I) Introduction

II) Concepts

III) Applications & cosmology
- Understanding of homogeneity
- Probing the diversity

Incomplete list of collaborators:
Baade (ESO/Garching); Fesen et al. (Dartmouth); Gamezo (NRL), Garnavich et al. (ND), Khokhlov et al. (Chicago); Krisciunas, Phillips, Suntzeff et al. (CTIO); Langer/Yoon (Amsterdam/NL); Limongi, Chieffi & Straniero (Italy); Meikle et al. (London, UK), Nomoto et al. (JP); Rudy (Lick); Stein/Livne (Jerusalem/Israel); Straniero et al. (Rome/Italy); Thielemann et al. (Basel/Ch); Howell, Wang (LBL/Berkely), UT Austin (Gerardy, Marion, Quimby, Wheeler ...)

Progenitor of a SNIa

Artist: R. Hynes
SNe Ia are **thermonuclear** explosions of White Dwarfs

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 $^{56}\text{Ni}$

The progenitor evolution and explosion go through several phases of **“stellar amnesia”**

$\Rightarrow$ Homogeneity does not imply a unique explosion scenario !!!

$\Rightarrow$ Revolution in observations allows to probe physics of SN !!!
Some Key Questions on SN Ia

- Signatures of the progenitor system/environment

- Accretion process on the WD (accretion process, helium flashes, ...)

- Thermonuclear runaway and pre-conditioning of explosive phase (rotation, progenitor, metallicity, etc.)

- Explosive burning during the deflagration, DDT etc.

Rem.: 3D simulations have shown the importance of RT instabilities and calculations show agreement (Khokhlov 1995, 2001, Reinecke et al. 2002, Gamezo et al. 2002, 2003) but simplified initial model and, mostly, limited to large scale instabilities

Observational constains are showing up for all of these by light curves, flux and polarization spectra
Cooking of a Supernovae

A) Stellar evolution of a low mass star \( (M < 7 M_\odot, 1E9 \text{ years}) \) + mass-loss

\[ \Rightarrow \text{initial structure of the WD} \]

B) Quasi-static evolution of the progenitor \( (1E6...8 \text{ yrs}) \) + accretion

\[ \Rightarrow \text{initial structure of the WD at the time of the explosion (SS-X-ray sources)} \]

C) The thermonuclear runaway (few hours)

\[ \Rightarrow \text{preconditioning of the explosive phase} \]

D) Hydrodynamical phase of explosion (1 to 60 sec)

\[ \Rightarrow \text{nucleosynthesis + release of explosion energy} \]

E) Light curve and spectra (month to years)

\[ \Rightarrow \text{time evolution of the expanding envelope} \]

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.)
Why consistent treatment of RT is needed??

Example: Typical structure of a SN Ia at about maximum (SN1994D, from Hoeflich 1995)

- no well-defined photosphere and depth-dependent luminosity
- high expansion velocities (PdV, no radiative equilibrium) $\Rightarrow$ hydro terms needed
- gamma-ray deposition within the photosphere & multi-scattering
- $+\,$ low density $\Rightarrow$ high scattering + small optical depth $\Rightarrow$ NLTE throughout
- similar time scales for diffusion and hydro hydro
  \[ dt(RT) \approx \frac{\text{tau2/3c}}{*dr} = (10)2*1E15/3E10/3 = 12 \text{ days} \] $\Rightarrow$ time-dependent problem

Rem: Both terms of absorption and emission are critical !!!

