Dynamics and Nonthermal Emission of Shell Supernova Remnants

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I. SNR Physics and Astrophysics: Some Big Questions

II. Theory

    Dynamics: evolution of SNR evolution theory

    Shock acceleration in an SNR context

III. Applications

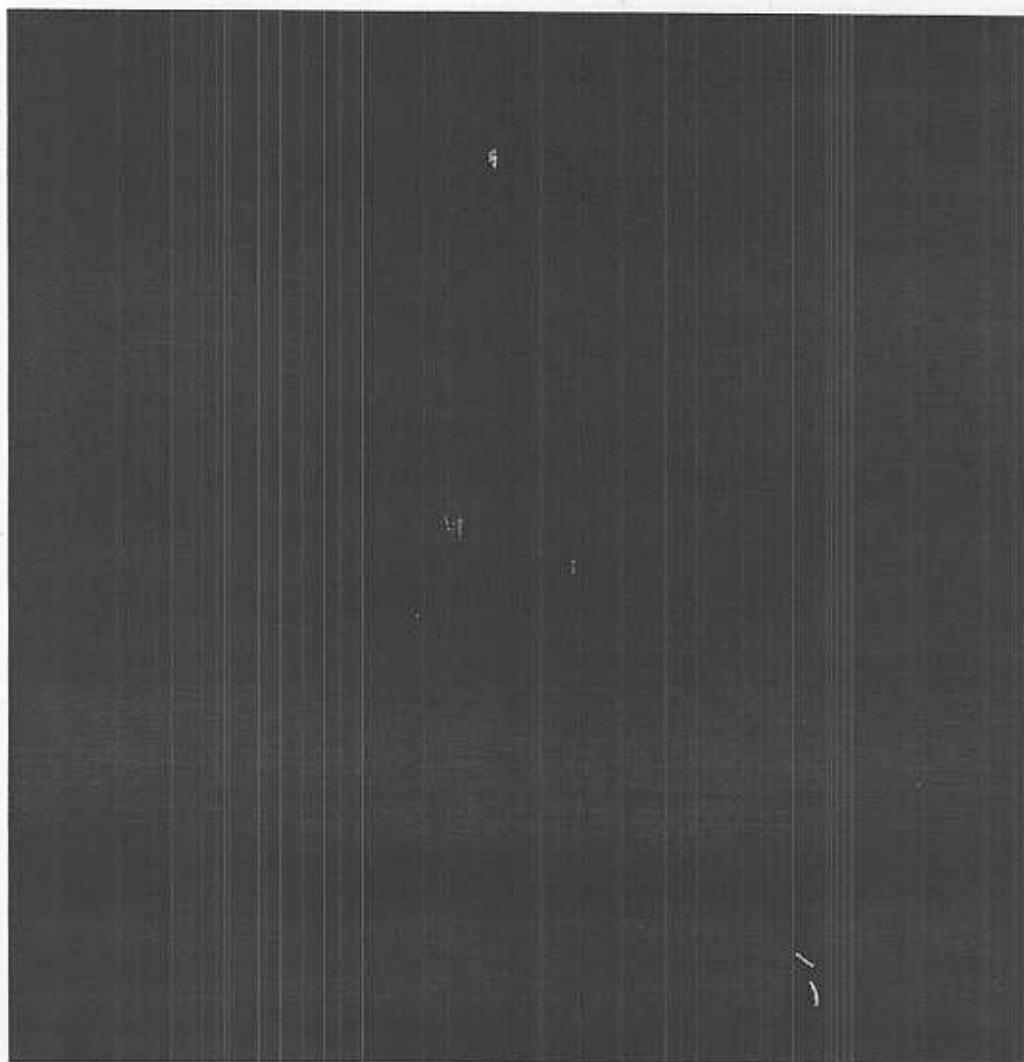   SN 1006; RCW 86; G347.3–0.5

IV. Frontiers

    Theory: modified shocks; amplified B; halos

    Observations: spectral curvature; spatially resolved high-resolution X-ray spectroscopy

    Polarimetry!

LMC SNR B0453-685
Gaensler, Hendrick, Reynolds, Borkowski 2003

Blue: 1.4 GHz (AT); red, 0.2–0.8 keV; green, 0.8–2.0 keV

Note central blue pulsar-wind nebula, but also radio extension beyond X-rays to SW. Cooling shock? Absorption?

Why You Should Care About Supernova Remnants:

Primarily thermal issues:

SN energies? SN types? Nucleosynthetic yields?

Progenitor mechanisms? Type Ia: poorly known! Core-collapse: GRB progenitors?

Primarily nonthermal issues:

Electron and/or ion acceleration? Maximum energies?

Efficiencies? How much shock energy goes into particles?

Plasma microphysics: turbulence and diffusion; magnetic geometry; "injection problem"

Turbulent (stochastic) acceleration?

Interactions

Accelerated particles modify the shock: increased compression, lowered T_e

Synchrotron X-ray continuum can artificially reduce line strengths

Unseen energy: $T_e < T_i$? Particle acceleration?

Accelerated particles and shocks are ubiquitous in astrophysics. SNRs can provide the laboratory for refining our understanding of particle acceleration.

Some Big Questions, and Answers

1. How high are maximum particle energies inferred?

   Answer: Electrons: ~ 200 TeV in SN 1006 (but spectrum has steepened from radio). Ions: no evidence yet

2. Has the problem of the origin of cosmic rays up to the "knee" ($\sim 3 \times 10^{15}$ eV) been solved yet?

   Answer: We should be so lucky.

   Electrons: In all SNRs studied so far, electron spectrum steepens well short of knee energies (losses, maybe, but in every case?)

   Efficiencies: There's room to hide $\sim 10^{50}$ erg of cosmic-ray ions in most SNRs. Claimed detections are model-dependent.

3. Do reverse shocks accelerate particles?

   Answer: Combination of spatial and thermal and nonthermal spectral analysis of RCW 86 suggests electron acceleration to TeV energies at reverse shock, identified by strong Fe overabundance.

What can radio observations tell us?

Morphology

- Find SNRs! Most are still radio objects
- Locate shock (e.g., thermal composites)
- Magnetic-field orientation, degree of disorder
- Halos? (constrain turbulence on scales $\sim 10^{13}$ cm)

Spectra

- $N(E)$ at relatively low energies (~ 1 GeV). Evidence for nonlinear shock modification?
- 1720 MHz OH masers: track dense regions, give **B**
- Radio recomb. lines: foreground thermal gas

What can X-ray observations tell us?

Morphology

- Where is the hot gas? (Since $\rho v_{\mathrm{shock}}^2 \sim$ const, hottest shocked gas is where density is low)
- Synchrotron halos? (constrain turbulence on scales $\sim 10^{18}$ cm)

Spectra

- $T_e \Rightarrow v_{\mathrm{shock}}$ (but caveats); apply Sedov relations to get age, upstream density ρ_0, explosion energy
- Abundances (but many assumptions)
- Most cases: upper limits to synchrotron emission $\Rightarrow$ limits on E_{max}

SNR Evolution

1970's: Four phases.

Free expansion $\rightarrow$ Sedov $\rightarrow$ radiative $\rightarrow$ dissipation

$(R \propto t)$ $(R \propto t^{0.4})$ $(R \propto t^{0.25})$

Since then: **Drastically revised!**

Transitions may last longer than phases themselves.

Phase 1:

- Dominated by reverse shock into ejecta. Power-law density profiles: "self-similar driven wave," SSDW (Chevalier 1982; Nadyozhin 1985). More realistic, exponential profiles: different. Expansion rate $R \propto t^m$, $m \sim 0.5 - 0.9$.

- Ejecta morphology may differ: radial structure. Even worse: 3-D effects (bubbles)
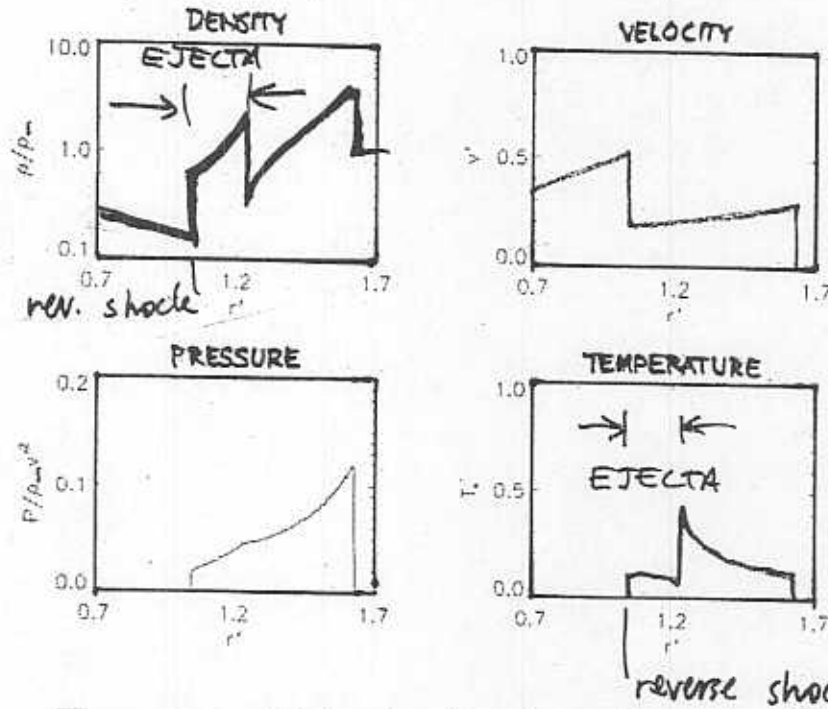
Later phases:

- Phase 2: Effects of reverse shock may linger until $M_{\text{swept}} \sim 10 M_{\text{ejecta}}$ or even greater. (But outer structure may not care much.)

