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 ~10^5 yr.

Young ("adiabatic phase") SNRs: $t < t_{cool}$ ~ 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.

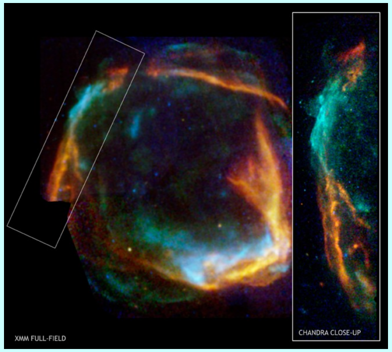
Important exception: Historical supernovae.
    Chinese, European records document “new stars” visible with naked eye for months. In last two millenia:
    185 CE, 386, 393, 1006, 1054 (Crab Nebula), 1181 (?),
    1572 (Tycho's SN), 1604 (Kepler's SN)

“Quasi-historical:” deduced to be < 2000 yr old, but not seen due to obscuration: Cas A (~ 1680), G1.9+0.3 (~ 1900).

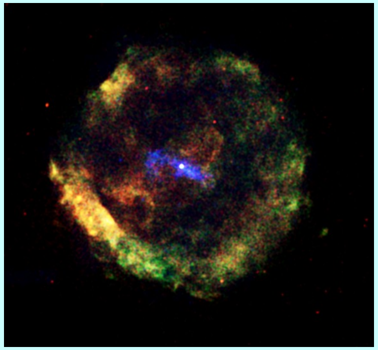
Unique testbed: SN 1987A (Large Magellanic Cloud)

A supernova-remnant gallery

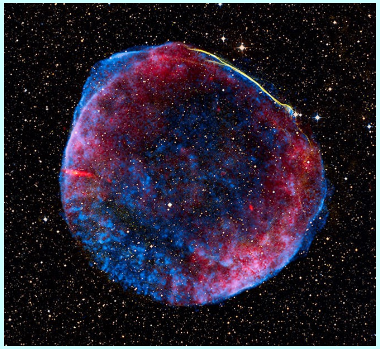
1. Remnants of historical supernovae



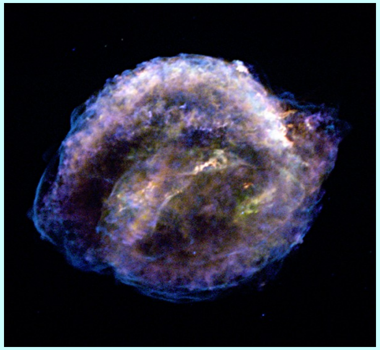
RCW 86 (SN 185?)
(XMM/Chandra; CXC)



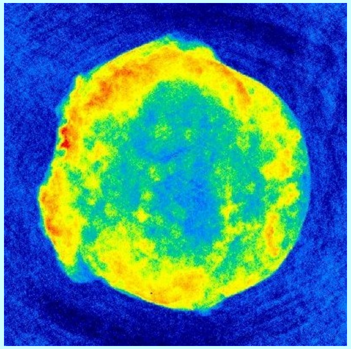
G11.2+0.3 (SN 386)
(Chandra; CXC)



SN 1006
(Chandra, radio; CXC)



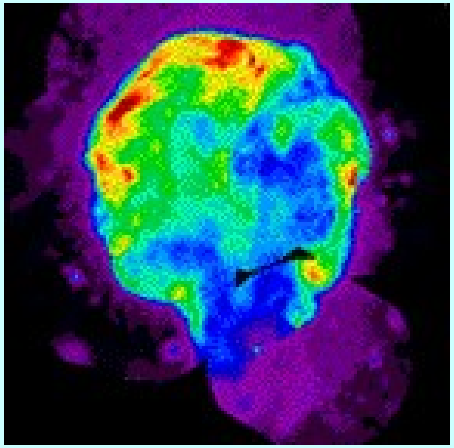
Kepler's SNR
(Chandra; CXC)



Tycho's SNR
(VLA; SPR)

