The Radio Sky

Lecture 13

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PHY-236.3



Class I and Class II masers: methanol as the example

CH_3OH masers split by pump (Menten 1991), so they sit in different places.

Class I: collisional

- 36.2, 44.1, 95.2 GHz.
- Pumped by H_2 collisions in shocks.
- Offset from protostars: outflows, cloud collisions.

Class II: radiative

- 6.668, 12.178 GHz.
- Pumped by infrared photons from protostellar dust.
- Coincident with the protostar; very bright.

The 6.668 GHz line appears only in massive star formation: a signpost and a VLBI parallax target.

Recap: plasma emission, and why the Sun is full of it

Mechanism (Lecture 9)

An electron beam makes Langmuir waves at $\nu_{\rm p} = 8.98\,{\rm kHz}\,(n_{\rm e}/{\rm cm}^{-3})^{1/2}$, which convert to escaping radio waves at $\nu_{\rm p}$ or $2\nu_{\rm p}$: coherent, $T_{\rm b} \gg 10^{10}$ K.

Frequency measures density

$n_{\rm e} \sim 10^6$–$10^{10}\,{\rm cm}^{-3}$ from the high to the low corona gives $\nu_{\rm p} \sim 10$ MHz–1 GHz.

Why the Sun

- Beams are common: flares accelerate electrons to ~ 0.1–$0.5c$.
- Plasma-dominated: with $B \sim 1$–10 G in the corona, $\nu_{\rm p} \gg \nu_{\rm G}$, so the electron-cyclotron maser (needs $\nu_{\rm p} \ll \nu_{\rm G}$) is suppressed.
- A density gradient: $n_{\rm e}$ falls steeply outward, so beam position is encoded in frequency.

Opening question

Retrieval (Lecture 9)

A Solar burst at metre wavelengths is bright, narrow at each instant, and its emission frequency *drifts* with time, from high to low. Which emission mechanism is most likely, and why does the frequency drift?

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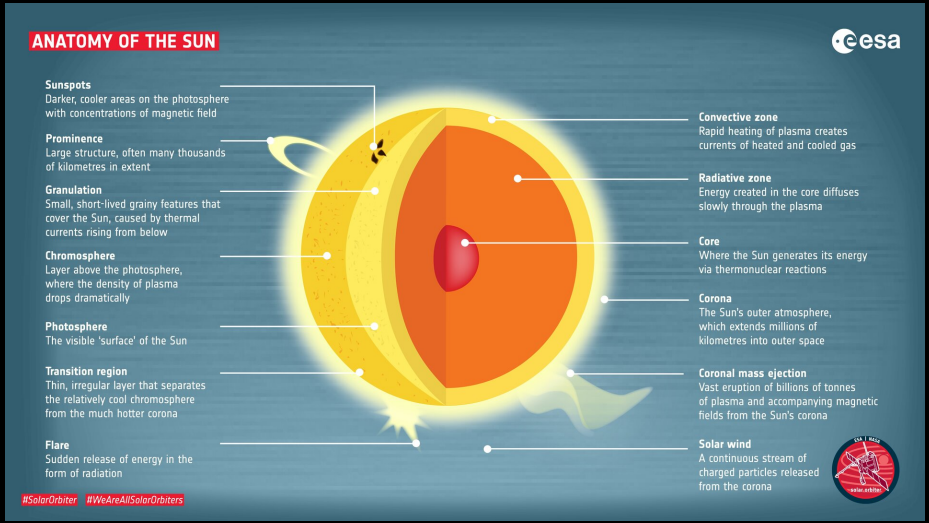
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- Plasma emission: an outward-moving exciter meets falling n_e, so $\nu_p \propto n_e^{1/2}$ drifts to lower frequency.
- The drift rate measures the exciter speed, given a density model.

Central question

How does the resolved Solar atmosphere demonstrate thermal, magnetic, plasma and coherent radio processes in one object?

The Solar atmosphere



Credit: ESA / Solar Orbiter, “Anatomy of the Sun” infographic (ESA and Solar Orbiter marks on the image). [exact ESA page to be confirmed]

Layers that matter for radio

Layer	T (K)	$n_{\rm e}$ (cm^{-3})	Radio window
Photosphere	$\sim 6 \times 10^3$	–	sub-mm (not reached at radio)
Chromosphere	$\sim 10^4$	$\sim 10^{10}$–10^{11}	mm, short cm
Transition region	$10^4 \rightarrow 10^6$	falling	cm
Corona (base)	1–2×10^6	$\sim 10^8$–10^9	dm, m

Representative orders of magnitude; the real atmosphere is structured and dynamic.

