Non-equilibrium ionization in mixed-morphology SNRs

What causes the recombining/overionization?

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Abstract

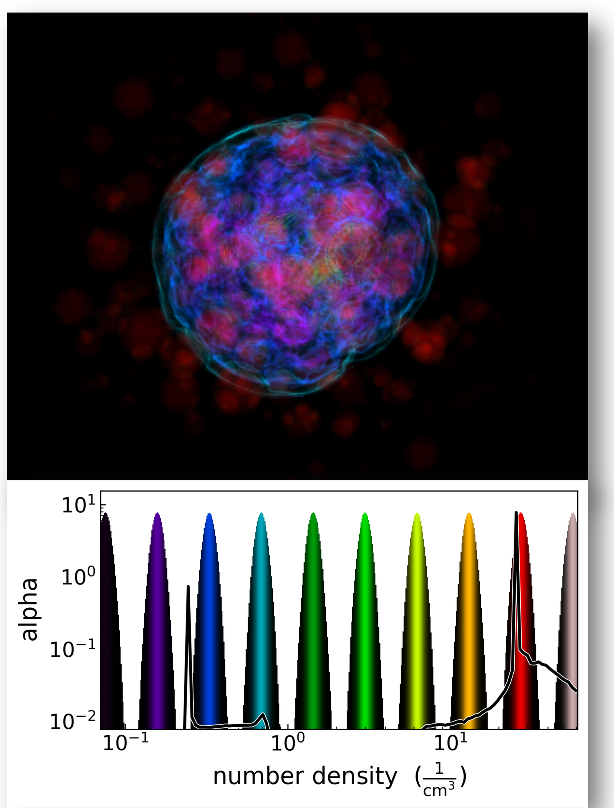
The mixed-morphology class of supernova remnants (MMSNRs) has many puzzles. A clue to their nature is the presence of regions that show X-ray evidence of recombining plasmas. We present numerical hydrodynamic models of MMSNRs in 2D and 3D, including explicit calculation of NEI effects. Both the spatial ionization distribution and temperature–density diagrams show that recombination occurs inside the simulated MMSNR.

- Both adiabatic expansion and thermal conduction can cause recombination, albeit in different regions.
- Thermal conduction and adiabatic expansion both contribute significantly to the cooling of high-temperature gas.
- Realistic observational data are simulated with both spatial and spectral input.
- We also discuss the possibility of analyzing the sources of recombination and dominant hydrodynamic processes in observations using temperature–density diagrams.

Methods

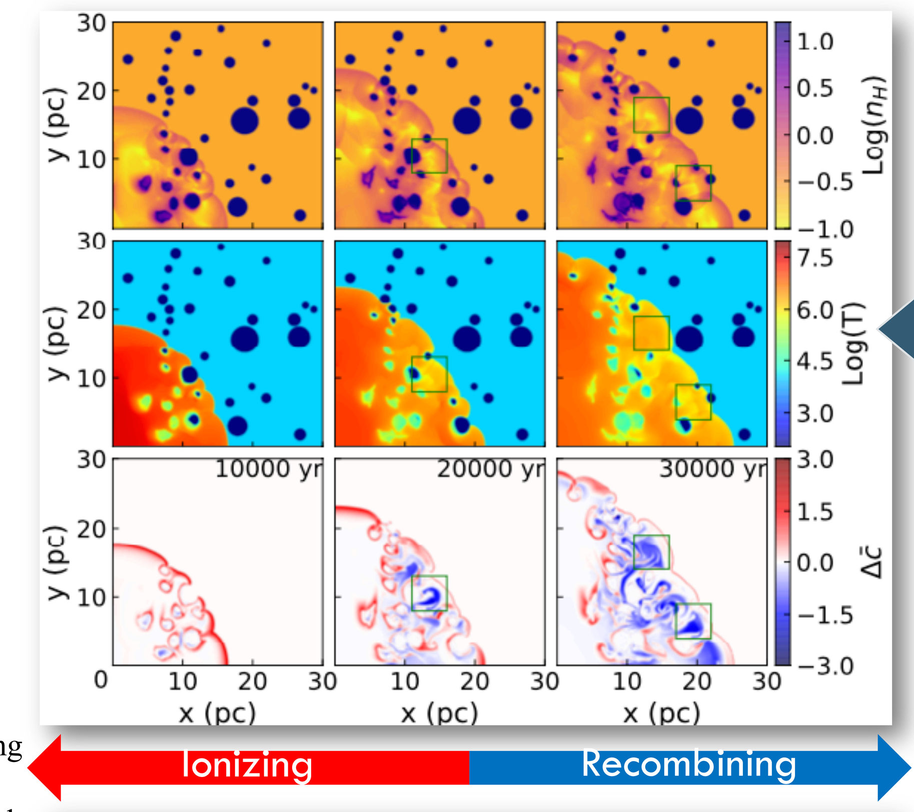
- We have performed some hydrodynamical simulations with the nonequilibrium ionization (NEI) calculation that we have developed for FLASH code (Zhang et al. 2018).
- SN exploding from the center in a cloudy environment.
- The clouds are randomly distributes.
- We have simulated a quadrant in 2D cylindrical symmetric system
- Also a full-volume 3D asymmetric system.
- Thermal conduction is enabled.
- But currently we did not include the magnetic field, cosmic rays, metal rich ejecta, or radiative cooling in hot gas.

