3D MHD simulations from the onset of the core-collapse SN to the full-fledged SNR

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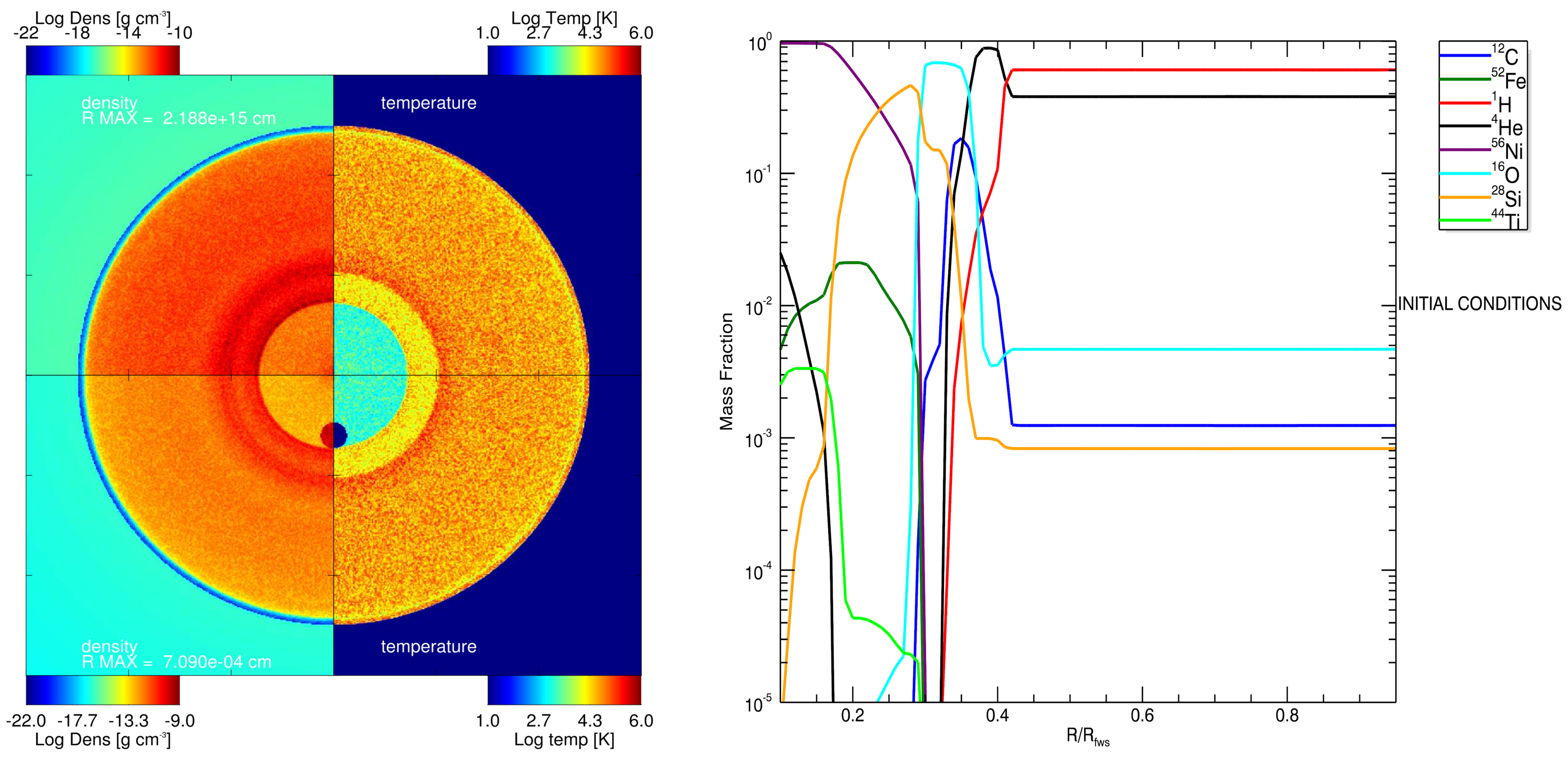
1. Introduction

The structure of the stellar progenitor and the complex phases in the evolution of the parent supernova (SN) play an important role in determining the physical, chemical, and morphological properties of the supernova remnant (SNR) [1]. In particular, the remnant may reflect possible asymmetries developed soon after the SN explosion and keep memory of the nature of the stellar progenitor.

