$	$1.1 \cdot 10^{-2}$ (9%)	$7.8 \cdot 10^{-3}$ (9%)	$4.4 \cdot 10^{-3}$ (8%)	$2.2 \cdot 10^{-3}$ (6%)	$6.8 \cdot 10^{-4}$ (5%)	$1.5 \cdot 10^{-4}$ (4%)
$M_{^{44}\mathrm{Ti}}$	$7.9 \cdot 10^{-3}$ (6%)	$5.4 \cdot 10^{-3}$ (6%)	$3.4 \cdot 10^{-3}$ (6%)	$1.8 \cdot 10^{-3}$ (5%)	$4.9 \cdot 10^{-4}$ (4%)	$6.2 \cdot 10^{-5}$ (2%)
$M_{^{40}\mathrm{Ca}}$	$4.7 \cdot 10^{-3}$ (4%)	$3.2 \cdot 10^{-3}$ (4%)	$2.2 \cdot 10^{-3}$ (4%)	$2.2 \cdot 10^{-3}$ (6%)	$6.8 \cdot 10^{-4}$ (5%)	$2.4 \cdot 10^{-4}$ (7%)
$M_{^{4}\mathrm{He}}$	$8.4 \cdot 10^{-2}$ (66%)	$5.3 \cdot 10^{-2}$ (63%)	$3.3 \cdot 10^{-2}$ (60%)	$2.0 \cdot 10^{-2}$ (52%)	$6.9 \cdot 10^{-3}$ (54%)	$1.7 \cdot 10^{-3}$ (48%)
M_L	$2.0 \cdot 10^{-1}$	$3.7 \cdot 10^{-1}$	$5.7 \cdot 10^{-1}$	$8.0 \cdot 10^{-1}$	1.06	1.10
E_{kin} [10^{51} erg]	0.90	1.04	1.20	1.40	1.59	1.68

IGE = iron group elements - ^{44}Ti, ^{48}Cr, ^{52}Fe

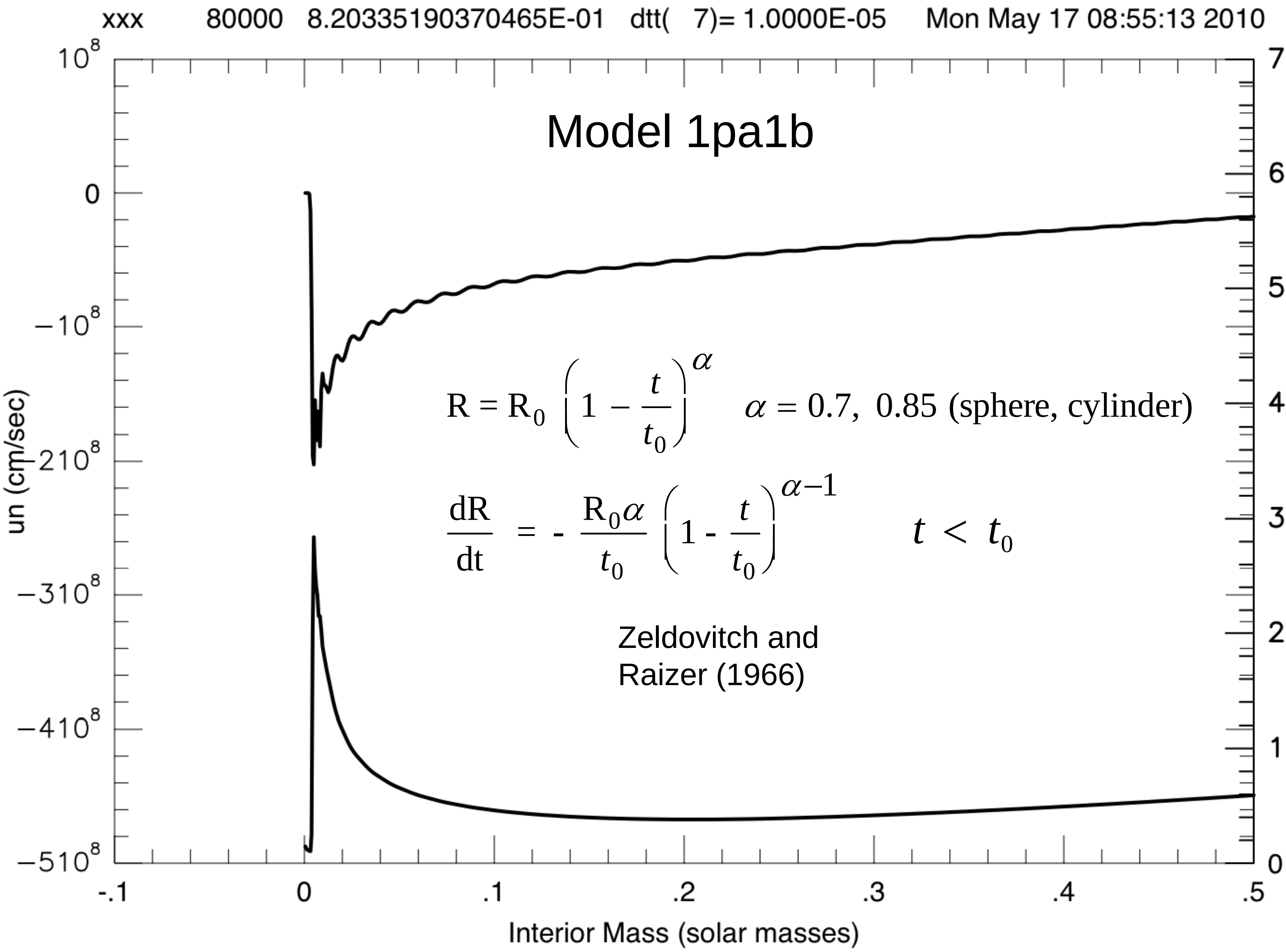
IME = intermediate mass e;ements - Si, S, Ar, Ca

1.0 Solar Mass White Dwarf Accreting at 5 x 10^{-8} solar masses per year Convective luminosity just before runaway




Velocity
^{4}He
^{56}Ni
^{12}C, ^{16}O
^{4}He
^{56}Ni
0.5
0.0
−0.5
−1.0
−1.5
−2.0
Log mass fraction
2×10^9
1×10^9
0
−1×10^9
Velocity (cm/s)
0.96
0.98
1.00
1.02
1.04
1.06
1.08
1.10
Mass (solar masses)

