Shell supernova remnants as cosmic accelerators: I

Stephen Reynolds, North Carolina State University

I. Overview

II. Supernovae: types, energies, surroundings

III. Dynamics of supernova remnants
   A) Two-shock (ejecta-dominated) phase
   B) Adiabatic (Sedov) phase
   C) Transition to radiative phase

IV. Diffusive shock acceleration

V. Radiative processes
Supernova remnants for non-astronomers

Here: “SNR” means gaseous shell supernova remnant.
Exploding stars can also leave “compact remnants:”
  -- neutron stars (which may or may not be pulsars)
  -- black holes
We exclude pulsar-powered phenomena (“pulsar-wind nebulae,”
  “Crablike supernova remnants” after the Crab Nebula)

SN ejects 1 – 10 solar masses ($M_\odot$) at high speed into surrounding
material, heating to X-ray emitting temperatures ($> 10^7$ K). Expansion
slows over $\sim 10^5$ yr.
Young (“adiabatic phase”) SNRs: $t < t_{cool} \sim 10,000$ yr. Observable primarily
through radio (synchrotron), X-rays (if not absorbed by intervening ISM)
Older (“radiative phase”): shocks are slow, highly compressive; bright
optical emission. (Still radio emitters, maybe faint soft X-rays).
SNRs: background II

Supernovae: visible across Universe for weeks ~ months
SNRs: detectable only in nearest galaxies, but observable for $10^4$ – $10^5$ yr
So: almost disjoint sets.

Important exception: Historical supernovae.
Chinese, European records document “new stars” visible with naked eye for months. In last two millenia:
185 CE, 386, 393, 1006, 1054 (Crab Nebula), 1181 (?), 1572 (Tycho's SN), 1604 (Kepler's SN)

“Quasi-historical:” deduced to be < 2000 yr old, but not seen due to obscuration: Cas A (~ 1680), G1.9+0.3 (~ 1900).
Unique testbed: SN 1987A (Large Magellanic Cloud)
A supernova-remnant gallery

1. Remnants of historical supernovae

- RCW 86 (SN 185?) (XMM/Chandra; CXC)
- G11.2+0.3 (SN 386) (Chandra; CXC)
- SN 1006 (Chandra, radio; CXC)
- Kepler's SNR (Chandra; CXC)
- Tycho's SNR (VLA; SPR)

2. Older remnants

- W 28 (radio+IR) (VLA; NRAO)
- Cygnus Loop (X-rays) (ROSAT; NASA/GSFC)
- Vela SNR (optical) (AAO)
- Vela SNR (X-rays) (ROSAT; NASA/GSFC)
Supernova remnants as particle accelerators: a brief history

Cas A: first radio source identified as SNR (Shklovskii 1953; Minkowski 1957).

Shklovskii (1953) proposed synchrotron radiation for radio emission:

1. power-law spectrum \( S_\nu \propto \nu^\alpha, \alpha \sim -0.5 \)

2. (later): Polarization

Synchrotron physics: Electron with energy \( E \) in magnetic field \( B \) emits peak at

\[
\nu = 1.82 \times 10^{18} E^2 B \text{ Hz} \quad \text{or}
\]

\[
E = 15 \left( \nu \frac{\text{GHz}}{B(\mu \text{G})} \right)^{-1/2} \text{ GeV} \Rightarrow \text{extremely relativistic electrons.}
\]
Supernova remnants as particle accelerators -- II

More synchrotron physics: Power-law photon distribution requires power-law electron distribution, \( N(E) \propto E^{-s} \) electrons cm\(^{-3}\) erg\(^{-1}\), with \( s = 1 - 2\alpha \). Observed values of \( \alpha \) (–0.5 to –0.7) give \( s = 2 - 2.4 \).

Another power-law particle distribution: Cosmic rays!
Below about 3000 TeV: \( s \sim 2.7 \) (ions)

Do SNRs borrow CR electrons, or produce them?

Young radio-bright SNRs: would require far too high compressions (also spectrum of low-frequency Galactic synchrotron background is wrong)
Cosmic-ray energetics

Galactic disk is full of cosmic rays (electrons: Galactic synchrotron background; ions: diffuse gamma-ray emission from \( p(\text{cr}) + p(\text{gas}) \rightarrow \) pions; \( \pi^0 \rightarrow \) gammas).