2. Aims

This work combines 1D hydrodynamic (HD) models of core-collapse SN explosions with 3D magnetohydrodynamic (MHD) models describing the subsequent evolution of the blast wave expanding through the circumstellar medium (CSM). The aim of this work is to bridge the gap between SNe and their remnants by investigating how post-explosion anisotropies of ejecta may influence the structure and chemical properties of the remnant at later times.

3. Methods



Left panel: Density (left-hand boxes) and temperature (right-hand boxes) distributions in the [x, z] plane showing an example of initial conditions about 20 hours after the SN event. The figure shows the case of a spherically symmetric explosion (upper boxes), and a case including a dense, isobaric spherical clump of ejecta (lower boxes). Right panel: Mass fraction of elements as a function of radial distance for spherically symmetric explosion at the initial conditions.

We describe the evolution of a core-collapse SN by considering a ~ 20 $M_{\odot}$ red-supergiant (RSG) progenitor [2] and using a 1D HD model [3]. The latter provides the initial conditions for SNR calculations about 20 hours after the SN event. We map the 1D profile of ejecta in 3D and start simulations describing the transition from the SN to the SNR using the 3D MHD Eulerian numerical code PLUTO [4]. We follow the evolution for 5000 years and investigate how a post-explosion large-scale anisotropy in the SN affects the ejecta distribution and the matter mixing of heavy elements in the remnant. The simulations span a large range of distances, from ≈ 20 A.U. (at the beginning of the simulations) up to ≈ 15 pc (at the end). The initial anisotropy (the clump) is parametrized by its distance from the center of the explosion, its radius (R), its density (D), and its velocity (V). Initially the clump is located either at the interface between the ^{56}Ni and ^{28}Si layers or within the ^{56}Ni layer. We explore clump densities ranging between 500 and 750 times larger than that of the surrounding ejecta, and clump velocities ranging between 3 and 7 times larger than that of the surrounding ejecta.