Model 1pa1b

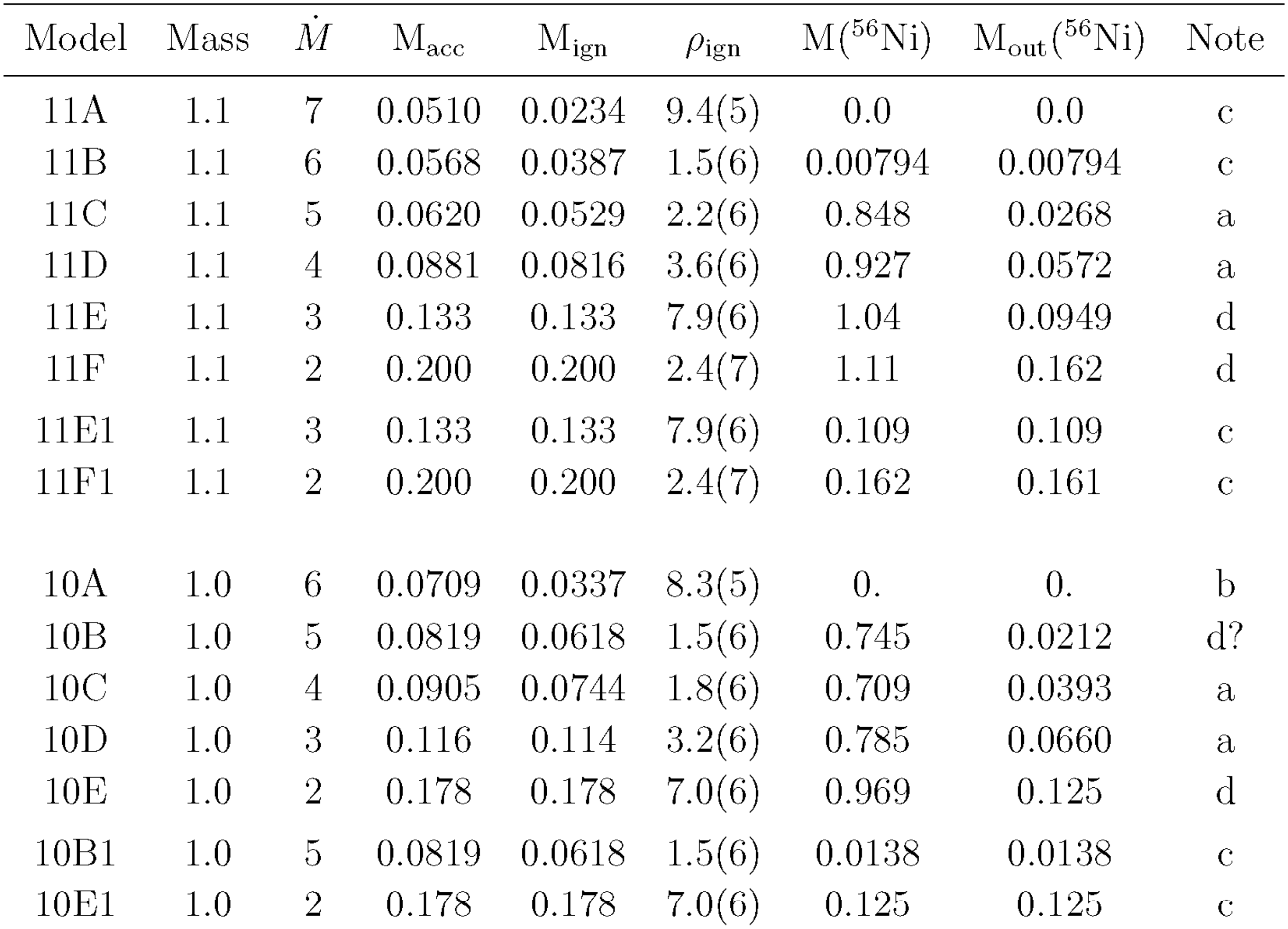


$$R = R_0 \left(1 - \frac{t}{t_0}\right)^{\alpha} \qquad \alpha = 0.7,\ 0.85 \text{ (sphere, cylinder)}$$

$$\frac{dR}{dt} = -\frac{R_0 \alpha}{t_0}\left(1 - \frac{t}{t_0}\right)^{\alpha - 1} \qquad t < t_0$$

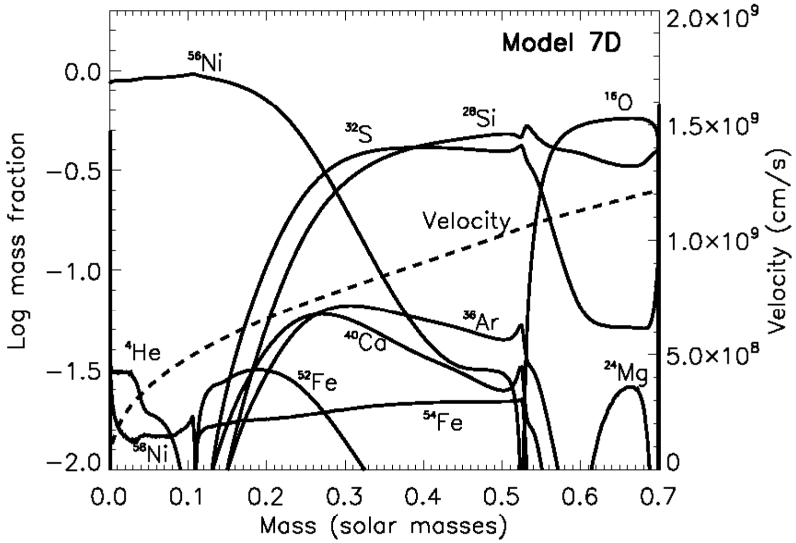
Zeldovitch and
Raizer (1966)

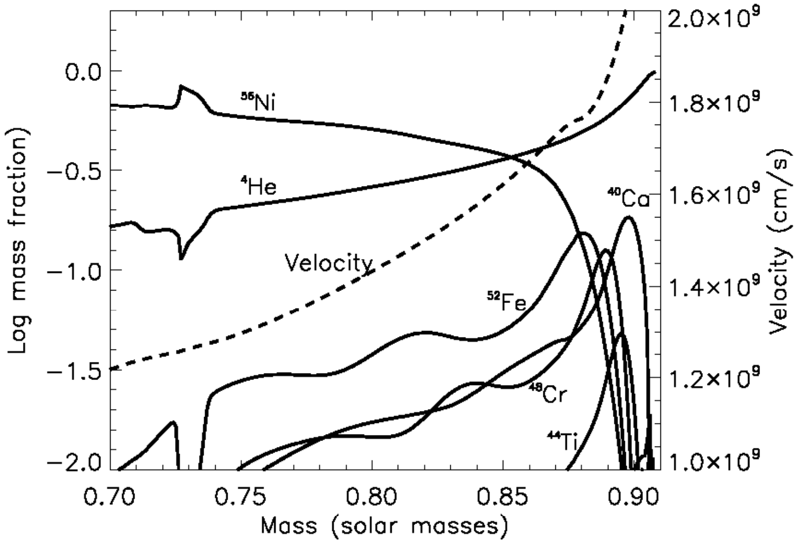
One Dimensional Models

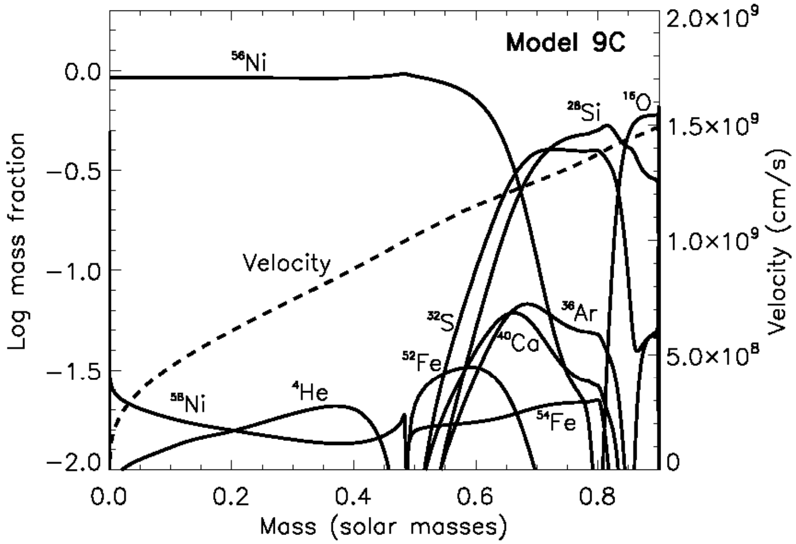


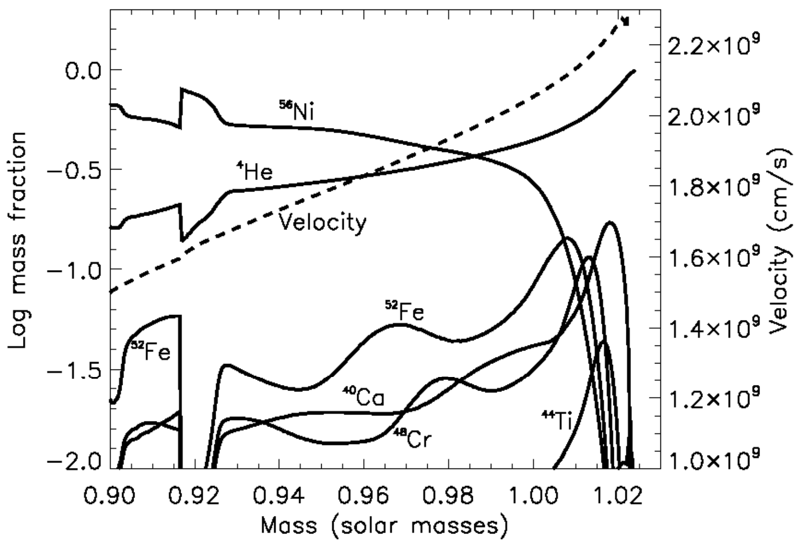
Model	Mass	$\dot{M}$	$\mathrm{M_{acc}}$	$\mathrm{M_{ign}}$	ρ_{ign}	$\mathrm{M(^{56}Ni)}$	$\mathrm{M_{out}(^{56}Ni)}$	Note
11A	1.1	7	0.0510	0.0234	9.4(5)	0.0	0.0	c
11B	1.1	6	0.0568	0.0387	1.5(6)	0.00794	0.00794	c
11C	1.1	5	0.0620	0.0529	2.2(6)	0.848	0.0268	a
11D	1.1	4	0.0881	0.0816	3.6(6)	0.927	0.0572	a
11E	1.1	3	0.133	0.133	7.9(6)	1.04	0.0949	d
11F	1.1	2	0.200	0.200	2.4(7)	1.11	0.162	d
11E1	1.1	3	0.133	0.133	7.9(6)	0.109	0.109	c
11F1	1.1	2	0.200	0.200	2.4(7)	0.162	0.161	c
10A	1.0	6	0.0709	0.0337	8.3(5)	0.	0.	b
10B	1.0	5	0.0819	0.0618	1.5(6)	0.745	0.0212	d?
10C	1.0	4	0.0905	0.0744	1.8(6)	0.709	0.0393	a
10D	1.0	3	0.116	0.114	3.2(6)	0.785	0.0660	a
10E	1.0	2	0.178	0.178	7.0(6)	0.969	0.125	d
10B1	1.0	5	0.0819	0.0618	1.5(6)	0.0138	0.0138	c
10E1	1.0	2	0.178	0.178	7.0(6)	0.125	0.125	c

