The Radio Sky

Lecture 15

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Recognizing synchrotron contamination

- Spectral index: thin free-free cannot be steeper than ≈ -0.15. A steeper index needs a non-thermal component.
- Polarization: free-free is unpolarized; any significant linear polarization is non-thermal (or foreground leakage).
- RRL-predicted continuum: with $T_{\rm e}$ known, the line flux predicts the thermal continuum; an excess is non-thermal.
- Mid-IR: H II regions have a tight mid-IR/radio flux ratio (warm dust); SNRs and radio galaxies are radio-bright relative to mid-IR.

Observational pitfalls

Interferometers filter out extended emission differently at different frequencies. Spectral indices from mismatched *uv* coverage can be spuriously steep. Compare images at matched resolution and *uv* range.

Ionizing photons from thin free-free flux

Recap (L4): thin free-free L_ν and ionization balance Q share the same $\int n_\mathrm{e} n_\mathrm{p}\,\mathrm{d}V$, so Q/L_ν depends only on T_e and ν. With $L_\nu = 4\pi D^2 S_\nu$ (He ionization ignored):

$$Q \approx 7.5 \times 10^{46}\,\mathrm{s}^{-1} \left(\frac{S_\nu}{\mathrm{Jy}}\right) \left(\frac{D}{\mathrm{kpc}}\right)^2 \left(\frac{\nu}{\mathrm{GHz}}\right)^{0.1} \left(\frac{T_\mathrm{e}}{10^4\,\mathrm{K}}\right)^{-0.45}$$

- Equivalent to Condon (1992) eq. for Q in terms of L_ν, doi:10.1146/annurev.aa.30.090192.003043. The $T_\mathrm{e}^{-0.45}$ and $\nu^{0.1}$ factors are power-law fits to g_ff and α_B.
- Q is linear in S_ν: flux $\rightarrow$ photon rate needs only D and T_e.

Worked example: how many O stars?

An optically thin H II region: $S_{5\,\mathrm{GHz}} = 3.0\,\mathrm{Jy}$, $D = 4.0\,\mathrm{kpc}$, $T_\mathrm{e} = 8000\,\mathrm{K}$ (RRL). Illustrative values.

$$Q \approx 7.5 \times 10^{46} \times 3.0 \times 4.0^2 \times 5^{0.1} \times 0.8^{-0.45} \approx 4.7 \times 10^{48}\,\mathrm{s}^{-1}$$

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- Comparable to a single mid-O main-sequence star [Martins et al. 2005, doi:10.1051/0004-6361:20042386], *or* several later-type O stars: radio alone cannot tell.
- The radio Q is a lower limit on the stellar output: dust and leakage (above), and any optically thick component is underestimated.
- D enters squared: an error in D changes Q by a large factor.

Concept test

Question

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Answer: it is four times higher

1. Optically thin free-free flux traces $n_{\mathrm{e}} n_{\mathrm{p}} V$, which ionization balance sets equal to Q/α_{B}.
2. At fixed T_{e} and D the relation $Q \propto S_{\nu}$ is linear: $4\times$ the flux gives $4 \times Q$.

Retrieval: shells versus H II regions

From Lectures 4 and 6 and earlier in this lecture

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- SNR shells: synchrotron from a power-law population of relativistic electrons, $N(E) \propto E^{-s}$, giving $\alpha = -(s-1)/2 \approx -0.5$ for $s \approx 2$.
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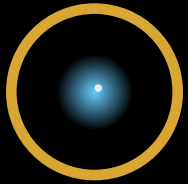
Central question

How do radio remnants reveal shocks, relativistic particles, magnetic fields, and compact-object energy input?

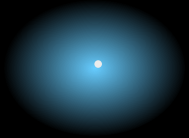
Three radio morphologies



shell-type
$\alpha \approx -0.5$



composite
shell + central nebula

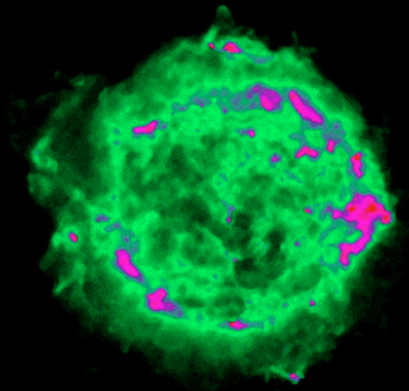


plerion / PWN
$-0.3 \lesssim \alpha \lesssim 0$

Schematic. White dot: pulsar.