- Rule of thumb: lower frequency $\Rightarrow$ emission forms higher in the atmosphere.
- Two reasons: free-free opacity $\kappa_\nu \propto n_{\rm e}^2 T^{-3/2} \nu^{-2}$ (Lecture 4), and the plasma cutoff: waves with $\nu < \nu_{\rm p}$ cannot propagate,

$$\nu_{\rm p} = 8.98\,{\rm kHz}\,(n_{\rm e}/{\rm cm}^{-3})^{1/2}.$$

Worked estimate: coronal free-free optical depth (cgs)

Free-free absorption coefficient for $T > 2 \times 10^5\,\mathrm{K}$ (Dulk 1985, doi:10.1146/annurev.aa.23.090185.001125):

$$\kappa_\nu \approx 9.78 \times 10^{-3}\,\frac{n_\mathrm{e}^2}{\nu^2\,T^{3/2}}\,(24.5 + \ln T - \ln \nu)\ \ \mathrm{cm}^{-1}$$

Illustrative corona: $n_\mathrm{e} = 10^8\,\mathrm{cm}^{-3}$, $T = 1.5 \times 10^6\,\mathrm{K}$, path $L \approx 7 \times 10^{10}\,\mathrm{cm}$ ($\approx 1\,R_\odot$).

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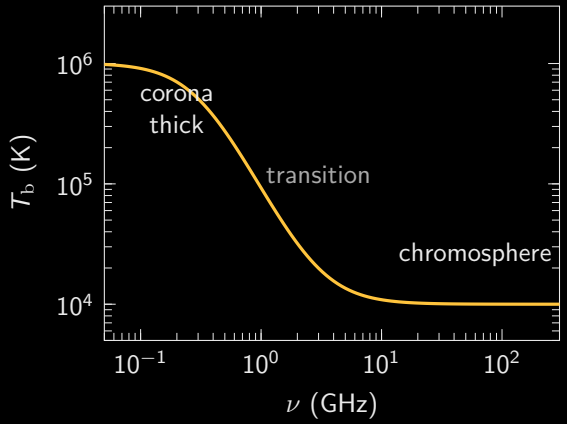
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ν	τ_ν	Consequence
150 MHz	≈ 3	corona optically thick: $T_\mathrm{b} \approx T_\mathrm{corona} \sim 10^6$ K
3 GHz	$\approx 7 \times 10^{-3}$	corona thin: adds $T\tau \approx 10^4$ K to the chromosphere

The same plasma is opaque at metre and transparent at centimetre wavelengths: frequency selects the layer we see.

Quiet-Sun brightness temperature spectrum



- $T_\mathrm{b} \sim 10^6$ K at metre wavelengths: the corona.
- $T_\mathrm{b} \sim 10^4$ K at mm: the chromosphere.
- Quiet-Sun emission is thermal free-free: weakly polarized, slowly varying.
- Refraction and scattering lower metre-wave T_b below T_corona.

Schematic curve, not a fit to data.

Worked example: the 10.7-cm flux

The F10.7 index is the whole-disc flux density at 2.8 GHz in solar flux units: $1\,\mathrm{sfu} = 10^4\,\mathrm{Jy} = 10^{-22}\,\mathrm{W\,m^{-2}\,Hz^{-1}}$. Near Solar minimum it is $\sim 70\,\mathrm{sfu}$.

$$\Omega_\odot = \pi\,(16')^2 = \pi\,(4.65\times10^{-3}\,\mathrm{rad})^2 = 6.8\times10^{-5}\,\mathrm{sr} \qquad \text{(SI)}$$

$$T_\mathrm{b} = \frac{c^2 S_\nu}{2k_\mathrm{B}\nu^2\Omega_\odot} = \frac{(3\times10^8)^2\times7\times10^{-21}}{2\times1.38\times10^{-23}\times(2.8\times10^9)^2\times6.8\times10^{-5}} \approx 4\times10^4\,\mathrm{K}$$

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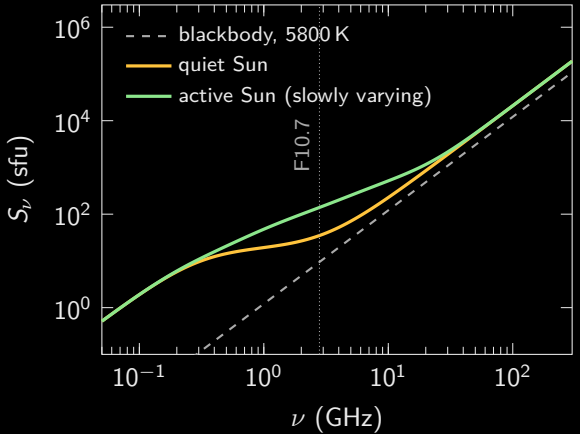
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- Disc-averaged, above the chromospheric 10^4 K: coronal free-free and active regions contribute.
- F10.7 rises to a few hundred sfu at Solar maximum: an activity index driven by active regions.