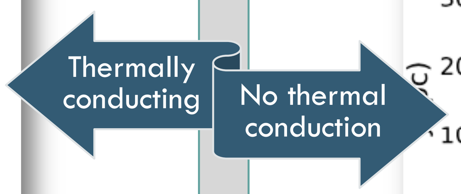
In this figure, a volume rendering image of the density in a simulation (3D) is shown in the top panel. The bottom panel shows transfer function. The black curve is the density histogram. With a high density peak, the red is the dense clouds surrounding (and inside) the SNR. With a shocked density peak, cyan (and blue) shows the shocking front (and shocked ISM).

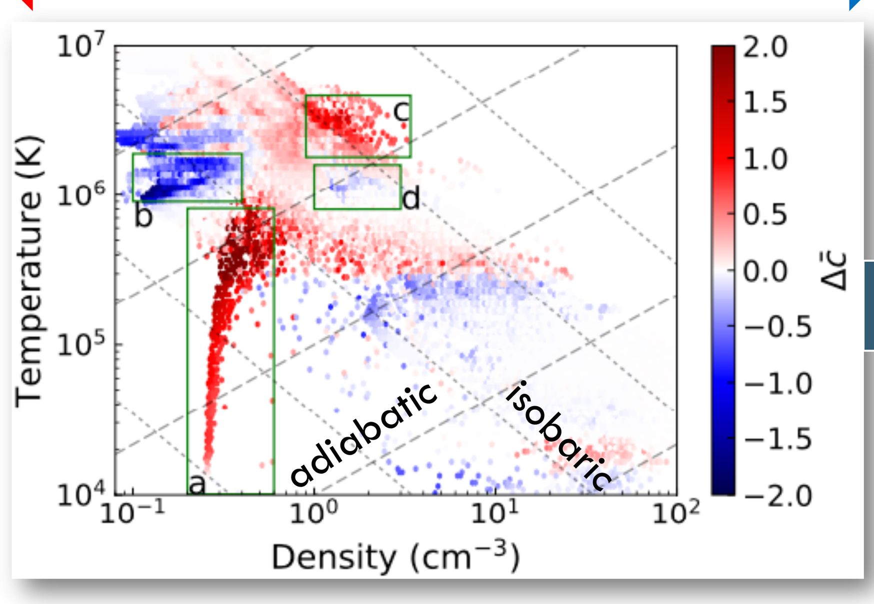


Results

- The clouds are evaporating into the hot gas.
- The hot gas density radial distribution profile is center-filled that could generate a MMSNR.
- The shock front is always ionizing.
- But you will find the recombining mushroom features behind shock (expansion).