Energy density \( \sim 1 \text{ eV cm}^{-3} \)

Residence time: CR radioactive nuclei (e.g., \( ^{10}\text{Be} \)) ⇒ ages \( \sim 20 \text{ Myr} \)

Galactic volume \( \sim 10^{67} \text{ cm}^{-3} \) ⇒ require \( \sim 10^{41} \text{ J/yr} \) to replenish CR's.

SN rate \( \sim 2/\text{century} \) (except where are their remnants??) ⇒ need \( \sim 10\% \text{ of SN energy into cosmic rays} \) (primarily ions).

Electrons: \( \sim 2\% \) of energy in ions (steeper CR spectrum too)
History III

Origin of cosmic rays: Fermi 1949, 1954

1. “Collisions” (magnetic mirroring) between particles (speed $v$) and interstellar clouds (speed $v_{\text{cloud}} \ll v$) cause energy changes

$$\Delta E/E \sim \pm v_{\text{cloud}}/v$$ (approaching or receding), but approaches are more frequent: \((\Delta E/E)(\text{average}) \sim (v_{\text{cloud}}/v)^2\).

“Second-order” (stochastic) Fermi acceleration.

Get observed power-law only for particular escape and collision timescales

Acceleration rate is slow
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2. If all collisions are approaching, \(\Delta E/E \sim (v_{\text{cloud}}/v)\). If scattering centers embedded in fluid flow at a shock, can have this.

“First-order” Fermi acceleration (diffusive shock acceleration, DSA)
Get power-law spectrum depending only on shock compression ratio \(r\):
strong adiabatic shocks have \(r = 4 \Rightarrow s = 2\), similar to observations
Applications to supernova remnants

Bell 1978: radio energetics, spectra
R. & Chevalier 1981: extension to nonthermal X-rays
Lagage & Cesarsky 1983: maximum particle energies ~ 1000 TeV
Koyama et al. 1995: confirm nonthermal X-rays from SN 1006

Theoretical developments:
  Nonlinear DSA
  SNR-specific modeling

Observational developments:
  Discovery of X-ray synchrotron emission in other SNRs
  “Thin rims” imply magnetic-field amplification
  TeV detections with ground-based air-Čerenkov telescopes
Stellar death: bangs or whimpers

$> 8 \, M_\odot$ (solar masses) at birth: Fusion cycles continue up to Fe core formation. Lack of further energy source causes collapse and photodisintegration of core. Quasi free fall until nuclear densities are reached: form proto-neutron star; outer layers bounce out in core-collapse supernova event.

SN 1987A in Large Magellanic Cloud, before and after.

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Stars born with $< 8 \ M_\odot$ shed most of this in *stellar winds*, *planetary nebulae*, end with $< 1.4 \ M_\odot$ (Chandrasekhar limit), supported by electron degeneracy pressure: **white dwarfs**

Single white dwarfs simply cool and fade, but white dwarfs in *close binary systems* can accrete material from a companion star. Accreted H-rich material can initiate new nuclear burning in brief flares, widely separated outbursts, or in extreme cases, **thermonuclear (Type Ia) supernovae** resulting in complete disruption of the white dwarf and conversion of much of the mass to **iron**.

Binary system with compact object accreting from a normal star (hydrodynamic simulation by J. Blondin)
Supernova physics I

**Core-collapse:** gravity powered.

Liberate binding energy of neutron star $U \sim GM^2/R$

$M \sim 1 \, M_\odot \sim 2 \times 10^{30} \text{ kg}; \ R \sim 10 \text{ km}: \ U \sim 3 \times 10^{46} \text{ J}.$

99.7% carried off by neutrinos, $\sim 10^{44} \text{ J}$ in KE of explosion.

(So hydrodynamic simulations must conserve energy to 1 part in 1000 just to get explosions!)

Nucleosynthesis: mainly produce intermediate mass elements. 

$O/Fe \sim 70$ by number.
Supernova physics II

**Thermonuclear:** nuclear energy powered.

Excess BE/nucleon of Fe over initial C/O $\sim 0.8$ MeV

$1 \, M_\odot \sim 10^{57}$ nucleons $\Rightarrow 10^{44}$ J (similar to core-collapse!)