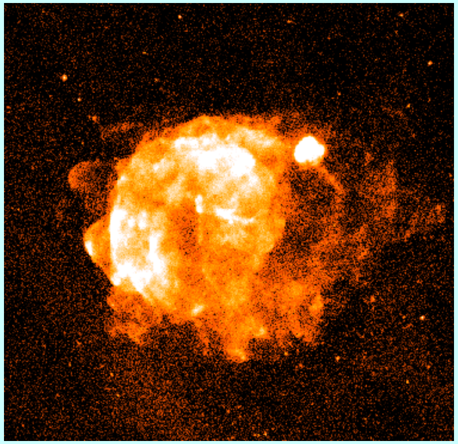
2. Older remnants

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

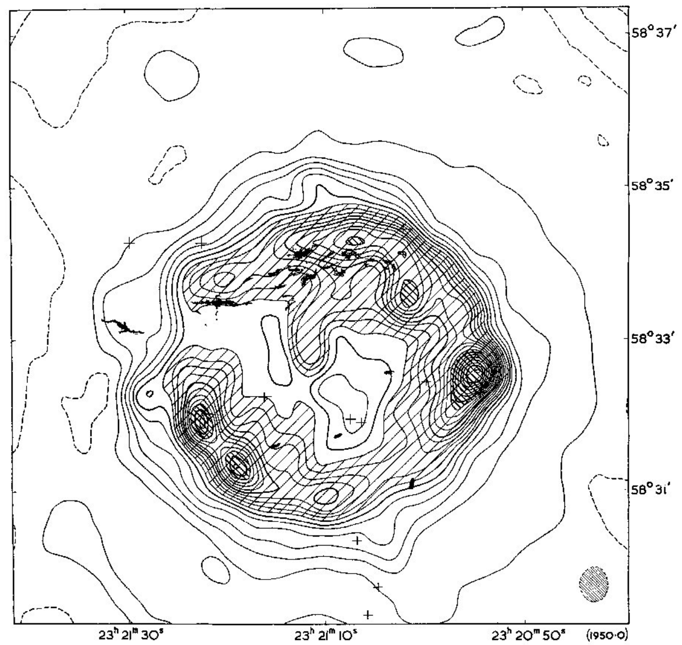


Fig. 5. Contour map of Cassiopeia *A* showing also the main optical filaments. The contour interval is 3,000° K. The positions of some of the brighter stars in the field are indicated by crosses

First interferometric map of Cassiopeia A (Cambridge; Ryle, Elsmore, & Neville 1965)

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

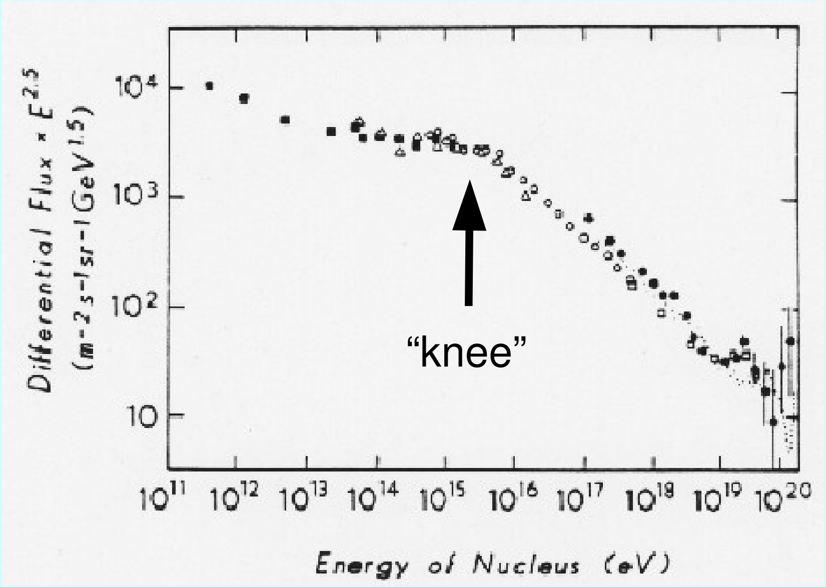
$\nu = 1.82 \times 10^{18} E^2 B$ Hz or

$E = 15\ (\nu(\mathrm{GHz})/B(\mu\mathrm{G}))^{-1/2}$ GeV $\Rightarrow$

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 α (-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(cr) + p(gas) $\rightarrow$ pions; $\pi^0 \rightarrow$ gammas).
Energy density ~ 1 eV cm^{-3}

Residence time: CR radioactive nuclei (e.g., ^{10}Be) $\Rightarrow$ ages ~ 20 Myr

Galactic volume ~ 10^{67} cm^{-3} $\Rightarrow$ require ~ 10^{41} J/yr to replenish CR's.
SN rate ~ 2/century (except where are their remnants??) $\Rightarrow$
need ~ **10% of SN energy into cosmic rays** (primarily ions).
Electrons: ~ 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 $v_{cloud} \ll v$) cause energy changes $\Delta E/E \sim \pm v_{cloud}/v$ (approaching or receding), but approaches are more frequent: $(\Delta E/E)(\text{average}) \sim (v_{cloud}/v)^2$.

