Coupling of radiation and Non-LTE plasma in supernovae: challenges and solutions

Demonstration on the Dense Shell Method (DSM)

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Outline

- Short introduction about Dense Shell Method (DSM) - the method of measuring cosmological distances based on supernovae of type IIn
- Verification of DSM: two examples
- The SN IIn model: the photosphere is glued to the Dense Shell (DS)
- The SN IIn model: without the assumption of local thermodynamic equilibrium (LTE)
- Case Study: SN 2010jl

SN IIn and Dense Shell Method (DSM): short introduction

The method of measuring cosmological distances based on supernovae of type IIn.

Sn IIn

- SNe IIn are one of the type of supernovae, which indicates the presence of narrow emission lines in the spectra.
- SNe IIn are one of the most powerful light sources in the Universe.
- SNe IIn have very bright the light curves for months.
- SNe IIn may be used as primary distance indicators.

Idea: Baade-Wesselink

$$
\begin{aligned}
v_{ph} &\; - \; \text{Doppler shift} \\
\Delta R_{ph} &= \int_{t_1}^{t_2} v_{ph} dt \\
F_\nu(obs) D^2 &= 4\pi R_{ph}^2 F_\nu(model)
\end{aligned}
$$

Simple version of the DSM

$$
\begin{aligned}
R(t_2) - R(t_1) &= v_{ph}(t_2 - t_1) \\
F_\nu(model) &= \pi \zeta^2 B_\nu(T_{color})
\end{aligned}
$$

DSM: in details

The research was performed on the model sn09ipbp3 computed by a multi-group radiation hydrodynamics code STELLA .
We've constructed this model to apply DSM for SN 2009ip.

Model assumptions

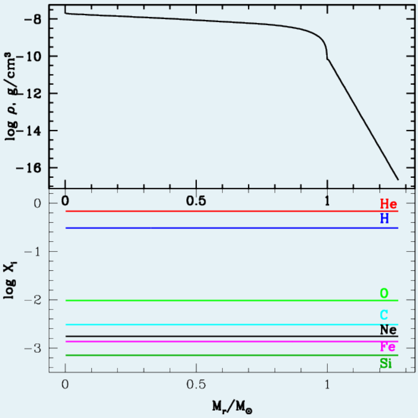
- The equations were written in one-dimensional spherical geometry.
- The levels and ions populations are computed under LTE.
  This strong assumption was verified in this work.
- Our total opacity included contributions from photoionization, bremsstrahlung, lines, and electron scattering.
- The line opacity with expansion effect in lines was computed using atomic data from the Kuruzc's list with approximately 150,000 lines.

STELLA solves the time-dependent equations implicitly for the angular moments of intensity averaged over fixed frequency bands.
No assumption of radiative equilibrium

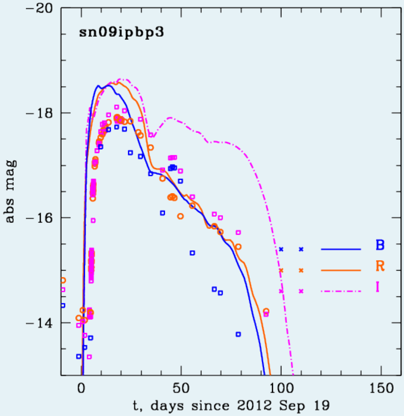
DSM: model `sn09ipbp3`

The model presupernova star had $Renv = 700R_\odot$, $M_{env} = 1.3M_\odot$, $E_{burst} = 10^{51} erg$

Density and composition



The light curves

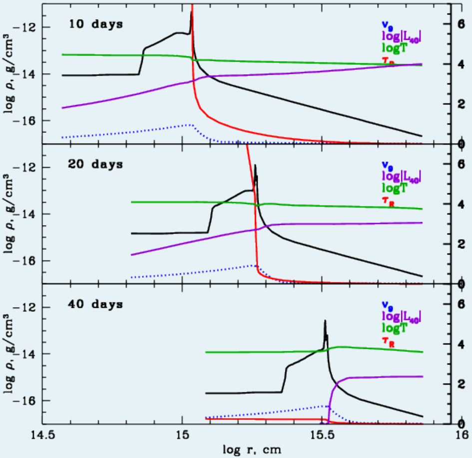


DSM: the formation of the Dense Shell (DS)

Shock wave

- The DS is moving along radius (density-black)
- The photosphere is glued to the DS (optical depth-red)
- Temperature is approximately constant (temperature-green)
- Thus Baade-Wesselink method can be applied at these conditions.

Evolution of model sn09ipbp3



Verification of DSM

The method has been tested at the two famous supernova with the known distances to the host galaxies.