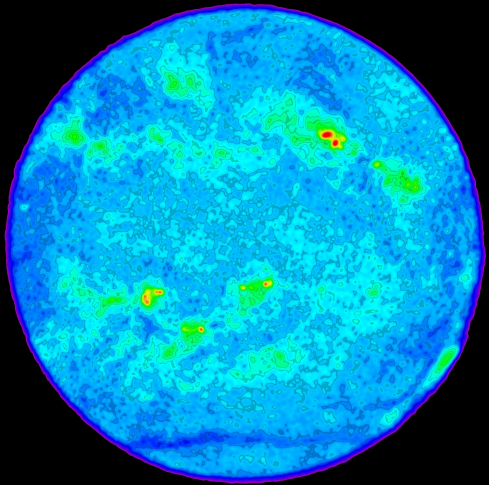
The Sun's radio spectrum: blackbody, quiet and active



Schematic cartoon, not a fit to data; $S_\nu = 2k_\mathrm{B}T_\mathrm{b}\nu^2\Omega_\odot/c^2$.

- Blackbody: $S_\nu \propto \nu^2$ at 5800 K.
- Quiet Sun: above it at metre–cm wavelengths (hot corona), and approaching it at mm (chromosphere).
- Active Sun: sunspot-region emission raises it most near a few GHz; flares add bursts far above.

The radio Sun: quiet disc and active regions



Credit: VLA image of the Sun at 4.6 GHz, S. White (Univ. of Maryland). Courtesy NRAO/AUI/NSF, via NASA Science, "NASA-funded science projects tuning in to eclipse radio" (M. Hatfield, 2024).

Gyroresonance emission above sunspots

- Electron gyrofrequency (Lecture 9):

$$\nu_B = 2.80\,\mathrm{MHz}\,(B/\mathrm{G})$$

- Thermal electrons absorb strongly at low harmonics, $\nu = s\,\nu_B$ with $s = 2, 3$ (sometimes 4).
- Each harmonic layer is optically thick in a thin shell: $T_\mathrm{b} \approx T_\mathrm{corona} \sim 10^6$ K at cm wavelengths, far above the free-free 10^4 K.

A coronal magnetometer

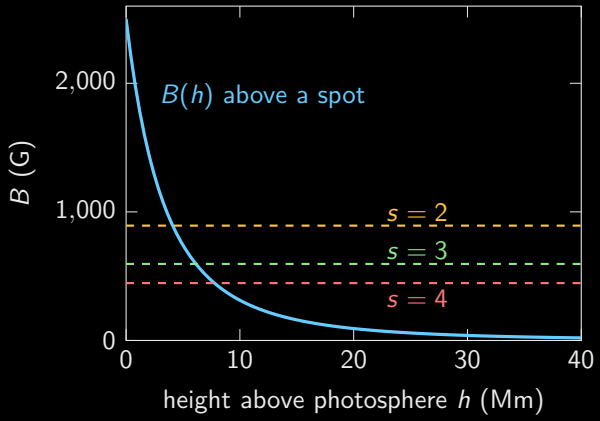
Bright 10^6 K source at $\nu \Rightarrow$ field $B = \nu/(2.8\,s\,\mathrm{MHz})$ G exists in the corona:

- 5 GHz, $s = 3$: $B \approx 600$ G
- 17 GHz, $s = 3$: $B \approx 2000$ G

- Extraordinary (x) and ordinary (o) modes have different opacity $\Rightarrow$ strong circular polarization.

White & Kundu 1997, doi:10.1023/A:1004975528106.

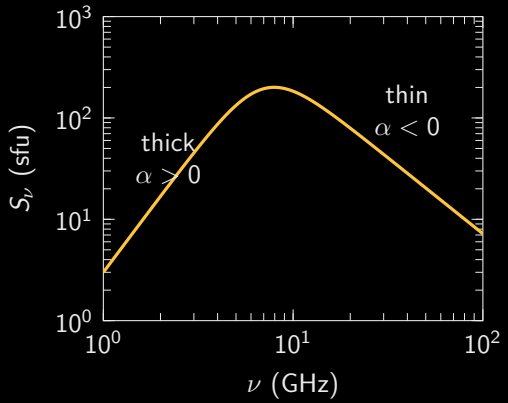
Where the gyroresonance layers sit



- At 5 GHz, the $s = 2, 3, 4$ layers lie at 893, 595 and 446 G.
- The highest thick layer that is still in hot coronal gas sets $T_{\rm b}$.
- Multi-frequency imaging scans B through height.

