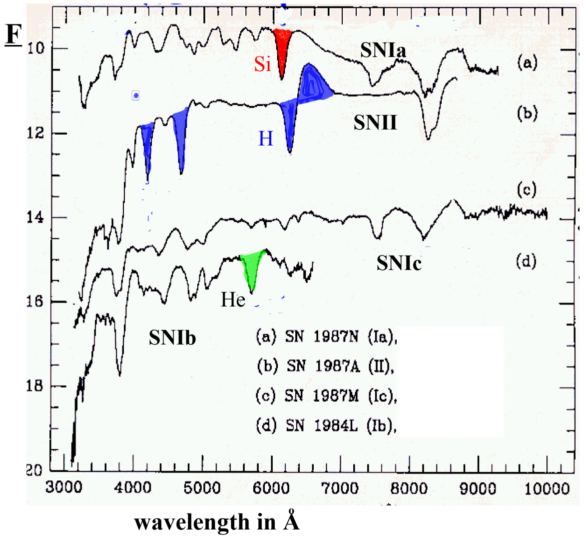
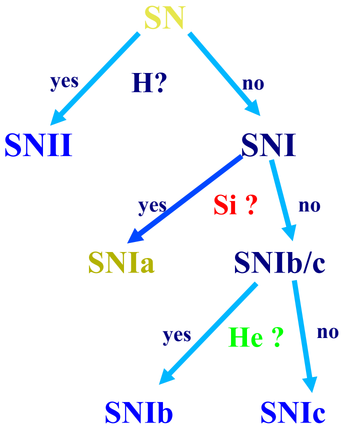
Explosive Nuclear Burning in a C/O Mixutre

- Intro to Thermonuclear Supernovae
- Nuclear Processes
- Electron Capture

Literature: Rolfs & Rodney, Chapt. 2.7; Iliadis, Chap.5.6,
Thielemann et al. NewAR 48, 605; Hoeflich Nucl.Phys.A, 777

Classification of Supernovae by Spectra at Maximum




SN

yes H? no

SNII SNI

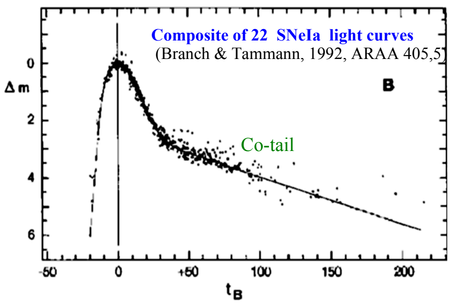
yes Si ? no

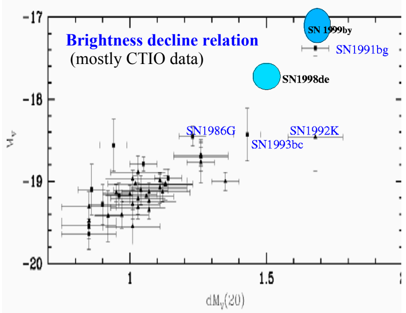
SNIa SNIb/c

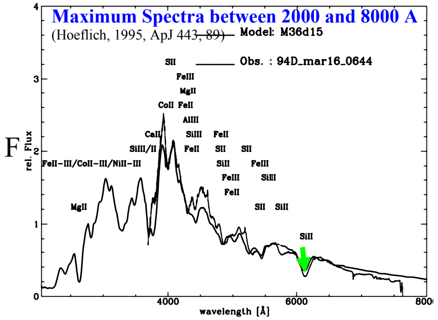
yes He ? no

SNIb SNIc

Observables in Type Ia Supernovae

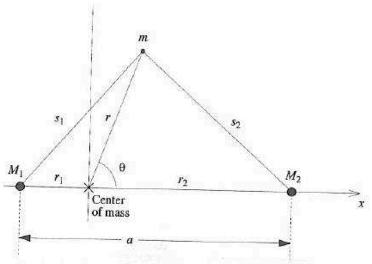






- LCs are rather similar
- decline rate is related to brightness (current accuracy 0.14...0.18 mag)
- maximum spectra are governed by elements of explosive C/O burning (Mg, Si, S, Fe, Co, Ni)
- Doppler shifts of about 10,000 km/sec

