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3D Hydrodynamic Modeling of SN 1987A from the SN explosion till the Athena Era

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Introduction

Supernova remnants (SNRs) show a complex morphology characterized by a complex spatial distribution of ejecta, believed to reflect pristine structures and features of the progenitor supernova (SN) explosion.

Filling the gap between SN explosions and their remnants is very important in Astrophysics for a comprehension of the origin of present-day structure of ejecta in SNRs and to probe and constrain current models of SN explosions.

The remnant of SN 1987A provides a unique opportunity to investigate the evolution of a core-collapse SNR during the early phase of its evolution. This is important to:

- Probe the structure of the CSM immediately surrounding the SN (clues on the final stages of the star's evolution)
- Probe the structure of the ejecta (clues on the dynamics of the SN explosion)

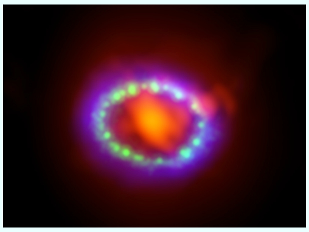

Fig. 1. Composite image from 3 sources: radio data from ALMA (red), visible data from HUBBLE (green) and X-ray data from Chandra (blue)

A detailed model connecting the SN explosion with the SNR evolution is presently missing.

The aim of this project is to identify the imprint of SN 1987A on the X-ray emission of its remnant and to constrain the structure of the environment surrounding the supernova.

To this end we use jointly a SN explosion model and a 3D hydrodynamic model of the following SNR evolution with unprecedented spatial resolution and completeness.

We investigate how fine ejecta structures form during the remnant evolution and how the final remnant morphology reflects the characteristics of the SN explosion.

Modeling the SN explosion

(Pumo & Zampieri 2011)

Our model describes the SN evolution from the breakout of the shock wave at the stellar surface up to the nebular stage.

The calculations are performed with a 1D relativistic, radiation-hydrodynamics Lagrangian code, specifically tailored to simulate the evolution of the main observables in core-collapse SNe.

The SN simulations provide the initial distribution of ejecta for the 3D SNR model ~ 24 hours after the shock breakout.

We explore a grid of SN models to fit simultaneously the observables of the SN (bolometric lightcurve, evolution of photospheric temperature and velocity) and the observables of the subsequent SNR (X-ray lightcurves, spectra, and morphology).

Modeling the SNR expansion

(Orlando+ 2015)

Our model describes the 3D expansion of the SNR 1987A through the HII region and dense equatorial ring surrounding SN 1987A.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0 ,$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot \rho \mathbf{u}\mathbf{u} + \nabla P = 0 ,$$

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot (\rho E + P)\mathbf{u} = -n_{\rm e} n_{\rm H} \Lambda(T) ,$$

where $E = \epsilon + \frac{1}{2}|\mathbf{u}|^2$,

The model includes:

- non-equilibrium ionization;
- Radiative cooling;
- Clumping of ejecta; (Orlando+ 2012)
- Passive tracers to follow the evolution of ejecta, HII region and ring material

Numerical code: FLASH

A major challange was capturing the enormous range in spatial scales (maximum resolution achieved 0.2 AU).

Exploration of parameter space and Best-fit parameters

Mass of ejecta ~ 17 Msun,
Energy of the explosion ~ 1.2e51 erg

			range of values explored	best-fit values
HII region	n_{HII}	$(10^2$ cm$^{-3})$	0.8 – 3	0.9
	r_{HII}	(pc)	0.08 – 0.2	0.08
ring	n_{rg}	$(10^3$ cm$^{-3})$	1 – 2	1
	r_{rg}	(pc)	0.16	0.16
	w_{rg}	$(10^{17}$ cm)	0.7 – 2	1.7
	h_{rg}	$(10^{16}$ cm)	3.5	3.5
clumps	$< n_{cl} >$	$(10^4$ cm$^{-3})$	1 – 3	2.2 – 2.8
	$< r_{cl} >$	(pc)	0.14 – 0.17	0.14 – 0.17
	w_{cl}	$(10^{16}$ cm)	1 – 3	1.7
	N_{cl}		40 – 70	50

Hydrodynamic Evolution of the Remnant and X-ray emission

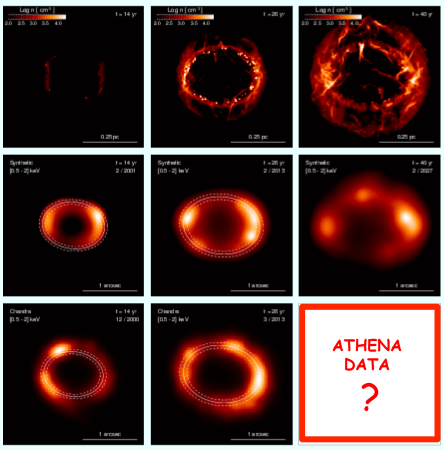

Fig. 2. Interaction of the blast wave with the nebula.