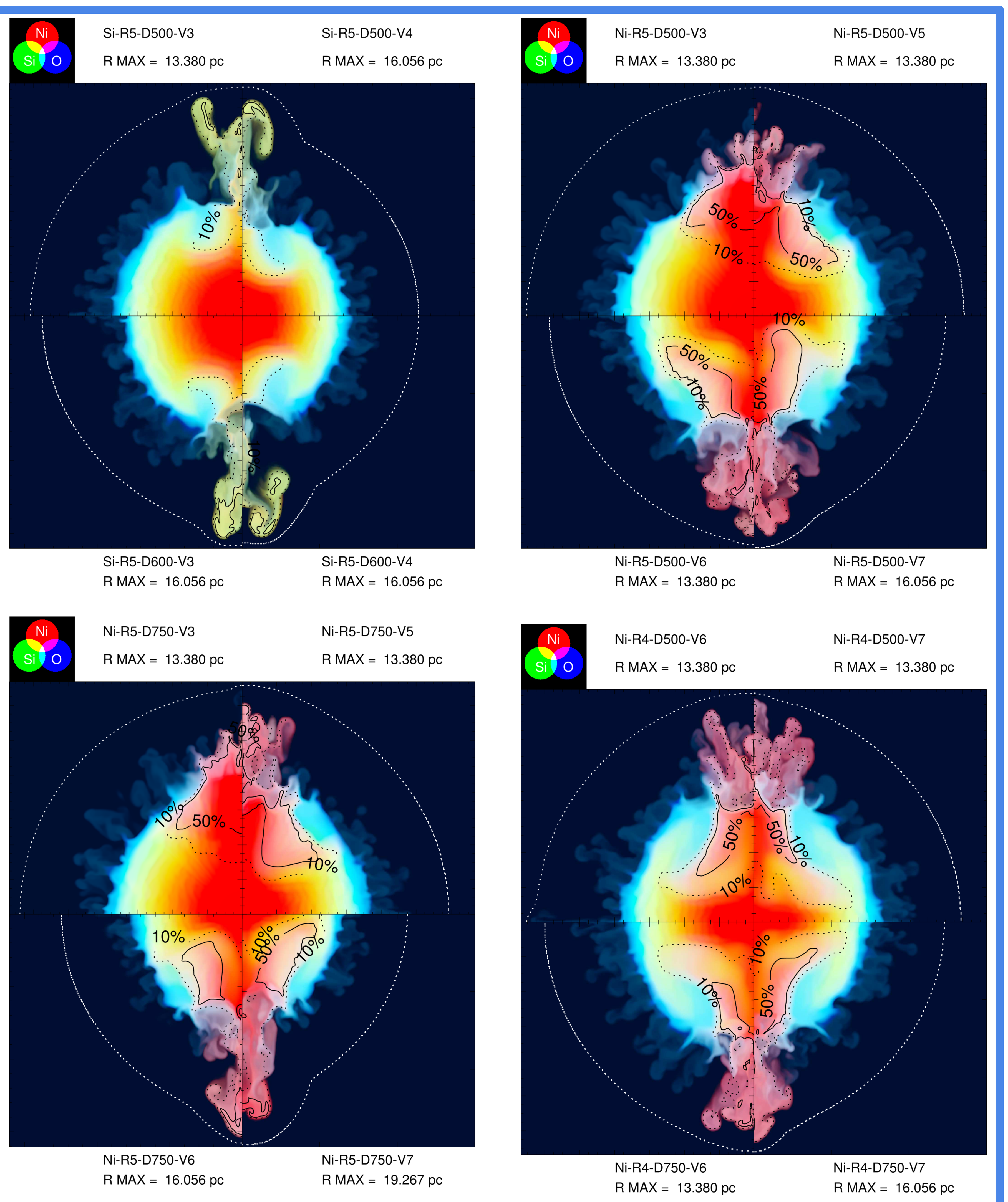
4. Results

The chemical stratification in the ejecta is strongly affected by the clump's passage.

- For an initial clump located in the Si(Ni) layer the initial classical onion-like structure is not preserved, as the clump, propagating through the remnant, forms a stream of Si(Ni)-rich ejecta, from the inner regions up to the intershock region.
- The clump makes its way out to the external layers of the remnant by piercing the chemical shells and pushing the layers on the side of the stream. These streams cause a spatial inversion of the chemical layers, bringing the Si/Ni externally to the O shell.
- For an initial clump located in the Si(Ni) layer, we found that the stream is able to protrude the forward shock if the clump has at least an initial energy of 3%(8%) of ejecta.

The parameters that describe the clump influence the amount of total shocked material.

- We found that the clump after 5000 years increases the amount of shocked Ni by at least ten times, whereas it do not increase the final amount of shocked Si, due to the Si-shell's interaction with the reverse shock that mitigates the contribution of the clump.
- The velocity contrast has an important role in determining the shocking time of the elements: a higher contrast anticipates it.



Color coded images of the logarithm of the mass fraction (> 10^{-4}) distributions of ^{56}Ni (red),^{28}Si (green) and ^{16}O (blue) in the [x,z] plane for different models at the age of 5000 years. Black contours in the remnant interior enclose the computational cells consisting of the original clump material by more than 50% (solid lines) and 10% (dotted lines). The white dotted lines represent the approximate position of the forward shock. The initial parameters of the clumps are summarized near every boxes: first two letters indicate the location, the dimension (% of the forward shock), density and velocity contrast.

5. References

[1] Lopez, L. A., et al. 2011, ApJ, 732, 114
[2] Sukhbold, T., et al. 2016, ApJ, 821, 38
[3] Ono et al. (2019, in preparation).
[4] Mignone, A., et al. 2007, ApJ, 170, 228

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