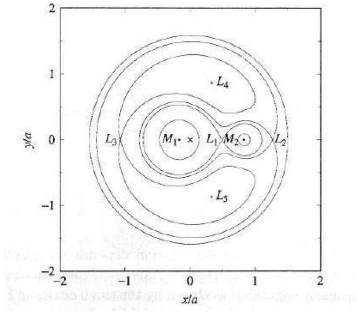
Orbits of close binary Stars



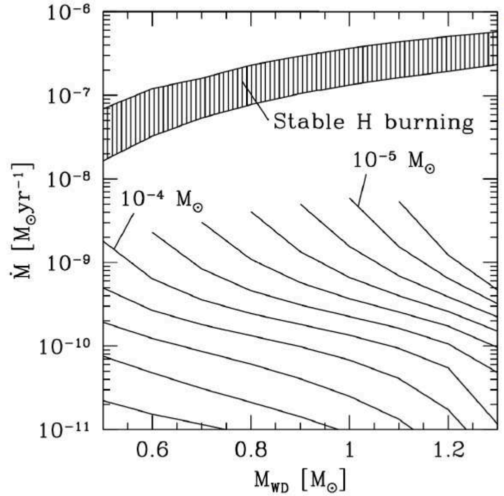
The effective potential energy on a test mass is

$$U = -G\left(\frac{mM_1}{s_1} + \frac{mM_2}{s_2}\right) - \frac{1}{2}m\omega^2 r^2 = m\Phi;\ \omega^2 = \frac{G(M_1+M_2)}{a^3}$$

The Roche Lobe: Mass Overflow



Regimes of Stabe Accretion (Sugimoto 1975)



- Stable burning
- hot CNO-cycle in thin shell
- H-He flashes

explosive H-burning

explosive He-burning

I) Scenarios

1) Progenitors: Accreting White Dwarfs

Artist: R. Hynes

Start: WD of 0.6 to 1.2 Mo
Evolution: Accretion of H, He or C/O rich material
Explosion: Ignition when t(nuc) < t(hydro)

2) Progenitors: Merging White Dwarfs

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Thumbnail Sketch of Thermonuclear SN

- SN Ia are **thermonuclear** explosions of White Dwarfs=> round
- SNe Ia are homogeneous because **nuclear physics** determines the WD structure, and the explosion
- The total energy production is given by the total amount of burning
- The light curves are determined by the amount of radioactive **^{56}Ni**
- The progenitor evolution and explosion go through several phases of ***"stellar amnesia"***

Nuclear Processes in Thermonuclear Supernovae I

Basic properties: Densities are between 1E6 to 5E9 g/ccm

C/O mixture

Structure determined by degenerate Electrons

Binding energy close to 7E50 erg

Chandrasekar Mass

Nuclear Processes in Thermonuclear Supernovae

Burning Condition: (Z,N) (alpha,gamma)(Z+2,N+2)

Compare burning with hydro timescales

t(hyd) = 1sec

rho Q = sigma T^4

=> rho > 2E7 g/ccm => T > 5E9 K => ^{56}Ni

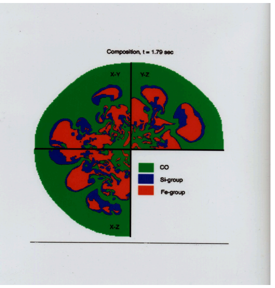
rho > 4E6 g/ccm => T > 3.E9K => ^{32}S/^{28}Si

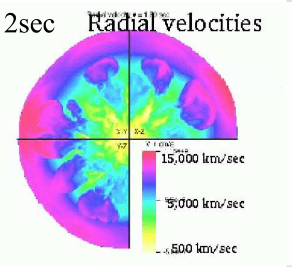
rho > 1E6 g/ccm => T > 1.3E9K => ^{20}Ne/^{24}Mg/^{16}O

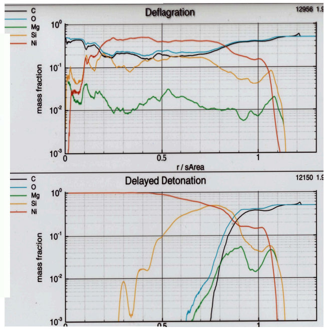
Problem: Electron Capture at densities > 1E9 g/ccm (see core collapse SN).

