Cloud Formation by Supernova Implosion

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The deposition of energy and momentum by supernova explosions has been subject to numerous studies in the past few decades. However, while there has been some work that focused on the transition from the adiabatic to the radiative stage of a supernova remnant (SNR), the late radiative stage and merging with the interstellar medium (ISM) have received little attention. Here, I present three-dimensional, hydrodynamic simulations, focusing on the evolution of SNRs during the radiative phase, considering a wide range of physical explosion parameters. I find that the radiative phase can be subdivided in four stages: 1) A pressure driven snowplow phase during which the hot overpressurized bubble gas is evacuated and pushed into the cold shell, 2) a momentum conserving snowplow phase which is accompanied by a broadening of the shell, 3) an implosion phase where cold material from the back of the shell is flooding the central vacuum and 4) a final cloud phase, during which the imploding gas is settling as a central, compact overdensity. The launching timescale for the implosion ranges from a few 100 kyr to a few Myr, while the cloud formation timescale ranges from a few to about 10 Myr. The highly chemically enriched clouds can become massive and self-gravitating within a few Myr after their formation, providing an attractive, novel pathway for supernova induced star and planet formation in the ISM.

EARLY STAGES OF SNR EVOLUTION

- Ejecta-dominated / Free-expansion phase [1]
  - Constant expansion speed
  - Lasts few hundred years
- Adiabatic / Sedov-Taylor phase [2]
  - Energy conserved / cooling negligible
  - Ends by shell formation, after [3] $t_{sf} = 4.4 \times 10^4 \text{ yr } E_{51}^{0.22} n_0^{-0.55}$

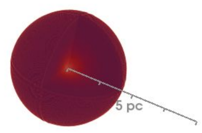
SIMULATION SUITE

Ideal hydrodynamics solved using AMR code **RAMSES** [4]

- Effective resolution $\Delta x_{eff} \lesssim 0.5$ pc
- Wide range of explosion energies $E_{51} \in \{1, 5, 14\}$
- And ambient densities $\log n_0 \in \{-1, 0, 1, 2\}$
- Ejecta traced using passive scalar Z_{ej}
- All simulations are run for 14 Myr

SNR EVOLUTION BEYOND SHELL FORMATION: AN OVERVIEW

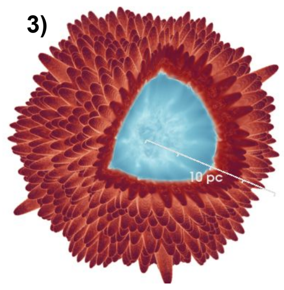
1)



1) Pressure-Driven Snowplow (PDS)

- Immediately following shell-formation
- Bubble pressure ≫ shell pressure
- Bubble loses mass to shell
- Shell momentum increases

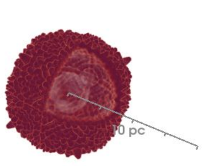
3)



3) Implosion

- Launching requires:
  - Shell pressure ≫ Bubble pressure
  - Shell pressure ≈ ISM pressure
- Inflowing mass grows
- Shell momentum decreases

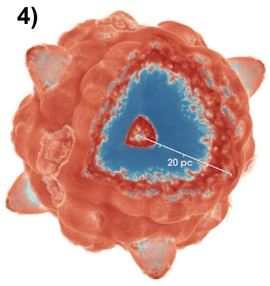
2)



2) Momentum-Conserving Snowplow (MCS)

- Follows PDS once shell is evacuated
- Shell pressure ≫ Bubble pressure
- Shell momentum conserved

4)



4) Cloud Formation

- Pile-up of mass in bubble center
- Efficient dissipation of energy
- Central cloud grows
  - 10^3 - 10^4 $M_\odot$ reached within 10 Myr

Fig. 1 Four stages in the radiative phase of SNR evolution. Red (blue) coloring indicates outward (inward) radial mass flux. Opacity is scaled with the logarithm of the density.

DETAILED TIME EVOLUTION

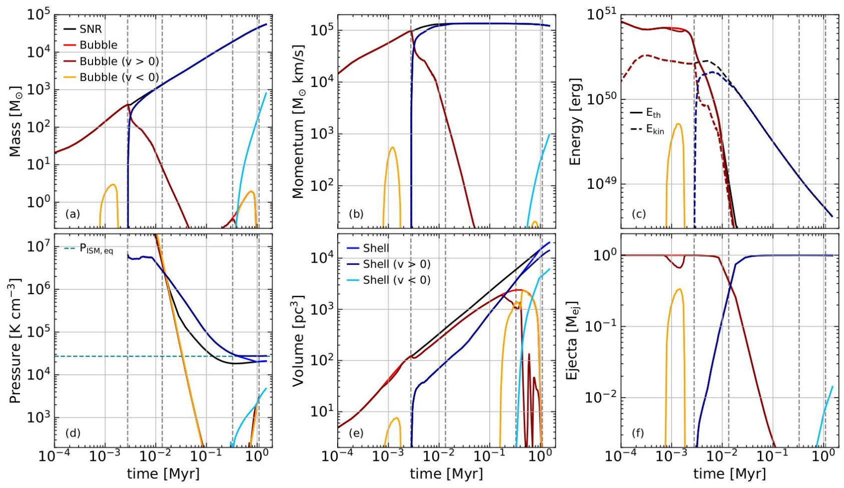


Fig. 3 Time evolution of various quantities for a SNR in medium with n_0 = 100: (a) mass, (b) momentum, (c) energy, (d) pressure, (e) volume, (f) ejecta. Differently colored lines correspond to different gas components as described in the legend. The vertical dashed lines mark the onset of the different stages of SNR evolution described in Figure 2. In panel (c) the thermal (solid) and kinetic (dashed) energy is shown. The horizontal green dashed line in panel (d) marks the equilibrium pressure of the ISM. The bubble pressure is initially very high (≳ 10^9 K cm−3) and thus outside of the axis limits.

CLOUD PROPERTIES

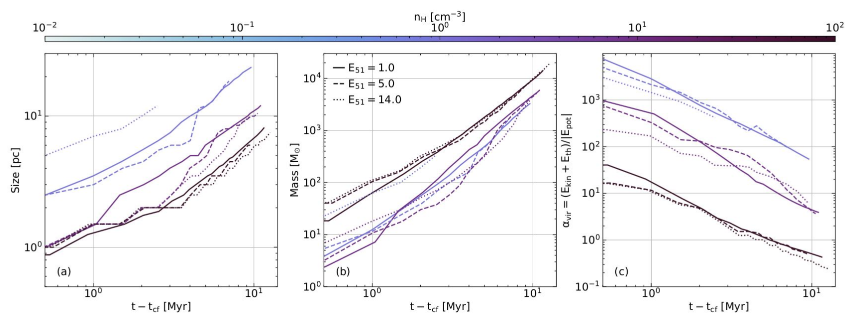


Fig. 4 Time evolution of a) size, b) mass and c) virial parameter of the central cloud after its formation. Darker lines correspond to higher ambient densities. Solid, dashed and dotted lines correspond to an explosion energy of E_{51} = 1.0, 5.0 and 14.0, respectively.

SUMMARY & OUTLOOK

- SNRs Implode once the shock becomes sufficiently weak, leading to the formation of a massive central cloud
- Clouds formed by SN Implosion are highly enriched with SN ejecta, providing attractive initial conditions for star- and planet formation
- Simulations to explore the importance of SN Implosion in a more realistic environment are underway (Romano et al, in prep.)

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REFERENCES

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