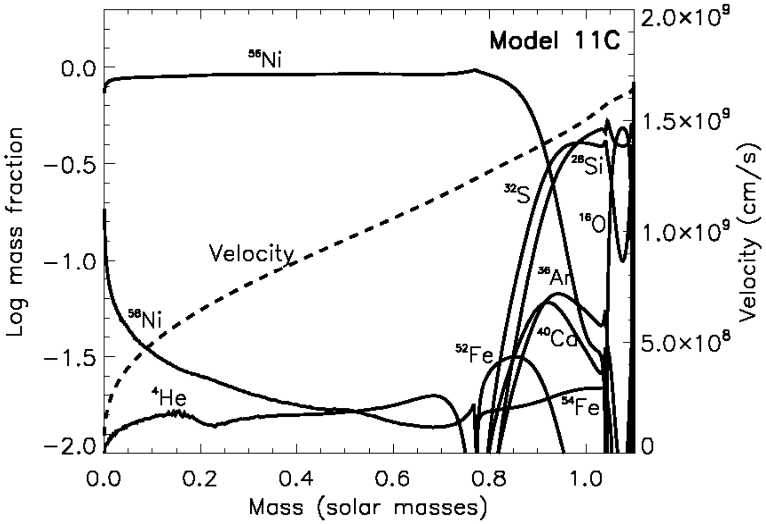
Model	Mass	$\dot{M}$	M_{acc}	M_{ign}	ρ_{ign}	$M(^{56}Ni)$	$M_{out}(^{56}Ni)$	Note
9A	0.9	5	0.100	0.0562	9.0(5)	2.5(-4)	2.5(-4)	c
9B	0.8	4.5	0.109	0.0803	1.3(6)	0.0143	0.0143	c
9C	0.9	4	0.114	0.0972	1.6(6)	0.611	0.0397	d
9D	0.9	3	0.126	0.108	1.8(6)	0.639	0.051	d*
9E	0.9	3	0.126	0.108	1.8(6)	0.620	0.0542	a
9F	0.9	2	0.154	0.154	3.0(6)	0.727	0.0833	d
9C1	0.9	4	0.114	0.0972	1.6(6)	0.0397	0.0397	c
9F1	0.9	2	0.154	0.154	3.0(6)	0.0832	0.0832	c
8A	0.8	5	0.117	0.0690	7.4(5)	0.	0.	c
8B	0.8	4	0.142	0.114	1.3(6)	0.388	0.0460	a
8C	0.8	3	0.157	0.141	1.6(6)	0.419	0.0644	a
8D	0.8	2	0.175	0.175	2.4(6)	0.579	0.0833	d
8E	0.8	1	0.280	0.280	6.3(6)	0.841	0.197	d
8D1	0.8	2	0.175	0.175	2.4(6)	0.0833	0.0833	c
8D2	0.8	1	0.280	0.280	6.3(6)	0.197	0.197	c
7A	0.7	5	0.121	0.082	5.9(5)	0.	0.	b
7B	0.7	4	0.153	0.105	8.3(5)	5.5(-4)	5.5(-4)	c
7C	0.7	3	0.186	0.175	1.6(6)	0.262	0.068	a
7D	0.7	2	0.209	0.182	1.8(6)	0.327	0.0928	a
7E	0.7	1	0.261	0.261	3.3(6)	0.615	0.154	d
7E1	0.7	1	0.261	0.261	3.3e6	0.154	0.154	c

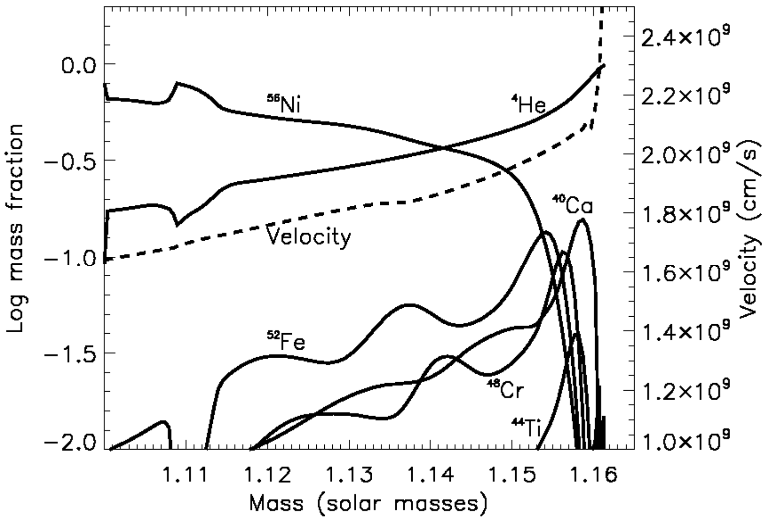

Model 7D
Log mass fraction
Velocity (cm/s)
Mass (solar masses)
0.0
−0.5
−1.0
−1.5
−2.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
2.0×10⁹
1.5×10⁹
1.0×10⁹
5.0×10⁸
0
⁵⁶Ni
³²S
²⁸Si
¹⁶O
Velocity
⁴He
³⁶Ar
⁴⁰Ca
⁵²Fe
⁵⁴Fe
²⁴Mg
⁵⁸Ni

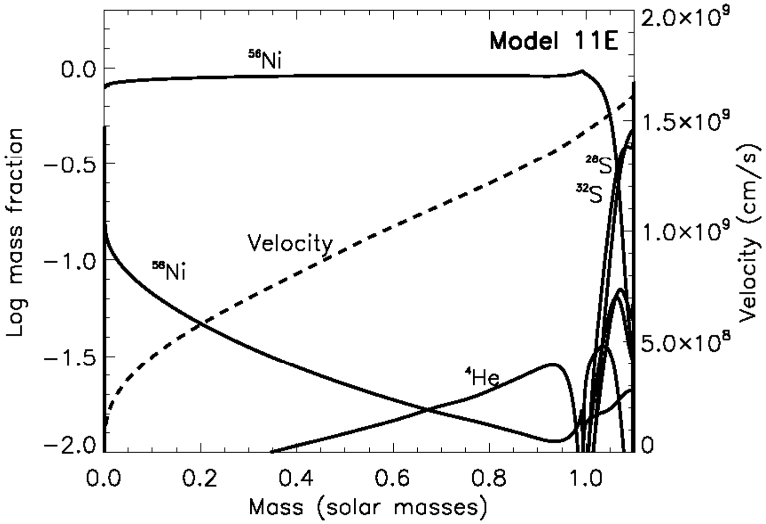

Log mass fraction)
Velocity (cm/s)
Mass (solar masses)
0.0
−0.5
−1.0
−1.5
−2.0
0.70
0.75
0.80
0.85
0.90
2.0×10⁹
1.8×10⁹
1.6×10⁹
1.4×10⁹
1.2×10⁹
1.0×10⁹
⁵⁶Ni
⁴He
Velocity
⁴⁰Ca
⁵²Fe
⁴⁸Cr
⁴⁴Ti

