Supernova Remnants II: An Odyssey in Space after Stellar death
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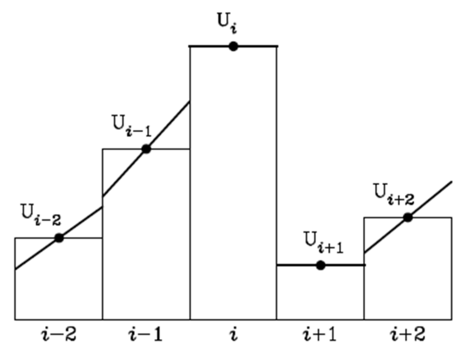
Hydrodynamical simulations of supernova remnant in fractal interstellar medium: morphology of the shock-wave

PETAR KOSTIĆ pkostic@aob.rs
BRANISLAV VUKOTIĆ bvukotic@aob.rs
Astronomical Observatory, Volgina 7, P.O.Box 74 11060 Belgrade, Serbia

Summary
We present a 3D hydrodynamical simulation of supernova remnants in adiabatic phase, based on the MUSCL-Hancock finite volume scheme. The remnants are evolved in uniform as well as in fractally structured interstellar medium. The fractal medium is modelled as fractally distributed ensemble of clumps of matter. The morphological features of calculated synchrotron radiation from the shock-wave region resemble the *X*-ray synchrotron emission readily observed in well studied supernova remnants. This implies that these remnants are likely to evolve in a similar non-uniform environment, although their spherical appearance might suggest that they are evolving in a highly uniform medium.

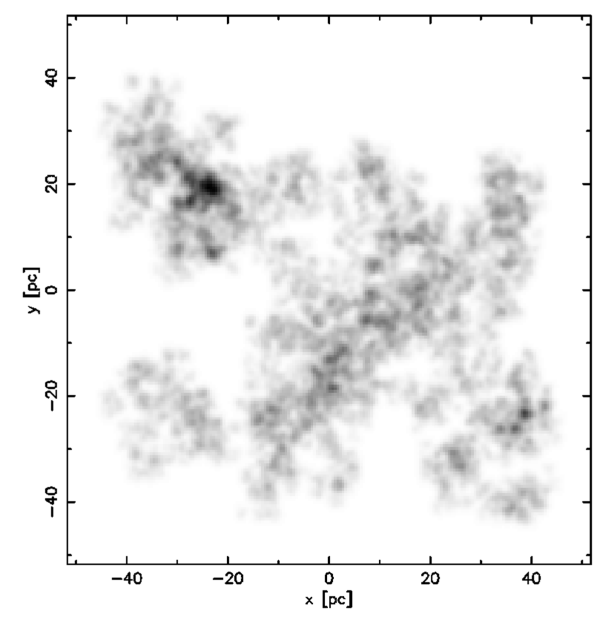
MUSCL-Hahncock method (see Toro, 2009)
- Data reconstruction.
- Evolution.
- Riemann problem.



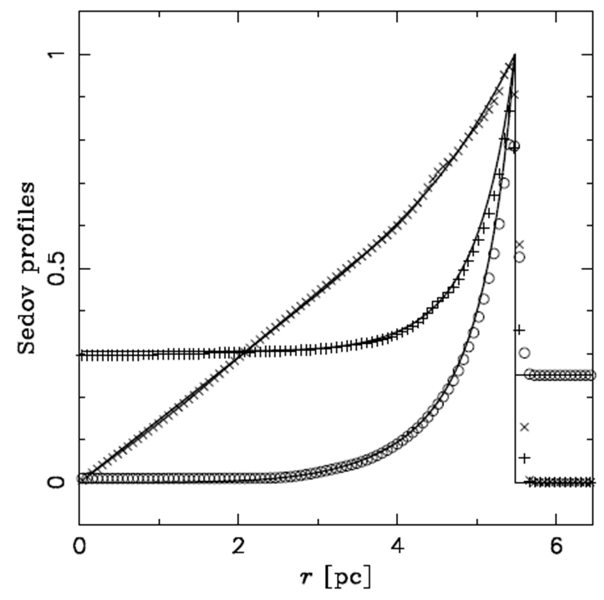
Solution update:

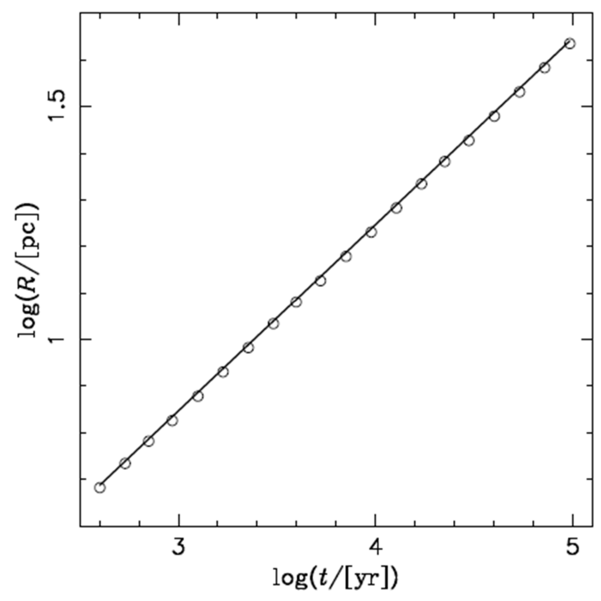
$$\mathbf{U}_i^{n+1} = \mathbf{U}_i^n + \frac{\Delta t}{\Delta x}[\mathbf{F}_{i-\frac{1}{2}} - \mathbf{F}_{i+\frac{1}{2}}]$$

