DSM - supernovae IIn for cosmology

P.Baklanov, S.Blinnikov, M.Potashov

ITEP

February 5, 2014

Outline of this talk

- Introduction
- Expanding Photosphere Method (EPM)
- Dense Shell Method (DSM)
- The SN IIn model: LTE VS NLTE
- Case Study: SN 2010jl
- Fluorescence

Luminosity distance

Definition

By definition luminosity distance is

$$d_{\mathrm{L}}^2 = \frac{L}{4\pi F} \ ,$$

where L - absolute luminosity of the light source, F - detected flux by observer.

Cosmology

Redshift (z) is determined by the cosmological model:

$$d_{\mathrm{L}}(z)(\Omega_m, \Omega_{DE}, w(z))|_{\text{theory}}$$

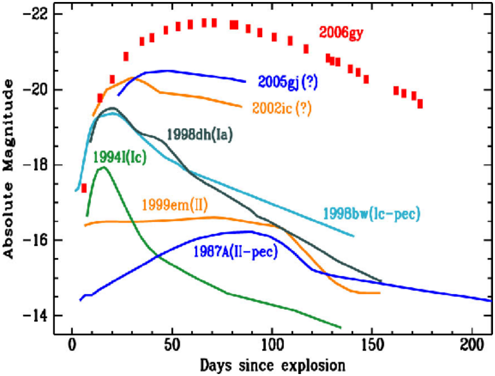
Observations yield $d_{\mathrm{L}}(z)$(observed) from which you can get $\Omega_m, \Omega_{DE}, w(z)$, etc.

Supernovae are the instruments of cosmography

Methods:

- **SN Ia** - main tool, "standard candles"
- **SN IIP** - direct methods EPM and SEAM
- **SN IIn** - new direct method DSM for Superluminous Supernovae

The light curves SNs (N.Smith ea'07)



SN Ia: great success

Nobel Prize in Physics 2011

"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae".

Adam Riess

Riess, Adam G., et al.

Observational evidence from supernovae for an accelerating universe and a cosmological constant.

The Astronomical Journal, 116(3), (1998).

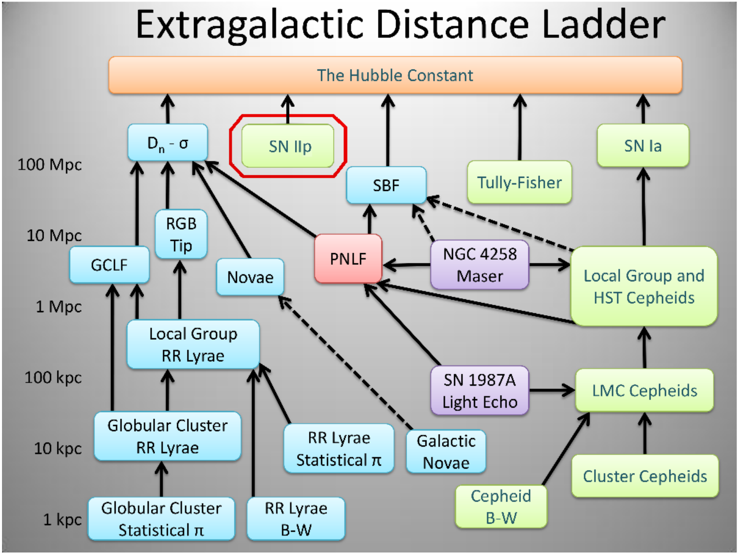
Saul Perlmutter

Perlmutter, Saul, et al.

Measurements of Ω and Λ from 42 high-redshift supernovae

The Astrophysical Journal, 517(2), (1999).