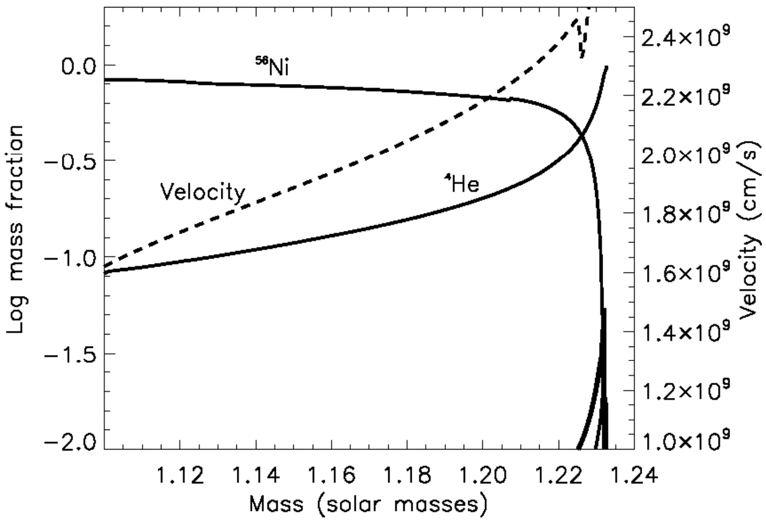

Model 9C
Log mass fraction
Velocity (cm/s)
Mass (solar masses)
0.0
−0.5
−1.0
−1.5
−2.0
0.0
0.2
0.4
0.6
0.8
2.0×10⁹
1.5×10⁹
1.0×10⁹
5.0×10⁸
0
⁵⁶Ni
²⁸Si
¹⁶O
Velocity
³²S
³⁶Ar
⁴⁰Ca
⁵²Fe
⁵⁸Ni
⁴He
⁵⁴Fe


Log mass fraction
Velocity (cm/s)
Mass (solar masses)
0.0
−0.5
−1.0
−1.5
−2.0
0.90
0.92
0.94
0.96
0.98
1.00
1.02
2.2×10⁹
2.0×10⁹
1.8×10⁹
1.6×10⁹
1.4×10⁹
1.2×10⁹
1.0×10⁹
⁵⁶Ni
⁴He
Velocity
⁵²Fe
⁵²Fe
⁴⁰Ca
⁴⁸Cr
⁴⁴Ti

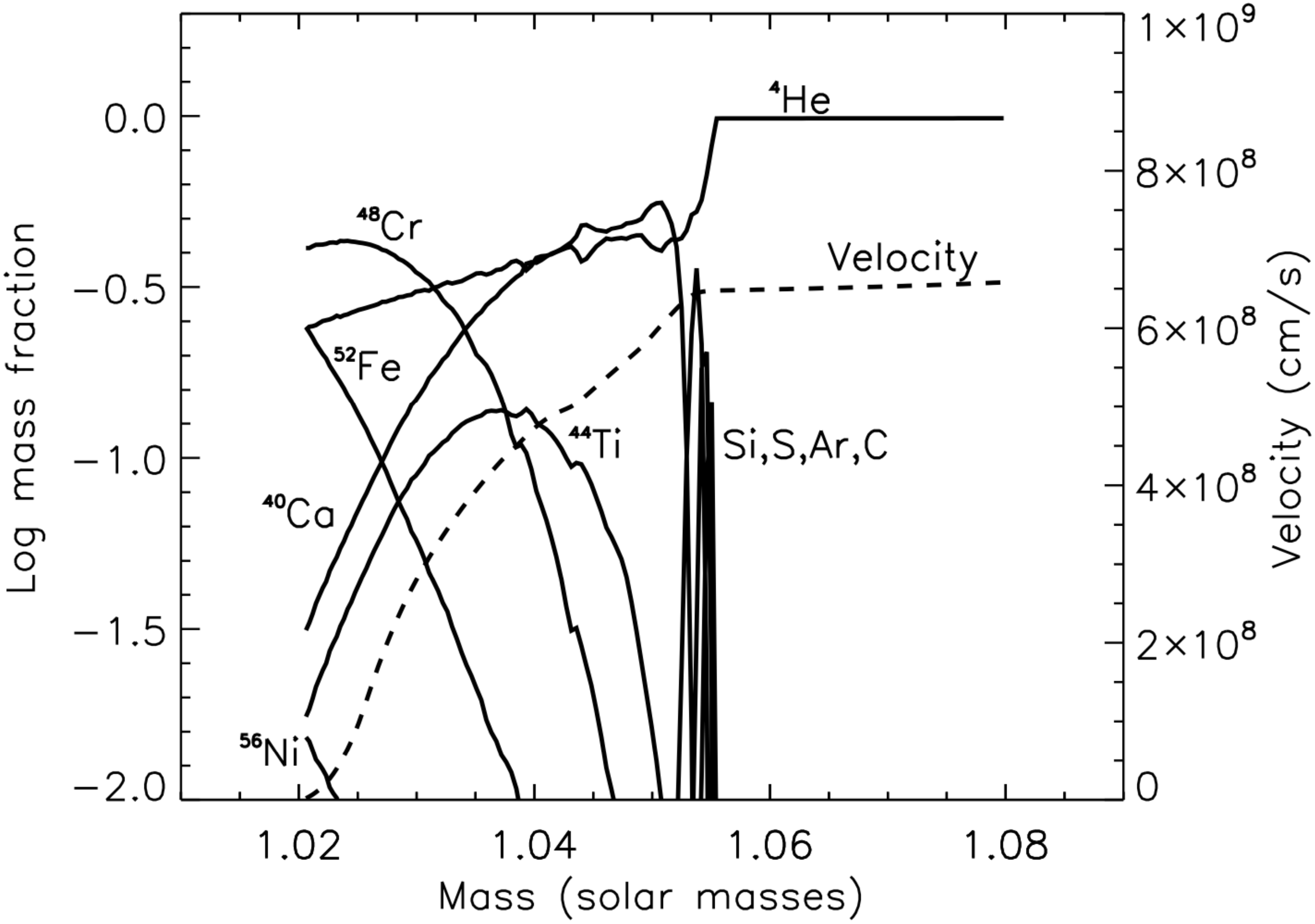

Model 11C
^{56}Ni
^{58}Ni
^{4}He
Velocity
^{32}S
^{28}Si
^{16}O
^{36}Ar
^{40}Ca
^{52}Fe
^{54}Fe
Log mass fraction
0.0
−0.5
−1.0
−1.5
−2.0
Velocity (cm/s)
2.0×10^9
1.5×10^9
1.0×10^9
5.0×10^8
0
0.0
0.2
0.4
0.6
0.8
1.0
Mass (solar masses)


^{56}Ni
^{4}He
Velocity
^{40}Ca
^{52}Fe
^{48}Cr
^{44}Ti
Log mass fraction
0.0
−0.5
−1.0
−1.5
−2.0
Velocity (cm/s)
2.4×10^9
2.2×10^9
2.0×10^9
1.8×10^9
1.6×10^9
1.4×10^9
1.2×10^9
1.0×10^9
1.11
1.12
1.13
1.14
1.15
1.16
Mass (solar masses)


Model 11E
^{56}Ni
^{58}Ni
Velocity
^{4}He
^{28}S
^{32}S
Log mass fraction
0.0
−0.5
−1.0
−1.5
−2.0
Velocity (cm/s)
2.0×10^9
1.5×10^9
1.0×10^9
5.0×10^8
0
0.0
0.2
0.4
0.6
0.8
1.0
Mass (solar masses)