- Shell: particles accelerated at the expanding blast wave.
- PWN (plerion, "filled"): particles and field injected by a central pulsar.
- Most catalogued Galactic SNRs are shells; catalogue in Green (2025), doi:10.1007/s12036-024-10038-4.

Cassiopeia A: a young shell remnant



Credit: Cas A, VLA radio continuum. NRAO/AUI/NSF, public domain, via Wikimedia Commons

Dynamical stages (only what radio interpretation needs)

Units: cgs. $E = 10^{51} E_{51}$ erg, ejecta mass $M_{\rm ej}$, ambient density $\rho_0 = 1.4 m_{\rm p} n_0$ (uniform medium assumed).

1. Free expansion: ejecta coast at $v_{\rm ej} \approx (2E/M_{\rm ej})^{1/2}$ until they sweep up $\sim M_{\rm ej}$:

$$R \approx \left(\frac{3M_{\rm ej}}{4\pi\rho_0}\right)^{1/3} \approx 2\,{\rm pc}, \quad t \approx 250\,{\rm yr} \quad (1.4M_\odot,\ n_0 = 1).$$

2. Sedov–Taylor (energy-conserving blast wave): $R \propto t^{2/5}$ [Taylor 1950, doi:10.1098/rspa.1950.0049].
3. Radiative (snowplough): once post-shock $T \lesssim 10^6$ K, cooling removes pressure; a dense cool shell forms after a few $\times 10^4$ yr; expansion slows further.

- A reverse shock propagates back into the ejecta (composite remnants, below).
- Full treatment: Truelove & McKee (1999), doi:10.1086/313176.

Which electrons does radio see?

From L4 and L7: characteristic frequency $\nu \approx \frac{3}{2}\gamma^2\nu_{\rm g}$, with $\nu_{\rm g} = 2.8\,{\rm Hz}\,(B/\mu{\rm G})$; synchrotron lifetime (cgs, pitch-angle averaged) $t_{\rm sync} = 6\pi m_{\rm e}c/(\sigma_{\rm T}\gamma B^2)$.

	B	γ	E	$t_{\rm sync}$
1 GHz radio	$10\,\mu$G	4.9×10^3	2.5 GeV	5×10^7 yr
1 GHz radio	$100\,\mu$G	1.5×10^3	0.8 GeV	1.6×10^6 yr
1 keV X-ray	$100\,\mu$G	2.4×10^7	12 TeV	≈ 100 yr

- Radio electrons ($\sim$GeV) hardly cool over an SNR lifetime: the radio spectrum reflects acceleration and transport, not ageing.
- X-ray synchrotron electrons cool in ~ 100 yr: thin X-ray rims imply $B \sim 100\,\mu$G, far above the $\sim$few μG ISM field [Reynolds 2008, doi:10.1146/annurev.astro.46.060407.145237].

Magnetic-field amplification and polarization

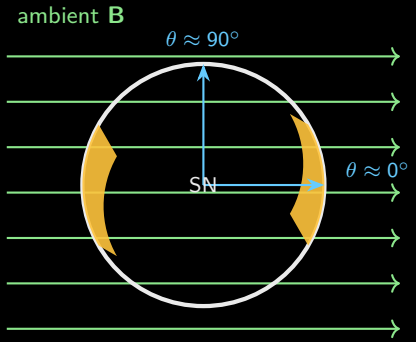
- Compression of the ambient field alone gives at most a factor $r = 4$ (perpendicular component).
- Cosmic-ray-driven instabilities can amplify turbulent fields far more [Bell 2004, doi:10.1111/j.1365-2966.2004.08097.x].
- Year-scale X-ray variability suggests mG fields in places [Uchiyama et al. 2007, doi:10.1038/nature06210].