SN 2006gy

$$D_{host} = 71 Mpc$$

Our result:

$$D_{DSM} \approx \; 68^{+19}_{-15} Mpc$$

Blinnikov S., Potashov M., Baklanov P.,Dolgov A.
Direct determination of the hubble parameter using type IIn supernovae
JETP, arXiv: 1207.6914

SN 2009ip

$$D_{host} = 20.4 Mpc$$

Our result:

$$D_{DSM} \approx \; 20.1 \pm 0.8 Mpc$$

Potashov M., Blinnikov S., Baklanov P.,Dolgov A.
Direct distance measurements to SN 2009ip
MNRAS, arXiv: 1212.6893

The conditions in the envelope

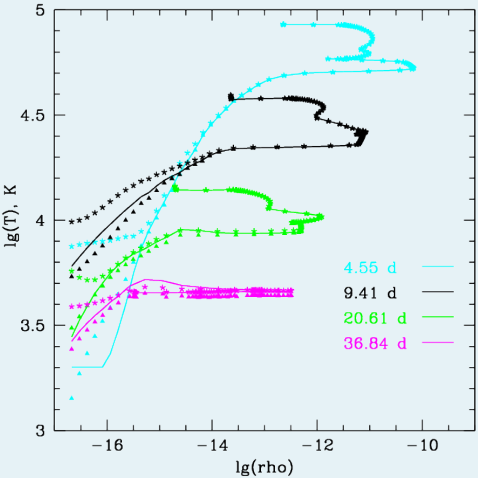
Conditions

- Density:
  $\rho < 10^{-12} g/sm^{-3}$
- Temperature: $T \approx 10^4 K$
- $T_J < T < T_{color}$
  $(\sigma T_J^4 = \pi J \rightarrow \blacktriangle$,
  T_{color} – bb fit of $J_\nu \rightarrow *)$

Coupling radiation and matter

We have the hot diluted radiation in the cold matter.
LTE conditions are not satisfied.

Model evolution: $lg(T) - lg(\rho)$



Equation of state

Equation of state

Using code `Levels` by Marat Potashov, we compute two variants of plasma state WITH/WITHOUT the collisional processes for the same initial conditions on density, chemical composition and temperature.

Non-LTE approach

Under these conditions the role of collisional processes can be neglected.

Ion populations

	Ion populations $N_{ijk}[^{-3}]$, with collisional / no collisional
H	
1.01	1.7161e+08 / 1.7735e+09
1.02	5.6416e+03 / 5.6815e+03
2.01	1.8353e+11 / 1.8193e+11
He	
1.01	1.0393e+11 / 1.0392e+11
2.01	2.5296e+07 / 2.5517e+07
C	
1.01	3.4388e+04 / 3.4085e+04
1.02	3.4781e+03 / 3.4475e+03
2.01	1.5254e+08 / 1.5254e+08
2.02	2.4570e+05 / 2.4570e+05
3.01	4.2105e+03 / 4.2474e+03
Fe	
1.01	1.8969e+00 / 1.8682e+00
2.01	1.7754e+06 / 1.7636e+06
2.02	1.1765e+06 / 1.1687e+06
3.01	1.1634e+07 / 1.1658e+07

Equation of state: Non-LTE approach

Modified nebular approximation, Lucy (1999)

Adopted excitation formula:

$$\frac{n_i^{ju}}{n_i^{jl}} = W \frac{g_i^{ju}}{g_i^{jl}} e^{-\frac{h\nu_{ul}}{kT_{rad}}}$$

Adopted ionization formula:

$$\frac{N_i^{j+1} n_e}{N_i^j} = \eta W \frac{2U_i^{j+1}}{U_i^j} \frac{(2\pi m_e k T_{rad})^{3/2}}{h^3} \left(\frac{T_e}{T_{rad}}\right)^{1/2} e^{-\frac{\chi_j^i}{kT_{rad}}}$$

T_e - electron temperature

$T_{rad} = \frac{h<\nu>}{kx}$

$T_J^4 = \frac{\pi<J>}{\sigma}$ - effective temperature

$W = \frac{\pi<J>}{\sigma T_{rad}^4}$ - dilution factor

$<\nu> \equiv \int_0^\infty \nu J_\nu d\nu \;/ <J>, \;\; <J> \equiv \int_0^\infty J_\nu d\nu$

$\eta = \zeta + W(1-\zeta)$

ζ - fraction of recombinations going directly to the ground state

$x \approx 3.8324$

Model sn09ipbp3: Non-LTE calculation

Influence of Non-LTE

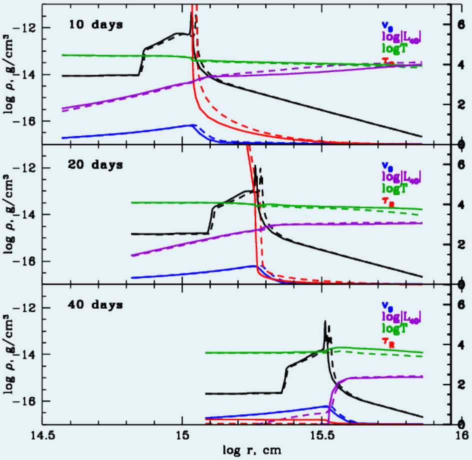
- The higher ionization makes it less transparent. τ shows more rapid growth.
- The higher opacity increases the radiative corrections in the equation for v.
- Velocity v has raised a little.
- The DS is shifted along the radius.

