Radio predictions of core-collapse supernovae

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Abstract

We present a theoretical prediction of radio supernovae (RSNe) emission in preparation for the upcoming next generation facilities e.g., MeerKAT and SKA, which due to their ultra-sensitivity and high spatial resolution will further probe the remnants of these transient events. Using the cutting edge massively parrallel, multi-method, multi-physics magnetohydrodynamics and gravity code `GIZMO`, we simulate the interaction of the supernova blastwave with the circumstellar medium and examine the behaviour of the hydrodynamic characteristics in the interaction region. We employ various geometrical configurations and initial densities of the circumstellar medium in our simulation. We discuss the existing efforts and approach to investigate the source of variability from a handful of well studied bright RSNe. With the advent of SKA's capabilities, this work will open up a systematic study of a larger population of RSNe.

Introduction

Our understanding of the radio properties of core-collapse supernovae (CCSNe), which is related to the pre-supernovae circumstellar structure of these violent events remain poorly understood and difficult to probe observationally. Current radio interferometers are scheduled primarily around targeted observations (see, Fig. 1 below by the Very Large Array telescope in New Mexico). In light of future radio interferometers, which include the Square Kilometer Array (SKA), and its precursor prototype array MeerKAT, planned for the "Great Survey" era, these telescopes will operate primarily as wide-field survey instruments. MeerKAT and SKA will be far better suited to focus on key science projects such as all classes of transient and time-variable radio sources, including RSNe.

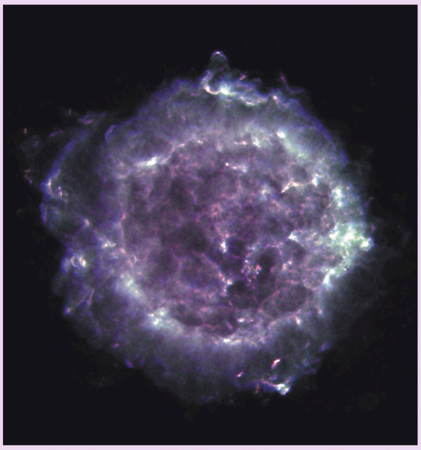

Figure 1: Radio image of Cassiopeia A showing evidence of synchrotron emission. The material that was ejected from the supernova explosion can be seen in this image as bright filaments. Photo credit: https://public.nrao.edu/gallery/cassiopeia-a/

Radio properties of SNe

RSNe emission can be understood in terms of interaction between the blastwave and the circumstellar medium (see Fig. 2). The common characteristics that need to be incorporated in a radio supernova (RSN) model are:

- Non-thermal synchrotron emission with high brightness temperature
- A decrease in absorption with time, resulting in a smooth (see, e.g., Fig. 3), rapid turn-on first at shorter wavelengths and later at longer wavelengths
- A power-law decline of the flux density with time at each wavelength.
- Asymptotic approach of the spectral index to the optically thin, non-thermal constant value

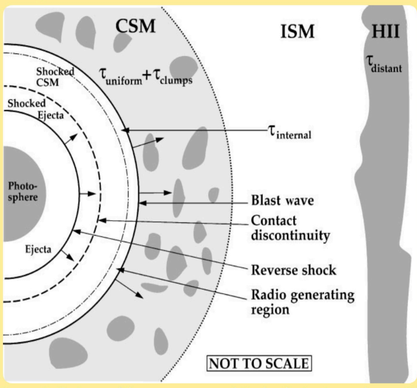

Figure 2: Cartoon of the supernova and its shock structure, along with the stellar wind established circumstellar medium (CSM), the interstellar medium (ISM), and more distant ionized hydrogen (H II) absorbing gas. The radio emission is thought to arise near the blastwave front. Credit: Weiler et al, 2002

CCSNe radio lightcurves

From the radio light curves (see, e.g., Fig. 3) it is possible to classify the properties of supernovae and to develop and test models for the radio emission which match the light curves. This results in estimates of:

- Density and structure of the circumstellar material around supernovae
- The density evolution of the presupernova stellar wind
- Insight into the last stages of stellar evolution before the explosion

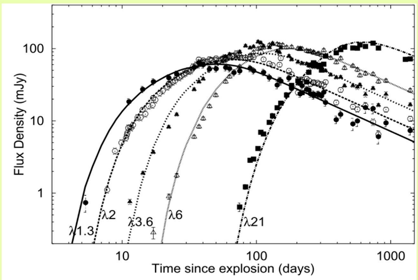

Figure 3: Radio light curves of SN 1993J showing competing effects of a rapid turn-on and slower turn-off of the radio emission at any single frequency. Credit: figure taken from Figure 2 of Weiler et al. (2004)

Some radio light curves have bizzare variability (see, Fig. 4) compared to the relatively smooth light curve in Fig. 3.