Stability of LC due to global conservation of energy !!!
Hydrodynamics (PPM)
- a) 1-D Lagrangian (spherical + front tracking)
- b) 3-D Eulerian (Cartesian, Fryxell et al. 1992)
- c) Free expansion

MC gamma-ray transport
- a) 1-D spherical
- b) 3-D (given Cartesian grid)

Radiation transport (3 modules)
- a1) Spherical, comoving Rybicki scheme (MKH75, 76, 81) for spherical LCs and atmospheres
- a2) Formal integration of RT in observes frame (spherical)
- b) Variable Eddington Tensor solver (implicit) for given Tensors
  - b1) 1-D spherical (comoving) + energy
  - b2) 3-D Cartesian (observer)
- c) Monte Carlo Scheme
  - c1) for Eddington tensor: 3-D, solve for difference between diffusion and R.T. equation (ALI2)
  - c2) Polarization: stationary transport

EOS
- a) \(1E10 > \rho < 1 \text{ g/ccm}\)
- b) \(1\text{ g/ccm} > \rho\)

Statistical equations for ionization and level population

Nuclear network
- a) NSE
- b) Full network & decays (based on Thielemann’s lib)

LTE

Opacities

Rem.: Not all modules can be combined simultaneously (Perturbation strategies and CPU-time: e.g. 3D-struc.+NLTE)

1) Spherical or full 3D geometry (entire envelope)

2) Explicit hydro (PPM, 1D comoving, 3D observer) and implicit radiation transport (3D-hydro is based on/derived from Prometheus, Fryxell et al.)

3) Detailed nuclear networks (based on Thielemann's reaction lib.)

4) Multi-frequency transport (1E3 ...1E5 for 1D/1-5 for 3D/1...1E4 for P)

5) Time dependent rate equations and RT (for polarization, snapshot) (For polarization, see Hoeflich 1991, 95, H et al. 96, Wang et al. 96, Howell 2001)

6) Full NLTE with superlevels (500 - 1000 super-levels, 10000 bf-t, 1,000,000 lines, e.g. H02)

7) Coupling of rate, RT and hydro by Accelerated Lambda Iteration

8) AMR for radiation transport (only)

9) Parallel code (PVM -> MPI2)

Rem.: HydRa has been merged by previously independent codes

Interfaces and iterative methods are still in the process of 'streamlining'

Limitations: Currently, implemented methods and approaches are tuned for rapidly expanding atmospheres.
Explosion of a White Dwarfs (Defl., Delayed Det. & Merger)

Initial WD

Deflagration phase (2...3 sec)
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, $v \ll v(\text{sound}) \Rightarrow$ ignition of unburned fuel (C/O)

**Detonation:** Ignition of unburned fuel by compression, $v = v(\text{sound})$

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

Rem.2: Result hardly depends on the point where DDT occurs
Radial/v-Structures of 3-D Deflagration and DD Models
(from Gamezo et al. 2002/2003, Science)

Deflagration:
- no radially stratisfied chemesty
- about 1/3 of WD remains unburned => $E(\text{kin}) = 4\cdot7\times10^{50}$ erg
- importance of RT instabilities for burning front
- 3D effects are important (Livne & Arnett 93, Khokhlov 1995, 2001, Reinecke et al. 2002, Gamezo et al. 02, 04)
- current 3D deflagration models show consistent results (Roepke et al. 2003)

DDT:
- radially startisfied and detonation signatures are almost wiped out (Livne 99, Gamezo et al. 2004)
- almost entire WD is burned and outcome $F(\text{amount of burning before DDT})$ (H95, L99)

Rem.: Spectral analyses strongly suggest radially stratisfied chemesty as and Ekin as in DD
(for DD: e.g. Hoeflich 1995, 98, 02, Fisher et al. 1995, HK96, Wheeler et al. 98, Lentz01, Branch 03)
W7: e.g. Harkness 1986, ...
PROBLEM: Reconditioning & Run away (see also Stan et al.)


Longest velocity vector in black = 50 km/sec ; $600 \times 10^8 K < T < 1 \times 10^9 K$

- size of shown domain: 1600km/100 km
- size of inner boundary: 13.7 km
- evolution followed over 5 hours
- ignition close to the center at within one cell (about 35 km)
- ignition occurs due to compression of an element due to circulation.
- $v(turb) \gg v$ (RT close to center)
  -> early phase of nuclear burning is governed by preconditioning of WD

Physics Problems: Turbulence spectrum in reactive fluids & neutrino cooling
Delayed detonation models for various transition densities $\rho_{\text{tr}}$  
$M(\text{MS}) = 3\, \text{Mo}; Z = 1.\text{E}\,\text{-3 solar; } \rho(c) = 2\text{E}\,9\, g/\text{ccm with }\rho(\text{tr}) = 8, 16, 25\, g/\text{ccm}$

Rem.: similar explosion energies but very different chemical structures (Fact. 6 in $M(\text{Ni})$) !!!