- Densest parts of shock can become radiative long before overall energetics are affected.
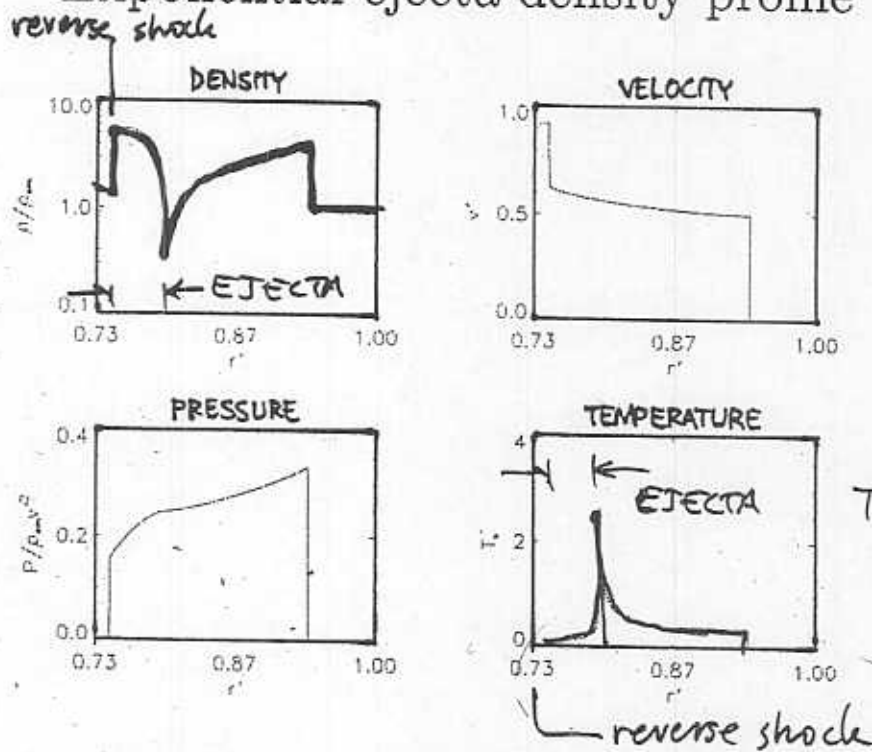
Two-Shock SNR Dynamics
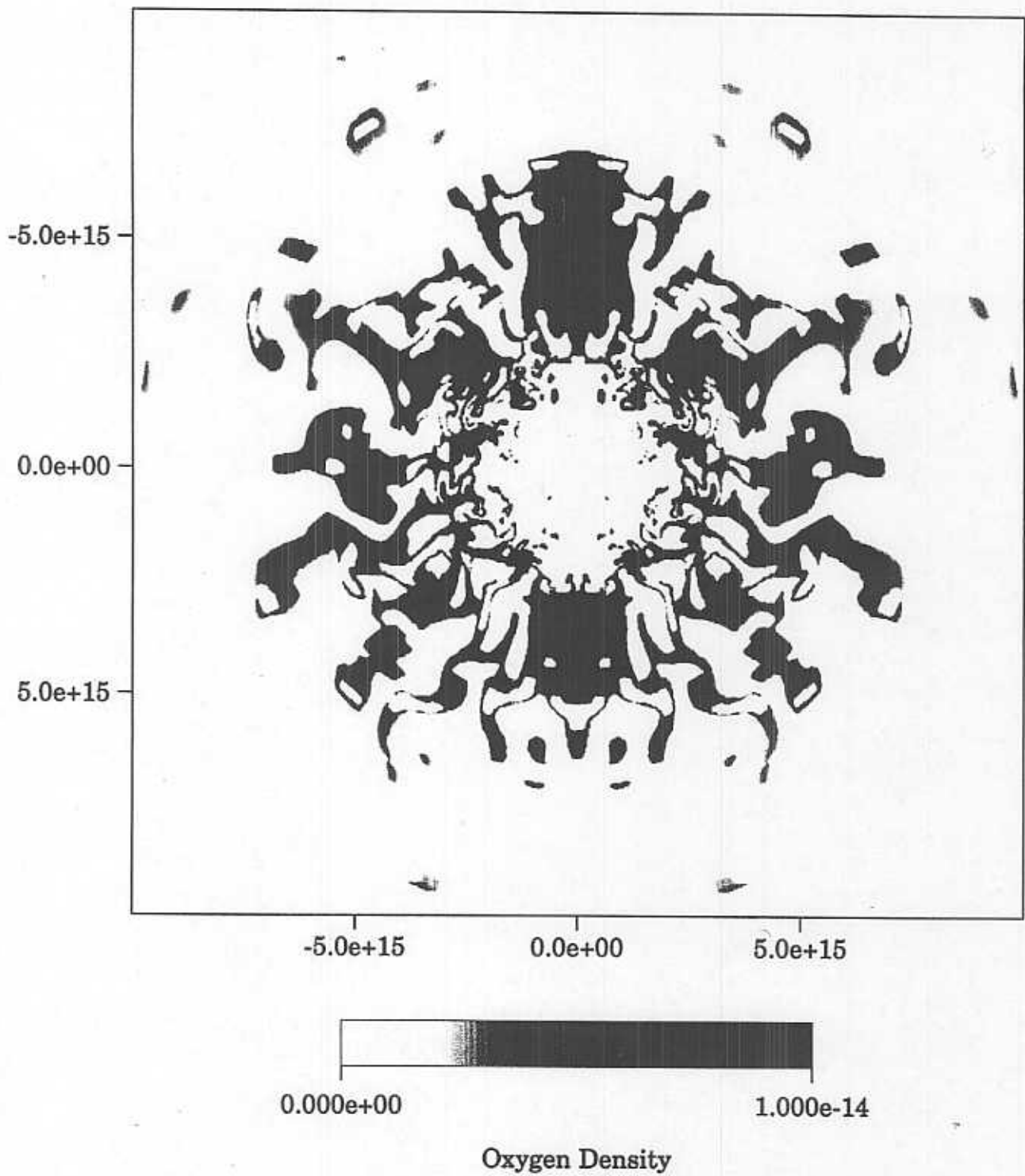## Dwarkadas & Chevalier 1998

ρ(ejecta)
rises behind
reverse shock

DENSITY

EJECTA

10.0

ρ/ρ_∞

1.0

0.1

0.7   1.2   1.7
r'

rev. shock

VELOCITY

1.0

v

0.5

0.0

0.7   1.2   1.7
r'

PRESSURE

0.2

$P/\rho_\infty v^2$

0.1

0.0

0.7   1.2   1.7
r'

TEMPERATURE

1.0

T

0.5

0.0

EJECTA

0.7   1.2   1.7
r'

reverse shock

T(ejecta)
~ const

Exponential ejecta density profile

reverse shock

DENSITY

10.0

ρ/ρ_∞

1.0

0.1

EJECTA

0.73   0.87   1.00
r'

ρ(ejecta)
falls behind
reverse shock

VELOCITY

1.0

v

0.5

0.0

0.73   0.87   1.00
r'

PRESSURE

0.4

$P/\rho_\infty v^2$

0.2

0.0

0.73   0.87   1.00
r'

TEMPERATURE

4

T

2

0

EJECTA

0.73   0.87   1.00
r'