Model of molecular cloud
- **Fractal structure**
  Inhomogeneus medium that is independent of the length scale. We adopt the model of such medium which is based on the work of Elmegreen (1997).
- **Clump profile**
  For this clump density distribution which will produce the cloud-like structure, we adopted two variants, **Gaussian** and **Lorentzian** distribution, based on appearance in literature.



Initialization of supernova remnant
- The initial state of the remnant is set by inputting analitical **Sedov profiles** for density, velocity and pressure into the grid. (left figure)
- The time evolution of SNR radius in simulation, compared to the Sedov law of expansion, is showed in the right figure.





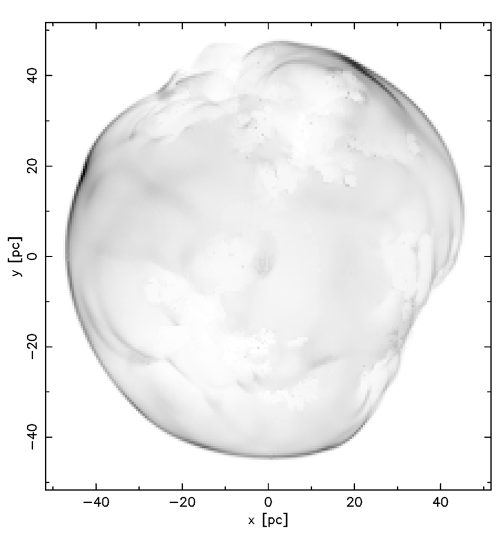
We calculated synchrotron radiation at the shock using the Bell's approach (Bell, 1978) in order to produce the images of SNR for this radiation. Bell's formula for radio synchrotron emissivity of a shocked gas:

$$\epsilon(\nu) = 2.94 \times 10^{-34}(1.435 \times 10^5)^{0.75-\alpha}\, \xi(2\alpha+1)\left(\frac{\phi_e}{10^{-3}}\right)\left(\frac{n}{\mathrm{cm}^{-3}}\right)\left(\frac{\psi_e}{4}\right)^{2\alpha}\left(\frac{\alpha}{0.75}\right)$$

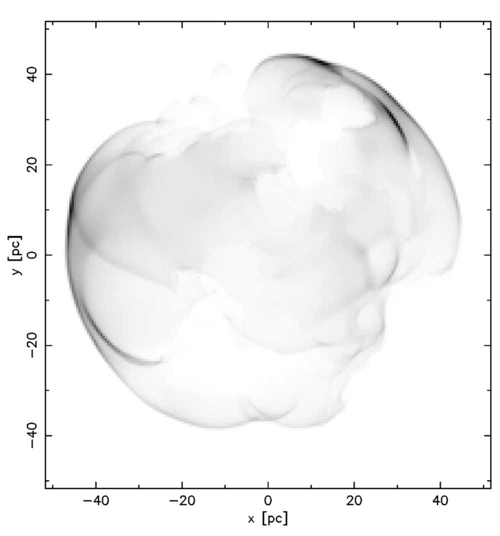
$$\times\left(\frac{v_s}{10^4\,\mathrm{km/s}}\right)^{4\alpha}\left(\frac{B}{10^{-4}\,\mathrm{G}}\right)^{\alpha+1}\left[1+\left(\frac{\psi_e}{4}\right)^{-1}\left(\frac{v_s}{7000\,\mathrm{km/s}}\right)^{-2}\right]^{\alpha}\left(\frac{\nu}{\mathrm{GHz}}\right)^{-\alpha}\ \mathrm{W\,Hz^{-1}\,m^{-3}}$$

As can be seen from obtained images, the arc and filamentary structures, knots and cavities resemble the ones from observed SNRs like Cygnus Loop in X-ray (fig. on the right).