Rem2.: DDT occurs before WD becomes unbound (0.2-0.3Mo burned)

Rem3: $\Rightarrow$ Minimum amount of Ni $\Rightarrow$ Not infinitely dim.

Rem4: Mg between 17,000 to 27,000 in Ricky Rudy's SN (see also Meikle)
Some Evolutionary Effects with Redshift

Environmental Effects: Properties or interstellar dust; lensing etc.

Intrinsic changes: the statistical properties of the sample
- the individual properties: metallicity, progenitor structure, accretion rate (free par.)
  density and chemical fluctuations and their amplitude

Attention: Effects may be coupled !!!

Example: Mean metallicity $Z$ decreases with redshift influences
- lifetime and chemical structure of the progenitor star (due to Fe opacity)
- cooling of accretion disk -> accretion rate -> central density of the exploding WD
- Electron/nucleon in WD -> pressure -> density and temperature structure of WD
- explosive nuclear burning (Ne22, HWK98) -> shift of equilibrium -> neutron rich-isotopes

Rem: Ne depends on CNO abundance and determines Ye where Z is measured by Fe!
  & $[\text{O/Fe}]$ is strongly metal dependent (+ B stars)

$$[\text{O/Fe}] \approx -Z/3 \implies \text{relative mild dependence}$$


Quest: A better understanding is needed to identify physical effect
  from its cause, to develop strategies to recognize, and to correct for them

Needed: Consistent models vs. observations (polarization, UV- and IR fluxes, statistical sample)

C/O changes energetics mainly (Het al98!!!)

**EXPLOSION MODELS:**

- Mass = 1.38 \( M_\odot \)
- \( \rho_c = 2.5 \times 10^9 \) g/ccm
- \( \rho_{tr} = 2.7 \times 10^7 \) g/ccm
- \( \alpha = 0.02 \) c.s
- \((C/O)_{\text{prior}} = 0.38/0.43\)

**In general:** \( \Delta M \cong 0.1 \Delta t(\text{rise}) \)
II) Diversity of Type Ia Supernovae:
The brightness decline relation and colors

- Generic: Brightness decline relation is an opacity effect (Hoeflich et al. 96, Mazzali et al. 2001)
- Small spread requires similar explosion energies (±0.5 mag 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 !!!
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Attention: Color change of about 0.2 mag -> reddening !!!
II.1) Are 'normal' and sub luminous SN the same beasts?

The brightness decline relation

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, PDD 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

\[ M(V) = F(\Delta(\text{tr})) \]

- 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

Thompson photosphere model

observation by C. Gerardy
IR-Analysis of SN1999 by (as followed from explosion without tuning)

- **M(WD) is both M(Ch)**
- The entire WD is burned
- for subluminous SN
  Si/S & O/Mg is increased on expense of Ni
- Ni is very concentrated

=> Density effect (e.g. not direct metallicity)
Imprint of the RT instabilities/rising plumes?

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

- No or different deflagration phase?
- Smoldering phase?

Polarization with axial symmetry (Howell et al. 2001) see also next talk by Lifan Wang

- Influence of rotation?

In any case, importance of preconditioning of the WD is obvious.
SN2002fk: A SN at the 'edge'
Observations based on Gemini (PI.: P. Garnavich) and IRTF (Marion)

- Low Mg velocity (11,000 - 12,000 km/sec)
- Extention up to more than 17,000 km/sec
- C lines at high velocities (around 9000 AA, v > 15,000 km/sec)
- Same for Ca, O etc.