   "Second-order" (stochastic) Fermi acceleration.

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

   Acceleration rate is slow

History III

Origin of cosmic rays: Fermi 1949, 1954

1. "Collisions" (magnetic mirroring) between particles (speed v) and interstellar clouds (speed $v_{cloud} \ll v$) cause energy changes $\Delta E/E \sim \pm v_{cloud}/v$ (approaching or receding), but approaches are more frequent: $(\Delta E/E)(\text{average}) \sim (v_{cloud}/v)^2$.
   "Second-order" (stochastic) Fermi acceleration.
   Get observed power-law only for particular escape and collision timescales
   Acceleration rate is slow
2. If all collisions are approaching, $\Delta E/E \sim (v_{cloud}/v)$. If scattering centers embedded in fluid flow at a shock, can have this.
   "First-order" Fermi acceleration (diffusive shock acceleration, DSA)
   (Axford, Leer, & Skadron 1977; Krymskii 1977; Bell 1978; Blandford & Ostriker 1978)
   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

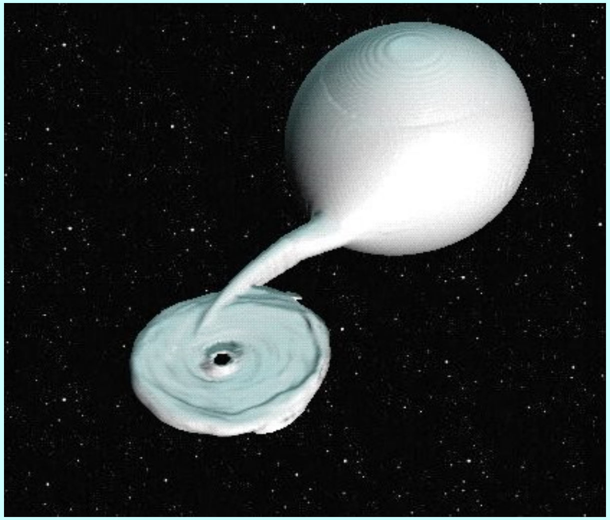
> 8 $M_{\odot}$ (solar masses) **at birth:** Fusion cycles continue up to Fe core formation. Lack of further energy source causes *collapse and photodisintegration* of core. Quasi free fall until nuclear densities are reached: form proto-neutron star; outer layers bounce out in **core-collapse supernova**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

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

Whimpers

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 $U \sim GM^2/R$

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

99.7% carried off by neutrinos, $\sim 10^{44}$ 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 ~ 70 by number.

Supernova physics II

Thermonuclear: nuclear energy powered.

Excess BE/nucleon of Fe over initial C/O ~ 0.8 MeV

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

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

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

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

Much less O; O/Fe ~ 0.3 – 0.8 by number.

Peak brightness: very similar, but slight variation with **mass of ^{56}Ni** produced.

Supernova-remnant dynamical evolution

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

v ~ $(2E/M)^{1/2}$ ~ 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 ~ 1 cm^{-3} , T ~ 10^4 K, B ~ 3 μG