Nucleosynthesis: turn $0.5 - 1 \, M_\odot$ into Fe-group elements

$^{56}\text{Ni}$ decays to $^{56}\text{Co}$, $\tau_{1/2} = 6.1$ d;

$^{56}\text{Co} \rightarrow ^{56}\text{Fe}$, $\tau_{1/2} = 77.3$ d. Power optical light emission.

Much less O; O/Fe $\sim 0.3 - 0.8$ by number.

Peak brightness: very similar, but slight variation with **mass of $^{56}\text{Ni}$** produced.
Supernova-remnant dynamical evolution

Dump 1 – 10 $M_\odot$ carrying $10^{44}$ J into surrounding material:

$v \sim (2E/M)^{1/2} \sim 3,000 – 10,000$ km/s initial expansion velocity

Surroundings: 1: undisturbed interstellar medium (ISM),
2: circumstellar material (CSM) shed by progenitor star in a stellar wind.

Either: number density $n \sim 1$ cm$^{-3}$, $T \sim 10^4$ K, $B \sim 3 \mu$G

Collisionless shock wave, Mach number $v/c_s \geq 100$.

Density structure: ISM, roughly constant; constant-velocity CSM wind, $n \propto r^{-2}$.

Ejected material:

CC: steep power-law in outer layers, $n \propto r^{-10} -- r^{-12}$; constant-density core
Type Ia: constant-density core; $n \propto r^{-7}$ outside, or (better) exponential
Ejecta-dominated evolution

**Outer shock** (blast wave) driven into surrounding material by ejecta
Ejecta rapidly cool adiabatically to ~100 K
Outer shock decelerates; freely expanding ejecta are forced to slow at inward-facing **reverse shock**, reheating ejecta to X-ray-emitting temperatures

Timescales: If $R \propto t^m$, sweep up ISM mass equal to ejected mass in
\[ t_s \sim (200/m) \times E_{44}^{-1/2} \times (M_{ej}/1 \, M_\odot)^{5/6} \times n_0^{-1/3} \, \text{yr} \quad (n_0 \text{ is external density}) \]
Shock evolution

Deceleration index $m \ (R \propto t^m)$

Outer blast wave

Reverse shock

Power-law density profiles allow similarity solutions: profiles of postshock quantities ($v$, $T$, $P$, $\rho$) maintain shape with time

1-D hydrodynamic simulation (J. Blondin)
Shock velocity evolution

Ejecta-dominated stages: \( v = mR/t \propto t^{m-1} \); \( m \sim 0.6 - 0.9 \)

Once ejected mass can be ignored, evolve to “Sedov-Taylor” (adiabatic) blast wave: \( R = 1.12 \left( E/\rho \right)^{1/5} t^{2/5} \)

Once cooling is important (\( t \sim 30,000 \) yr, weakly dependent on \( E, n_0 \)), when \( v \sim 200 \) km/s, deceleration is more rapid. Shock compressions rise; shock acceleration to high energies is much less likely
A pictorial overview of diffusive shock acceleration

Particles diffuse in fluid, scattering from MHD fluctuations
Most are swept downstream; a few scatter back, encounter approaching scattering centers, gain energy

**Efficient acceleration:** can't ignore energy in CR’s; they slow incoming fluid (except for viscous subshock)
Steady state, test-particle results

Compression ratio $r \equiv u_1/u_2 \leq 4$

Produce power-law distribution $N(E) = KE^{-s}$.

Spectral index $s$ (all particles): $(r + 2)/(r - 1)$ $(E \gg mc^2)$ independent of diffusion coefficient $\kappa$ (as long as $\kappa > 0$!)

$r = 4 \Rightarrow s = 2$; losses can steepen to required source value $s \sim 2.3$

(Axford, Leer, & Skadron 1977; Bell 1978; Blandford & Ostriker 1978)

Acceleration time to momentum $p$:

$$\tau_{\text{acc}} \sim \frac{3}{u_1^2} \frac{\kappa(p)}{r - 1} \frac{r (r + 1)}{r - 1}$$

in parallel shock ($\theta_{\text{Bn}} = 0 \Rightarrow \kappa_2 = \kappa_1$)
Diffusion

Expect $\kappa = \kappa(x, p)$. Common assumption:

$$\kappa = \frac{\lambda_{\text{mfp}} v}{3} = \frac{\eta r_g c}{3} \quad \text{where} \quad r_g = \frac{E}{eB} \quad (\text{ER limit})$$