=> consistent with DD at low transition density at the 'edge', i.e. the low end of normal bright SNeIa
SN2002fk: A SN at the 'edge'
Observations based on Gemini (PI.: P.Garnavich) and IRTF (Marion) wavelength range 0.8 to 2. μm

- Low Mg velocity (11,000 - 12,000 km/sec)
- Extension up to more than 17,000 km/sec
- Similar for other lines of Ca, O, etc.
- C lines at high velocities (around 9000 AA, v > 15,000 km/sec)

=> Consistent with DD at low transition density at the 'edge', i.e. the low end of normal bright SN Ia. (i.e. 5P0z13.16)

(for comparison: W7 spans 1500 km/sec in Mg)
SN2002fk: A SN at the 'edge'

Shock I: The light curve, i.e. IR spectra are 13 d before maximum.

For comparison: Benetti, PhD thesis & Barbon et al. 1990, AA 237, 79)
SN2002fk: A SN at the 'edge'

This we have seen before in models for SN1999by (H.et al. 2001)

Interpretation: Photospheric velocities increases with time when gamma rays leak out of the core

Normal bright SN (0.5Mo of Ni) : 0.5 to 1 day (-4 ..5 mag before max)
SN1991bg-like (0.08Mo ) : phase 6-8 days after explosion
SN2002fk-like (0.35 Mo ) : 3-4 days after explosion (-2...-1.5m bm)
SN2003du: A 'normal-bright' SNIa (with surprises)

Signatures of radioactive isotopes & consequences for LCs
(for more details, see poster of Gerardy et al.)

- LC and spectra of a typical SNeIa
(see e.g. HET-spectra & ESO campain/astro-ph)

- Evidence for the interaction with a
H or He rich envelope by Ca
(Gerardy, Hoeflich, Fesen, + the HET team Astro-ph & ApJ/May 20)

- Signatures of radioactive isotopes and consequences for the LCs
Observation: Feb 27\textsuperscript{th} & April 1, 2004 (Subaru) & March 27/ optical spectrum 2.7m )
Part 1: Search for the Signatures of DDT with Subaru IR at 300 days after maximum (Hoeflich, Gerardy, Nomoto, Motohara, Fesen, Maeda, Ohkubo, Tominaga, Wheeler)

Comparison with DD-model of $\rho = 2 \times 10^9$ g/ccm

- mixing of neutron rich isotopes as expected from 3D
- spherical model

Central $^{56}$Ni hole = 3000 km/sec
$^{56}$Ni wind = 9000 km/sec

$\Rightarrow$ not much of rising plumes

Possible solutions: pre-existing, small scale velocity fields or Flash-model (see Calder & Plewja's talk)
(larger than HS02 if k.spectrum)
Understanding of non-expl. burning
Summary:

- Ni symmetric in velocity space ( < 500 km/sec off-set)
- central hole in 56 Ni consistent with 1D
- no rising plumes -> RT instabilities do not dominate early phase
  (again/see SN1999by but, now, in a normal bright SNeIa)
- Pre-conditioning during smoldering phase of the WD !!!

Implications for SN Ia and Cosmology

- At maximum, central Ni does not contribute to LC
  (diffusion time scale 3 weeks)
- \( t(\text{diff}) \sim t-3 \) -> contributes increasingly to later times -> change of LC shape
  a) faster decline because less heating past maximum
  b) slower decline and higher tail because lesser gamma loss

Corrolars and questions

Is SN2003du looks normal but is it the rule? Hard to observe (8m +OH suppressor)
- dedicated observational programs
Signatures of Circumstellar Environments (Part 1)

Predictions:
- X-rays (e.g. Schlegel & Petri 1993)


Evidence (a SNIa turned to a SNIIp):
  -> High H densities are large radii (1E18 cm, 1E5 part/ccm)
  - PN wind, mass loss through L3, etc.

Basic Theory:
- Self similar solutions for shell/environment interactions (Chevalier 1982)
- Hydro solutions (Dwarakakis and Chevalier 2001)

- Interaction during the hydro phase of the explosion (Benz et al. 1990, Khokhov, Mueller & Hoeflich 1993, Marietta and Burrows 1998)

Are interactions rare or not, or do we miss the point?