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

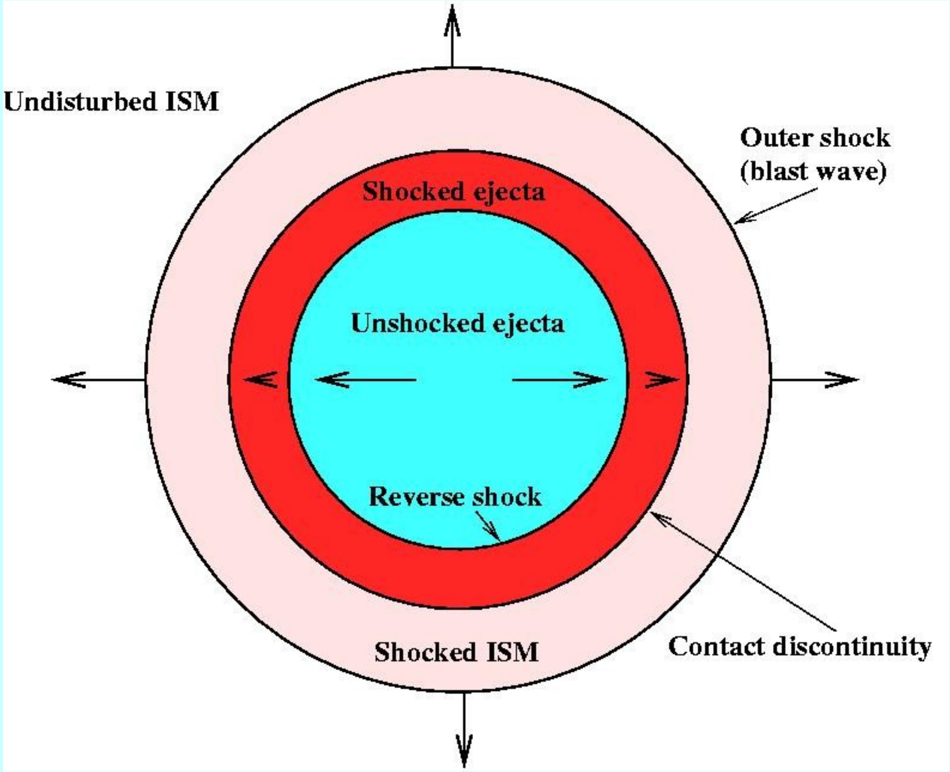
Density structure: ISM, roughly constant; constant-velocity CSM wind, $n \propto r^{-2}$.

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

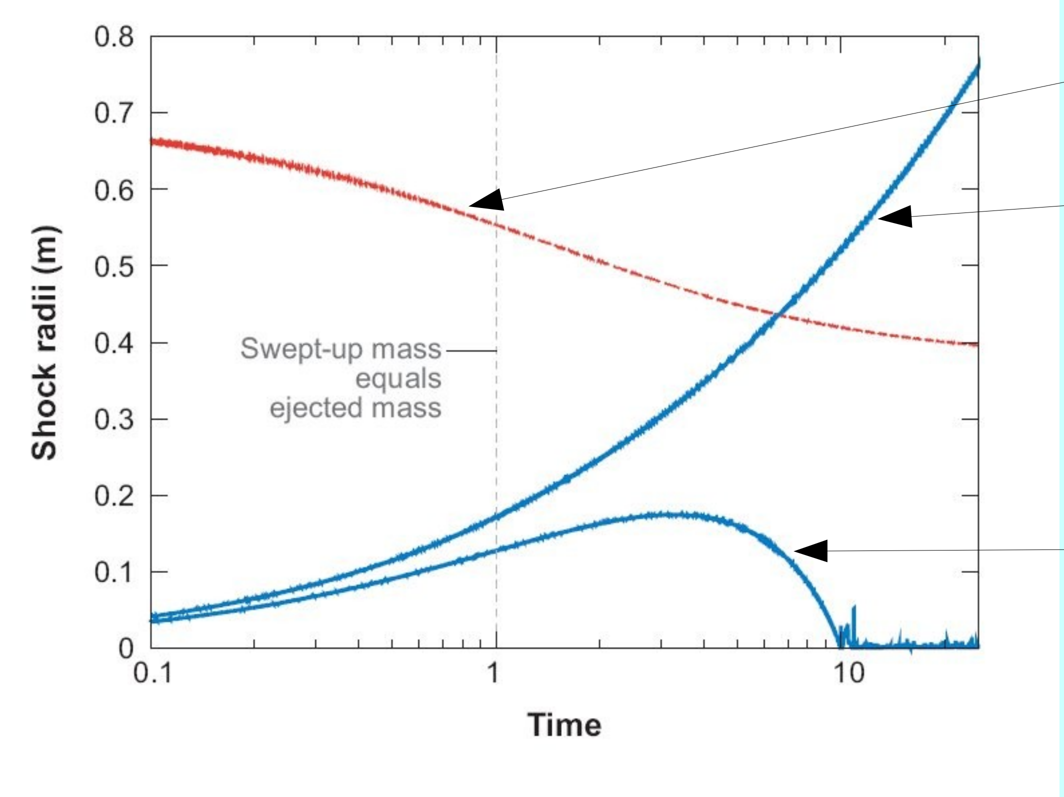
Ejecta rapidly cool adiabatically to ~ 100 K