Stability of DSM

- Important dR, not absolute value R
- Temperature T, Luminosity L have not changed significantly

So DSM method works well with the simple assumptions.

LTE(solid) VS Non-LTE(dashed)

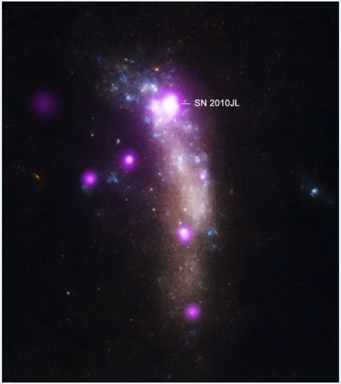


SN 2010jl: discovery

Discovery

- Newton and Puckett discovered SN 2010jl on 2010 November 3.
- It exploded in the irregular galaxy UGC 5189A at a distance of **50** Mpc
- Spectra on 2010 Nov 5 show that it is a Type **IIn** event [Benetti et al. 2010]
- Chandra have provided the first X-ray evidence of a supernova shock wave.
- The total V-band extinction was estimated to be $A_V = 0.084^m$ [Ofek et al. 2013]

SN 2010jl: A Supernova Cocoon Breakthrough



Chandra

http://chandra.harvard.edu/photo/2012/sn2010

SN 2010jl: optical light curves [fig.1 Ofek 2013]

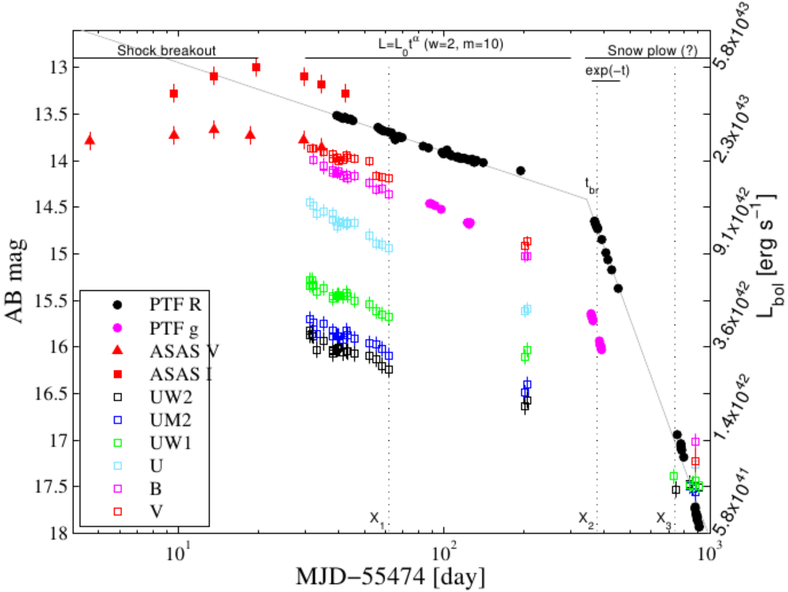


FIG. 1.— Optical light curves of SN 2010jl. The black filled cirles and magenta filled circles represent the PTF measurements, which are based on image subtraction. In this case the uncertainties include the Poisson error and a 0.015 mag systematic error added in quadrature (Ofek et al. 2012a, 2012b). See the

SN 2010jl: DSM

Observations

The parameters of the observations [Smith et al. 2010, Ofek et al.2013]

- $t_1 = 10^d \; F_V(t_1) = 13.7^m$ [fig. 1 Ofek]
- $t_2 = 14^d \; F_V(t_2) = 13.6^m$ [fig. 1 Ofek]
- $T = 7000$ K [fig.3 Ofek, fig.2 Smith]
- $v_{ph} = 5.5 \times 10^8$ sm/c [fig.12 Ofek]

DSM: used black body approximation

$$\begin{aligned} D &= r_{ph}\sqrt{\frac{F_\nu(model)}{F_\nu(obs)}} \\ &= r_{ph}\sqrt{\frac{\pi B_\nu(T_c)}{F_\nu(obs)}} \end{aligned}$$

Result (preliminarily)

$$D_{DSM} = 49Mpc \text{ (studies is underway)}$$

$$(D_{host} = 50Mpc)$$

Conclusions

- The Dense Shell Method (DSM) was tested on two supernovae: SN 2006gy and SN 2009ip.
- For conditions typical to the outer layers of the SN IIn, with time the radiative processes begin to dominate over the collisional processes.
- Thus a modified nebular approximation to the solution of the equation of state in Non-LTE regime may be used.
- The blackbody approximation in the DSM may be used to obtain the estimates of the distance in the early phase light curves.
- We have obtained by DSM the preliminary distance to SN 2010jl $D_{DSM} = 49Mpc$.