Radial/v-Structures of 3-D Deflagration and DD Models

(from Gamezo et al. 2002/2003, Science)







Deflagration:

- no radially stratified chemical structure
- already after a 2-3 seconds, outer layers expand with velocities comparable to sound speed

=> about 1/3 of WD remains unburned=> E(kin) = 4 -7E50 erg, 0.5 to 0.7 Mo are burned

- importance of RT instabilities for burning front (3-D problem)
  (Livne & Arnett 93, Khokhlov 95, 01, Reinecke et al. 02, Gamezo et al. 02,04, Plewa et al. 04)
- Large scale RT solution does not depend on details of the flame if t(burn)<<t(hydro)
  (Zeldovich 68, Khokhlov 95, Niemeyer et al. 98)

DDT:

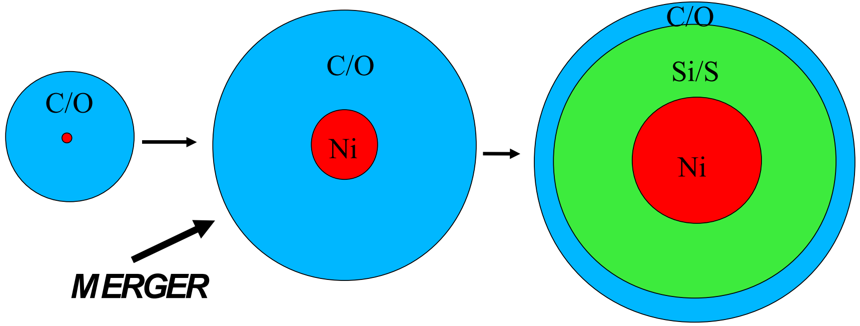
- radially stratified and deflagration signatures are almost wiped out (Livne 99, Gamezo et al. 2004)
- almost entire WD is burned and outcome F(amount of burning before DDT) (H95, W98, L99)

Explosion of a White Dwarfs (Defl., Delayed Det. & Merger)

Initial WD

Deflagration phase(2...3sec)
pre-expansion of the WD
or smoldering phase, or merger

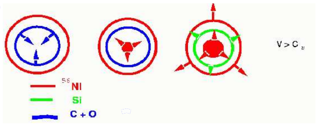
Detonation phase (0.2...0.3 sec)
hardly any time for further expansion



Deflagration: Energy transport by heat conduction over the front, v << v(sound)=> ignition of unburned fuel (C/O)
Detonation: Ignition of unburned fuel by compression, v = v(sound)

Rem1: Pre-expansion depends on the amount of burning. The rate of burning
hardly changes the final structure for DD-models

Rem.2: HeDs(sub-MCh)



· disagree with LCs and spectra
(Hoeflich et al. 95,Nugent et al. 96)

Transition from Deflagration to Detonation

Wanted: mechanism to increase rate of burning

Potential mechanisms:

1) **Crossing shock waves** during deflagration phase (e.g. Livne 1997)

2) **Zeldovich mechanism: Mixing from burned and unburned material**

a) **Mixing induced by RT instabilities** (e.g. Khokhlov et al. 1997, Niemeyer 97)

- Problem: works only for low fluctuations in the background (Niemeyer & Woosley 98)

=> 'Non-linear' instabilities (KH-, LD-) tend to stabilize flame (e.g. Zeldovich 57, Roepke et al. 03

Way out: Pulsating delayed detonation models (Khokhlov et al. 1993, Hoeflich et al. 1995)

b) **Shear flows** and instabilities induced by **differential rotating WDs**
on rising plumes (Hoeflich 2002, Langer et al. 2003).

3) **No deflagration front but single, rising plume** which shoots through the surface, wraps around the WD and may trigger a detonation on the 'backside' (Plewa et al 2004).

=> **demonstrates importance of initial conditions !!!**

Tell-tail: Where does the DDT occur?