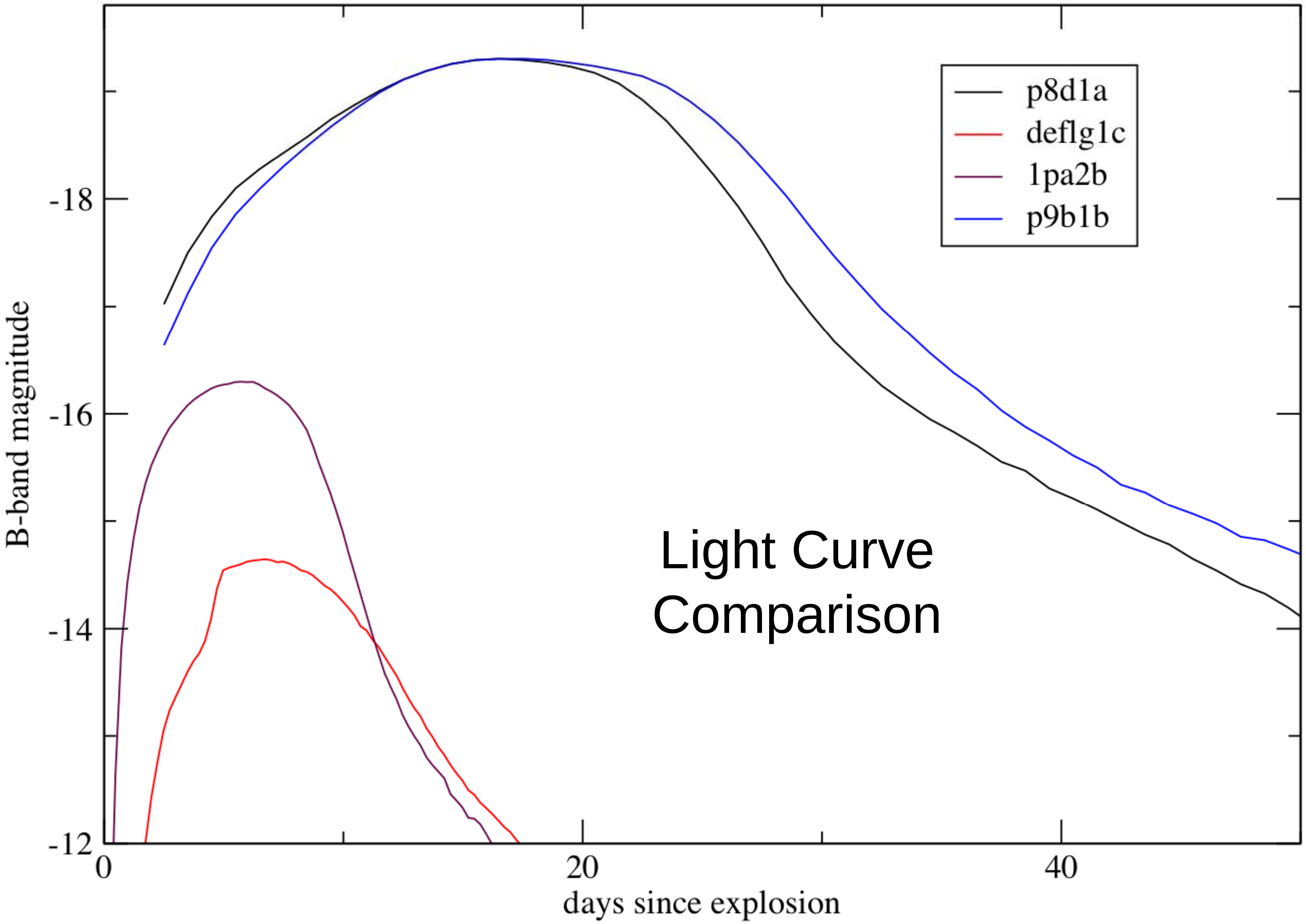

^{56}Ni
Velocity
^{4}He
Log mass fraction
0.0
−0.5
−1.0
−1.5
−2.0
Velocity (cm/s)
2.4×10^9
2.2×10^9
2.0×10^9
1.8×10^9
1.6×10^9
1.4×10^9
1.2×10^9
1.0×10^9
1.12
1.14
1.16
1.18
1.20
1.22
1.24
Mass (solar masses)

Helium Deflagration

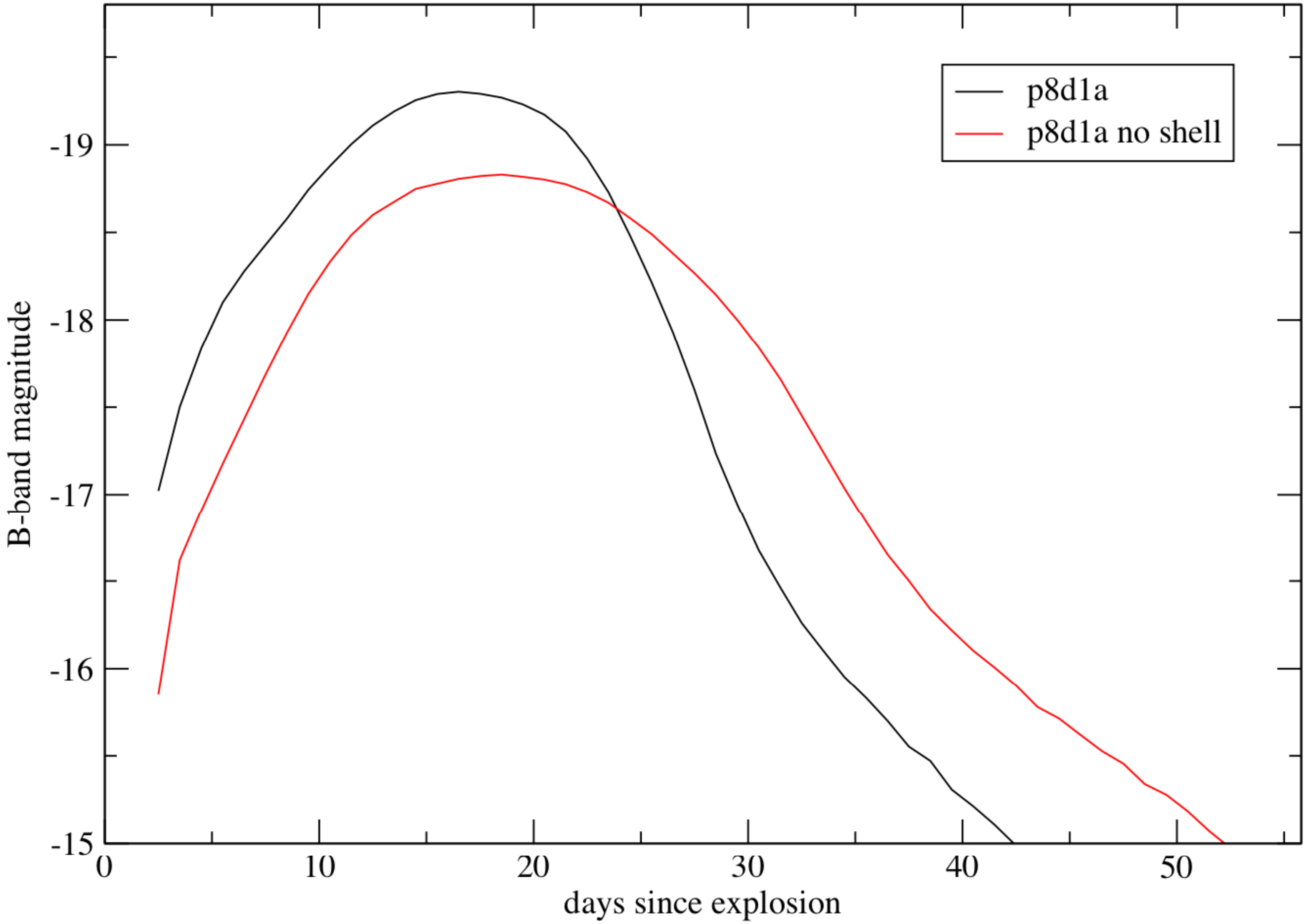


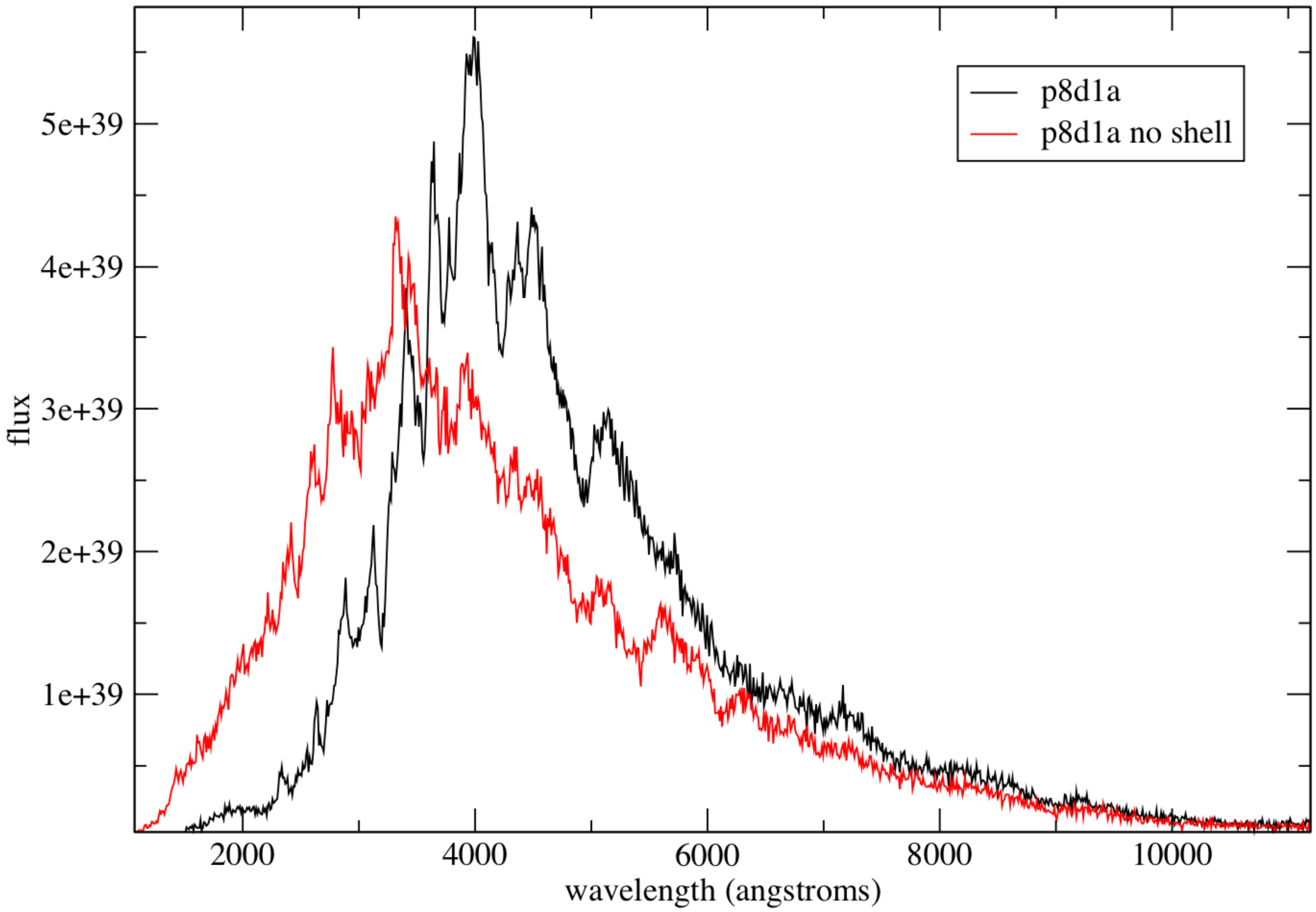
p8d1a = 0.8 + 0.18 (0.58,0.083)
deflg1g = 1.0 + 0.093 (0.,9 x 10^{-5})