reverse shock

T(ejecta) rises
steeply

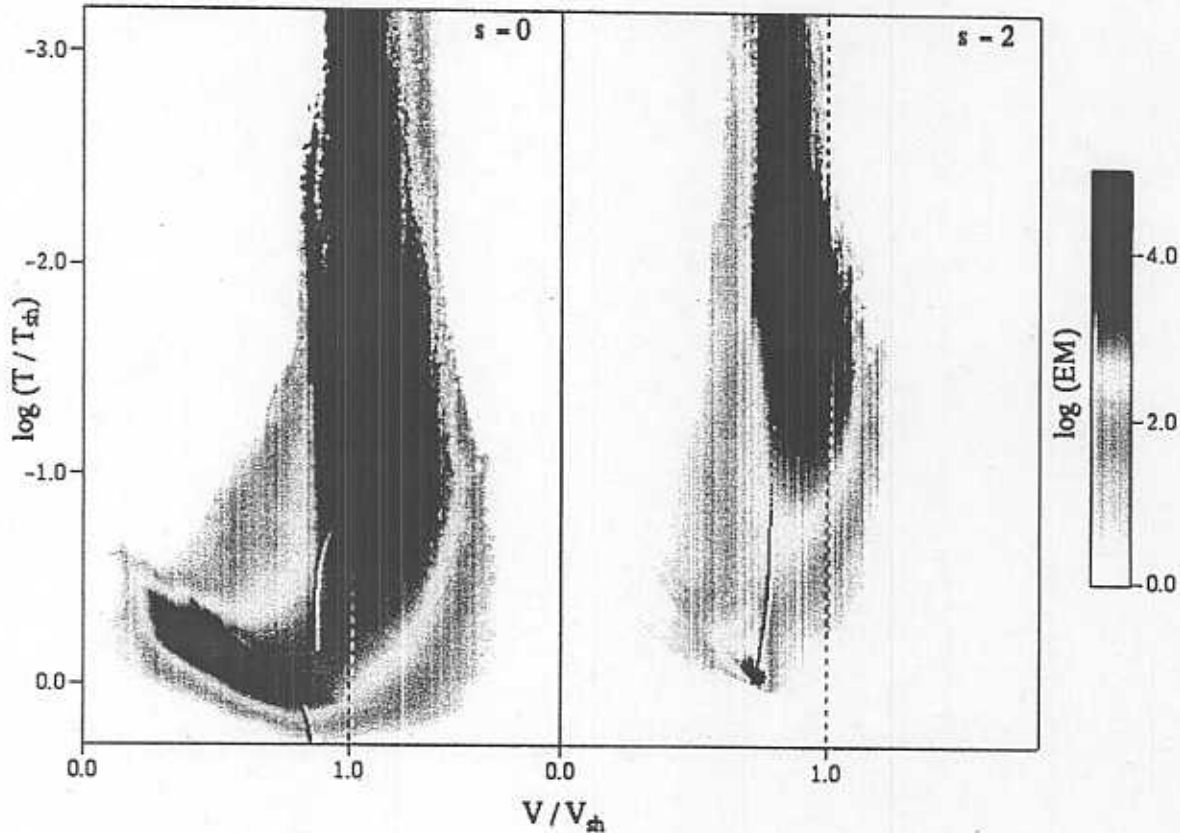## Power-law ejecta density profile

Oxygen Density

Ejecta structure from 3-D simulation of
core-collapse SN (Woosley progenitor model,
15 M⊙)   (Blondin 2003)

X-ray properties of bubbly SNRs
Blondin, Borkowski, Reynolds 2001

How much gas has which V and T?

Left: Uniform upstream medium; right, stellar wind. Horizontal axis: velocity in units of shock velocity. Vertical: temperature (decreasing up). Colors: emission measure ($\propto n^2$; measure of X-ray brightness) from 3-D hydro simulations. Solid lines: 1-D analytic results for $T(V)$, starting from shock values (stars). Note in left case, most material is **faster** and **cooler** than forward shock! (Obliquely shocked bubble walls aren't as efficiently decelerated or heated.)

Moral: Multi-D is different!

Particle Acceleration in SNRs

Shock (first-order Fermi) vs. second-order Fermi (stochastic) acceleration:

Acceleration time to a given energy:

$$\frac{\tau_I}{\tau_{II}} \sim \left(\frac{u_{\mathrm{sh}}}{v_A}\right)^{-2}$$

Now Alfvén speed $v_A^2 = B^2/4\pi\rho \sim P_B/P_{\mathrm{gas}}$ so $\tau_I < \tau_{II}$ unless magnetic pressure reaches equipartition with thermal pressure downstream. But rate of acceleration is not whole story.

Fermi II spectrum: depends on details of diffusion, magnetic-turbulence spectrum. Can operate on particles in highly turbulent post-shock flow.

What can we learn from observing power-law spectrum?

- Electrons only (except indirectly)

- Spectral index α ($S_\nu \propto \nu^{-\alpha}$)

- Write spectrum $N(E) = KE^{-s}$: learn electron index s ($= 2\alpha + 1$) $\Rightarrow r$ (but maybe $r(E)$)

- Synchrotron flux fixes product $KB^{1+\alpha}$

What can we learn from observing cutting-off tail?

- Characteristic rolloff frequency $\nu_r \propto E_{\max}^2 B$ depends on maximum energies $E_{\max}$, limited by various mechanisms

- For each mechanism ν_r is a different function of κ, u_{sh}, t, B, shock obliquity angle θ_{Bn}

Detailed models give range of spectral shapes.

What limits shock-accelerated particle energies?

1. Finite shock age t: need $t_{\mathrm{accel}} \lesssim t$. (Equivalent to finite shock size.) Affects ions and electrons.

$$E_{\max} \propto \int_{t_i}^{t} B u_{\mathrm{sh}}^2 dt$$

$$\lesssim 100 \left(\frac{B}{3\,\mu G} \right) \left(\frac{u_{\mathrm{sh}}}{3000\ \mathrm{km/s}} \right)^2 t_s(\mathrm{yr})\ \mathrm{GeV} \lesssim 100\ \mathrm{TeV}$$

2. Escape: absence of MHD waves above some $\lambda_{\max}$ means electrons and ions will escape without further acceleration. Need $\lambda_{\mathrm{wave}} \sim r_g(E)$.

$$E_{\max} \propto \lambda_{\max} B \sim 23 \left(\frac{\lambda_{\max}}{10^{17}\ \mathrm{cm}} \right) \left(\frac{B}{3\,\mu G} \right)\ \mathrm{TeV}$$

3. Synchrotron losses (electrons only): need $t_{\mathrm{accel}} \lesssim t_{\mathrm{loss}}$.

$$E_{\max} \sim 100 \left(\frac{B}{3\,\mu G} \right)^{-1/2} \left(\frac{u_{\mathrm{sh}}}{3000\ \mathrm{km/s}} \right)\ \mathrm{TeV}$$

Electrons with energy E radiate peak of their synchrotron emission at $\nu_c \propto E^2 B$, so for loss-limited acceleration, $\nu_c \propto u_{\mathrm{sh}}^2$, *independent* of B!
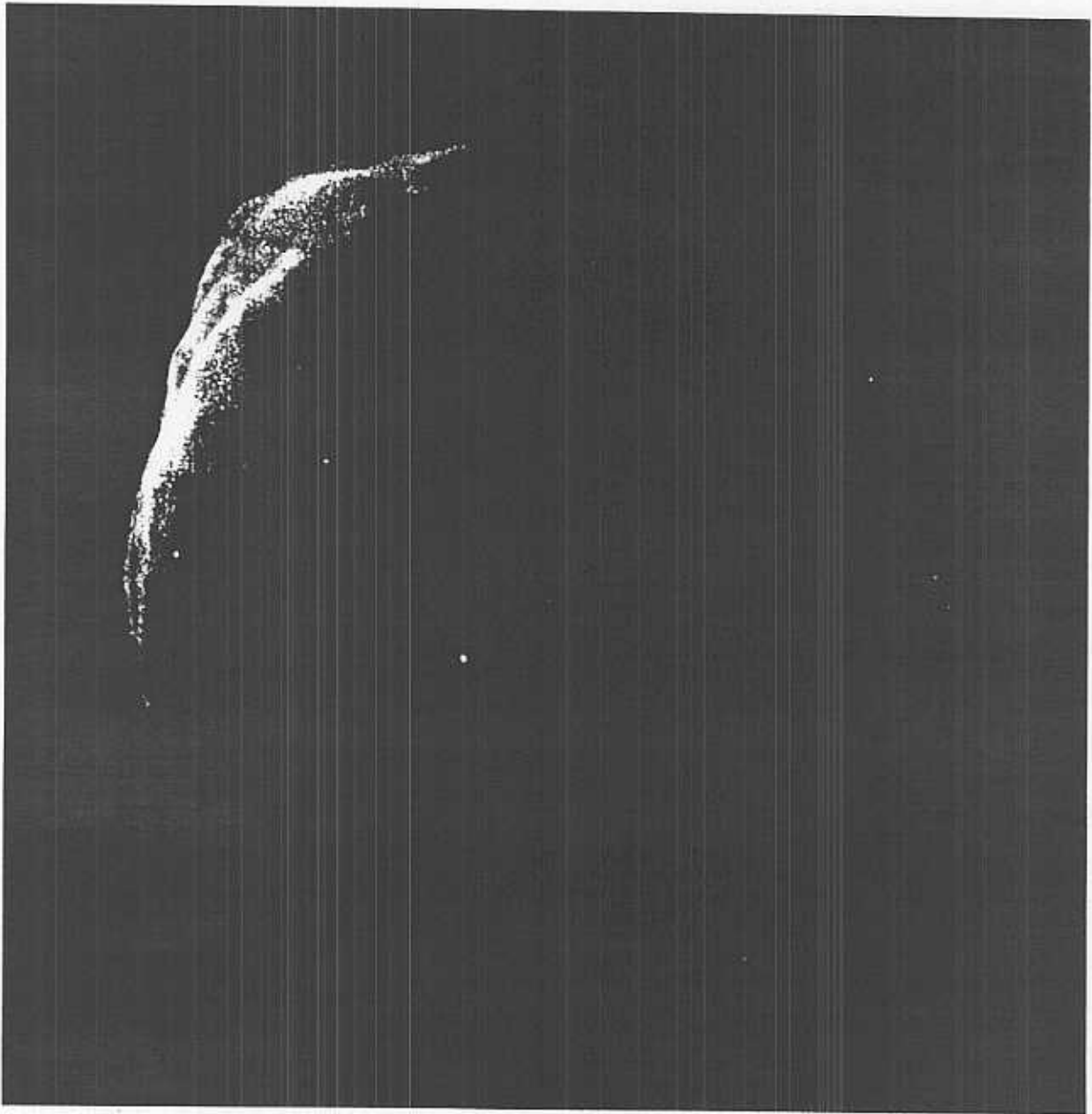
SN 1006 Radio Image