Cooking of a Supernovae

A) **Stellar evolution of a low mass star (M< 7Mo, 1E9 years) + mass-loss**
=> initial structure of the WD

B) **Quasi-static evolution of the progenitor (1E6...8 yrs) + accretion**
=> initial structure of the WD at the time of the explosion (SS-X-ray sources)

C) **The thermonuclear runaway (few hours)**
=> preconditioning of the explosive phase

D) **Hydrodynamical phase of explosion (1 to 60 sec)**
=> nucleosynthesis + release of explosion energy

E) **Light curve and spectra (month to years)**
=> time evolution of the expanding envelope

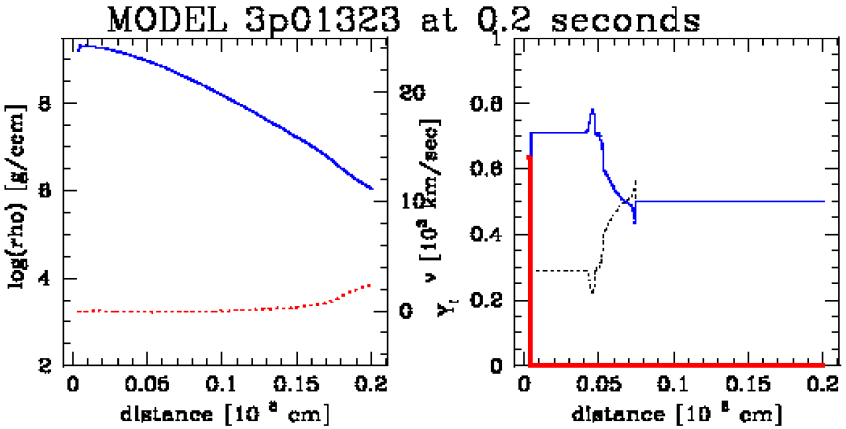
Free Parameters for the explosion

Central density of the WD (depends on the accretion rate)
Chemical profile of the WD (depends on the MS mass and metallicity)
Description of the nuclear burning (deflagration, defl det transition etc.)

Explosion of a delayed detonation model

- progenitor : 3Mo on MS with 1/30 of solar metallicity
- Properties of WD: a) Chandrasekhar mass b) central density 2E9 g/ccm

- Properties of deflagration front: a) v(defl.) with C1=0.15 b) rho(tr) = 2E7 g/ccm



red: complete b. (Fe, Co, Ni) ; **green:** incomplete b. (Si, S, ...) ; **blue:** C and O

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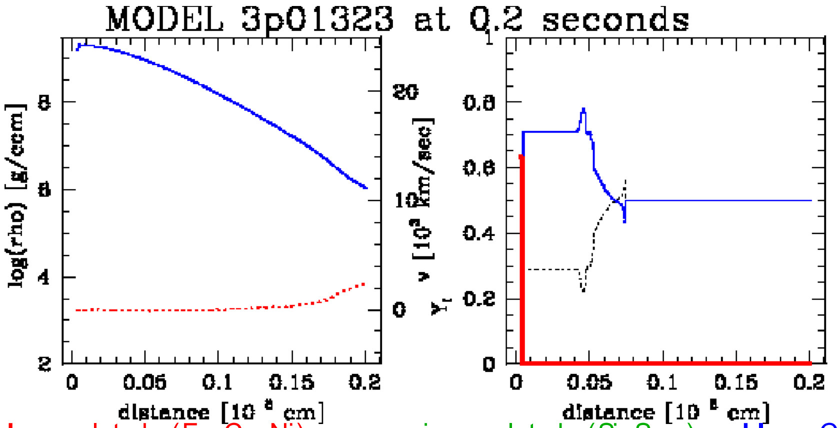

