Modelling and simulations of supernova remnants

Gilles Ferrand
Research Scientist
Astrophysical Big Bang Laboratory (ABBL) and Interdisciplinary Theoretical and Mathematical Sciences Program (iTHEMS)

+ A. Decourchelle, S. Safi-Harb
+ S. Nagataki, D. Warren, M. Ono, F. Röpke, I. Seitenzhal
Modelling and simulations of supernova remnants with a focus on morphological studies

**Introduction to SNRs**

Structure and evolution of a remnant
Multi-wavelength emission

**1. SNRs as particle accelerators**

Hydro-kinetic coupling for diffusive shock acceleration (DSA)
Non-equilibrium ionization and thermal emission from the plasma
Magnetic field amplification and non-thermal emission from the particles

**2. SNRs as probes of the explosion**

From the supernova to the remnant: Cas A, Tycho
Example: the N100 supernova model
X-ray image analysis
Supernova remnants
SNRs as a key link between stars and the ISM

**Tycho’s SNR**
- **age:** ~440 yr
- **distance:** 1.5–5 kpc
- **size:** 8’ ~3–12 pc

**enrichment in heavy elements**
- average stars: up to C-O
- massive stars: up to Fe
- supernovae: above Fe

**injection of energy**
- heating of the gas
- hydrodynamic turbulence
- magnetic field amplification

**acceleration of particles**
- most favoured Galactic sources
- up to the knee (< $10^{15}$ eV)

**hot, turbulent metal-rich plasma**

**large, powerful shock wave**

multi-wavelength composite image:
- X-rays (Chandra)
- Optical (Calar Alto)
- infrared (Spitzer)
Classification of SNRs

from radio + X-ray observations

**shell**

“mixed morphology”
= thermal composite: centrally peaked

**composites**

plerionic composite (= non-thermal composite):
PWN inside shell

(can be both)

**filled-centre**

isolated/shell-less pulsar wind nebula
= PWN (= plerion)
or

bow shock nebula
The evolution of a supernova remnant

values given for 1.4 solar masses of ejecta with kinetic energy of $10^{51}$ erg, expanding in a medium of density $0.1 \text{ cm}^{-3}$

radius $R$

G1.9+0.3
140 yr

Tycho
440 yr

RCW 86
2,000–10,000 yr

Simeis 147
∼40,000 yr

Monoceros Loop
∼300,000 yr

non-radiative
radiative
momentum-driven
pressure-driven
Sedov-Taylor
ejecta-dominated

600 yr
30,000 yr

$46 \text{ pc}$
$7 \text{ pc}$
The structure of a young shell SNR

Tycho’s SNR as seen by Chandra at age 433 yr

Warren et al. 2005

Energy bands:
- 0.95 – 1.26 keV
- 1.63 – 2.26 keV
- 4.10 – 6.10 keV
SNR broad-band emission

**SN 1006**

- **radio**: synchrotron in B field
- **optical**: Balmer lines, forbidden lines
- **X**: atomic lines of heavy elements + synchrotron
- **gamma**: Inverse Compton? pion decay?

Energy spectrum:
- cm: GeV e-
- μm: blast wave
- keV: hot ejecta + TeV e-
- TeV: > TeV e-? > TeV p?

**Reviews (high energies perspective)**: Reynolds 2008, Vink 2012
SNRs as particle accelerators
SNRs are widely believed to be the main producers of CRs in the Galaxy

- Available energy budget — but can we reach the knee?
- Known acceleration mechanism — but what spectrum?
- Observed energetic electrons — and protons?

If CRs are efficiently accelerated by the blast wave, it must impact its dynamics
- fluid becomes more compressible
- energy leaks from the system
→ non-linearly coupled system

CRs are a key ingredient of SNRs
Diffusive shock acceleration: the coupled system

conservation laws

$$\frac{\partial X}{\partial t} + \text{div}(F(X)) = 0$$

$$X = \begin{pmatrix} \rho \\ \rho u \\ P \end{pmatrix}, \quad F(X) = \begin{pmatrix} \rho u \\ \rho u \otimes u + pI \\ (e + P)u \end{pmatrix}$$

hydrodynamic treatment

magnetic waves (collective movements of charges)

shock wave (thermal magnetized plasma)

injection, acceleration, shock modification

cosmic-rays (non-thermal population)

particle distribution:

$$n(x,t) = \int_p f(x,p,t) \ 4\pi p^2 \ dp$$

transport equation:

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial x} (uf) = \frac{\partial}{\partial x} \left( D \frac{\partial f}{\partial x} \right) + \frac{1}{3p^2} \frac{\partial^3 f}{\partial p \partial x}$$

reviews on DSA: Drury 1983, Jones and Ellison 1991, Malkov and Drury 2001

on numerical techniques for DSA: Marcowith et al (in prep)
**SNR initialization:**