Distance ladder



Luminosity distance

$$d_{\mathrm{L}} = \sqrt{\frac{L_\nu}{4\pi F_\nu(d_{\mathrm{L}})}}$$

With photosphere R_{ph}

$L_\nu = 4\pi R_{\mathrm{ph}}^2 F_\nu(R_{\mathrm{ph}})$,
where R_{ph}- photospheric radius

$$d_{\mathrm{L}} = R_{\mathrm{ph}}\sqrt{\frac{F_\nu(R_{\mathrm{ph}})}{F_\nu(d_{\mathrm{L}})}}$$

Angular size of the star θ:

$$\theta = \frac{R_{\mathrm{ph}}}{d_{\mathrm{L}}} = \sqrt{\frac{F_\nu(d_{\mathrm{L}})}{F_\nu(R_{\mathrm{ph}})}}. \qquad (1)$$

From known $F_\nu(d_{\mathrm{L}})$ and $F_\nu(R_{\mathrm{ph}})$ $\Rightarrow \theta$.
If R_{ph} can be measured, it follows from (??) you can calculate the distance d_{L}.

SN IIP: Expanding Photosphere Method (EPM)

Baade(1926) – Wesselink(1946) – Kirshner & Kwan (1974).

Let's make an assumption, that the flux is dilute blackbody spectrum:

$$F_\nu(R_{\mathrm{ph}}) = \zeta^2 \pi B_\nu(T_c)\,,$$

where ζ – dilution factor, T_c – color temperature (from observations)
Dilution factor we should get from our supernova model:

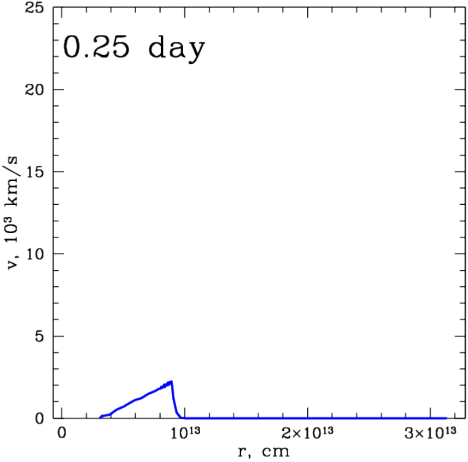
$$\zeta \sim \frac{R_{\mathrm{therm}}}{R_{\mathrm{ph}}}$$

Let's think that we know ζ, so we can get the angular size of SN

$$\theta = \sqrt{\frac{F_\nu(d_{\mathrm{L}})}{F_\nu(R_{\mathrm{ph}})}}. \tag{2}$$

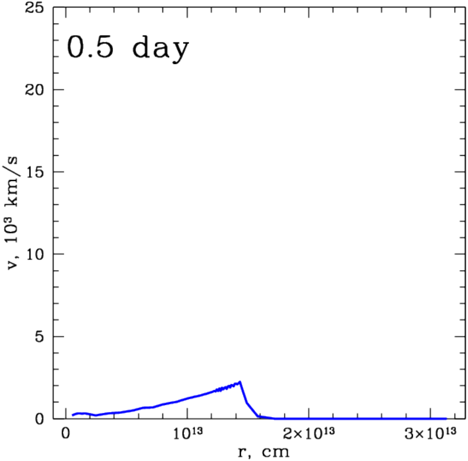
Expanding Photosphere Method (EPM)

SN 1999em: Velocity v evolution over time



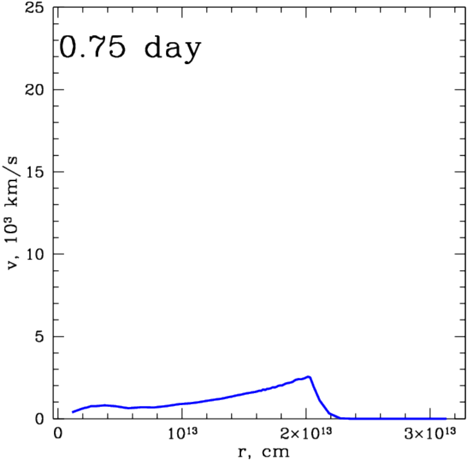
Expanding Photosphere Method (EPM)