VLA 20 cm

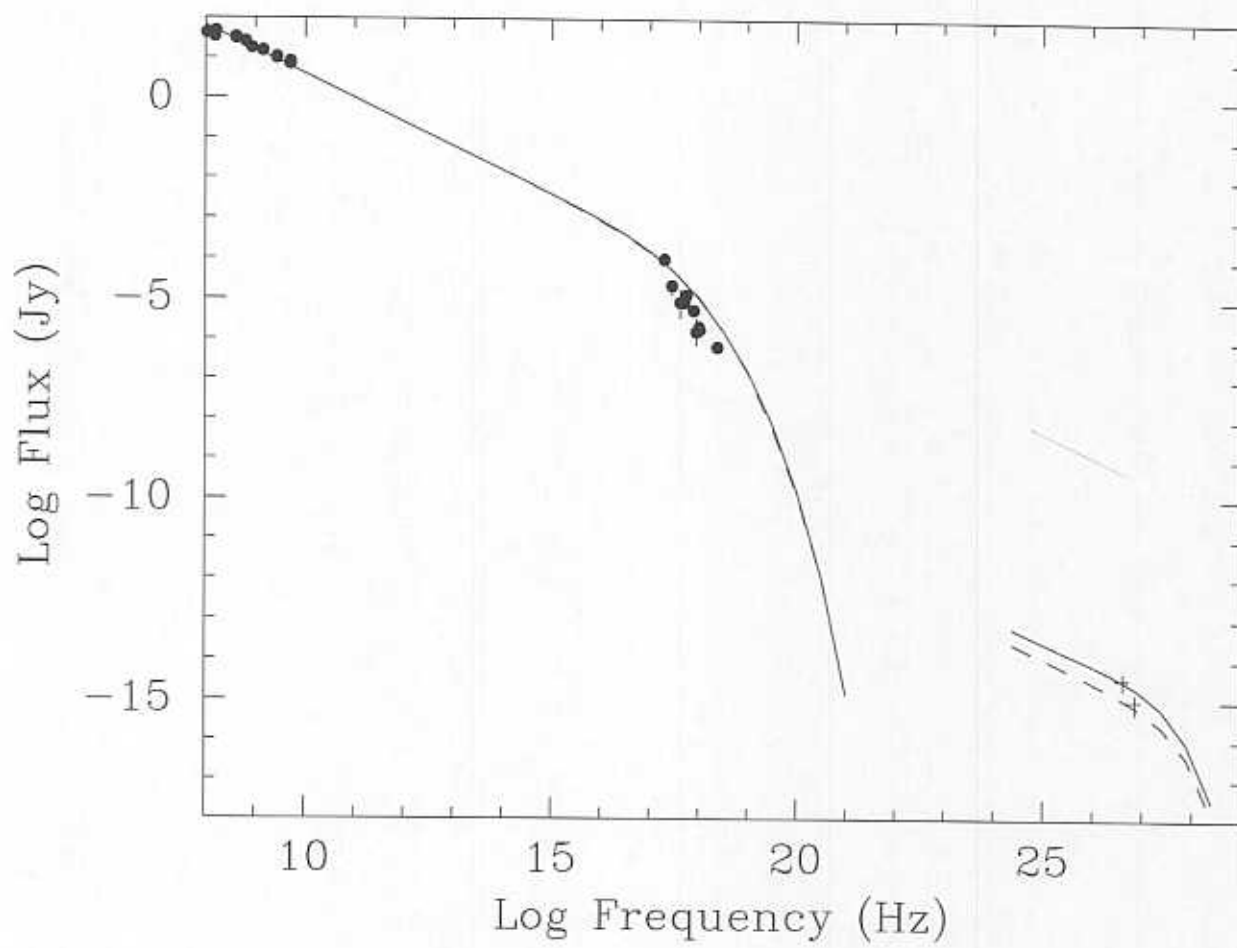SN1V.FITS_0
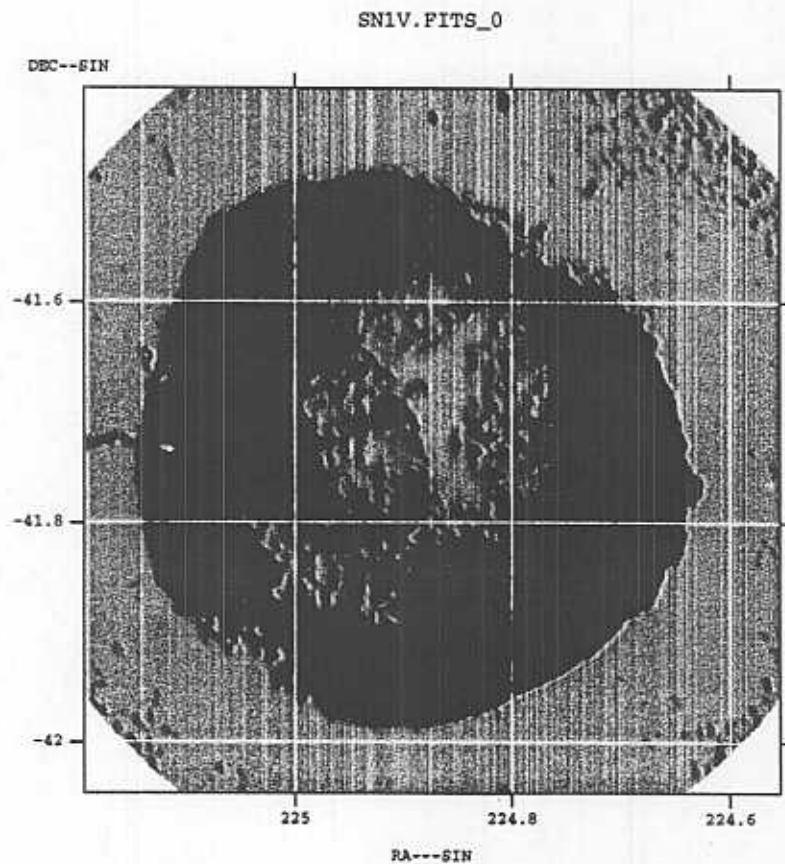
Reynolds & Gilmore 1986

SN 1006   Chandra image   (Long et al. 2003)