Polarization patterns

- Young SNRs: predominantly radial projected field (Rayleigh–Taylor stretching at the contact discontinuity).
- Older SNRs: tangential field (compressed ambient field).
- Fractions typically a few to $\sim 20\%$: turbulence and Faraday depolarization (L6) reduce them.

Review: Reynolds, Gaensler & Bocchino 2012, doi:10.1007/s11214-011-9775-y.

Why a round shock is not uniformly bright

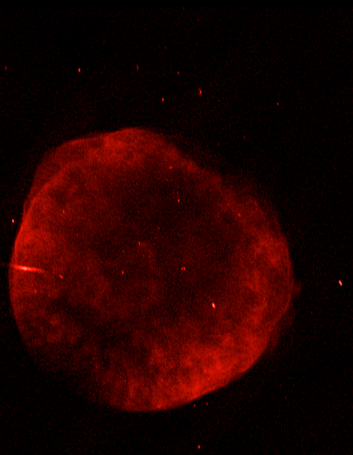


Shaded: shock normal nearly parallel to **B**.

- The explosion is round; the ambient field is not: it gives one preferred axis.
- θ = angle between **B** and the shock normal. It runs from $0°$ (quasi-parallel) to $90°$ (quasi-perpendicular) around the shell.
- Electron injection and acceleration efficiency depend on θ, so only part of the shell is bright.
- Result: two bright limbs (bilateral SNR), as in SN 1006 (next slide).

Which θ is favoured is debated; a density gradient can mimic the effect.

SN 1006: acceleration depends on shock geometry



Credit: SN 1006 radio continuum: VLA + GBT, K. Dyer, R. Maddalena & T. Cornwell, NRAO/AUI/NSF. Public domain, via Wikimedia Commons. Note the two bright limbs (bilateral morphology)

Concept test

Question

A resolved shell source has $\alpha = -0.5$ and appreciable linear polarization. Is thermal free-free or synchrotron emission more likely?

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Answer: synchrotron

1. $\alpha = -0.5$ is much steeper than optically thin free-free (≈ -0.1), and thick free-free would be rising ($+2$).
2. Significant linear polarization requires an ordered field acting on relativistic electrons: synchrotron. Free-free is unpolarized.

Pulsar-wind nebulae: central injection

- A young pulsar loses rotational energy at

$$\dot{E} = 4\pi^2 I \dot{P} / P^3$$

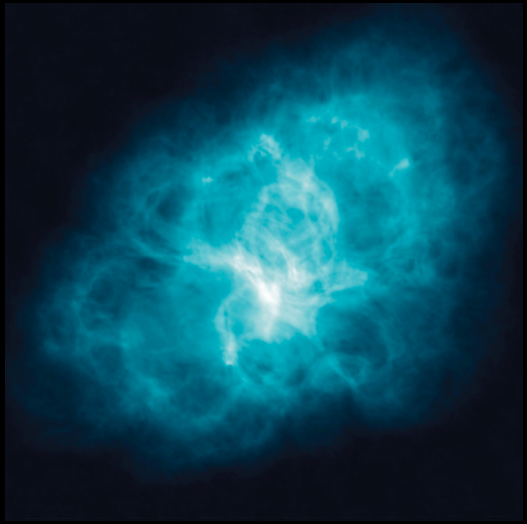
  ($I \approx 10^{45}\,\mathrm{g\,cm^2}$, cgs).
- Crab: $P = 33\,\mathrm{ms}$, $\dot{P} = 4.2 \times 10^{-13}$ $\Rightarrow \dot{E} \approx 4.5 \times 10^{38}\,\mathrm{erg\,s^{-1}}$.
- The energy leaves as a relativistic wind of $e^{\pm}$ and field; a termination shock turns it into a synchrotron nebula confined by the ejecta.