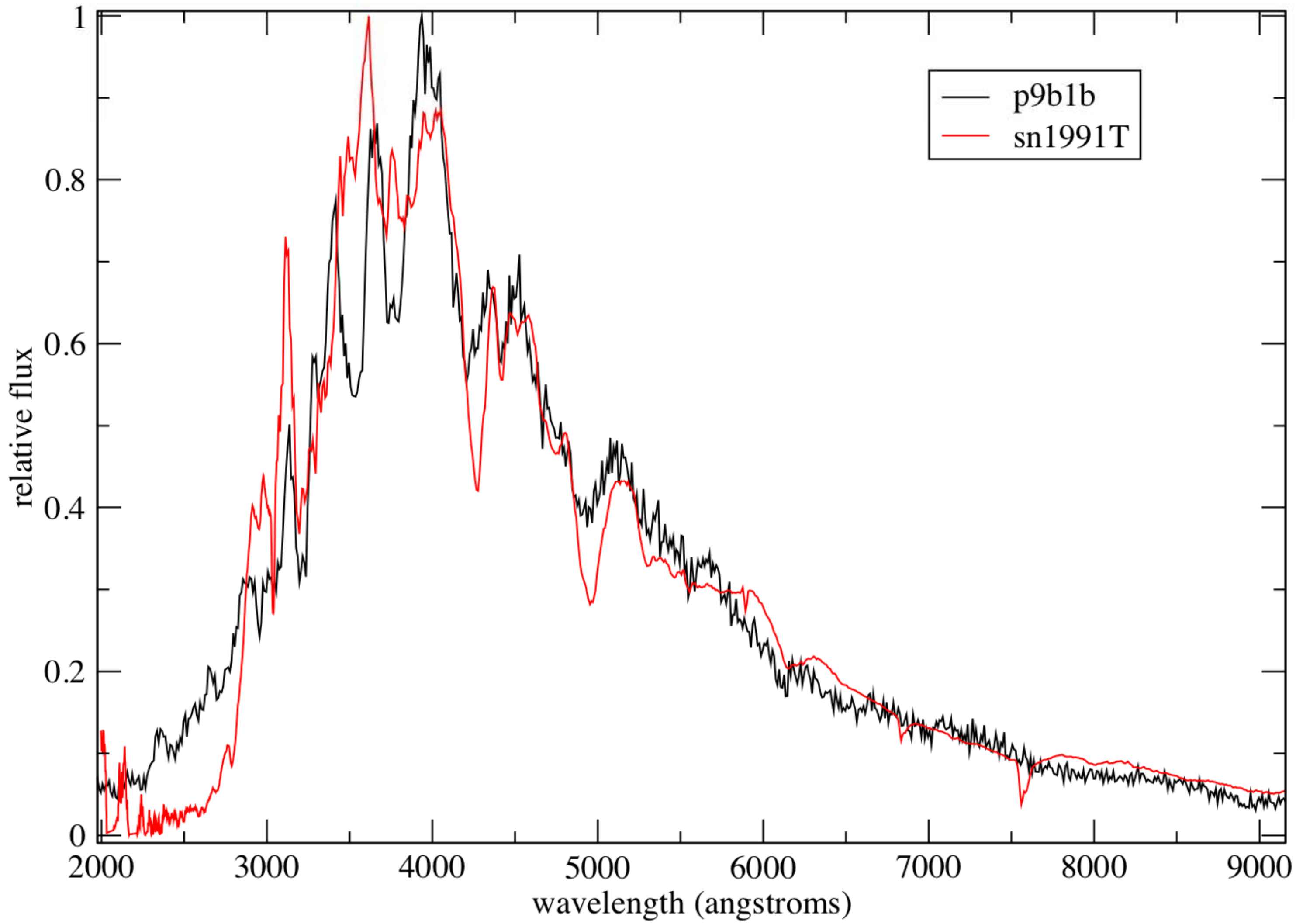
1pa2b = 1.0 + 0.082 (0.,0.014)
p9b1b = 0.9 + 0.114 (0.61, 0.040)

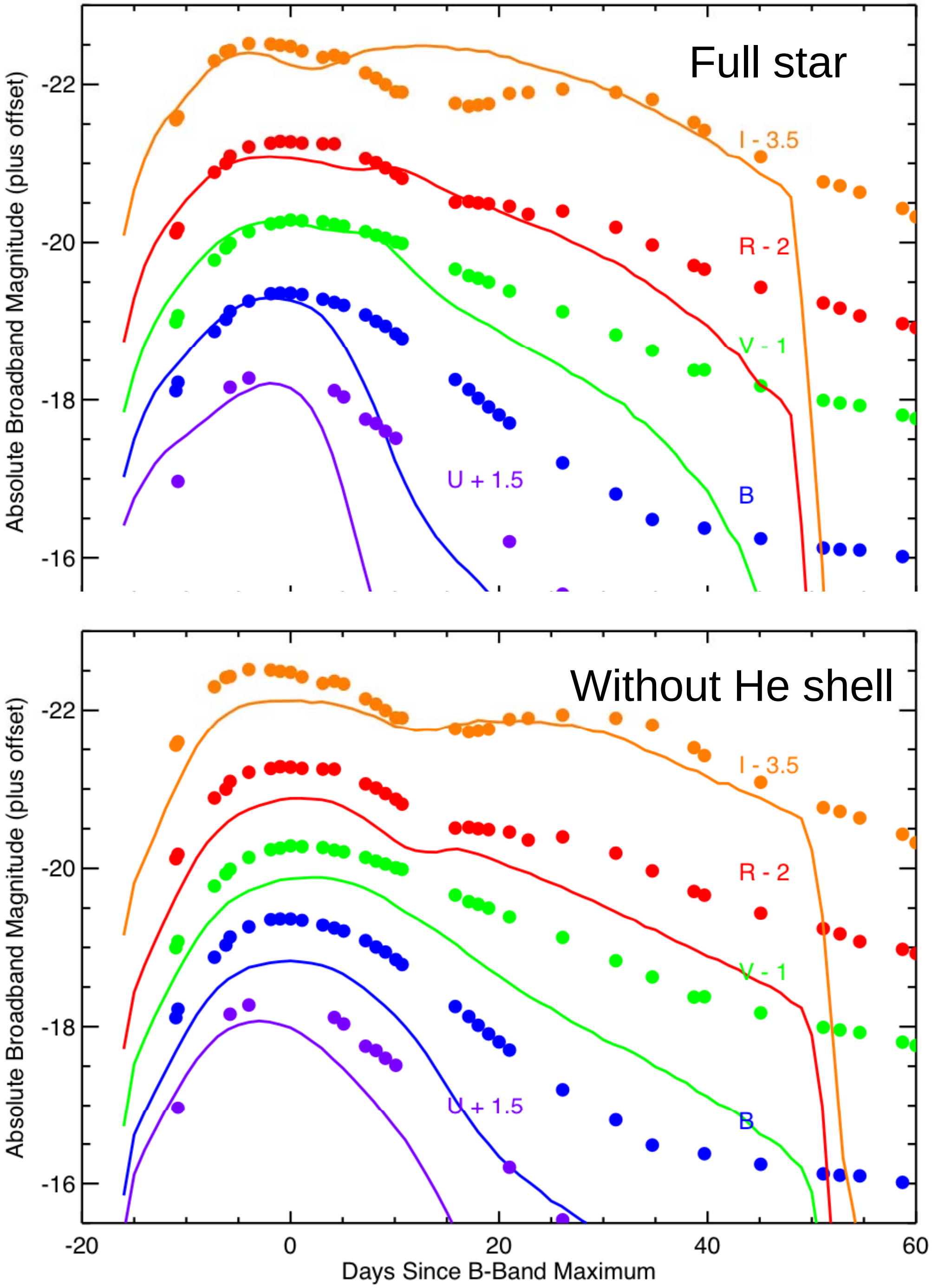


Light Curve Comparison


p8d1a
p8d1a no shell
B-band magnitude
-19
-18
-17
-16
-15
0
10
20
30
40
50
days since explosion


p8d1a
p8d1a no shell
flux
5e+39
4e+39
3e+39
2e+39
1e+39
2000
4000
6000
8000
10000
wavelength (angstroms)


p9b1b
sn1991T
relative flux
wavelength (angstroms)
0
0.2
0.4
0.6
0.8
1
2000
3000
4000
5000
6000
7000
8000
9000