Physics Problems: Magnetic fields in accretion discs, impact of high velocity matter on nucleons, etc.
Evolution of the high velocity Ca II feature

Signature of

- Ionization front:
  - very transient (2...3 days)
  - changing Doppler shift

- Shell:
  - persistent (>10 ...14 days)
  - almost constant velocity
What else? Light Curves

- little changes in LC
- early colors are redder by 0.1 to 0.2 mag

Rem.: Change due to optical thickness of shell for electron scattering
Final Discussion and Conclusions

- Supernovae are **thermonuclear** explosions of C/O WDs.

- SN are homogeneous because **nuclear** physics determines the structure of the WD, and the explosion. **CONSISTENTENCY** between evolution, explosion + LC/Spectra.

- Light curve are determined by the radioactive decay of Ni -> Co -> Fe. => homogeneity does not imply a unique scenario (partial stellar amnesia) !!!

- Light curves, and flux and polarization spectra allow for a **detailed** analysis of SN. New IR observations + polarization are a key to probe the physics.

- All chemical layers are radially structures + almost complete burning => signature of detonation (but inconsistent with pure deflagration models).

- Most observations can be understood by **delayed detonation** models.

- **Density** effect/pre-expansion is responsible for luminosity/decline relation.

- Metallicity and rho(c) produces spread around the M/DM relation.

- No evidence for rising plumes in subluminous (SN99by) or normal bright SN(03du).

- For SN2002bk, V(ph) increase with time => early reheating by gamma's => above

- **Preconditioning of the WD** prior to the explosion is a key to understand the differences.

- Models allow to probe **evolutionary** effects with redshift.

- We start to **probe the progenitor** system.
Adaptive Mesh Refinement for radiation tr.

Why?
- discretization error in explosion because grid is optimized for hydro (e.g. $\Delta M = \text{const.}$)
- errors are small for large optical depths (diffusion) but large at small tau.
  Example: 500 ... 1000 depths needed
- reason: radiation field changes from isotropic to un-isotropic at decoupling region. $\Rightarrow$ AMR

**Question:** Where does a photon decouple?
**Problem:** 'Photosphere' is not related to a local physical property (rho, v, T etc.)

**AMR by a Monte Carlo Torch:**
**Solution:** Shoot photons from outside and see where it interacts
**Recipes:** - number of test photons $1E6 ... 1E7$
  - Spherical case: $n(\text{AMR})=1E3$ & $n(\nu \ (\text{repr.}))$, 3D case: $n(\text{AMR})=5E5$ & $n(\nu(\text{repr.}))$
  - divide a cell + neighbors by 2 if actual count exceeds average by about 10.
  - dezone only after 10 to 20 failors
(Rem.: cavities H2002)
Gamma-ray spectra (photon numbers)

Background model HeD6 (Hoeflich & Khokhlov, 1996)

- Classical detonation models: pure Ni
- Deflagration models: unburned C/O at the outer layers; large variations of the explosion energy
- Delayed detonation models: small variation of the explosion energy
- Merger models
- He triggered, sub-Chandrasekhar models

(Comparison spectra by Pinto and Barker provided by Milne/ Spring 2003)

Remarks:
1D version according (Hoeflich et al. 1991, 1998)
3D MPI2 and PVM versions (Hoeflich 2001) with updated bound-free opacities
Note the 511keV line (positron vs. positronium)

Rem: Pinto's and Barker's fluxes have been scaled by factors of 1.44 and 0.87, respectively.
Transition from Deflagration to Detonation

Wanted: mechanism to increase rate of burning
(or, even better, avoid the problem altogether by changing potential see previous speakers)

Possible mechanism:

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 (Khokhlov et al. 1997, Niemeyer et al. 1997)
      - Problem: works only for low fluctuations in the background
   b) Shear flows and instabilities induced by differential rotating WDs on rising plumes (Hoeflich et al. 2001, Langer & Yoon 2003).