SN 1999em: Velocity v evolution over time



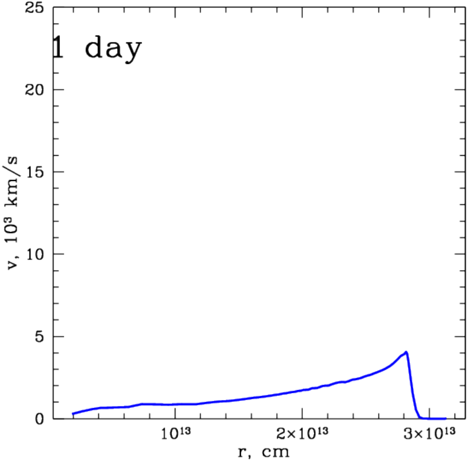
Expanding Photosphere Method (EPM)

SN 1999em: Velocity v evolution over time



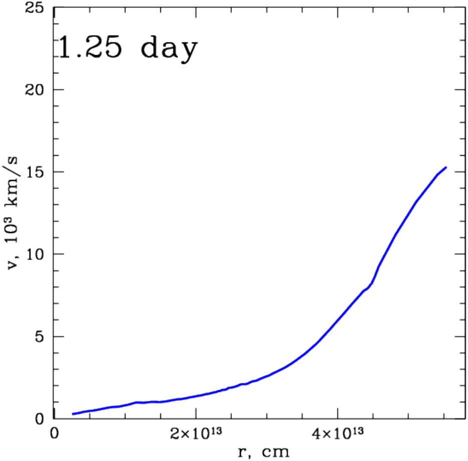
Expanding Photosphere Method (EPM)

SN 1999em: Velocity v evolution over time



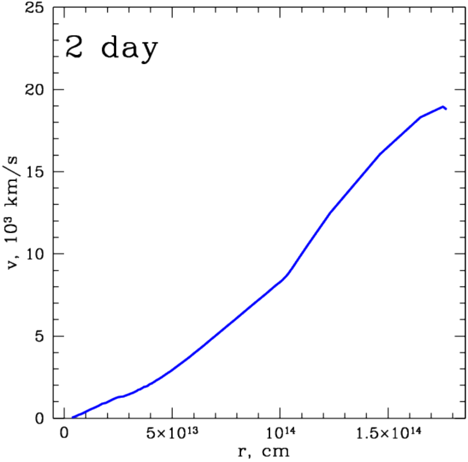
Expanding Photosphere Method (EPM)

SN 1999em: Velocity v evolution over time



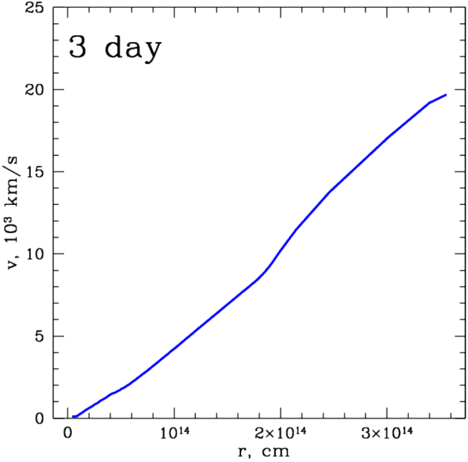
Expanding Photosphere Method (EPM)

SN 1999em: Velocity v evolution over time



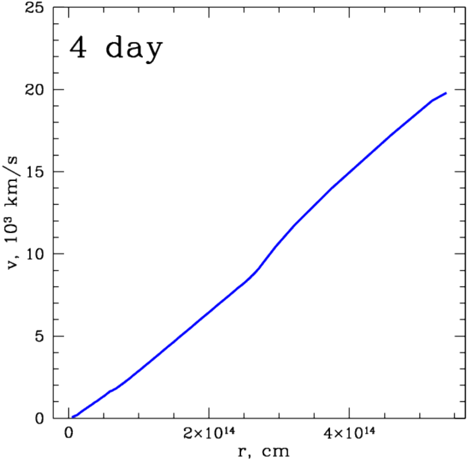
Expanding Photosphere Method (EPM)