Self-similar profiles from **Chevalier**

**SNR evolution:**

3D hydro code **ramses**

**Back-reaction:**

Varying gamma

**SNR initialization:**

Self-similar profiles from **Chevalier**

**SNR evolution:**

3D hydro code **ramses**

**Back-reaction:**

Varying gamma

**parameters: Tycho (SN Ia)**

\[
\begin{align*}
t_{SN} &= 440 \text{ years} \\
E_{SN} &= 10^{51} \text{ erg} \\
n &= 7 , M_{ej} = 1.4 M_{\odot} \\
s &= 0 , n_{H,\text{ISM}} = 0.1 \text{ cm}^{-3}
\end{align*}
\]

**Teyssier 2002, Fraschetti et al 2010**

**Ellison et al 2007**


**Anne Decourchelle**

Head of Astrophysics Dpt. at CEA Saclay / Irfu

Using a comoving grid to factor out the expansion
Computing the emission from the SNR

Thermal emission from the shocked plasma

Non-thermal emission from the accelerated particles

Samar Safi-Harb
Prof. at the University of Manitoba
Canadian Research Chair
1.5 Hydro- and thermodynamics of the plasma

Thermal emission in each cell depends on:

- **plasma density** $n^2$

- **electron temperature** $T_e$
  progressive equilibration with protons temperature $T_p$ via Coulomb interactions

- **ionization states** $f_i(Z)$
  computation of non-equilibrium ionization
  - solving the coupled time-dependent system of equations
    Patnaude et al 2009, 2010
  - using the exponentiation method in post-processing
    
    $$\tau_I = \int_{t_S}^{t} n(t').dt'$$
    Smith & Hughes 2010

all these parameters depend on the **history** of the material after it was shocked.

Ferrand, Decourchelle, Safi-Harb 2012
Thermal emission

emissivity [erg/s/cm³/eV]

energy [eV]

1024^3 cells

Ferrand, Decourchelle, Safi-Harb 2012

using an emission code adapted from Mewe, with rates from Arnaud

1024^3 cells
t = 500 yr

test particle vs. back-reaction
Magnetic field and radiative losses

Non-thermal emission in each cell depends on:

- pion decay: *plasma density* $n(x, t)$
- synchrotron: *magnetic field* $B(x, t)$ (amplified at the shock, then frozen in the flow)
- Compton: ambient photon fields (CMB)

Note: the acceleration model gives the CR spectra just behind the shock $f_{p}(p, x, t), f_{e}(p, x, t)$ they must be transported to account for losses:

- adiabatic decompression $\alpha = \frac{\rho(x, t)}{\rho(x_S, t_S)}$
- radiative losses $\Theta \propto \int_{t_S}^{t} B^2 \alpha^\frac{1}{3} \, dt$

Ferrand, Decourchelle, Safi-Harb 2014
Non-thermal emission

- Synchrotron (e)
- Inverse Compton (e)
- Pion decay (p)

Using the emission code from P. Edmon

- Efficient MF amplification \(\rightarrow\) high B
- No net MF amplification \(\rightarrow\) low B

1024\(^3\) cells

Ferrand, Decourchelle, Safi-Harb 2014

\(t = 500\) yr
Thermal + non-thermal emission

Energetic protons, accelerated at the shock front, don’t radiate as efficiently as electrons, however:

1/ they impact the dynamics of the shock wave, and therefore the thermal emission from the shell (optical, X-rays)

2/ they impact the evolution of the magnetic field, and therefore the non-thermal emission from the electrons (radio – X-rays – γ-rays)
SNRs as probes of the explosion
2 main types:
Type Ia: thermonuclear explosion of white dwarf
still many competing models
Type II, Ibc: core-collapse of massive star
need to revive the shock: probably neutrinos

Supernova simulations in 3D explode. Sometimes. Successful explosions have a complex structure: does it impact the morphology of the remnant? What can the observed (morphology of the) SNR tell us about the explosion?

It is time to bridge SN studies and SNR studies
Conclusions: the bulk of asymmetries observed are intrinsic to the explosion.
CC SNe: asymmetric explosions

a grid of parametrized core-collapse neutrino-driven explosions from different stellar evolution models from shock revival to shock breakout

Wongwathanarat et al 2015

mass fraction of $^{56}\text{Ni}$, color-coded by velocity
2.4 Cas A from the SN (to the SNR)

The morphology of Cas A SNR happens to mimic showing everything Cas A from the SN (to the SNR) circled the locations of the forward and reverse shocks, respectively. These emitting compact object, respectively; and the outer and inner white dashed the arrow the current location and the direction of motion of the central, X-ray-Chandra.

The geometrical center of the expansion of the explosion; the white cross and the 4

of Wongwathanarat et al.

The explosion
a kick opposite to the direction of the stronger shock the side of the weaker blast wave. Thus, the NS receives and by the gravitational attraction from more inert, typically accrete for a longer period of time before the mass infall is outward more slowly. On this side the nascent NS can therefore are weaker, the shock and the postshock material accelerate included in their nucleosynthesis treatment with a small kick velocity of the NS depends on the stochastic explosion

This means that the NS experiences a recoil acceleration that

spatial distribution of Fe distribution courtesy of U. Hwang; Hwang et al.

for detailed discussions, see Scheck et al.

for nuclear species not

seen by Riethmuller & Hillebrandt 2014, or for nuclear species not

and X-ray-bright Fe

and extended data Figure 1 of Gabler et al 2016

2.4 Ti are considerably more extended than those of

56Ni including volumetric information.