(Top) Three-dimensional volume rendering of particle density of the shocked plasma at the labeled times.

(Middle) Corresponding synthetic maps of X-ray emission in the [0.5, 2] keV band integrated along the line of sight. Each image has been normalized to its maximum for visibility and convolved with a Gaussian of size 0.15 arcsec to approximate the spatial resolution of Chandra observations (Helder+ 2013).

(Bottom) Maps of X-ray emission of SN 1987A collected with Chandra at the labeled times, and normalized to their maximum for visibility. The overplotted ellipsoids represent the projection ofcircles lying in the equatorial plane of SN 1987A and fitting the position of the maximum X-ray emission in each observation. The dashed lines show an uncertainty of 10%.

Contribution to X-ray emission from different plasma components

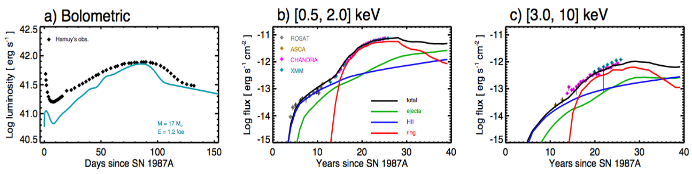

Fig. 3. (a) Bolometric lightcurve of the model (cyan line) compared to the lightcurve of SN 1987A (filled and empty diamonds; Hamuy et al. 1988). (b) X-ray lightcurve in the [0.5,2] keV band synthesized from the model (black line) compared to the lightcurve of SNR 1987A observed with several X-ray observatories (see the legend; Haberl+ 2006, Maggi+ 2012, Helder+ 2013). Green, blue and red lines mark the contribution to emission from shocked ejecta, shocked plasma from the ring, and shocked plasma from the HII region, respectively. (c) Same as in panel b but for the lightcurve in the [3, 10] keV band.

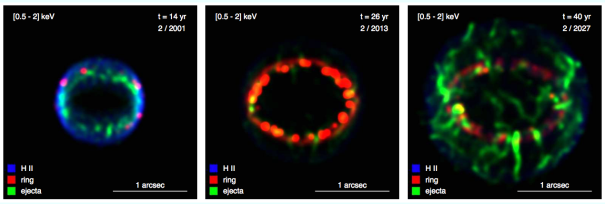

Fig. 4. Three-color composite images of the X-ray emission in the [0.5,2] keV band integrated along the line of sight at the labeled times. Each image has been normalized to its maximum for visibility and smoothed with a Gaussian of size 0.025 arcsec. The colors in the composite show the contribution to emission from the different shocked plasma components, namely the ejecta (green), the ring (red), and the H II region (blue)

X-ray spectra and relative contribution of the different plasma components

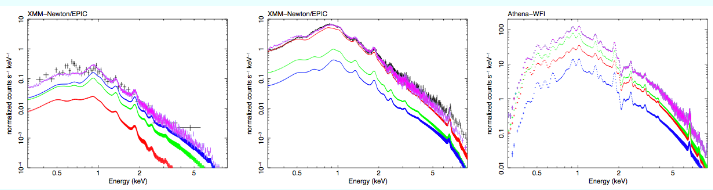

Fig. 5. Synthetic and observed X-ray spectra of SN 1987A.

(a) XMM-Newton/EPIC-pn spectra at t = 14 yr. The true spectrum is marked in black; the synthetic spectrum from the whole shocked plasma is marked in magenta; the contributions to emission from the different shocked plasma components are marked in green (ejecta), red (ring), and blue (HII region).

(b) As in panel (a) for t = 26 yr.

(c) As in panel (a) for t = 40 yr and for simulated spectra as collected with **Athena/WFI**.

References

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Acknowledgments

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