SN 1999em: Velocity v evolution over time



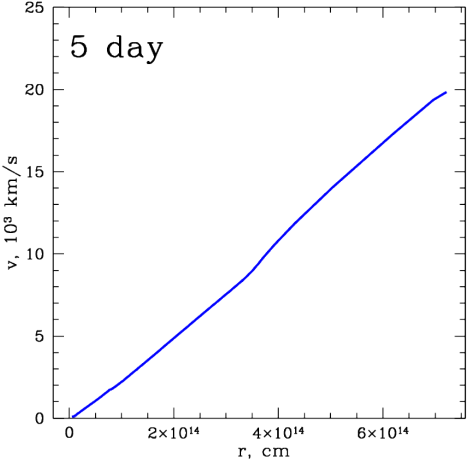
Expanding Photosphere Method (EPM)

SN 1999em: Velocity v evolution over time



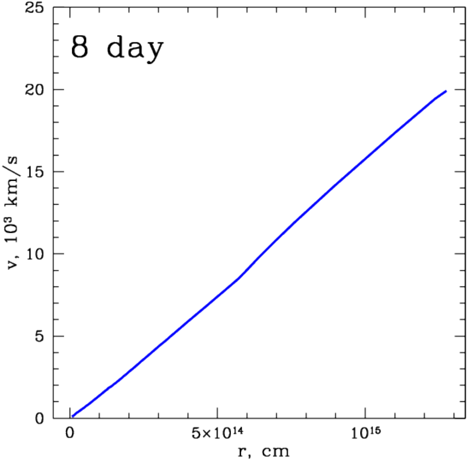
Expanding Photosphere Method (EPM)

SN 1999em: Velocity v evolution over time



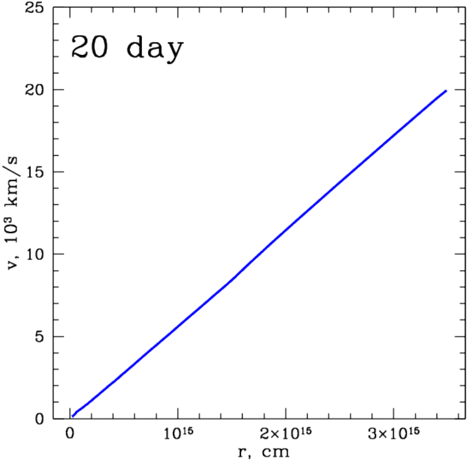
Expanding Photosphere Method (EPM)

SN 1999em: Velocity v evolution over time



Expanding Photosphere Method (EPM)

SN 1999em: Velocity v evolution over time



SN IIP: Expanding Photosphere Method (EPM)

Kirshner & Kwan (1974):

Using weak lines you can measure the velocity of matter at the level of the photosphere u and calculate $R_{\rm ph}$ as:

$$R_{\rm ph} = u(t - t_0)\,,$$

where t_0 - time explosion.

Then $d_{\rm L}$ is

$$d_{\rm L} = \frac{\Delta R_{\rm ph}}{\Delta\theta} = \Delta R_{\rm ph}\sqrt{\frac{F_\nu(R_{\rm ph})}{F_\nu(d_{\rm L})}}$$

EPM: success

An independent evaluation of the Hubble constant H_0 was obtained by EPM method.

$H_0 = 73 \pm 6$ km/s/Mpc

Schmidt, Brian P., et al.
The distances to five Type II supernovae using the expanding photosphere method, and the value of H_0

The Astrophysical Journal 432 (1994): 42-48.

$\zeta - T_{color}$ correlation

Eastman R. G., Schmidt B. P. and Kirshner R.