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

$t_s \sim (200/m)\, E_{44}^{-1/2}\, (M_{ej}/1\ M_{\odot})^{5/6}\, n_0^{-1/3}$ yr (n_0 is external density)

Shock evolution



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

Outer blast wave

Reverse shock

1-D hydrodynamic simulation (J. Blondin)

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

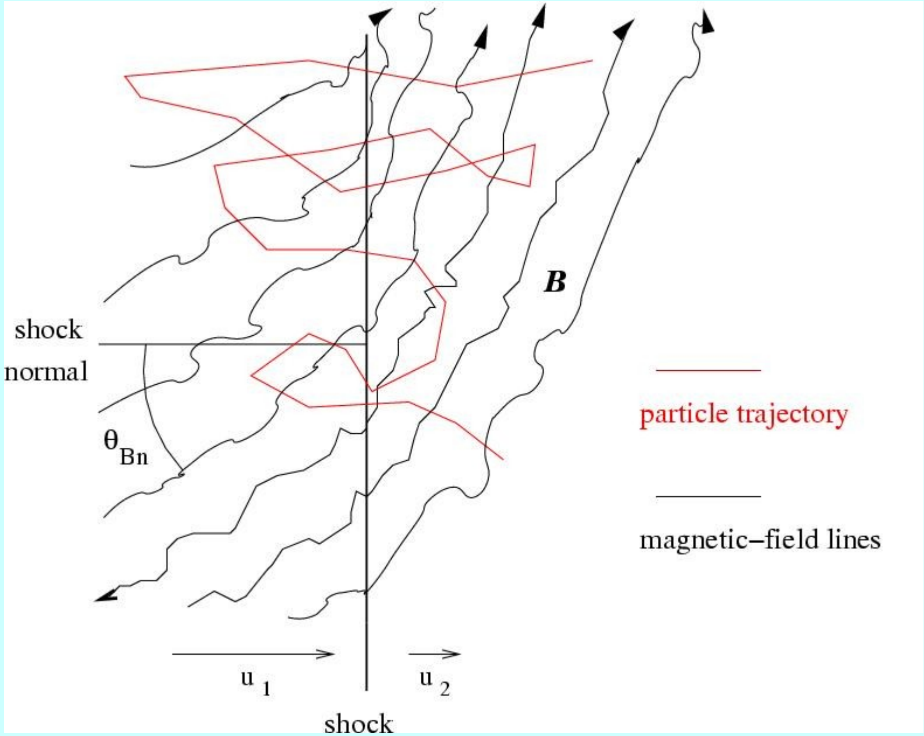
Shock velocity evolution

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: $R = 1.12\,(E/\rho)^{1/5}\, t^{2/5}$

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

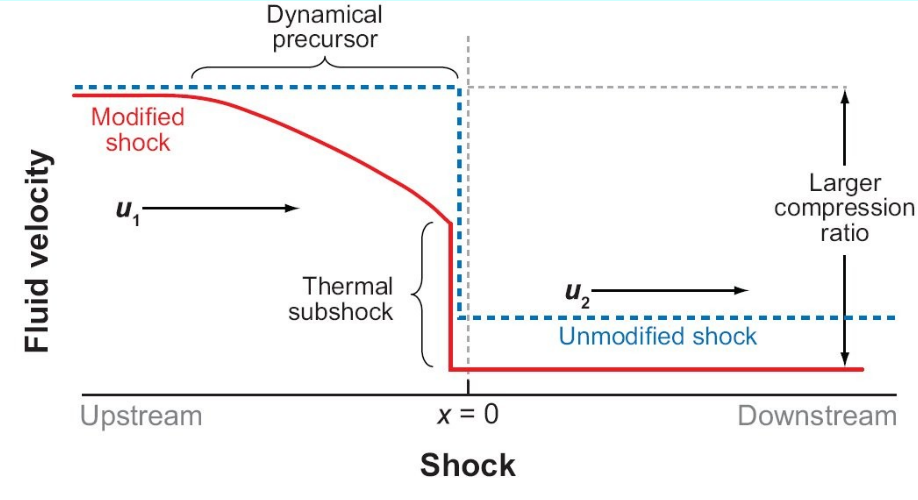
A pictorial overview of diffusive shock acceleration