red: 0.5 - 0.8 keV
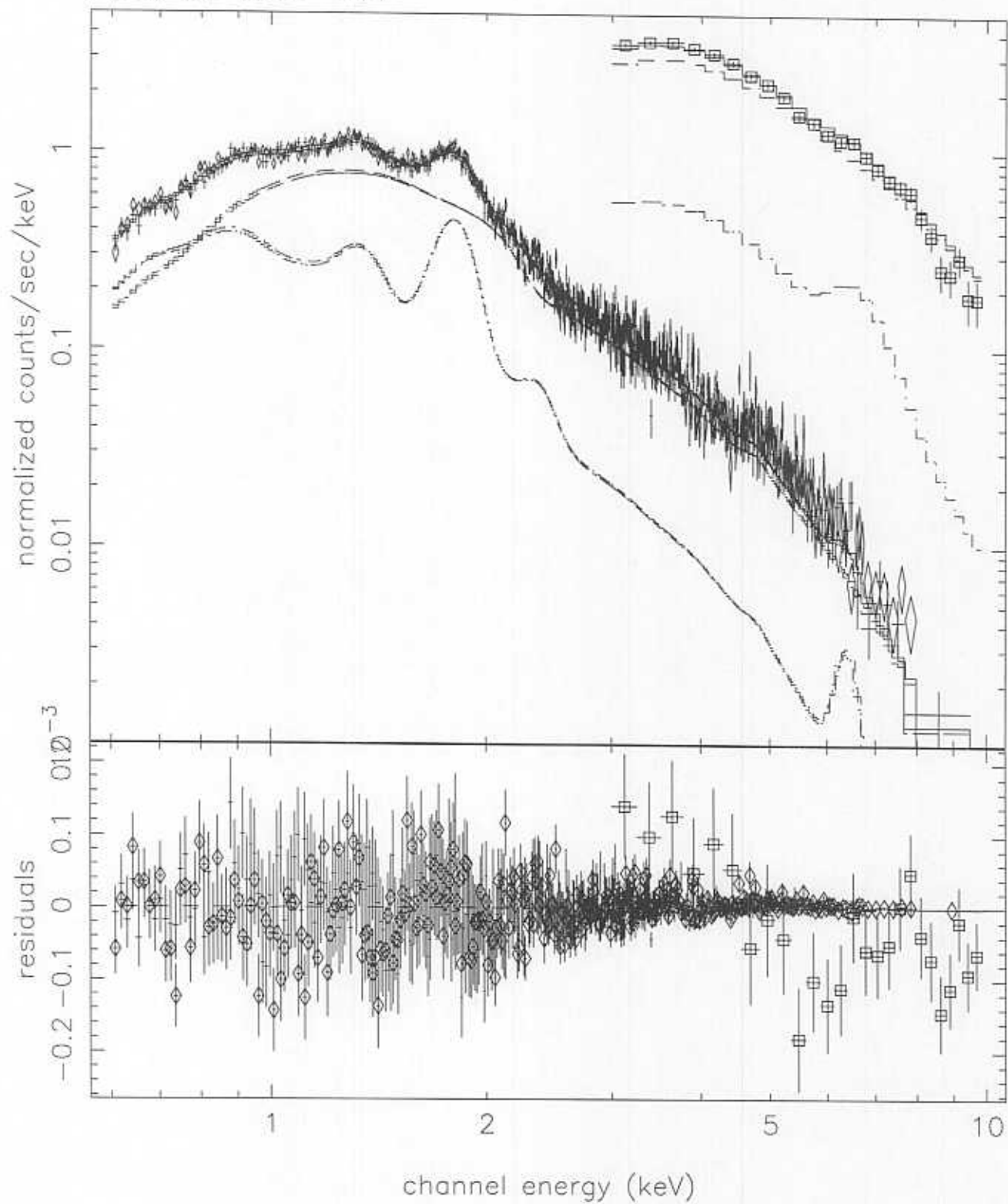blue: 1.2 - 5 keV

SN 1006 Model Synchrotron and IC Spectrum

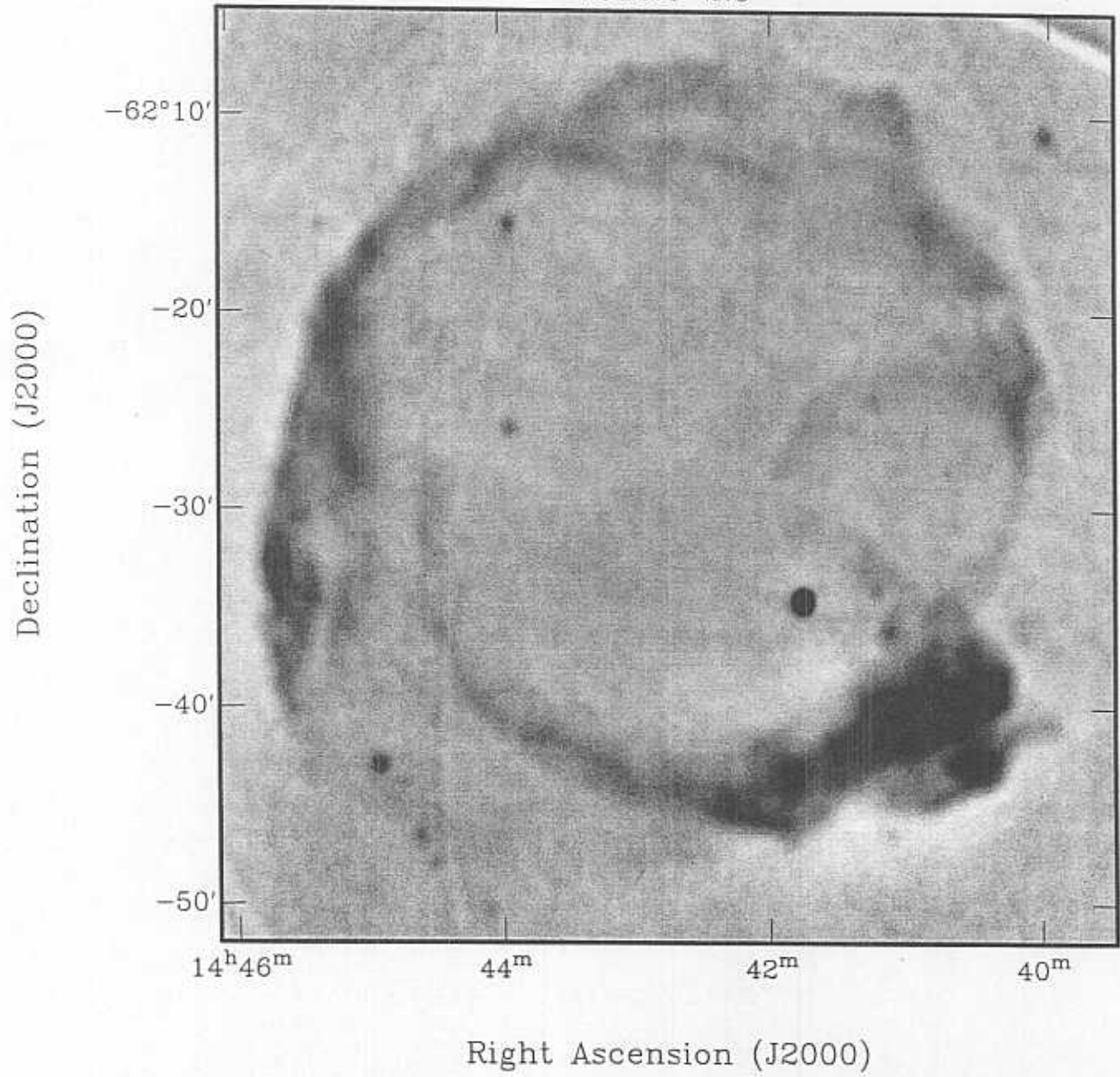Solid line: Escape, $B_1 = 3$ μG
Dashed line: Escape, $B_1 = 5$ μG

SN 1006 AD

ASCA-GIS RXTE-PCA

RCW 86

G315.4−2.3

Declination (J2000)

Right Ascension (J2000)
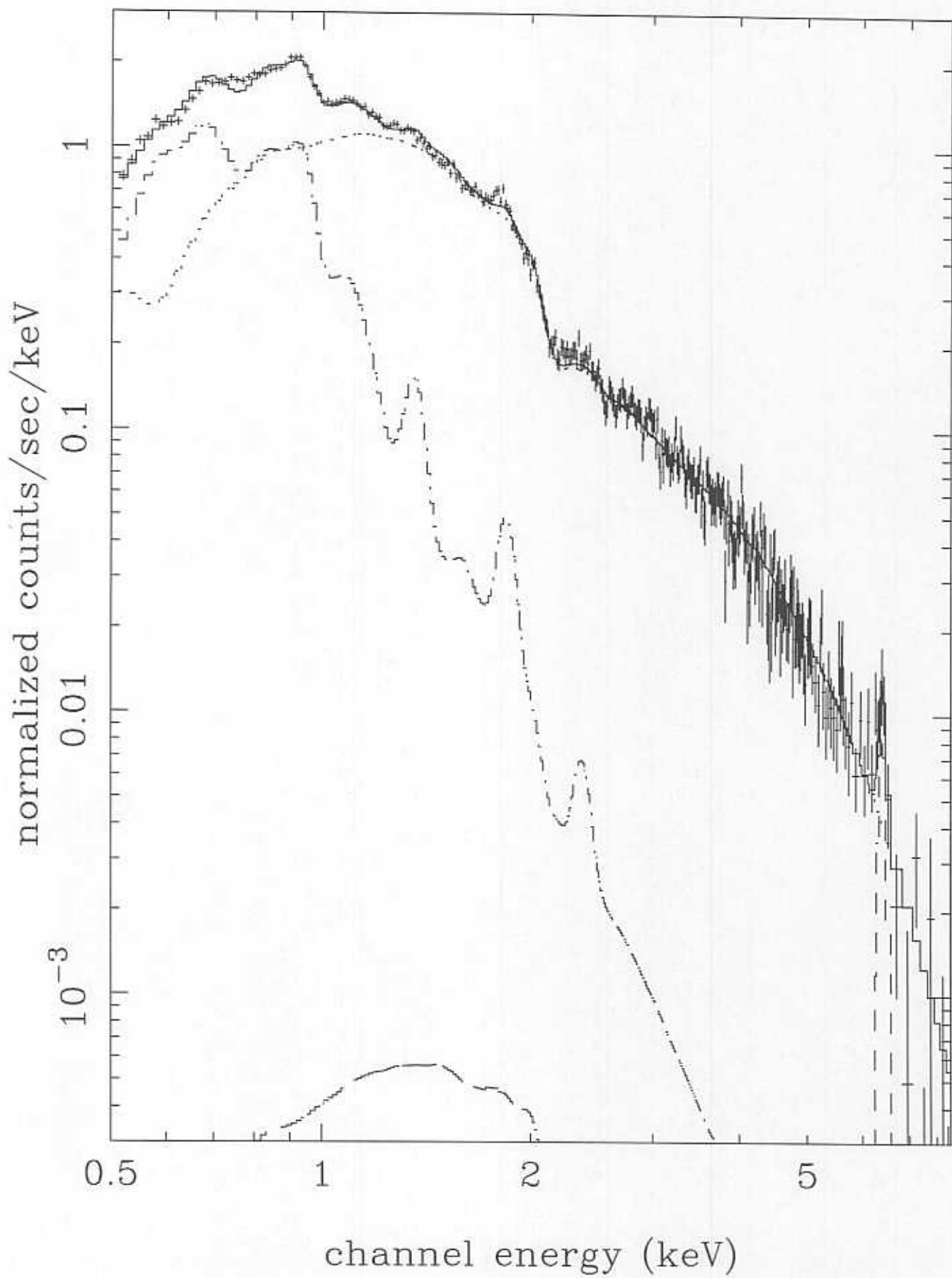
RCW 86 Chandra image
< 1 keV