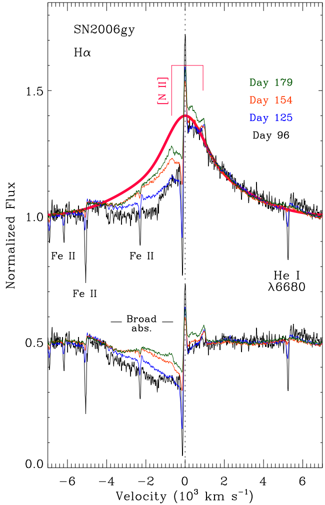
The Atmospheres of Type II Supernovae and the Expanding Photosphere Method

Astrophysical Journal v.466, p.9116 (1996)

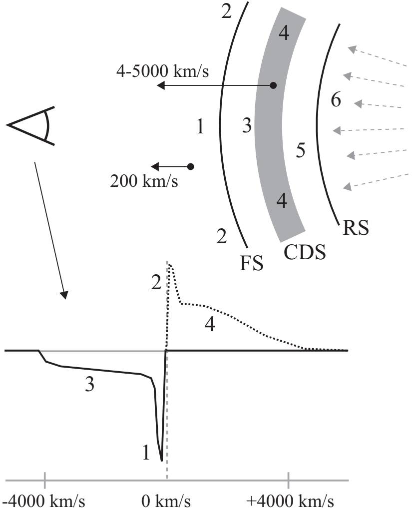
SN IIn— supernova with narrow lines

N.Smith et al., arXiv:0906.2200

SN 2006gy: H_α profile



Line structure



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.

Baade-Wesselink's idea

$$
\begin{aligned}
v_{ph} &- \text{Doppler shift} \\
\Delta R_{ph} &= \int_{t_1}^{t_2} v_{ph} dt \\
\theta &= \frac{R_{\rm ph}}{d_{\rm L}} = \sqrt{\frac{F_\nu(d_{\rm L})}{F_\nu(R_{\rm ph})}}.
\end{aligned}
$$

Simple version of the DSM:

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

DSM: simulations

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

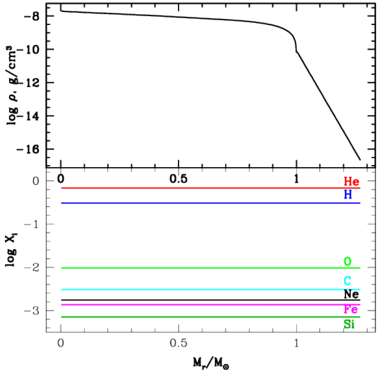
- The equations were written in one-dimensional spherical geometry.
- The levels and ions populations are computed under LTE. This strong assumption was verified in this work.
- Our total opacity included contributions from photoionization, bremsstrahlung, lines, and electron scattering.
- The line opacity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

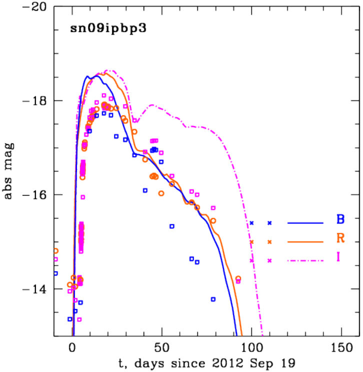
DSM: model sn09ipbp3

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

Density and composition



The light curves

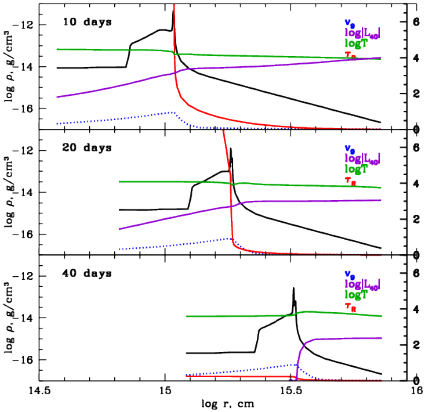


DSM: the formation of the Dense Shell (DS)