$\eta$ is “gyrofactor” (mfp in units of $r_g$); expect $\eta \geq 1$

Accelerated particles diffuse upstream: *precursor* on length scale $\kappa/u_1$

From quasi-linear theory, $\eta \equiv (\delta B/B)^{-2}_{\text{res}}$ (so $\eta^{-1} = \text{fractional energy density in MHD waves resonant with particles of energy } E$)
Maximum energies

Maximum rate of energy gain: $\eta = 1$ ("Bohm limit"; saturated MHD turbulence)

Oblique shocks ($\theta_{Bn} > 0$): For $\eta > 1$, may have more rapid acceleration for quasi-perpendicular shocks ($\theta_{Bn} \sim 90^\circ$; Jokipii 1987)

Finite age (or size), escape, or radiative losses can limit energies.
Finite shock age $t$ ($t = \tau_{\text{acc}}(E_{\text{max}})$) or size scale $R$

$R = \kappa(E_{\text{max}})/u_1 \Rightarrow$

$$E_{\text{max}1} \sim 0.5 \ t_3 \ u_8^2 \ B_{\mu G} \ \eta^{-1} \ \text{TeV}$$

**Escape** due to absence of MHD waves above $\lambda_{\text{max}}$:

$$E_{\text{max}2} \sim 10 \ B_{\mu G} \ \lambda_{17} \ \text{TeV}$$

Both should apply equally to electrons, ions

Radiative losses on electrons *(synchrotron, inverse-Compton)*:

$$\tau_{\text{acc}} = \tau_{\text{loss}} \Rightarrow E_{\text{max}3} \sim 100 \ u_8 \ (\eta \ B_{\mu G})^{-1/2} \ \text{TeV}$$

In all cases, particle spectrum should cut off exponentially $\propto e^{-E/E_{\text{max}}}$
Diffusive shock acceleration: summary

1. **Spectrum.** Test-particle result: $N(E) \propto E^{-s}$, $s = (r + 2)/(r - 1)$

   ($r =$ shock compression, $\sim 4$ for strong shocks)

   Nonlinear calculation: Slight curvature: steeper at lower $E$, flatter (harder) at higher $E$.

2. **Maximum energy.** Typical SNR parameters get to $\sim 100$ TeV easily.

   “Knee” in CR spectrum at 3000 TeV: difficult – but $E_{\text{max}} \propto B$, so much larger $B$ could help.
Radiation mechanisms

1. Protons: \( p_{cr} + p \rightarrow \text{stuff} + \pi^0; \) \( \pi^0 \)'s decay to \( \gamma \)-rays.
   
   \( E_p \geq 300 \text{ MeV} \) and \( h\nu \geq 70 \text{ MeV} \). Spectrum: \( F_\nu \propto (h\nu)^{-s} \)

2. Electrons:
   
   (a) Synchrotron. \( h\nu \sim 1.9 \left( \frac{E}{100 \text{ TeV}} \right)^2 \left( \frac{B}{10 \mu \text{G}} \right) \) keV.
      Spectrum: \( F_\nu \) rolls off smoothly above this energy

   (b) Nonthermal bremsstrahlung. \( h\nu \sim E/3 \).
      Spectrum: same as electrons of those energies

   (c) Inverse-Compton (IC) emission
      
      i. IR seeds: \( h\nu \sim 190 \left( \frac{\lambda}{25 \mu} \right)^{-1} E_{\text{GeV}}^2 \) keV
      
      ii. CMB seeds: \( h\nu \sim 2.5 E_{\text{GeV}}^2 \) keV.
      
      Spectrum: same as radio synchrotron (very hard)

Gamma rays from $\pi^0$-decay

Threshold for $p + p \rightarrow p + p + \pi^0$: 1.2 GeV; cross-section $\sigma \sim (10^{-13} \text{ cm}^2)$

$\pi^0$'s decay to 2 photons (68 MeV each). At photon energy $h\nu$, production is dominated by protons near threshold; so photon spectrum follows proton spectrum after turning on near 70 MeV ("$\pi^0$ bump").

Rough estimate: emissivity $\sim 10^{-16} n_H N(h\nu)$ photons/(GeV s cm$^3$)

where $N(E)$ is the proton distribution.