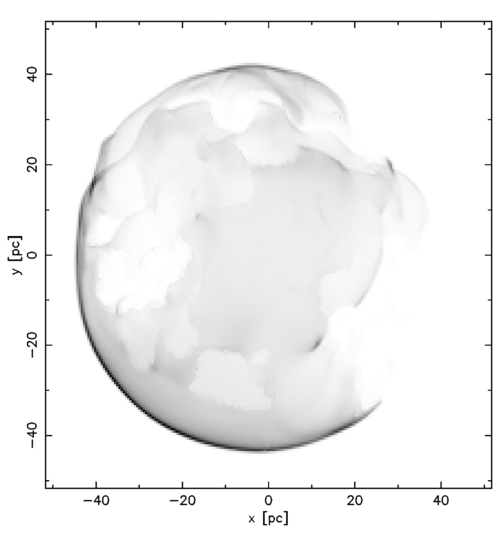
Gaussian clump

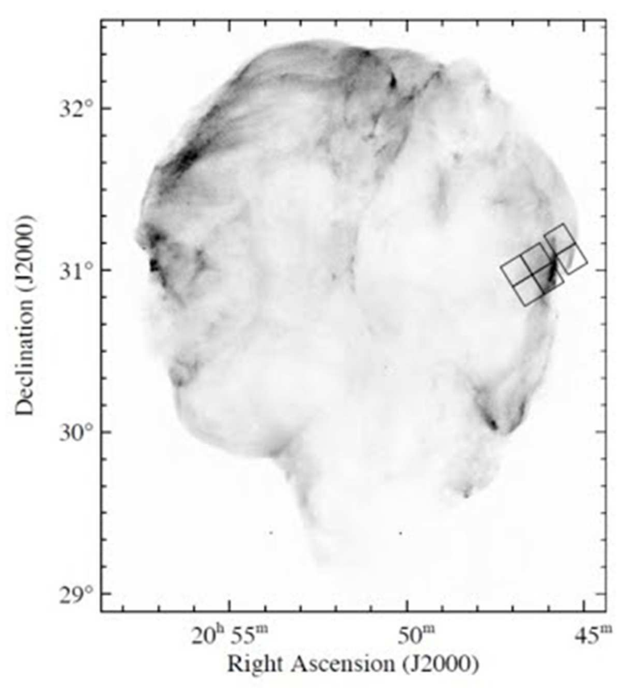


Lorentzian clump

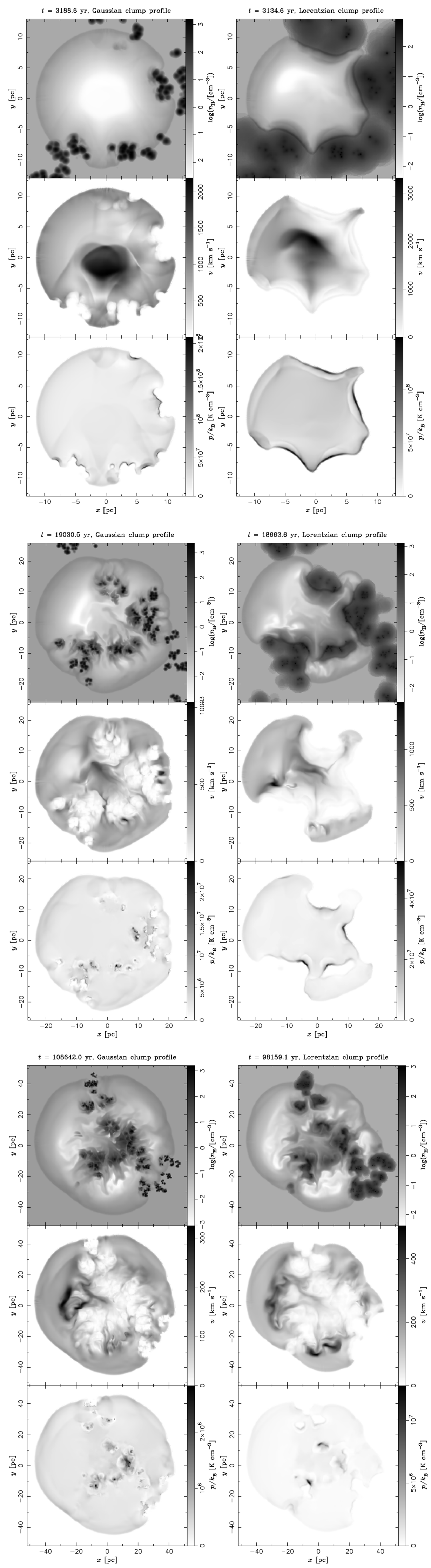


Another example





ROSAT HRI mosaic of the Cygnus Loop (Fig. 1 in Levenson et al, 2002)



Density, velocity and pressure fields for Gaussian (left) and Lorentzian (right) clump profile. The grayscale palette shows range of values between minimum and maximum cell value throughout the slice. The time *t* above the images is the simulation time from the beginning of SNR expansion.

Literature
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Elmegreen, B. G.: 1997, Intercloud Structure in a Turbulent Fractal Interstellar Medium, *Astrophys. J.*, 477, 196.
Bell, A. R.: 1978, The acceleration of cosmic rays in shock fronts. II, *Mon. Not. R. Astron. Soc.*, 182, 443-455
Levenson, N. A., Graham, James R., Walters, Julie L.: 2002, Shell Shock and Cloud Shock: Results from Spatially Resolved X-Ray Spectroscopy with Chandra in the Cygnus Loop, *Astrophys. J.*, 576, 2, 798-805

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