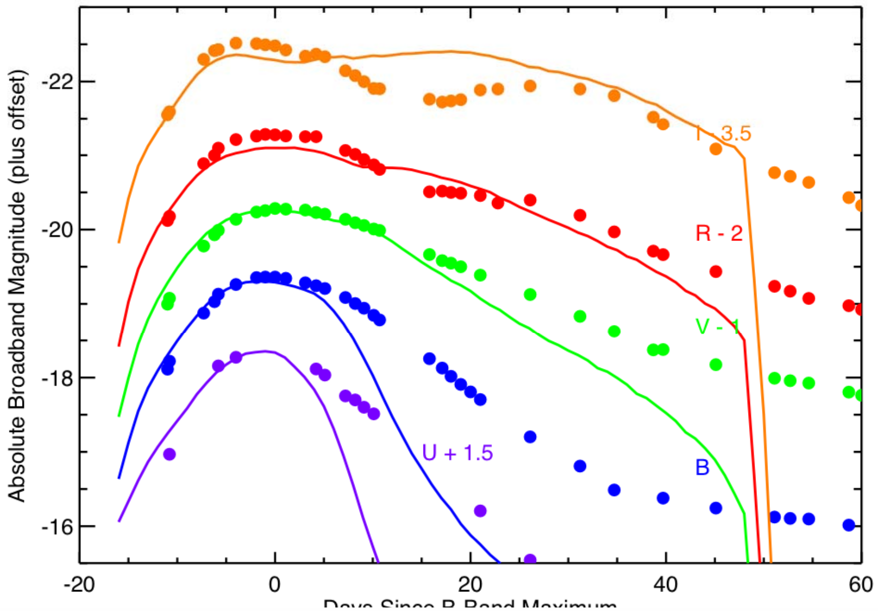


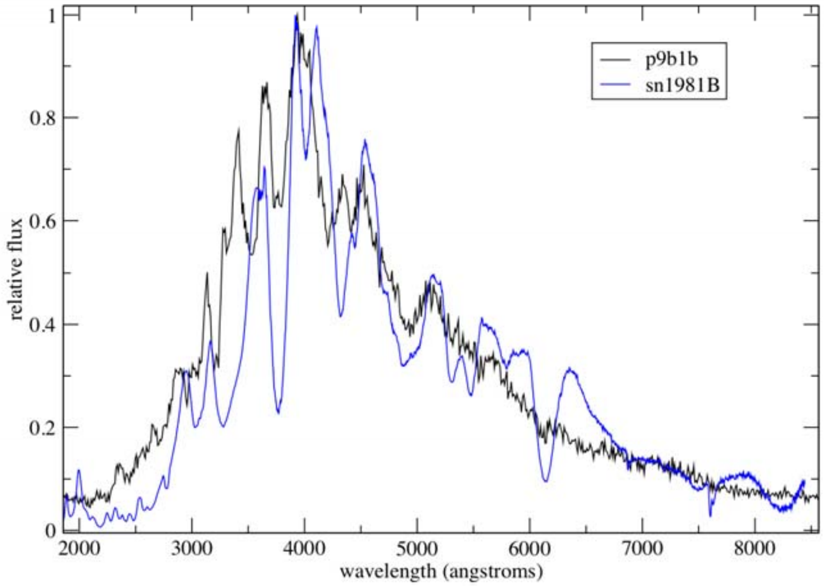
0.8 solar mass CO dwarf accreting at 2×10^{-8} solar masses y^{-1}

0.175 solar masses of He

makes 0.58 solar masses of ^{56}Ni, 0.08 of which is in the helium shell

Compared with a typical SN Ia





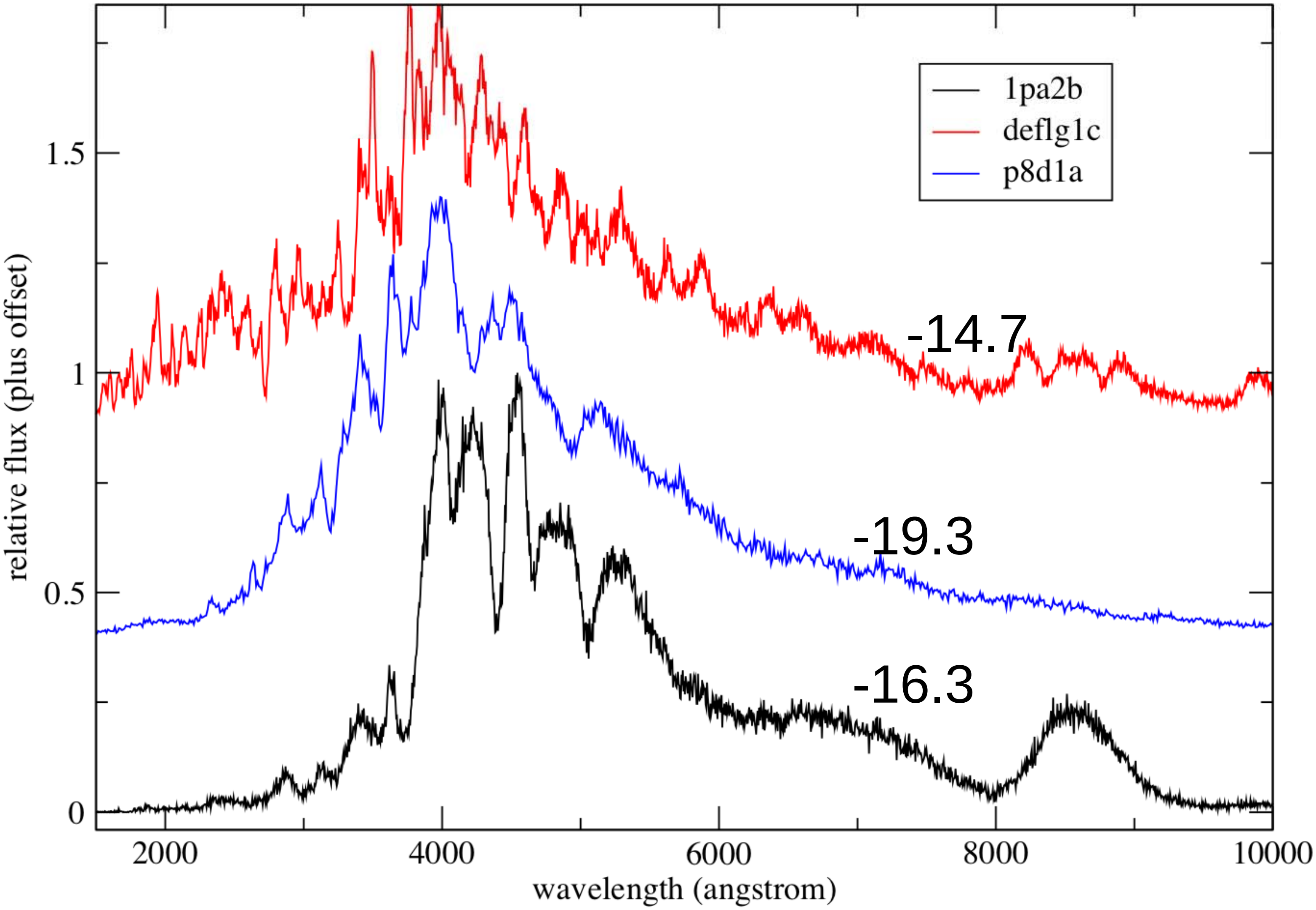
0.9 solar mass CO dwarf accretes at 4 x 10^{-8} solar masses per year

0.114 solar mass He layer

Makes 0.61 solar masses of ^{56}NI, 0.04 of which is in the He shell

Compared with a typical (faint) SN Ia, SN 1981B.

p8d1a - ^{56}Ni powered
deflg1c - ^{48}V,^{52}Fe powered
1pa2b - ^{56}Ni, ^{48}V, and ^{52}Fe powered



Summary

- Need over 0.05 solar masses of helium shell or detonation never develops
- Difficult to develop strong inwards compression front without making ~ 0.01 solar masses of ^{56}Ni
- Outcome very sensitive to the treatment of pre-explosive convection.