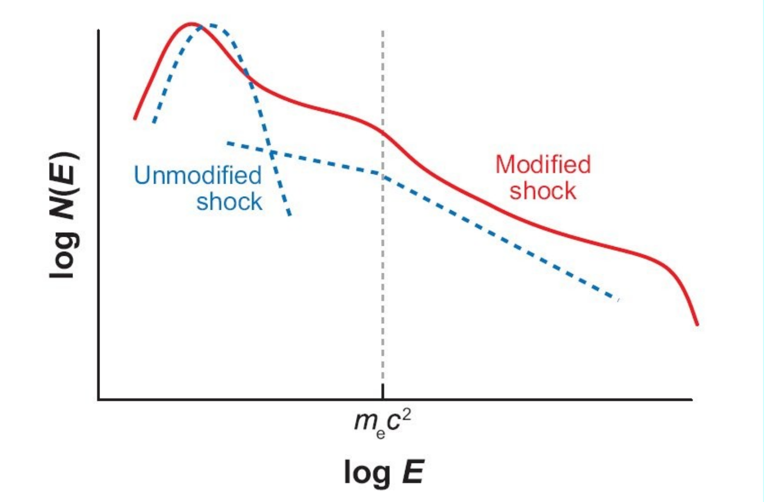


Particles diffuse in fluid, scattering from MHD fluctuations

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 κ (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:

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

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

Diffusion

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

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

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

Accelerated particles diffuse upstream: *precursor* on length scale κ/u_1

From quasi-linear theory, $\eta \equiv (\delta B/B)^{-2}_{\rm res}$ (so η^{-1} = 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 ($\theta_{\rm Bn} > 0$): For $\eta > 1$, may have more rapid acceleration for quasi-perpendicular shocks ($\theta_{\rm Bn} \sim 90^\circ$; Jokipii 1987)

Finite age (or size), escape, or radiative losses can limit energies.

Finite shock age t $(t = \tau_{\rm acc}(E_{\rm max}))$ or size scale R $(R = \kappa(E_{\rm max})/u_1) \Rightarrow$

$$E_{\rm max1} \sim 0.5\ t_3\ u_8^2\ B_{\mu{\rm G}}\ \eta^{-1} \quad {\rm TeV}$$

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

$$E_{\rm max2} \sim 10\ B_{\mu{\rm G}}\ \lambda_{17} \quad {\rm TeV}$$

Both should apply equally to electrons, ions

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

$$\tau_{\rm acc} = \tau_{\rm loss} \Rightarrow E_{\rm max3} \sim 100\ u_8 \quad (\eta\ B_{\mu{\rm G}})^{-1/2} \quad {\rm TeV}$$

In all cases, particle spectrum should cut off exponentially $\propto e^{-E/E_{\rm max}}$

Diffusive shock acceleration: summary

1. Spectrum. Test-particle result: $N(E) \propto E^{-s}$, $s = (r + 2)/(r -- 1)$
(r = shock compression, ~ 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 ~100 TeV easily.
"Knee" in CR spectrum at 3000 TeV: difficult – but $E_{max} \propto B$, so much larger B could help.

Radiation mechanisms

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

2. Electrons:
   (a) Synchrotron. $h\nu \sim 1.9\ (E/100\ \mathrm{TeV})^2\ (B/10\ \mu\mathrm{G})$ keV.
   Spectrum: F_ν 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: $h\nu \sim 190\ (\lambda/25\ \mu)^{-1}\ E_{\rm GeV}^2$ keV
      ii. CMB seeds: $h\nu \sim 2.5\ E_{\rm GeV}^2$ keV.
      Spectrum: same as radio synchrotron (very hard)

Drury, Aharonian, & Völk 1993; Mastichiadis 1996; Pohl 1996; SPR 1996, 1998; Sturner et al. 1997; Berezhko & Völk 1997; Gaisser, Protheroe, & Stanev 1998; Baring et al. 1999; Ellison, Berezhko, & Baring 2000

Gamma rays from π^0-decay

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

π^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 ("π^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

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

where u_{rel} is the energy density in relativistic protons.

Synchrotron radiation

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

$$E = 72\ (h\nu/1\ \mathrm{keV})^{1/2}\ (B/10\ \mu\mathrm{G})^{-1/2}\ \mathrm{TeV}$$

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 ν_{max}; then emissivity $\propto \exp(-(\nu/\nu_{\mathrm{max}}))$ roughly.