Rho et al. 2003

> 2 keV

(RCW 86; Rho et al. 2003)
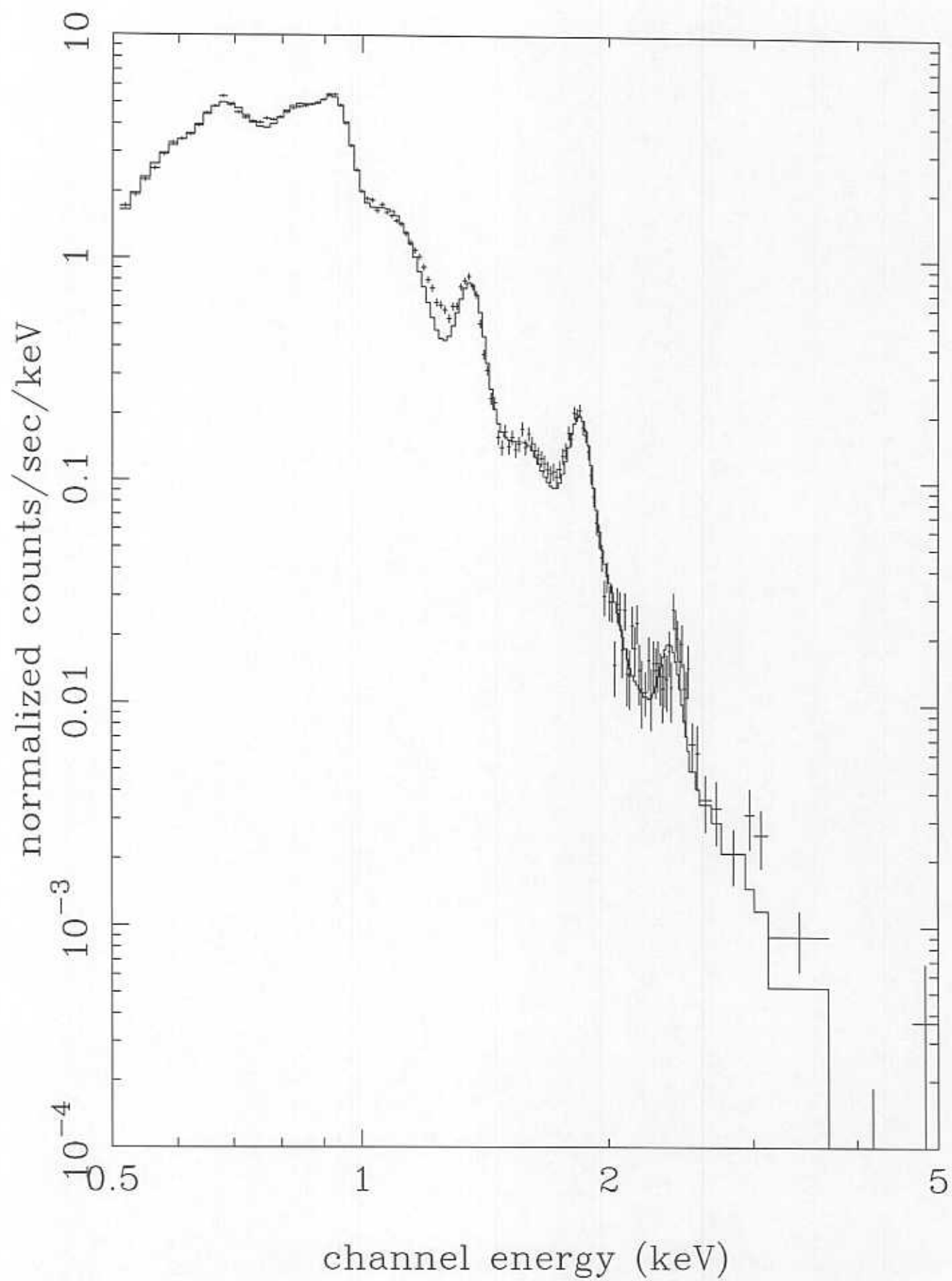
Synchrotron X-ray observations of remnants

1. SN 1006

- Well fit by model of electron escape above some E_{max}. Characteristic frequency 7×10^{17} Hz (Long et al. 2002) with known mean field (from inverse-Compton TeV emission, $\langle B \rangle \sim 10\ \mu\text{gauss}$) $\Rightarrow E_{max} = 53$ TeV

- Known shock velocity $\Rightarrow$ observed electron spectral cutoff energy too low to result from synchrotron losses ($t_{1/2}(E_{max}) \gtrsim 1200$ yr) or finite age ($t_{accel} \lesssim 800$ yr) $\Rightarrow$ change in diffusive properties for $\lambda_{MHD} \gtrsim 2 \times 10^{17}$ cm

2. RCW 86

- Weak lines in SW corner: nonsensical abundances if continuum is thermal. Energetics problems with nonthermal bremsstrahlung continuum. Solar abundances + synchrotron work well.

Rolloff frequencies $\nu_c \sim (7 - 10) \times 10^{16}$ Hz consistent with loss-limited acceleration (shock velocities from Hα emission: $600 - 900$ km s^{-1}). Loss-limited acceleration:
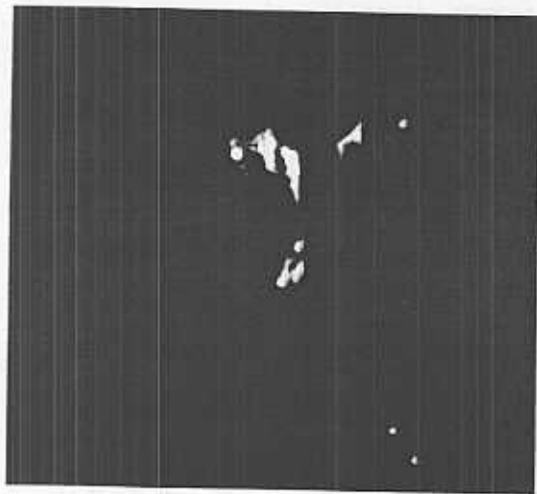
$$\nu_c = 5 \times 10^{16}\ \eta\ \frac{r}{4} \left(\frac{u_{sh}}{1000\ \text{kms}^{-1}} \right)^2 \text{Hz}$$

so need $\eta > 1$ and/or $r > 4$ again, even for perpendicular shock

G347.3-0.5
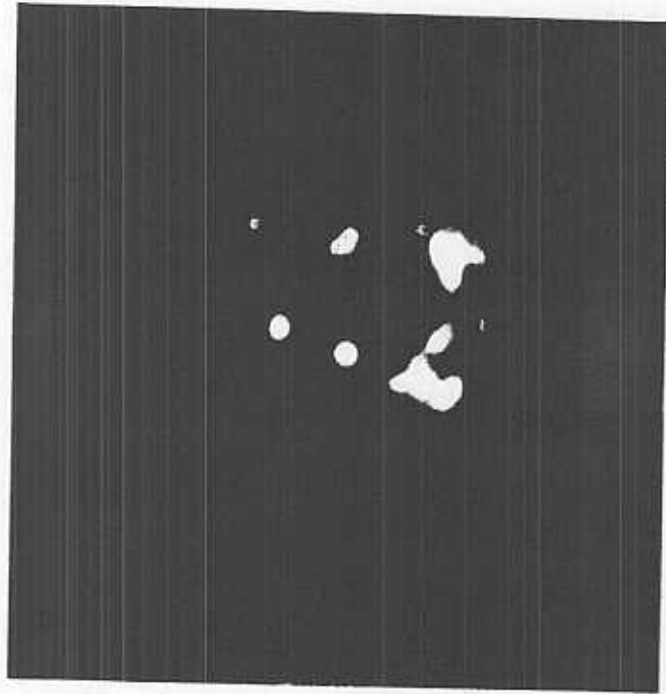
ROSAT PSPC (Slane et al. 1999)

Chandra closeup of NW corner
(Lazendic et al. 2003)

TeV observations

- All three detections have relatively steep spectra between 1 and 10 TeV: photon indices -2.5 ± 0.5 (Cas A), -2.3 ± 0.2 (SN 1006), -2.8 ± 0.2 (G347.3-0.5).

  Implication: If IC, due to dying tail of electron distribution. G347: too steep for brems. or π^0 unless on cutoff.

- Simple relations between amplitudes and peaks (in νS_ν) of synchrotron, ICCMB "echo", as functions of $\langle B \rangle$ and filling factor f_B of magnetic field:

$$B \cong 9 \times 10^4 \left(\frac{\nu_m(IC)}{\nu_m(SR)} \right)^{-1} \text{Gauss}$$

$$f_B \sim 2 \times 10^{-14} \left(\frac{S_{\text{synchr}}(\nu_m(SR))}{S_{\text{IC}}(\nu_m(SR))} \right) B^{-(s+1)/2}$$