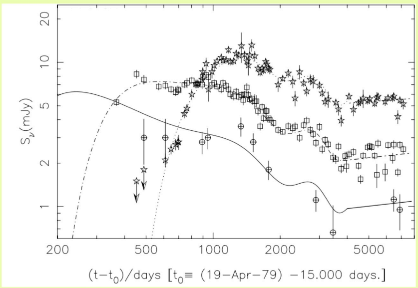

Figure 4: Radio light curves of SN 1979C at 2 cm (14.9 GHz; crossed circles, solid line), 6 cm (4.9 GHz; open squares, dash-dot line), and 20 cm (1.5 GHz; open stars, dotted line). Credit: figure and caption taken from Figure 2 of Weiler et al. (2004)

MeerKAT Radio telescope

MeerKAT consists of 64 antennas, of 13.5 meters in diameter each, located on baselines of up to 8 km (see Fig. 5 below).

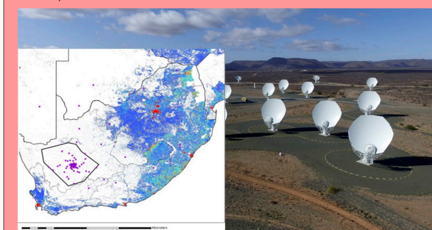

Figure 5: MeerKAT radio telescope with its location in the Southern Africa. photo credit: https://www.ska.ac.za/gallery/

- With its unprecedented sensitivity, MeerKAT will be capable of synoptic search for core-collapse RSNe.

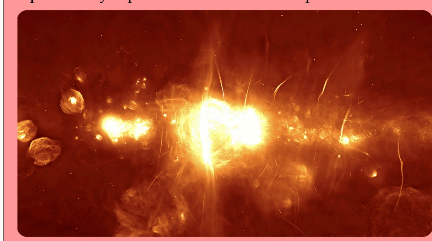

Figure 6: Radio image showing the central region of our Milky Way galaxy. photo credit:https://www.ska.ac.za/media-releases

Numerical methods

GIZMO can be run as a Lagrangian mesh-free finite-volume code (where the mesh moves with the fluid) and can as an SPH code (using state-of-the-art SPH methods). The code uses a hybrid MPI+OpenMP parallelization strategy with a flexible domain decomposition and hierarchical adaptive timesteps, which enable it to scale efficiently on massively-parallel systems with problem sizes up to and beyond many billions of resolution elements.

Smoothed particle hydrodynamics

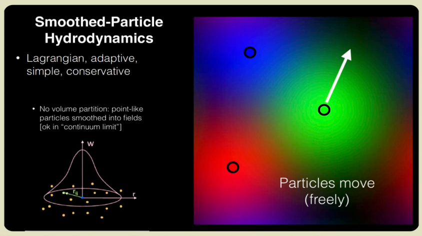

Figure 7: photo credit:editor http://www.tapir.caltech.edu/ phopkins/public/

Cutting-edge Mesh-Free hydrodynamics

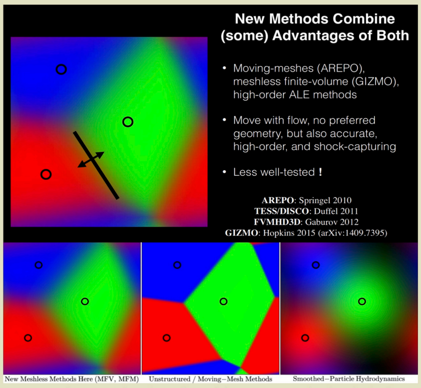

Figure 8: photo credit:editor http://www.tapir.caltech.edu/ phopkins/public/

Sedov-Taylor blastwave test

Fig. 9 below provides a powerful test of the accuracy of code conservation, as well as of how well codes capture shock jumps and preserves symmetry in three dimensions.

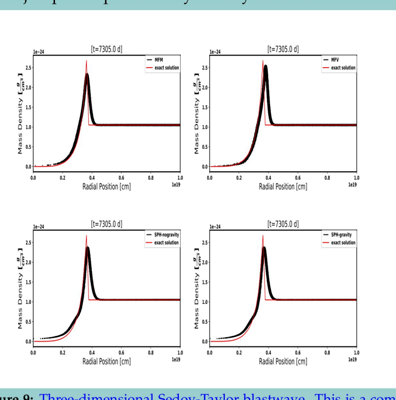

Figure 9: Three-dimensional Sedov-Taylor blastwave. This is a comparison plot of radial density profiles at time t = 7 305d for SPH and the new class of meshfree methods.

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