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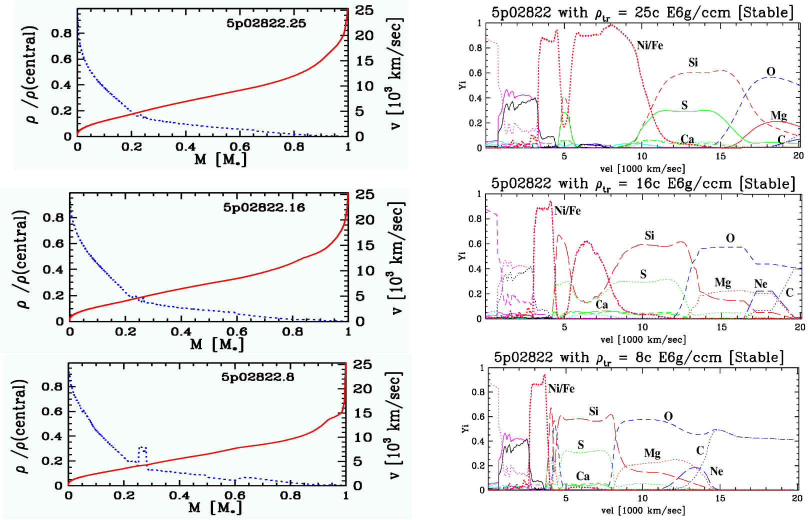
Delayed detonation models for various transition densities rho(tr)

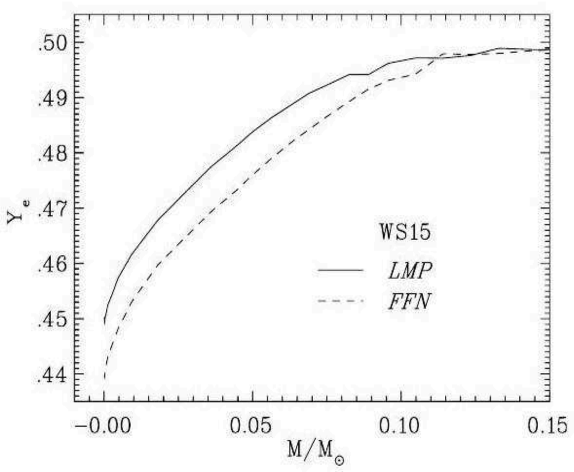
[M(MS)= 3 Mo; Z = 1.E-3 solar; rho(c)= 2E9 g/ccm with rho(tr)=8, 16, 25 g/ccm]



Rem.: Similar explosion energies but very different chemical structures (Fact. 8 in M(Ni)) !!!

Rem2: For typical SN Ia, only 0.3 Mo need to be burned (!) => well before non-linear regime

Electron Capture Rates and the central Ye

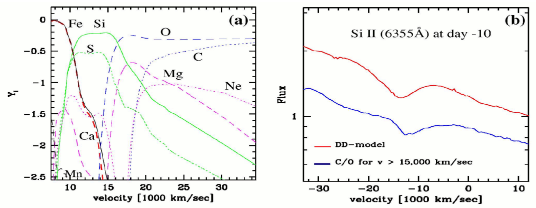


Outer Layers of Type Ia Supernovae are mostly burned

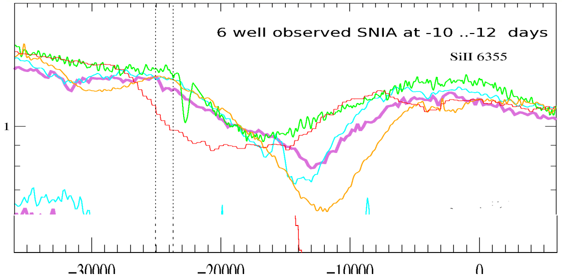
- **IR spectra show high velocity Mg II, O I and II but hardly any C (Bowers et al. 1998, Wheeler et al. 1998, Hoeflich et al. 2001, Marion et al. 2003, ...)**

- **Line profiles of early time spectra (-10 days) show burned matter (e.g. Harkness 1986, Benetti et al. 2005, Quimby, Hoeflich, Gerardy et al. 2005, ...).**

Two classes of early line profiles are observed (HK96, Quimby et al. 2005) :



red: DD- model
blue: W7-like



Observations:

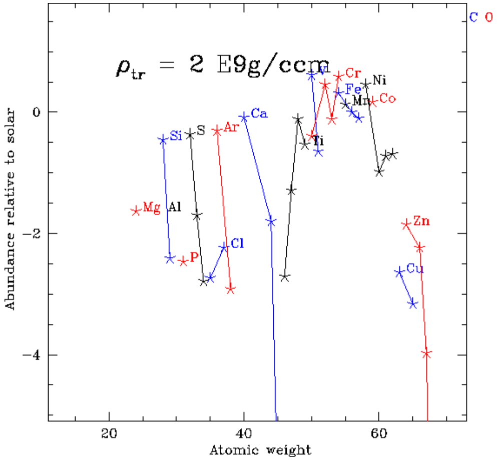
a) DD-like in most cases

b) View cases with cutoff but at high v
-> PDDs or mergers
=> Two classes of SNIa

Effect of central WD density on nucleosynthesis

Production of neutron rich Isotopes

Example: Delayed detonation model (Hoeflich et al. 1998)



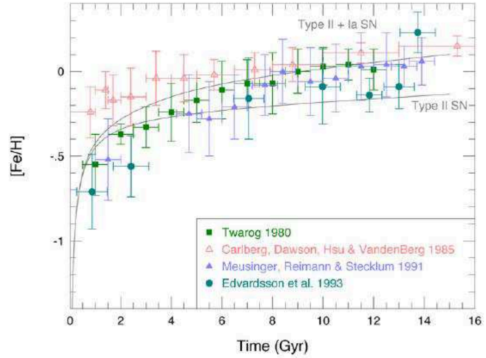
- Rho(c) changes all isotopes WD structure & explosion

Ye	'typical' products
0.5	^{56}Ni, ...
0.470..0.485	^{54}Fe, ^{58}Ni
0.46 ...0.47	^{56} Fe
0.425 ... 0.452	^{50}Ti, ^{54}Cr, ^{58}Fe
0.425	^{48}Ca

Rem.: Old electron capture rates would have prohibited high central densities

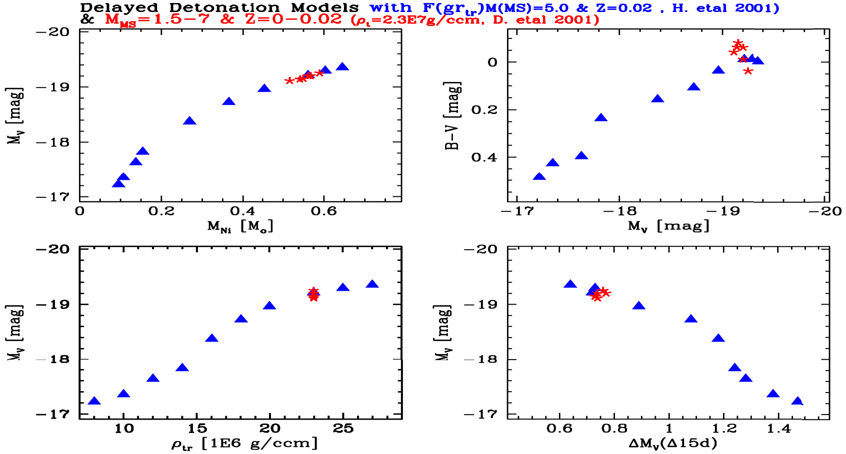
Now: Explosions close to AICs (r-process ???)

Contribution of the SNIa and CC-SNe to the solar Abundance



The Relation for DD-Model & the Diversity of SNe Ia

The brightness decline relation and colors (Hetal. 93,96)