Schematic: $B = 2500\,\mathrm{G}\,(1 + h/10\,\mathrm{Mm})^{-3}$, an illustrative dipole-like decay.

Gyrosynchrotron emission from flares

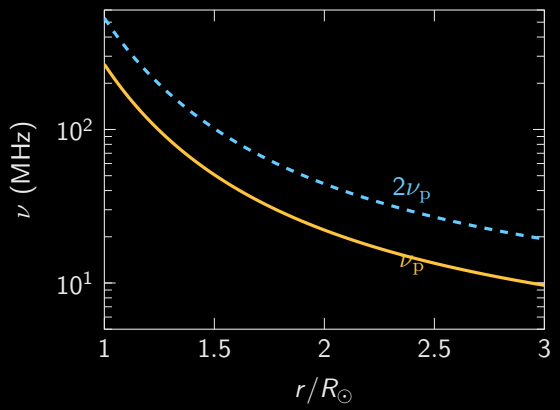


Schematic microwave burst spectrum, illustrative normalization.

- Flare electrons (tens of keV to MeV) spiral in the coronal field: gyrosynchrotron (Lecture 9).
- Spectrum peaks at a few GHz: rising where self-absorbed, falling where thin.

Bastian, Benz & Gary 1998, doi:10.1146/annurev.astro.36.1.131.

A coronal density model



Newkirk (1961, doi:10.1086/147104), an empirical fit:

$$n_\mathrm{e}(r) = 4.2 \times 10^4 \times 10^{4.32\,R_\odot/r}\ \mathrm{cm}^{-3}$$

ν_p (MHz)	$r/R_\odot$
200	1.06
100	1.24
50	1.51
30	1.78

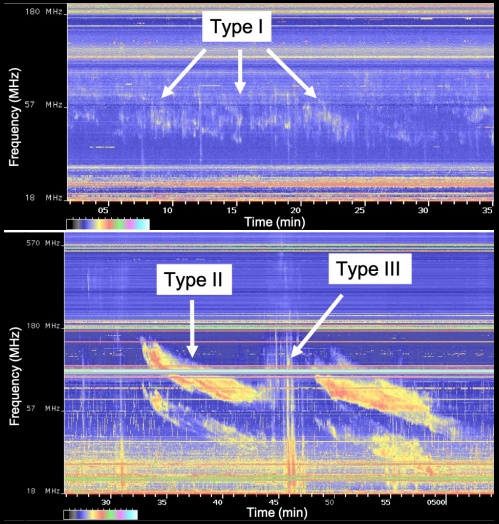
Other models differ by factors of 2–4 in n_e; Newkirk's describes active-region streamers.

A taxonomy of metre-wave Solar bursts

Type	Drift	Duration	Interpretation
I	none; narrow-band spikes	hours to days (noise storms)	electrons trapped above active regions; strongly circularly polarized
II	slow, ~ 0.1–$1\,\mathrm{MHz\,s^{-1}}$	minutes	shock (often CME-driven), fundamental + harmonic lanes
III	fast, tens of $\mathrm{MHz\,s^{-1}}$	seconds	electron beams at a few tenths of c on open field lines
IV	broadband continuum	tens of minutes to hours	trapped electrons after flares; gyrosynchrotron or plasma
V	continuum after III	minutes	slower electrons following a Type III

Classification from Wild & McCready (1950, doi:10.1071/CH9500387) and later work; review: Pick & Vilmer 2008, doi:10.1007/s00159-008-0013-x. Drift values are typical at $\sim$100 MHz.

Dynamic spectra: Types I, II and III



Credit: Learmonth Solar Observatory spectrograph data (Australian Bureau of Meteorology, Space Weather Services); figure by P. McCauley, CC BY-SA 4.0, Wikimedia Commons

Derivation: drift rate and exciter speed

Emission at $\nu = \nu_{\rm p}(r)$ (or $2\nu_{\rm p}$) from an exciter moving radially at speed v:

$$\boxed{\frac{{\rm d}\nu}{{\rm d}t} = \frac{{\rm d}\nu_{\rm p}}{{\rm d}r}\, v = \frac{\nu}{2}\, \frac{{\rm d}\ln n_{\rm e}}{{\rm d}r}\, v}$$