Energy losses: $-\dot{E} \propto E^2 B^2 \Rightarrow t_{1/2} \sim 637/(E\,B^2)$ sec

or $t_{1/2} \sim 1300/((E/100\ \mathrm{TeV})(B/10\ \mu\mathrm{G})^2)$ yr

Nonthermal bremsstrahlung

"Nonthermal": from non-Maxwellian electron energy distribution

Electrons with energy E emit photons with hν~E/3:
Power-law distribution $N_e(E) = K\,E^{-s}$ produces power-law photon distribution with photon index Γ = s:
$N(h\nu) \propto (h\nu)^{-\Gamma}$ photons cm^{-2} s^{-1} ($\Gamma \leftrightarrow \alpha + 1$)

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

Spectral emissivity ~ 7 x $10^{-16}\, n_H\, N_e(h\nu)$ photons erg^{-1} cm^{-2} s^{-1}

Inverse-Compton emission

Relativistic electrons can upscatter any photon fields to energies $h\nu_f \sim \gamma^2 h\nu_i$ (γ = 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: **ICCMB**

Radiation processes: summary

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

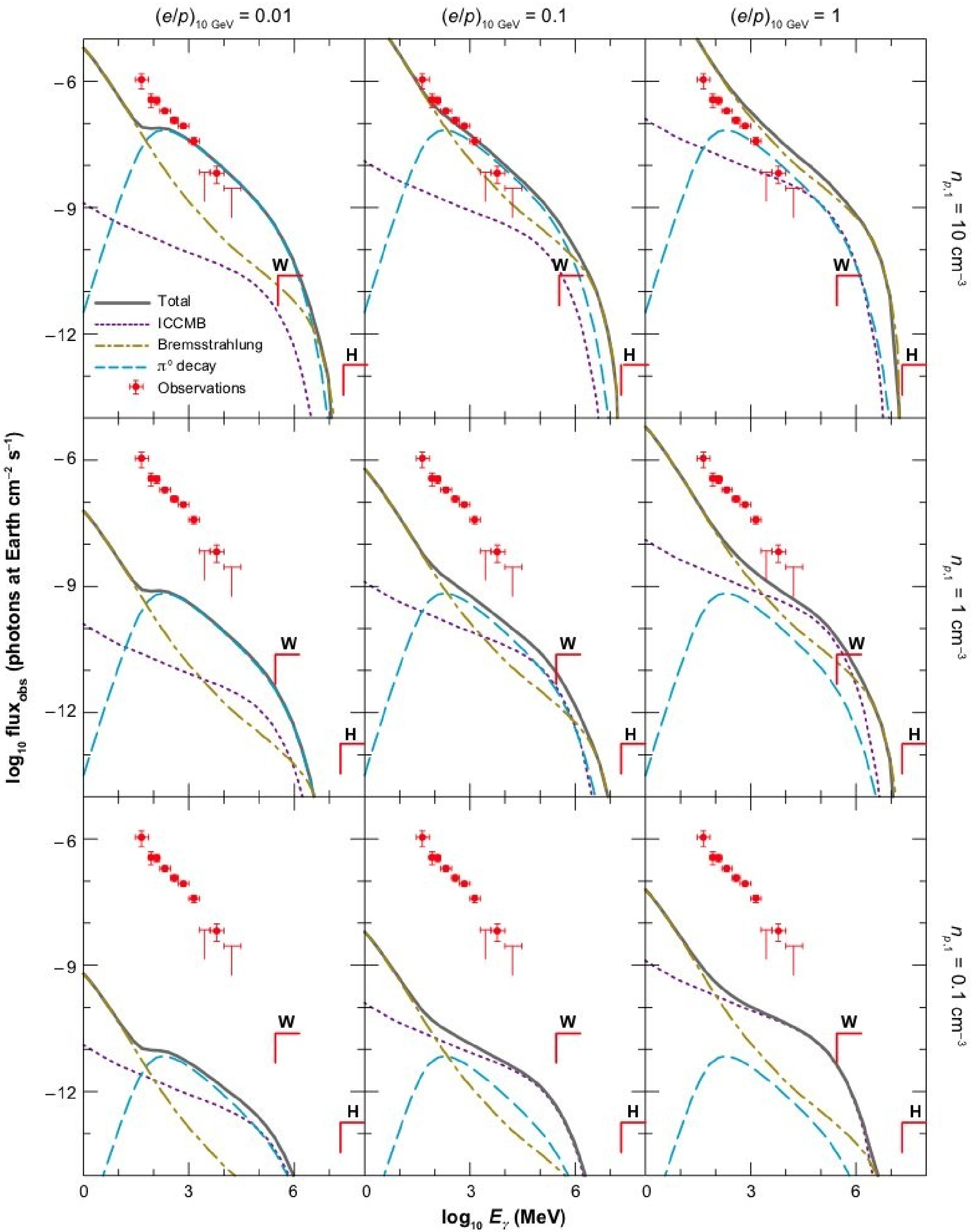
Three leptonic processes.