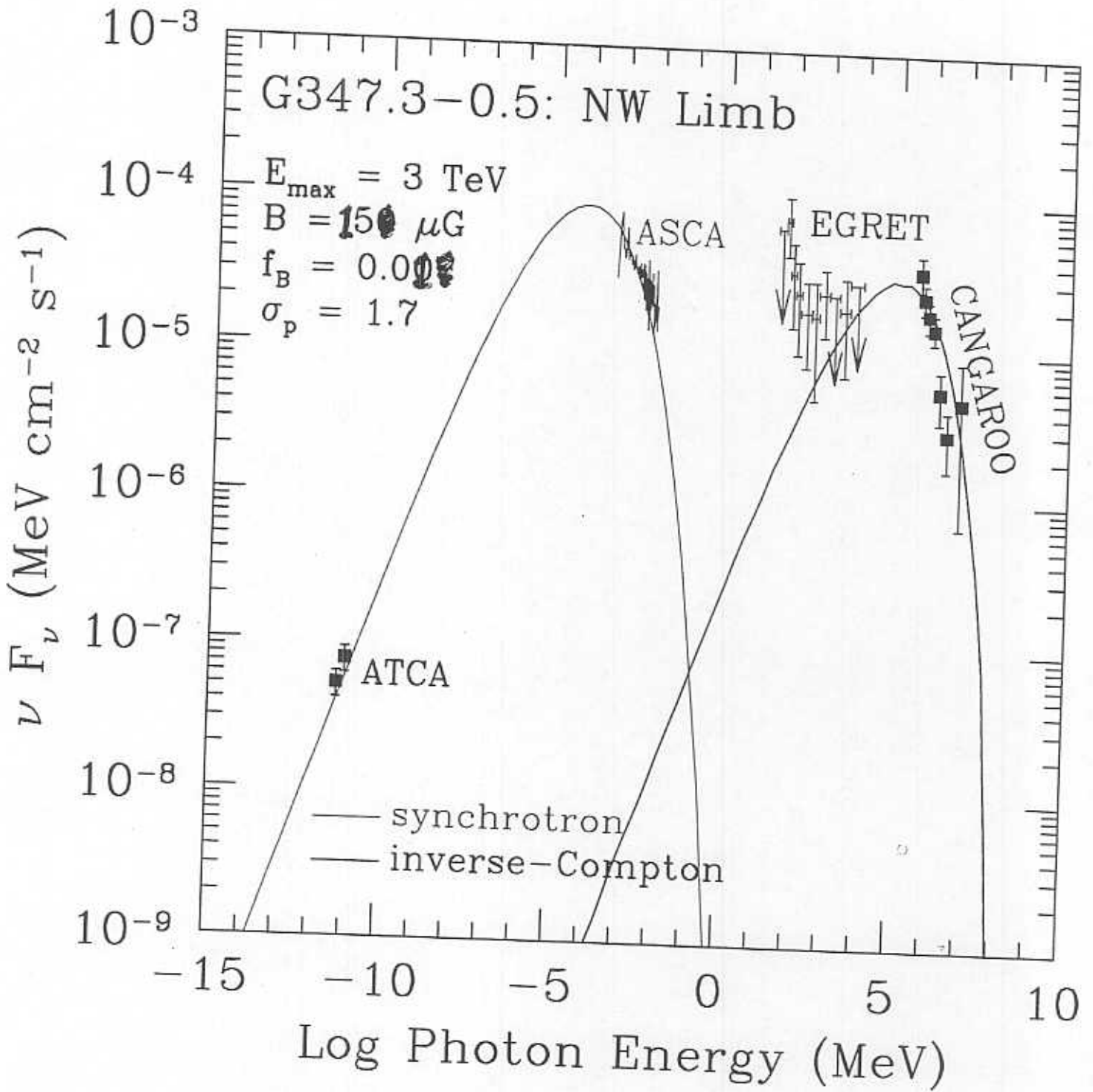G347.3-0.5 (Lazendic et al. 2002) : SR/IC model for TeV γ-rays is possible with

$$B = 15 \, \mu\text{G} \qquad\qquad f_B = 0.01$$

Energy in $B \sim 10^{46.5}$ erg – reasonable (close to equipartition with electrons)

Small f_B may be extreme, but consistent with filamentary X-ray (synchrotron) emission

Alternatives violate EGRET limits!

G347.3−0.5: NW Limb

E_{max} = 3 TeV
B = 15Ø μG
f_B = 0.00Ø2
σ_p = 1.7

ASCA

EGRET

CANGAROO

ATCA

—— synchrotron
—— inverse-Compton

νF_ν (MeV cm^{-2} s^{-1})

Log Photon Energy (MeV)

Latendic et al. 2003

Shock microphysics
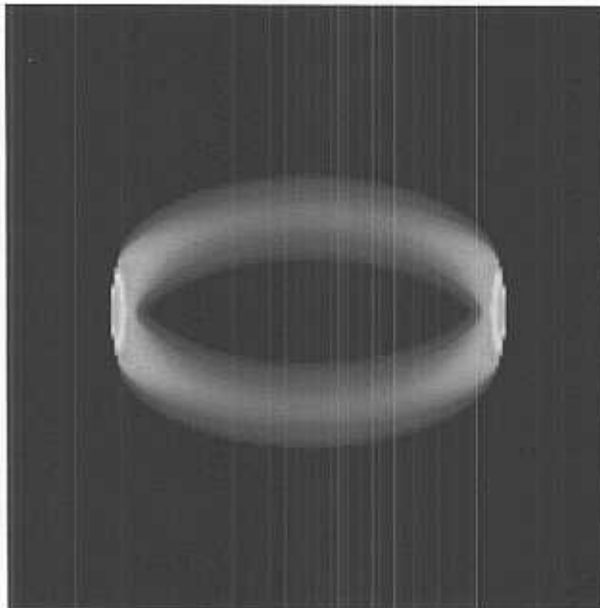
Acceleration rates depend on the diffusion coefficient $\kappa(E, \theta_{Bn}$ (θ_{Bn}: "obliquity angle" between shock normal and upstream **B**). Need *spatial simulations*. Here $\kappa \propto E^\beta$ (common: $\beta = 1$)
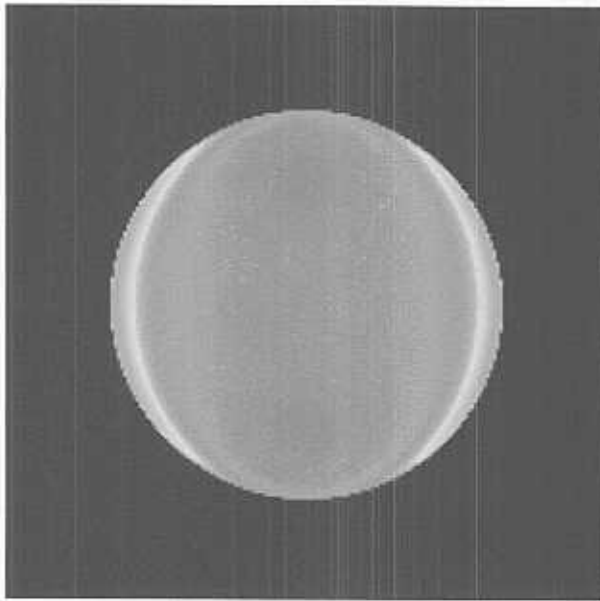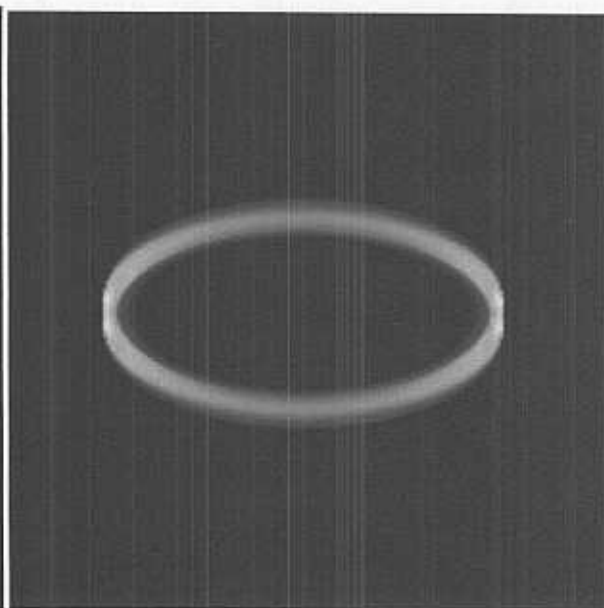

$\beta = 0.9$
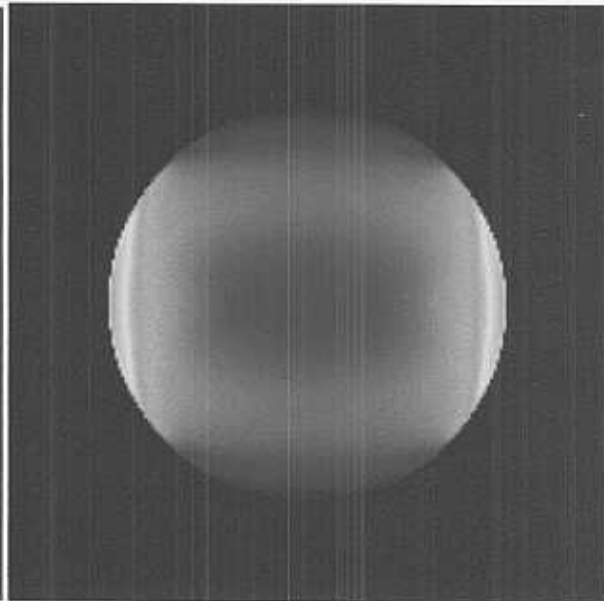
$\beta = 0.7$

$\beta = 0.5$ (Kraichnan)

$\beta = 0.33$ (Kolmogorov)

X-ray polarimetry:
a new channel to study shock-acceleration physics

1. Polarization is the bulletproof evidence of synchrotron emission.

   - Are best cases really synchrotron? (SN 1006, G347.3–0.5, G266.2–1.2)

   - How common is a contribution of synchrotron emission to thermal spectrum?

2. Polarization gives information on magnetic-field orientation and degree of order

   - Young remnants: radio polarization $\Rightarrow$ preponderance of radial field.

   - How disordered is magnetic field near the shock? Is ordered component radial in direction?

   - How do properties of acceleration depend on degree of order?

Radio observations are subject to Faraday effects (bandwidth and intrinsic depolarization) but X-ray observations will probably have poorer angular resolution. Combine for leverage.