3) Drastical change in the deflagration phase (Chicago/Flash-model)
   - single rising plume penetrating the WD, wrapping around and trigger a detonation from outside
Diversity: Influence of the Progenitor Properties on the LCs
Study of progenitors between 1.5 to 7 Mo and Z=0 to 0.02 (solar) and a DD-model

a) Influence of the mass on the main sequence

- progenitor mass is the dominant effect
- maximum off-set in the brightness decline relation 0.2 mag

b) Influence of the metallicity Z

- an off-set of 0.2 mag goes along with a reduced Doppler shift of lines by 2000km/sec
(Second parameter !!!)
Blue and UV are sensitive to metallicity (Hoeflich et al. 1998, Hatano et al. 2001)

Attention: UV is depends sensitively on density structure and fluctuations (HWT98)
& is highly variable with time
VI) Evolutionary Effects with Redshift  

**INFLUENCE OF THE C/O RATIO AND Z OF THE WD**

Example: DD, $\rho_e = 2.6E9$ c.g.s.; $\rho_w = 2.4E7$ c.g.s.

- **DD21**: C/O ratio = 1/1; Z = solar
- **DD23**: C/O ratio = 2/3; Z = solar
- **DD24**: C/O ratio = 1/1; Z = solar/3

- Si/S expands slower by 1000 km/s in DD23
- O expands slower 2000 km/s in DD23
- Metallicity has hardly any influence on dominant elements
- $M_{\text{Ni}}$ in $M_\odot$: DD21 (0.69); DD23 (0.59); DD26 (0.70)

![Graphs showing the influence of evolutionary effects with redshift](image)
INFLUENCE of Z ON RARE ELEMENTS

Example: DD. $\rho_c = 2.6 \times 10^9$ c.g.s.: $\rho_U = 2.4 \times 10^7$ c.g.s.

DD21: $Z = \text{solar}$
DD24: $Z = \text{solar}/3$
DD27: $Z = 10^8 \text{solar}$

- $^{56}\text{Fe}$ production depends sensitively on $Z$
- $^{54}\text{Fe}$ is the dominant isotope at outer layers
- Nuclear burning changes Fe-group abundances

$Ye = p/(p+n)$ comes from massive progenitors

$^{14}\text{N}(\alpha, \gamma)^{18}\text{F}(\beta^+)^{18}\text{O}(\alpha, \gamma)^{22}\text{Ne}$
3-D Structure for a deflagration model \( (H2002) \)

WD: Mch, \( \rho(c) = 2 \times 10^9 \) g/ccm

Day 01

Day 21

Contour: 2\% of maximum Ni deposition

- Energy deposition is highly aspherical early on but spherical later on
Asphericity: Polarization by Electron Scattering

Electromagnetic wave: \( \psi(z, t) = E e^{i(kz - \omega t)} \)
\( E = (E_x, E_y) \)

Intensity is defined as the time average over many waves
\[ I = I_0 + I_{90} = \frac{E_x}{E_x^* + E_y/E_y^*} = \frac{E_x^2 + E_y^2}{2} \]

Degree of polarization \( P \)
\[ P = (I_0 - I_{90})/(I_0 + I_{90}) \]
with position angle \( \chi \)

Stokes Parameter (equivalent)
\[
\begin{align*}
Q &= I_0 - I_{90} \\
U &= I_{45} - I_{-45} \\
V &= 0 \text{ for linear polarization}
\end{align*}
\]

Rem.: \( \tan 2\chi = U/Q \) and \( P = \sqrt{Q^2 + U^2} \)

3 basic cases (H95)
1) Aspherical envelope
2) Cover up (e.g. by opacity/line)
3) Aspherical energy input
Polarization of the subluminous SN1999by vs. prolate model
(from McDonald program: Howell, Hoeflich, Wang, Wheeler 2001 ApJ 550, 1030, error 0.25%, since 2000, systematic VLT program, PI: D. Baade, Hoeflich, Wang, Wheeler, error 0.02%)

- global asymmetry
- asphericity 17%
- seen equator on

Possible explanation: rapidly rotating WD

- larger axis + higher inclination does not work