Radio signatures

- Centre-filled (plerionic) morphology
- Flat spectrum: $-0.3 \lesssim \alpha \lesssim 0$ (Crab ≈ -0.3, Baars et al. 1977)
- High linear polarization, ordered field
- Spectral breaks between radio and X-ray

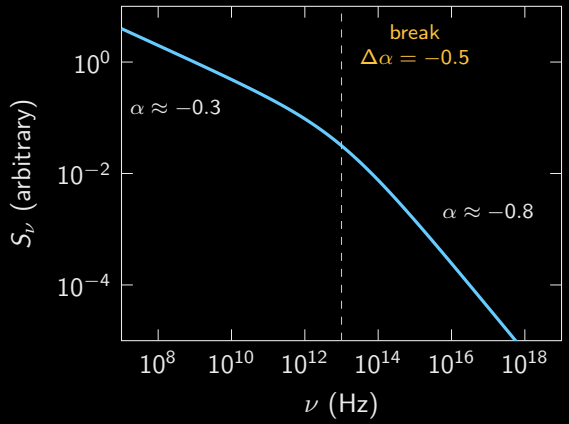
Review: Gaensler & Slane 2006, doi:10.1146/annurev.astro.44.051905.092528.

The Crab Nebula in radio



Credit: Crab Nebula, VLA radio continuum. NRAO/AUI and M. Bietenholz, CC BY 4.0, via Wikimedia Commons

PWN spectra: flat radio, breaks, and an open question



Schematic broken power law; break frequency arbitrary.

- Cooling break: above ν_b, electrons radiate faster than the nebula's age; continuous injection steepens α by 0.5 (L7). $\nu_\mathrm{b} \propto B^{-3} t^{-2}$.
- Observed breaks often differ from 0.5 and sometimes lie where cooling cannot explain them: an intrinsic break in the injected spectrum.
- Origin of the flat radio-emitting electrons (relic or injected?) is not settled.

Composite remnants and environmental shaping



Credit: W50: VLA radio continuum (green) on WISE infrared (red). NRAO/AUI/NSF, K. Golap, M. Goss; NASA WISE. CC BY 4.0, nrao.edu. The elongation is attributed to the jets of the central X-ray binary SS 433

Composite remnants: what to look for

- A synchrotron shell *plus* a central PWN.
- The reverse shock can collide with the PWN, displacing or crushing it: offset, distorted nebulae.
- A fast-moving pulsar can leave the PWN behind, or exit the shell (bow-shock nebula).
- Environmental shaping: density gradients, nearby molecular clouds, and jets (W50 / SS 433) distort the shell. Morphology alone does not give the explosion type.

Identification

A central compact source is a PWN only if its spectrum is flat, polarization high, and ideally a pulsar (radio or X-ray) is detected. A background radio galaxy can mimic a "central" source in projection.

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Answer: a pulsar-wind nebula

1. A central pulsar continuously supplies relativistic particles and field.
2. This produces a centre-filled (plerionic), flat-spectrum, polarized nebula rather than a limb-brightened shell.

Low-frequency turnovers: absorption or curvature?

- Free-free absorption by foreground or internal ionized gas: $S_\nu \propto \nu^\alpha \mathrm{e}^{-\tau_\nu}$, $\tau_\nu \propto T_\mathrm{e}^{-1.35} \nu^{-2.1} \mathrm{EM}$ (L4).
- $\tau_\nu = 1$ at 74 MHz needs $\mathrm{EM} \approx 10^4\,\mathrm{pc\,cm^{-6}}$ ($T_\mathrm{e} = 8000\,\mathrm{K}$): a foreground H II region or ionized envelope.
- Cas A: internal absorption by cold, unshocked ejecta [DeLaney et al. 2014, doi:10.1088/0004-637X/785/1/7].
- Intrinsic curvature: non-linear shock acceleration or multiple electron populations; gentle curvature, no exponential cutoff.