Helium deflagration
Helium deflagration-detonation
Helium detonation-carbon deflagration
Helium detonation-carbon detonation

- Munich studies have shown that a helium detonation will propagate once ignited. That does not necessarily mean that detonation occurs

- Secondary (carbon) detonation will depend on the 3D geometry of ignition.

- Outcome may be judged by observations before it is settled theoretically. A variety of transients are possible. Some resemble events that have been seen.

Fink et al.

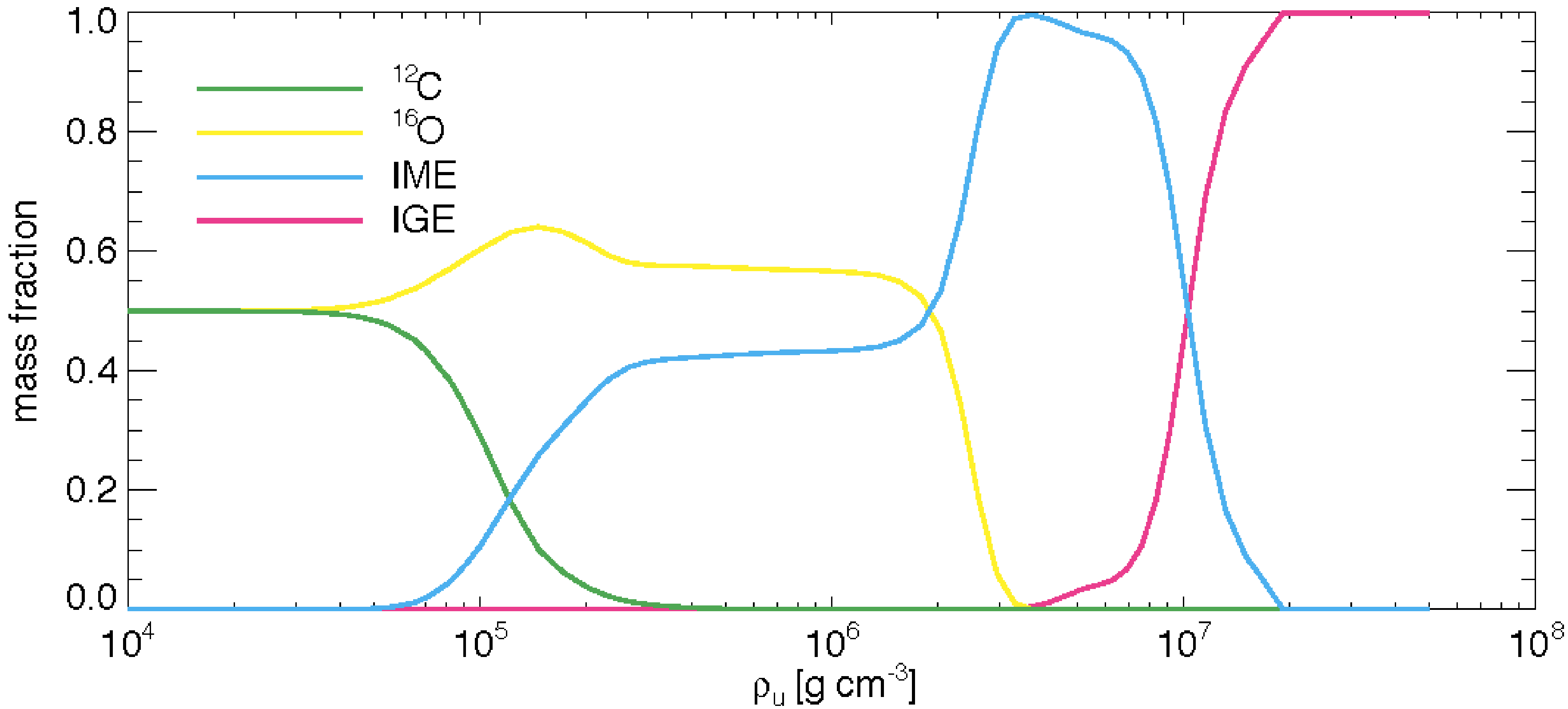


Fig. A.1. Mass fractions of the species in the C/O detonation table plotted against the density of the unburned fuel ρ_u

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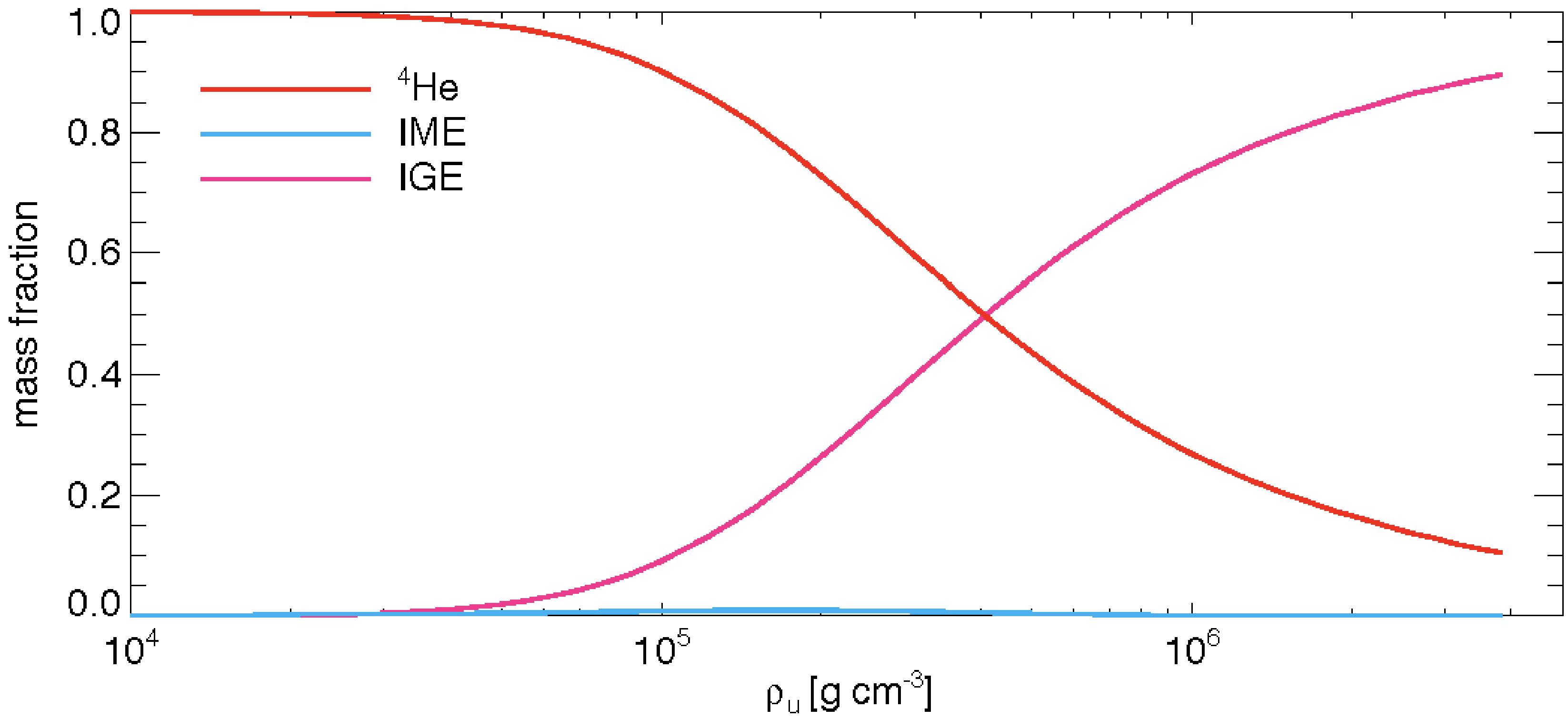

Fig. A.2. Mass fractions of the species in the helium detonation table against ρ_u. ^{12}C and ^{16}O abundances are not shown, as their values are too close to zero.