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`



Papers

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

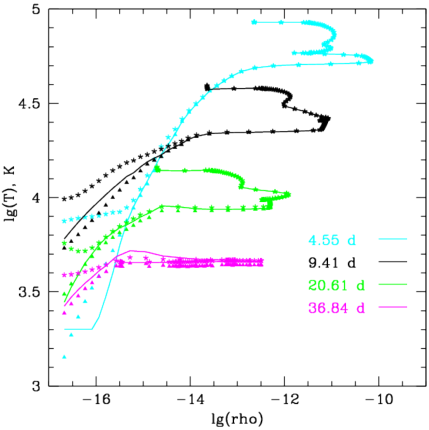
Nonequilibrium radiation field

The conditions in the envelope

- 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 $J_\nu \rightarrow *)$

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

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



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 N_{ijk}[см$^{-3}$], 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

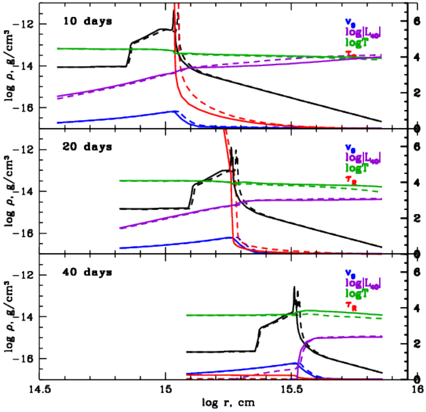
$x \approx 3.8324$

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.

LTE(solid) VS Non-LTE(dashed)



Stability of DSM

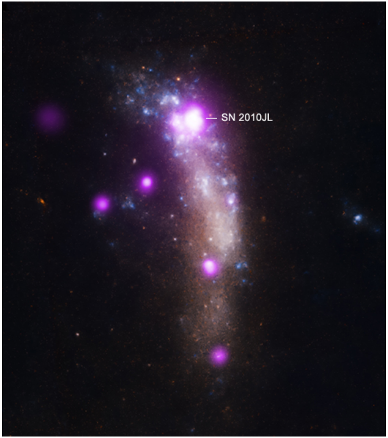
- Important dR, not absolute value R
- Temperature T, Luminosity L have not changed significantly

So DSM method works well with the simple assumptions.

SN 2010jl: 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]