SNR Simulations: Total Intensity
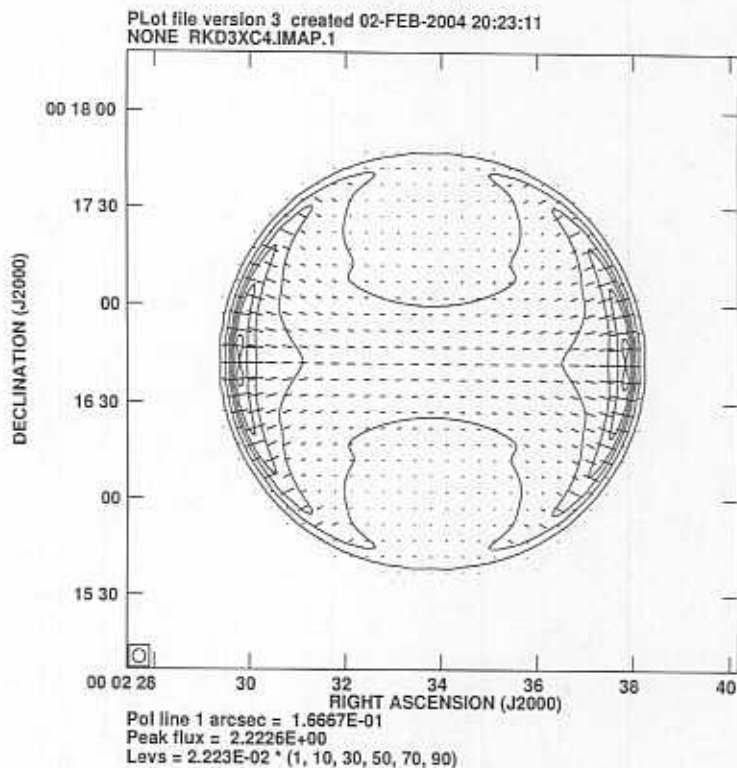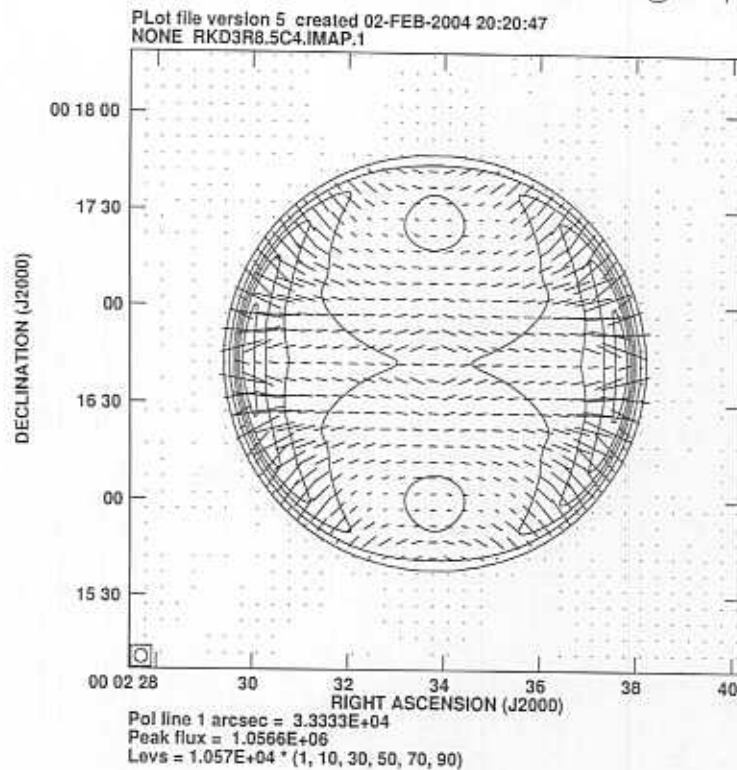## Ordered magnetic field, aspect angle $\phi = 60°$
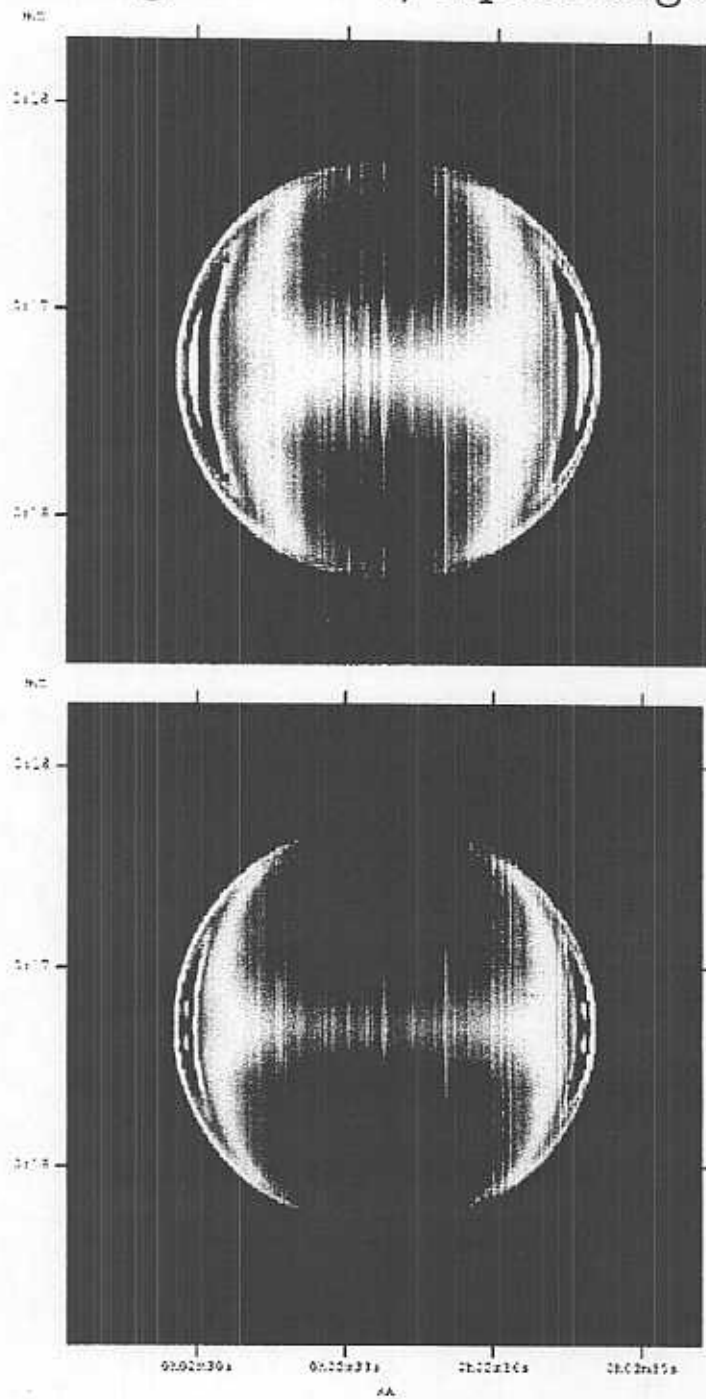
Top: Radio (300 MHz); Bottom: X-ray (1 keV)

Sedov dynamics, magnetic field compressed in shock, evolving by flux freezing thereafter.

SNR Simulations: Polarization
Ordered magnetic field, aspect angle $\phi = 60°$

PLot file version 5 created 02-FEB-2004 20:20:47
NONE RKD3R8.5C4.IMAP.1

Pol line 1 arcsec = 3.3333E+04
Peak flux = 1.0566E+06
Levs = 1.057E+04 * (1, 10, 30, 50, 70, 90)

PLot file version 3 created 02-FEB-2004 20:23:11
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Peak flux = 2.2226E+00
Levs = 2.223E-02 * (1, 10, 30, 50, 70, 90)

Top: Radio (300 MHz); Bottom: X-ray (1 keV)
Sedov dynamics, magnetic field compressed in shock, evolving
by flux freezing thereafter. Smoothed to 32 beams/diameter.

Summary: some recent results

- There is still no known shell remnant with unbroken radio-to-X-ray spectrum. All SNR electron spectra begin to steepen below $\sim$100 TeV.

- Simple radio-to-X-ray spectral models of synchrotron emission from an electron distribution $N(E) = KE^{-s}\exp(-E/E_{\mathrm{max}})$ (XSPEC: *SRCUT*) are surprisingly robust when applied to SNRs with synchrotron components.

- Proper-motion expansion results may differ between radio and X-rays if ejecta are highly inhomogeneous.

- RCW 86 appears to have electron acceleration to TeV energies in reverse shocks. Radio–X-ray morphological comparison supports this.

- Broad-band fitting (radio to TeV) can produce strong constraints (e.g., small filling factor for $\mathbf{B}$ in G347.3–0.5).

Important problems for the future

Theory

- How does efficiency of particle acceleration affect thermal properties of shocks? Can efficiency be unambiguously derived from thermal X-ray diagnostics?

- Amplification of magnetic field in efficient shocks?

- Electron *injection* is still not understood. Obliquity-dependence? (SN 1006: caps or equatorial barrel?)

- Shock precursors: not seen. Synchrotron halos? Broadening of narrow component of Balmer lines in Ia remnants?

- Nonthermal bremsstrahlung: need to include postshock Coulomb losses; effects on ionization and line excitation

Observations

- Curvature of integrated radio spectra? Spatial variations with longer frequency baselines?

- Routinely adding single-dish data to interferometer maps: eliminate missing-flux uncertainties

- High energy resolution X-ray spectra to separate thermal and nonthermal continua

- X-ray polarimetry?