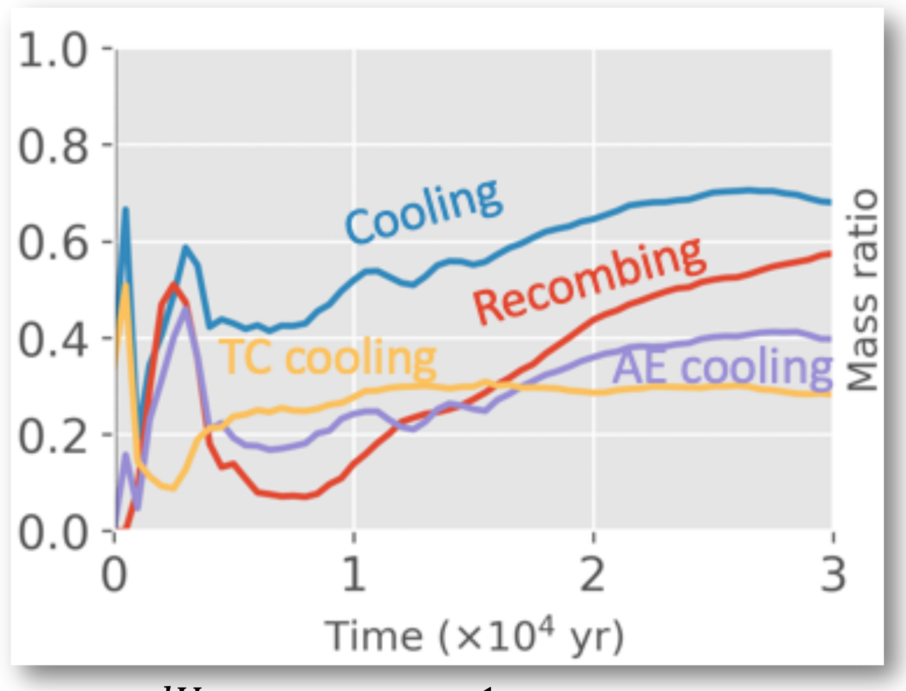






- Temperature-density phase diagram of the simulation shows the hydrodynamics.
  - Different evolution path means different hydrodynamics.
  - (b) region is roughly along an adiabatic line.
  - (c&d) regions seems roughly along isobaric.

- How much TC vs AE contribute to cooling?
  - We used mass ratio of different component:

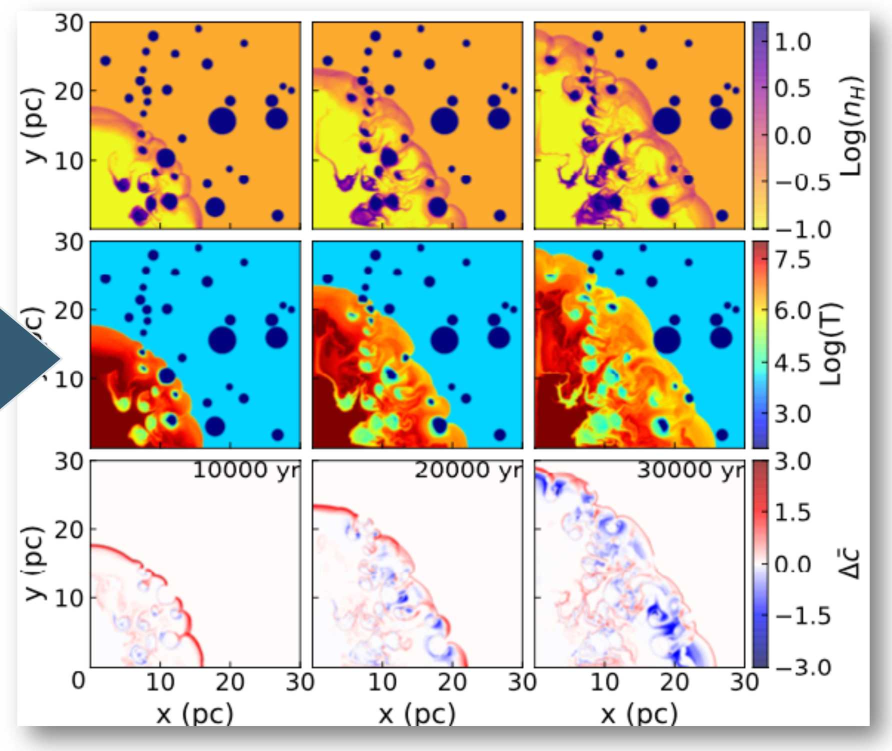


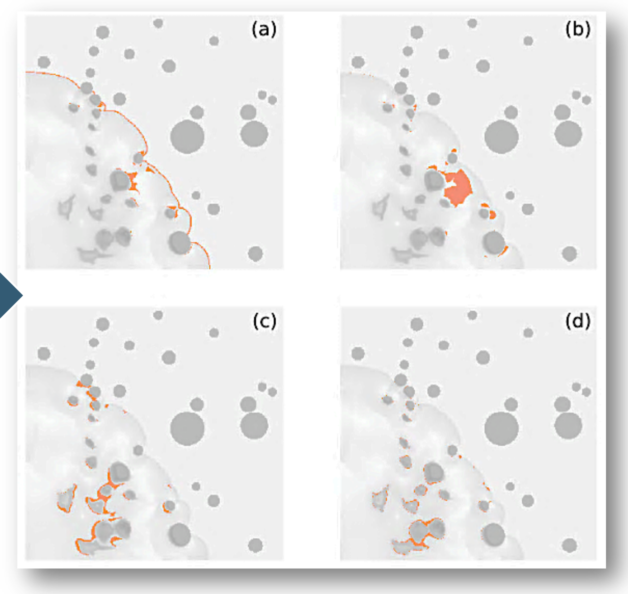
$$\frac{dU}{dt} = \underbrace{-c^2\nabla\cdot\vec{v}}_{\text{AE}} + \underbrace{\frac{1}{\rho}\nabla\cdot(\kappa\nabla T)}_{\text{TC}}$$

- It is mass ratio to the hot gas.
- AE dominated cooling is comparable to TC dominated cooling.
- Recombining comes up as the time goes.