For power-law spectra, gamma-ray yield $Q > 100$ MeV is about

$$Q \sim 5 \times 10^{-14} n_H u_{\text{rel}} \text{ photons/(s cm}^3)$$

where $u_{\text{rel}}$ is the energy density in relativistic protons.
Synchrotron radiation

See only highest-energy electrons in soft X-ray band:

\[ E = 72 \left( \frac{h\nu}{1 \text{ keV}} \right)^{1/2} \left( \frac{B}{10 \mu \text{G}} \right)^{-1/2} \text{ TeV} \]

Local power-law of electrons \( N(E) = K E^{-s} \) gives emissivity \( \propto \nu^{-\alpha} \).

Exponential cutoffs: approximate each electron's radiation as all at peak frequency \( \nu_{\text{max}} \); then
emissivity \( \propto \exp\left(-\frac{\nu}{\nu_{\text{max}}}\right) \) roughly.

Energy losses: \( -\dot{E} \propto E^2 B^2 \Rightarrow t_{1/2} \sim 637/(EB^2) \text{ sec} \)
or \( t_{1/2} \sim 1300/\left((E/100 \text{ TeV})(B/10 \mu \text{G})^2\right) \text{ yr} \)
Nonthermal bremsstrahlung

“Nonthermal”: from non-Maxwellian electron energy distribution

Electrons with energy $E$ emit photons with $h\nu \sim E/3$: Power-law distribution $N_e(E) = K E^{-\alpha}$ produces power-law photon distribution with photon index $\Gamma = \alpha$:

$$N(h\nu) \propto (h\nu)^{-\Gamma} \text{photons cm}^{-2} \text{s}^{-1} \quad (\Gamma \leftrightarrow \alpha + 1)$$

Above 100 MeV, same electrons emit both bremsstrahlung gamma rays and radio synchrotron photons

Spectral emissivity $\sim 7 \times 10^{-16} n_H N_e(h\nu)$ photons erg$^{-1}$ cm$^{-2}$ s$^{-1}$
Inverse-Compton emission

Relativistic electrons can upscatter any photon fields to energies
\[ h\nu_f \sim \gamma^2 h\nu_i \quad (\gamma = \text{electron Lorentz factor}) \]

Spectrum: same slope as synchrotron as long as \( \gamma h\nu_i \ll m_e c^2 \); then Klein-Nishina corrections reduce cross-section, steepen spectrum

Usually, local optical/IR radiation field is less important than upscattering cosmic microwave background photons: \textbf{ICCMB}
Radiation processes: summary

One hadronic process: $\pi^0$-decay. Only potential evidence for cosmic-ray ions in SNRs. Distinguishing feature: 70 MeV “bump.”

Three leptonic processes.

Synchrotron radiation: Important from radio to soft X-rays. Flux fixes only combination of magnetic field, electron energy density

Bremsstrahlung: Can be important from soft X-ray to TeV. Constrained above 100 MeV where same electrons produce radio synchrotron

Inverse-Compton: Present wherever relativistic electrons are present through ICCMB. Detection gives electron energy directly, allows inference of B from synchrotron fluxes.

All of these may contribute to high-energy photon emission from SNRs
Broadband modeling

Nonlinear shock-acceleration model with predictions for radiation (Baring et al. 1999; data: CGRO obs. of IC 443)

\[ (\rho/\rho_0)_{10 \text{ keV}} = 0.01 \]

\[ (\rho/\rho_0)_{10 \text{ keV}} = 0.1 \]

\[ (\rho/\rho_0)_{10 \text{ keV}} = 1 \]

\[ \nu = 10 \text{ cm}^{-3} \]

\[ \nu = 1 \text{ cm}^{-3} \]

\[ \nu = 0.1 \text{ cm}^{-3} \]

\[ \log_{10} E \text{ (MeV)} \]

\[ \log_{10} \text{ flux (photons at Earth cm}^{-2} \text{ s}^{-1}) \]

- \( \pi^0 \)-decay
- bremsstrahlung
- ICCMB
Broadband modeling

Nonlinear shock-acceleration model with predictions for radiation (Baring et al. 1999; data: CGRO obs. of IC 443)

- $\pi^0$-decay
- bremsstrahlung
- ICCMB
- GLAST bandpass

LAT sensitivity drops below 1 MeV, but “bump” may still be detectable