Our model

suggests that a considerable amount of

fraction. These isosurfaces were determined such that they

56Ni, meaning that titanium is clearly more diluted. Moreover,

Si
ejecta, where the explosion asymmetry is most extreme, are not

radionuclei as nucleosynthesis products in the innermost SN since

just expelled in one hemisphere, but some of this material can

or decompose them in the ejecta. Their distributions therefore closely resemble each other, and the two nuclei, overall, trace the 3D distribution of the ejected nickel the same 3D geometry.

The 3D distribution of the ejected nickel

The environmental density

proximity in regions of neutrino-processed and shock-heated in the region of explosive

neutrino-processed and shock-heated in the region of explosive

nucleosynthesis.

neutrino-processed and shock-heated in the region of explosive

nucleosynthesis.

to the outermost tips of the largest

radius, which is in line with the 3D data published recently by

Cas

for the two nuclei


g burden, model W15-2, which we consider in the present paper,

Wongwathanarat et al 2017

Figure 10

44 Ti flows

with acceleration continuing on a low level for an

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with acceleration continuing on a low level for an

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44 Ti
From the 3D thermonuclear SN to the 3D SNR

3D simulations of thermonuclear supernovae

Röpke 2007, Seitenzahl et al 2013

Friedrich (Fritz) Röpke
Prof. at Ruprecht-Karls-Universität Heidelberg,
Head of stellar group at Heidelberg Institute for Theoretical Studies

Ivo Seitenzahl
Research Fellow at School of Science,
University of New South Wales (UNSW), Australia

Shigehiro (Hiro) Nagataki
Chief Scientist, Astrophysical Big Bang Laboratory

Don Warren
Masaomi Ono
Research Scientists


3D simulations of a TN supernova remnant

shocked ejecta at 500 yr
Hydro evolution of the SNR

**slices of log(density)**
from 1 yr to 500 yr
on a 256^3 Cartesian grid
(simulation made in co-expanding grid, box size increases by factor ~150)

see movies in online article

Chevalier
1D initial profile
(power-law)

N100 angle-averaged
effectively 1D initial
profile (~exponential)

N100
full 3D initial profile

what SNR people used to do

what SN people are telling us

Ferrand et al 2019
Morphological signatures of the (thermonuclear) explosion can be seen clearly in the first hundred years, and may still be detected after a few hundred years.
Mapping the wavefronts (RS, CD, FS)

N100 3Di at $t = 500$ yr

maps stored using HEALPix
Spherical harmonics expansion of the wavefronts contact discontinuity (CD) from 1 yr to 500 yr

see movies in online article

Ferrand et al 2019
Rayleigh-Taylor from the SN and SNR phases

contact discontinuity (CD) at 500 yr

Ferrand et al 2019
Interestingly, using a realistic 3D SN model leads to larger scale and more irregular structures, which were not seen in SNR simulations made from (semi-)analytical SN models, and which **better match X-ray observations of Tycho’s SNR.**

projection along l.o.s. of the density squared = proxy for the thermal emission

⇒ next will compute the synthetic thermal (and non-thermal) emission
Perspectives for type Ia SNe

Future simulations will enable us to **make comparisons between different SN explosion models:**

- between different ignition setups for the DDT model, that produce different initial asymmetries and yields
- between different SN explosion models: pure deflagration, pure detonation, other detonations, other channels...

(Role of the companion star?)

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**Figure 5.** Distribution of density, star ID, and mass fractions of chemical elements at $t = 50$ s. Note that, if there is no material, the star IDs “0” are assigned. We change the mushroom-shaped, unburned materials to 100% $^{56}$Ni materials. This is also true for Figures 6–10.

**Figure 6.** Masses of chemical elements in the SN ejecta (red), companion-origin stream (blue), and surviving WD (black) at $t = 50$ s. The SN ejecta includes the companion-origin stream. Materials of the SN ejecta and surviving WD are gravitationally unbound and bound to the surviving WD, respectively.

**Figure 7.** Mass of chemical elements for the original data (black), 16 subgroups of SN ejecta (red) from the fiducial mass resolution simulation, and data from the higher mass resolution simulation (blue). The black and red curves overlay each other, since the chemical compositions are the same.

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Tanikawa et al 2018

Seitenzahl et al 2013

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grid of DDT explosions: varying ignition patterns
X-ray image analysis with genus statistics

“genus number” = no. of “clumps” - no. of “holes” for a black & white image, so for a given intensity threshold (Euler-Poincaré characteristic on the excursion set)

- can distinguish smooth vs. clumpy ejecta profiles
- can quantify (the obvious) that Tycho is not smooth

Williams et al 2017, Sato et al 2019
A new way of investigating SNR kinematics

"The Hot and Energetic Universe" **Athena+** supporting paper

Decourchelle, Costantini, et al 2013
Let’s explore the SNR in real 3D

Ferrand & Warren 2018 (CAPjournal)