Discussion

- The thermal conduction (TC) plays a role.
  - When thermal conduction is turned off, the density distribution is shell-like (no MM).
  - Recombination is less significant.
- The magnetic field could depress the thermal conduction, but not by a large factor.



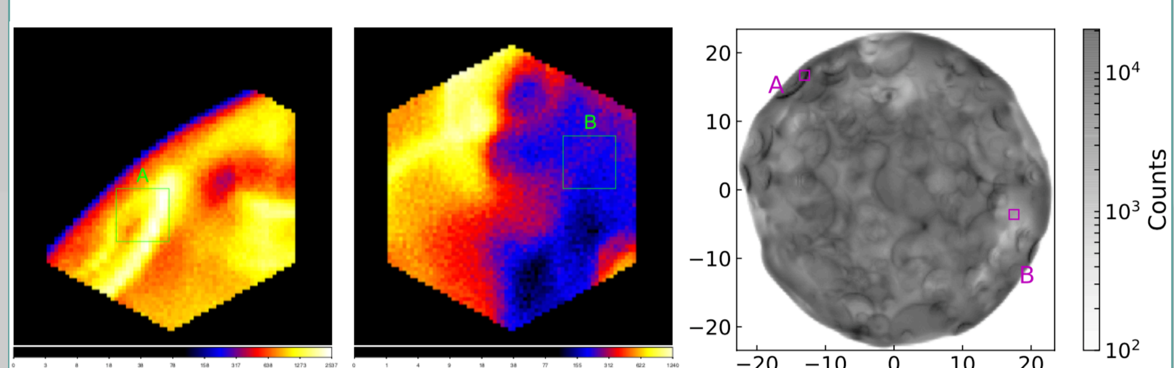


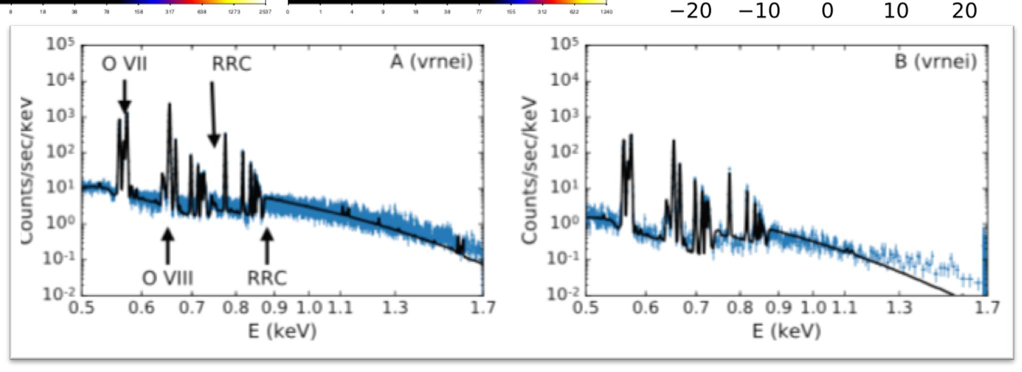
(a) Ionizing shock.

(b) Adiabatic Expansion (AE)

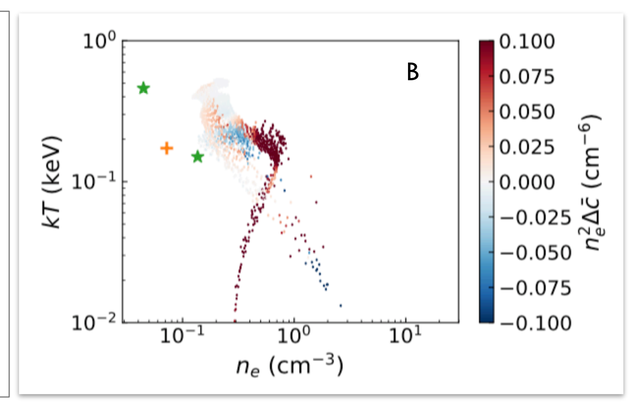
(c,d) thermal Conduction (TC)

- The phase diagram of other variables (e.g. $\nabla T, \nabla p, \nabla\cdot\mathbf{v}, \nabla\times\mathbf{v}$) can confirm the AE or TC for various regions.
- Simulated observations with ATHENA, XRISM, or Lynx from simulation results.
- ATHENA as an example (below).
- The top right panel shows the thermal X-ray emission map (consistent with a MMSNR).





- The spectra are extracted with all the information along LOS can also be extracted.
- Comparison between the simulation and simulated observations.



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