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



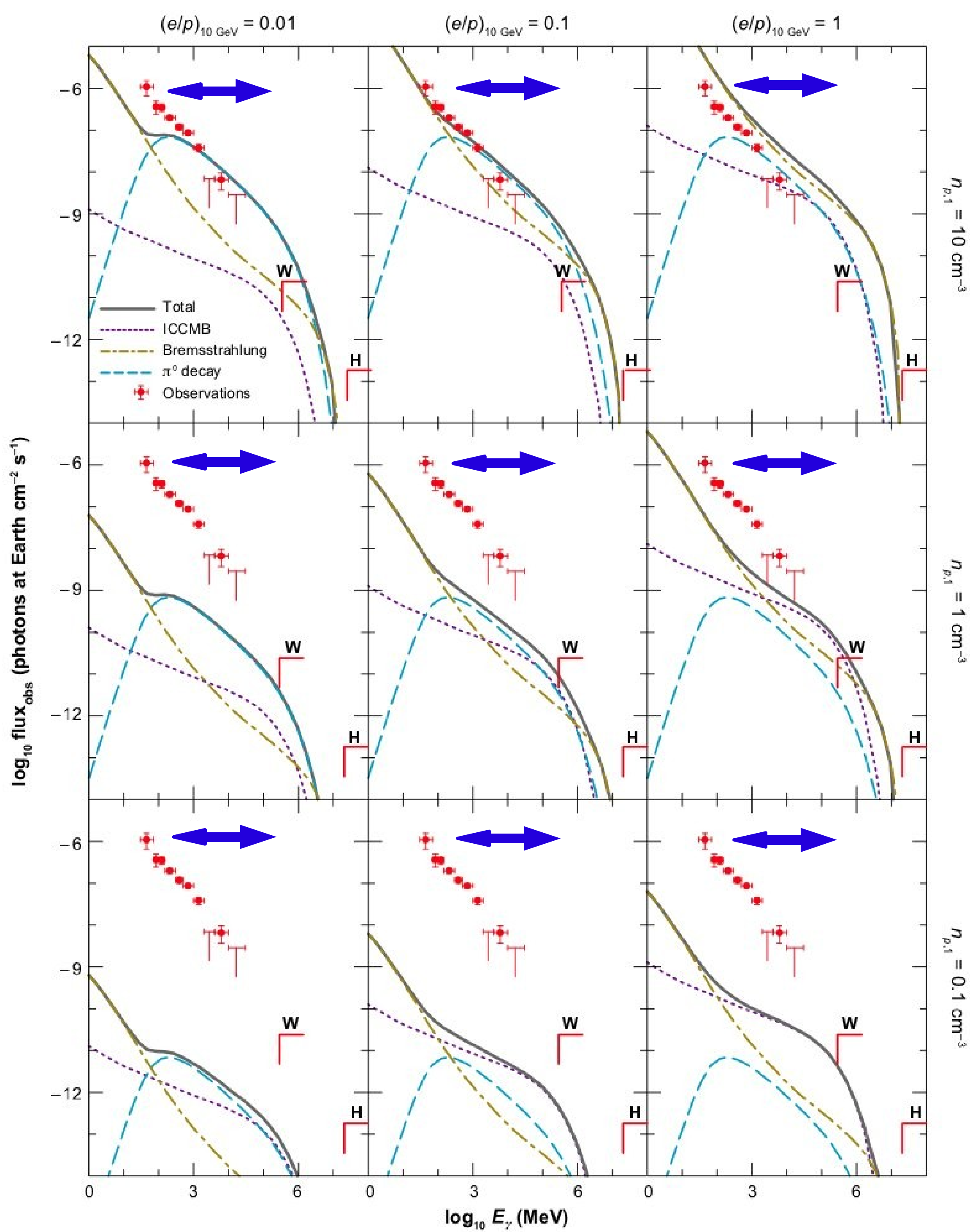
Broadband modeling

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

-- π^0-decay

-- bremss

-- ICCMB



Broadband modeling

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

-- π^0-decay

-- bremss

-- ICCMB

GLAST bandpass

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