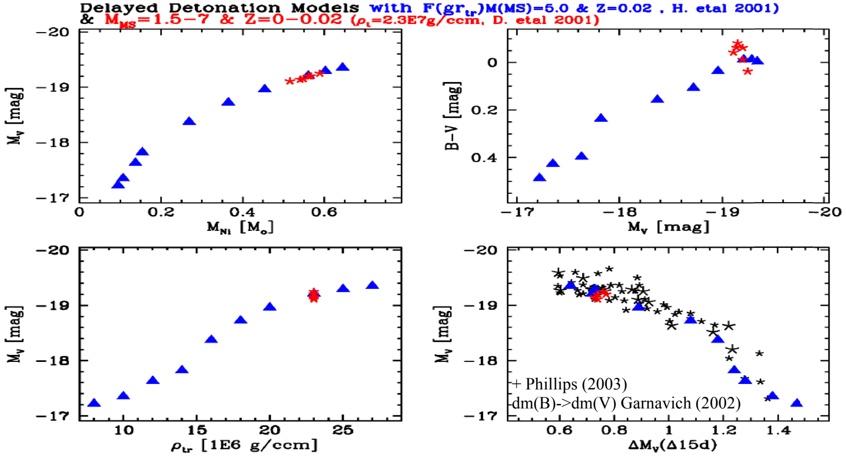


- **Generic: Brightness decline relation is an opacity effect** (Hoeflich et al. 96,Mazzali et al. 2001)
- **Small spread requires similar explosion energies** *(0.5mag for all scenarios H. et al. 96)*
- **Within DD models, relation can be understood as change of burning before DDT**
- **Progenitors (Z=0 ... solar) can produce systematics of about 0.3 mag.**

Attention: Color change of about 0.2 mag -> reddening !!!

Comparison with Observations

The brightness decline relation and colors



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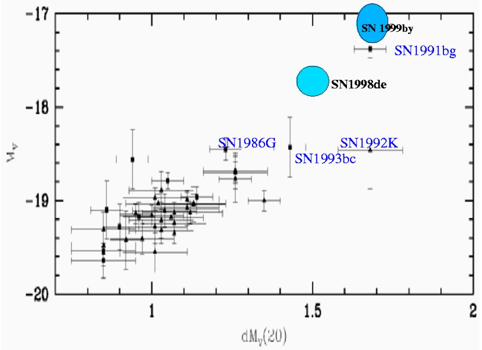
Example Application: Properties of Burning & Observables

The brightness decline relation



Why span SNIa the brightness range we observe?

Are normal and subluminous SN the same kind of objects?

Why is there a brightness decline relation?

How can we test the explanation by spectra and spectropolarimetry?

Prototype: SN1991bg
- low velocities of Ni (< 4000 km/sec)
- Si rich spectra at maximum light

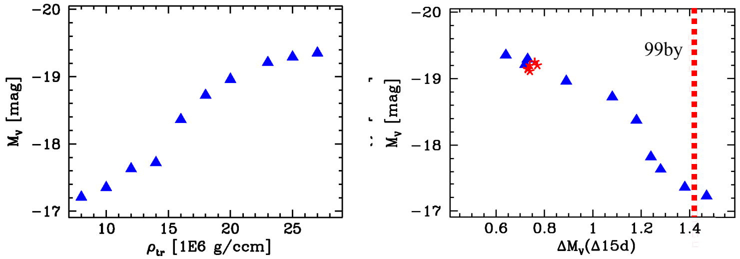
Problem: Optical spectra give no information about C/O, ie the outer layers

=> All models are possible including:

a) Sub-Chandrasekhar mass models
b) Mergers (merging of two WDs)
c) M(Ch): DD and pure deflagration models

III.2) The nature of the subluminous SN1999BY

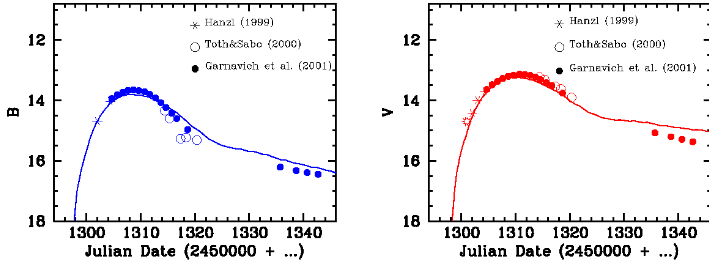
Select model based on optical LC and spectra: here, the brightness decline ratio



- M(V) = F(❒(tr))