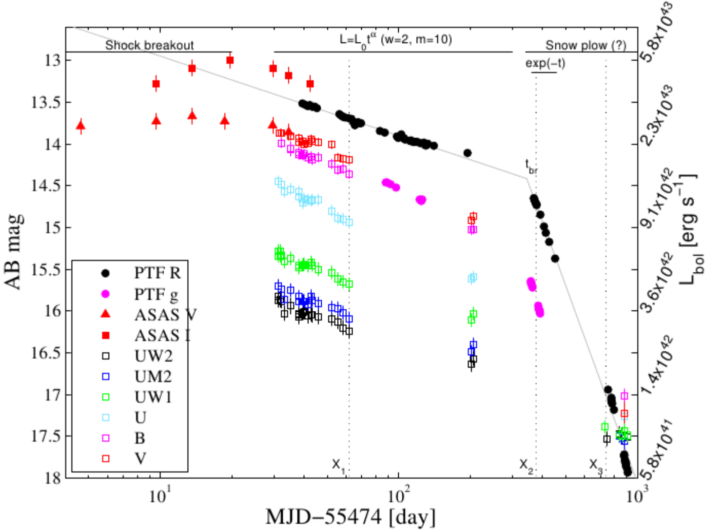


FIG. 1.— Optical light curves of SN 2010jl. The black filled cirles and magenta filled circles represent the PTF measurements, which are based on image subtraction. In this case the uncertainties include the Poisson error and a 0.015 mag systematic error added in quadrature (Ofek et al. 2012a, 2012b). See the legend for ASAS and *Swift*-UVOT measurements. The gray lines show the best-fit broken power law to the PTF *R*-band data. The power-law index before (after) the break is −0.38 (−3.14). The power-law break is at day 344 (with respect to MJD 55474). The epochs of the *Chandra* and *NuSTAR*+*XMM* observations are marked by vertical dotted lines. The right-hand ordinate axis shows the bolometric luminosity for the PTF *R*-band data, assuming the bolometric correction is −0.27 mag. Time is measured from 20 days prior to *I*-band maximum light. The various physical stages are indicated at the top of the plot. These are the shock breakout phase, the early power-law decay, and the snow-plow phase (see §4). Also shown is the section of the light curve which is fitted well by an exponential decay (i.e., "exp(−t)").

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: blackbody approximation

Simple version of the DSM:

$$
\begin{aligned}
R(t_2) - R(t_1) &= v_{ph}(t_2 - t_1) \\
F_\nu(d_\mathrm{L}) &= \pi B_\nu(T_{color}) \\
\theta = \frac{R_\mathrm{ph}}{d_\mathrm{L}} &= \sqrt{\frac{F_\nu(d_\mathrm{L})}{F_\nu(R_\mathrm{ph})}}.
\end{aligned}
$$

Result (preliminarily)

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

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

Fluorescence: prospects

In STELLA's radiation equations we use the invariant photon distribution function $f_\nu(r,\mu)$:

$$\frac{1}{c}\frac{\partial f}{\partial t} + \mu\frac{\partial f}{\partial r} + \frac{1-\mu^2}{r}\left(1 - \frac{Q\mu v}{c}\right)\frac{\partial f}{\partial \mu} - \frac{v(1+Q\mu^2)\nu}{cr}\frac{\partial f}{\partial \nu} = \eta_\nu - \chi_\nu^{\mathrm{tot}} f$$

Total opacity:

$$\chi_\nu^{\mathrm{tot}} = \chi_\nu^{\mathrm{scat}} + \chi_\nu^{\mathrm{abs}}$$

and we use emission as

$$\eta_\nu = \chi_\nu^{\mathrm{abs}} B_\nu(T) + \chi_\nu^{\mathrm{scat}} J_\nu$$

No fluorescence, no re-emission in other frequency bands

Fluorescence

Replace $\nu \to k$ - number frequency group

$$\eta_k = \chi_k^{\mathrm{abs}} B_{\nu_k} + \chi_k^{\mathrm{scat}} J_{\nu_k} + \sum_{k'} \chi_{\mathrm{fluor}}^{k',k} J_{\nu_{k'}}$$

$\chi_{\mathrm{fluor}}^{k',k}$ - an analogue of the cascade matrix, it's show which part absorbed energy in k-group would be emitted in k'-group (see Pinto, Eastman (2000)).

Fluorescence: $\chi_{\text{fluor}}^{k',k}$

Summing all atomic transitions over the frequency bins we get $\chi_{\text{fluor}}^{k',k}$:

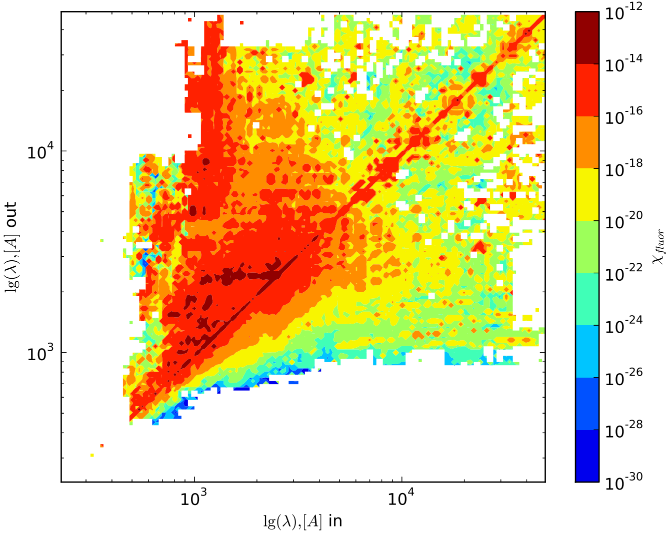
$$\chi_{\text{fluor}}^{k',k} \quad = \quad \frac{\nu}{\Delta\nu}\frac{\partial\beta}{\partial r} \sum_{(\forall\{u,l\}\in(\Delta\nu))} \left[\left(1 - e^{-\tau_{u,l}}\right)\left(1 - \epsilon_{u,l}\right) \sum_{\left(\forall\{u,l'\}\in(\nu_k',\nu_k'+\Delta\nu)\right)} b_{u,l'} \right]$$

