Modeling post-explosion anisotropies of ejecta in SNR Cassiopeia A  
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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.  

Cassiopeia A (Cas A; see Fig. 1) is an attractive laboratory for studying the early evolutionary phase of an SNR. In fact this remnant is one of the best studied and its 3D structure has been characterized in good detail (e.g. Delaney et al. 2010; Milisavljevic & Fesen 2013). An outstanding characteristic of the Cas A morphology is its overall clumping, most likely due to pristine ejecta clumping resulting from instabilities and mixing throughout the remnant evolution.  

Fig. 1. Composite image from 3 sources (courtesy NASA/PLST-Galtech): infrared data from Spitzer (red), visible data from Hubble (orange), and X-ray data from Chandra (blue and green).  

A detailed model connecting the SN explosion with the SNR evolution is presently missing. The aim of this project is to study the ejecta dynamics from the immediate aftermath of the SN explosion to their expansion in the SNR with accurate model resolution and completeness.  
To this end we jointly use a SN explosion model and a 3D hydrodynamic model of the following SNR evolution.  
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 SNRs.  
The SN simulations provide the initial distribution of ejecta for the SNR model ~ 30 hours after the shock breakout.  
We explore a grid of SN models to fit the current positions and velocities of forward and reverse shocks in Cas A.  
The best-fit model is characterized by mass of ejecta $Mej = 4 \text{ M}_\odot$ and energy of explosion $E = 2.3 \times 10^{51} \text{ erg}$.  

Modeling the SNR expansion  
(Orlando et al. 2016)  
The model includes:  
- Radial distribution of element abundances of the ejecta (Thielemann et al. 1996)  
- non-equilibrium ionization of the most important elements: Space- and time-dependent cosmic ray back-reaction (Orlando et al. 2012);  
- Radiative losses from optically thin plasma  

Numerical code: FLASH (The University of Chicago).  

Asymmetries in ejecta distributions: jets and clumps  
The post-explosion structure of the ejecta in the immediate aftermath of the SN explosion is described by small-scale clumping of material and larger-scale anisotropies.  

Fig. 2. 3D view of plasma density with temperature above $1 \text{ MK}$ in one octant of the spatial domain for 4 models with $Mej = 4 \text{ M}_\odot$ and $E = 2.3 \times 10^{51} \text{ erg}$. The models differ for the energy and mass of the initial ejecta inhomogeneity that evolves in a jet after 330 yrs. The greencontour shows the Si-rich material; the slice shows the distribution of mass density.  

Fig. 3. The same as in Fig. 2 for 3 models differing for the energy and mass of the initial ejecta clump that leads to the formation of an iron bubble at $t = 330$ yrs. Each color represents the ejecta material rich of Si and Fe (blue).  

Spatial distribution of ejecta in our best-fit model  

Fig. 4. 3D spatial distribution of shocked Fe (blue) and Si/S (green). Panels (A) and (C) and (D): 3D distribution assuming the vantage point at Earth. Panels (B) and (D): the same perspective but with the vantage point from behind Cas A. The transparent image in panels (A) and (B) is a Cassiopeia A morphology reflection; that in panels (C) and (D) is a composite Hubble Space Telescope image. The transparent red sphere marks the fiducial reverse shock.  

Effects of back-reaction of accelerated cosmic rays  
Our model reproduces the density of the outermost shocked wind derived from X-R observations ($n = 4 \text{ cm}^{-3}$; Lee et al. 2013) and predicts that the pre-shock density of the RSG wind at 25 pc is $0.4 \text{ cm}^{-3}$ for efficient cosmic rays (CR) acceleration, and $1 \text{ cm}^{-3}$ for negligible CR acceleration.  

We computed the energy loss due to CR acceleration derived from the model with that derived from the analysis of Cas A observations (Abdo et al. 2010; Yuan et al. 2013). Our model reproduces the observed energy loss for injection efficiency lower than $1 \times 10^{-4}$.  

Fig. 5. For comparison, we report the 3D projections of the infrared [Ar ii] (red), high infrared [Ne ii]/[Ar ii] ratio (blue), X-ray Si xiii (black), X-ray Fe-K (green), outer optical ejecta (yellow), and fiducial reverse shock (sphere) derived by Delaney et al. (2010) from the analysis of observations of Cas A.  

Acknowledgments  
This work was partially funded by the PRIN INAF 2014 grant. The FLASH code is developed by the ASC/Alliance Center for Astrophysical Thermonuclear Flashes (University of Chicago). We acknowledge PRACE Award N.2012060993 and the Barcelona Supercomputing Center (Spain) for the availability of HPC resources and support. Additional computations were carried out at the SCAN HPC facility of INAF-OAPN.  

References  