Discriminating observations

- Sample below the turnover: exponential drop vs mild bend
- Resolved low-frequency α maps: patchy absorption follows foreground gas
- RRLs or Hα toward the absorbing gas
- Matched-resolution images at all frequencies

Opening retrieval: choose the first tracer

For each target, name the single best first radio tracer

1. Dense ($n \gtrsim 10^4\,\mathrm{cm}^{-3}$), cool molecular gas
2. Diffuse ionized gas at $T_\mathrm{e} \sim 10^4\,\mathrm{K}$
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1. Molecular lines (e.g. NH_3 inversion at 23.7 GHz, or mm CO): excited only in dense gas.
2. Free-free continuum with $\alpha \approx -0.1$ when thin, plus radio recombination lines for T_e and velocity (Lectures 4, 14).
3. Synchrotron continuum: steep α and linear polarization (Lectures 4 and 6).

Today all three occur along the same sight line, within a few arcminutes of each other.

Central question

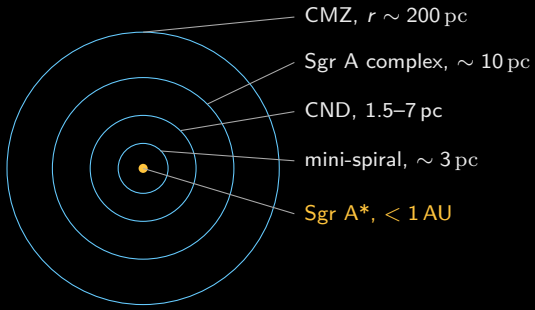
How can multi-tracer radio observations disentangle the densest and most confused region in the Milky Way?

- Lectures 3–15 built each diagnostic in isolation: free-free, synchrotron, H I, molecules, masers, H II regions, SNRs.
- The Galactic Centre puts them all in one field of view, at one distance, with severe projection.
- The skill today is combining tracers and stating which conclusions are observed and which are inferred.

Units: SI unless stated; radio quantities in Jy, pc, cm^{-3}, $\mathrm{pc\,cm^{-6}}$ as is conventional.

Geometry and scales

- Distance $R_0 = 8.18\,\mathrm{kpc}$ (GRAVITY Collaboration 2019, doi:10.1051/0004-6361/201935656).
- At R_0: $1'' \approx 0.040\,\mathrm{pc}$, $1' \approx 2.4\,\mathrm{pc}$, $1^\circ \approx 143\,\mathrm{pc}$.
- Central Molecular Zone (CMZ): inner $\sim 200\,\mathrm{pc}$ in radius, $|l| \lesssim 1.5^\circ$; a few $\times 10^7\,M_\odot$ of dense molecular gas.
- Visual extinction $A_V \sim 30\,\mathrm{mag}$: the optical centre is invisible.



Schematic: nested scales, not to scale.

CMZ mass: Henshaw et al. 2023 review, doi:10.26624/rlid5348. CND = circumnuclear disk.

Why radio, and what radio pays for it

Advantage

- Dust is transparent: $A_V \sim 30$ mag is an optical attenuation of 10^{-12}.
- Continuum separates thermal and non-thermal plasma; lines give velocities through the whole column.
- Interferometers give arcsecond (sub-pc) resolution.

Costs

- Projection: 8 kpc of disc in front, more behind; no depth information in an image.
- Scattering: turbulent ionized gas blurs compact sources as λ^2.
- Free-free absorption at low frequency by dense H II.
- Velocity confusion: all circular-orbit disc gas along $l = 0$ has $v_{\rm LSR} \approx 0$.

These are not details: each one has produced a published misinterpretation. We treat them as part of the measurement.

Summary and further reading

- Q from thin free-free flux is linear in S_ν and D^2; a steep index, polarization or a mid-IR deficit flags synchrotron contamination.
- Shell SNRs: synchrotron from shock-accelerated electrons ($\alpha \approx -0.5$, young remnants steeper); the shock geometry relative to the ambient field makes limbs bright (SN 1006).
- PWNe: flat radio spectrum, central injection, composites combine both components; low-frequency turnovers need care.
- The Galactic Centre is read through several tracers, each with its own selection effects.

Further reading

Reynolds, Gaensler & Bocchino 2012 (SNR radio); Condon 1992 (ARA&A, free-free); Truelove & McKee 1999 (SNR evolution); Morris & Serabyn 1996 (Galactic Centre); ERA Ch. 4 and TRA Ch. 11.