Where:

Fluorescence: $\chi_{\mathrm{fluor}}^{k',k}$

$$
\begin{aligned}
\tau_{u,l} &= \frac{hc}{4\pi}\frac{(n_l B_{l,u} - n_u B_{u,l})}{|\partial v/\partial r|} \\
&- \quad \text{Sobolev optical depth} \\
p_{ul} &= \frac{1 - e^{-\tau_{ul}}}{\tau_{ul}} \\
&- \quad \text{escape probability for a photon emitted} \\
\epsilon_{u,l} &= \frac{n_e \sum_l \mathrm{C}_{u,l}}{n_e \sum_l \mathrm{C}_{u,l} + \sum_l p_{u,l} A_{u,l}} \\
&- \quad \text{the probability of de-excitation by electron impact} \\
b_{u,l} &= \frac{p_{u,l} A_{u,l}}{\sum_l p_{u,l} A_{u,l}} \\
&- \quad \text{photon-emission probability}
\end{aligned}
$$

Fluorescence: $\chi_{\mathrm{fluor}}^{k',k}$



Fluorescence: self-testing

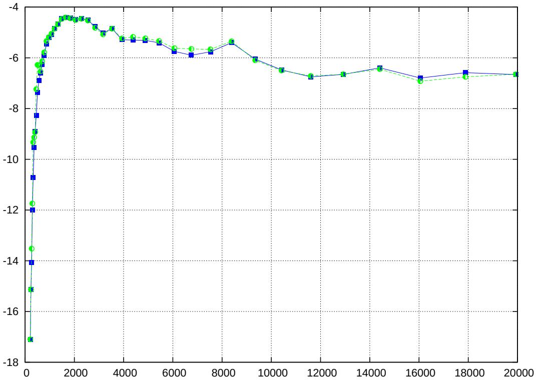
For self-testing fluorescence can be computed under LTE.
When:

$$-\chi_{\rm tot} B_{\nu_k} + \chi_{\rm abs} B_{\nu_k} + \sum_{k'} \chi_{\rm fluor}^{k',k} B_{\nu_{k'}} = 0$$

Then, for each k must be equal the following sums:

$$B_{\nu_k} \sum_{k'} \chi_{\rm fluor}^{k,k'} \quad = \quad \sum_{k'} \chi_{\rm fluor}^{k',k} B_{\nu_{k'}}$$

Fluorescence: self-testing



Blue line is $B_{\nu_k} \sum_{k'} \chi_{\rm fluor}^{k,k'}$.

Green line is $\sum_{k'} \chi_{\rm fluor}^{k',k} B_{\nu_{k'}}$.

Good agreement!

Final remarks

- The blackbody approximation in the DSM may be used to obtain the estimates of the distance in the early phase light curves.
- The Dense Shell Method (DSM) was tested on 3 supernovae: SN 2006gy, SN 2009ip and SN 2010jl.
- 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 fluorescence should be included to our simulations.

Finale

Thank you for your attention!

Questions?

Contacts

speaker: Petr Baklanov
e-mail: petr.baklanov@itep.ru