- SN1999BY is at the lower end

Comparison between observed and theoretical LC

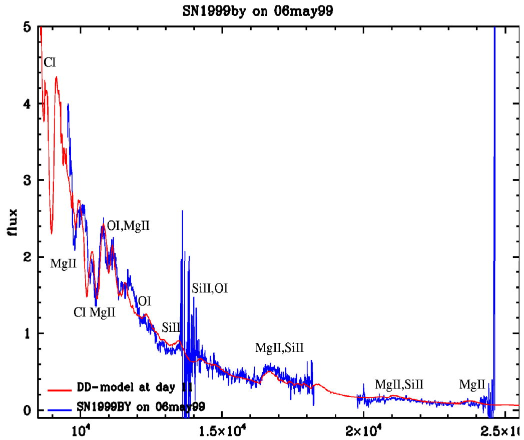


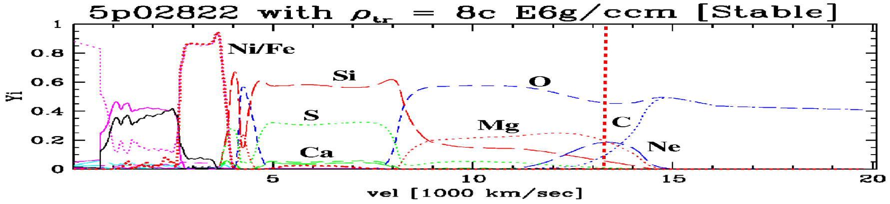
Discrepancy in B and V
- **0.05 mag (tmax)**
- **0.4 mag (tmax+30d)**

consistency error between NLTE and LC calculation
- **0.07 mag (tmax)**
- **0.2 mag (tmax+30d)**

Remark: Compare old LTE + calibration (HKW95) for subluminous SN error(tmax) in (B-V)=0.2 m

IR-Spectrum of SN1999by at -4 days before Maximum Light





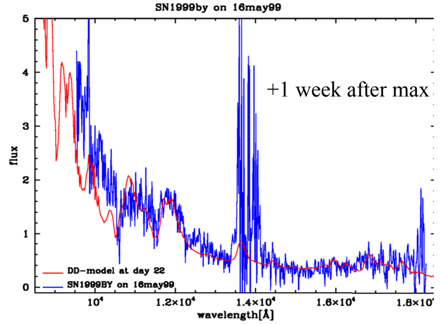
- Spectrum is formed in O-rich layers

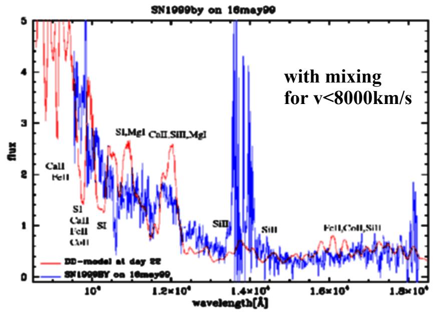
model

observation
by C. Gerardy

Thompson photosphere

Do we have a smoldering phase or a deflagration phase?





Mixing, predicted from 3-D deflagration model does not occur

- No 'classical; deflagration phase ?

- Smoldering phase ?

- Influence of rotation indicated by polarization ?

(Howell, Hoeflich, Wang, Wheeler, 2001)

In any case, importance of preconditioning of the WD is obvious.

III) 3D-Effects of individual SNe Ia

Part 1: Search for the Signature of DDTs

Intensive study of SN2003du, a 'normal-bright' SNIa (with surprises)

- LC and spectra of a typical SNeIa
  (see Benetti et al./ astro-ph & our HET spectra)

- Evidence for the interaction with a H or He-rich surroundings by Ca II
  (Gerardy, Hoeflich, Fesen, + the HET SN-team 2004, ApJ 607, 391)

Goal: Study of signatures of the nuclear burning front

(Hoeflich, Gerardy, Nomoto & Subaru-SN-collaboration, 2004, ApJ 617, 1258)

Experimental Setup: Late time observations of a normal SNeIa
IR-observations because lines are not blended

Observation: Feb 27 & April 1, 2004 (Subaru with OH-suppressor) & March 27)

Expectations: Co/ Fe spectrum dominated by forbidden lines from an optically thin envelope
Advanced 3D deflagration models predict mixing of inner isotopes -> triangular shaped profiles
Off-center DDT can be expected in a point rather a shell -> off-center shift of 56Ni