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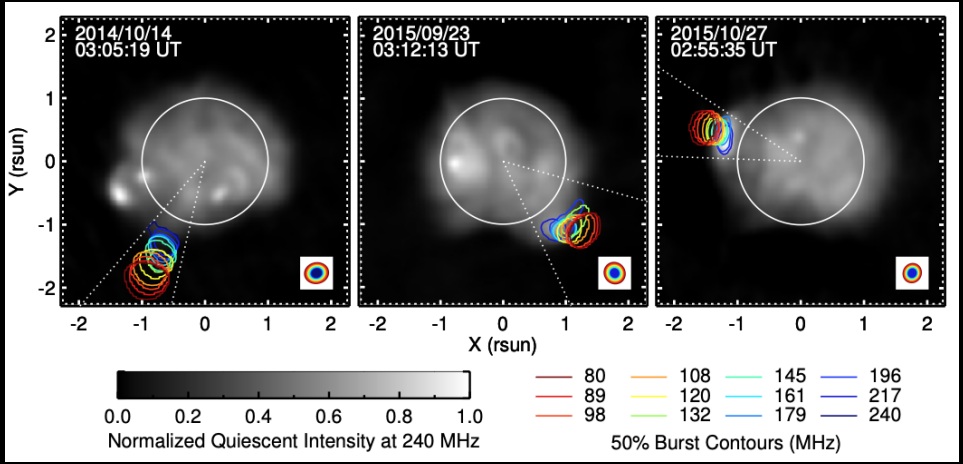
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Numbers from the Newkirk model at 100 MHz (fundamental, $r = 1.24\,R_\odot$):

Exciter	v	$\mathrm{d}\nu/\mathrm{d}t$
Electron beam (Type III)	$0.3c$	$\approx -40\,\mathrm{MHz\,s^{-1}}$
Shock (Type II)	$1000\,\mathrm{km\,s^{-1}}$	$\approx -0.5\,\mathrm{MHz\,s^{-1}}$

- Drift ratio $\approx$ speed ratio $\sim 10^2$: the morphology of the dynamic spectrum separates beams from shocks.
- Speeds inherit the density-model uncertainty and are projected (radial motion assumed).

Type III sources move outward with decreasing frequency



Credit: Murchison Widefield Array images: 240 MHz quiet Sun (greyscale) and Type III burst contours, 80–240 MHz. P. McCauley, CC BY-SA 4.0, Wikimedia Commons

Concept test

Question

A Solar burst drifts rapidly from high to low frequency. Which is more consistent with a Type III burst: an electron beam moving outward, or a static coronal loop?

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Answer: an outward-moving electron beam

1. Plasma frequency $\nu_{\mathrm{p}} \propto n_{\mathrm{e}}^{1/2}$ decreases as coronal density falls with height.
2. Outward motion samples lower density, hence lower frequency; fast drift requires a fast exciter.

What the Sun can and cannot teach about stellar flares

Transfers to stars

- Mechanism classification by T_b, polarization, spectral shape and drift.
- Flaring active stars and Solar flares share a radio–X-ray relation, $L_\mathrm{X}/L_\nu \sim 10^{15.5}$ Hz (Güdel & Benz 1993, doi:10.1086/186766).
- Coherent bursts: plasma emission or ECM (Lecture 9).

Does not transfer directly

- Stars are unresolved: no source height, only T_b lower limits.
- Stellar flares can be orders of magnitude more luminous; field and density scales differ.
- Without dynamic spectra, plasma emission and ECM are hard to separate.
- Coronal density models are not measured for other stars.

Discussion: list one Solar measurement that would be needed to apply each Solar diagnostic to an M-dwarf flare.

Retrieval: what does an ECM frequency measure?

From Lecture 9

Fundamental electron-cyclotron maser (ECM) emission: $\nu \approx \nu_c = eB/(2\pi m_e) \approx 2.8\,\mathrm{MHz}\,(B/\mathrm{G})$. Why does an observed ECM frequency constrain the *local* field strength but not necessarily the object's *global* magnetic moment?

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- Observed: ν. Inferred: $|B|$ where the emission is generated, for an assumed harmonic ($s = 1$ or 2).
- The dipole moment μ also needs the source location ($B \approx \mu/r^3$): a weak dipole near the surface or a strong one far above it give the same ν.
- The *highest* frequency bounds B at the lowest emitting altitude on active field lines only.

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Central question

What does radio emission reveal about magnetospheres, stellar activity, winds, and possible exoplanetary aurorae?

The Sun as a star: a radio non-detection

Quiet Sun at 2.8 GHz: $S_\nu \approx 70$ sfu at 1 AU ($1\,\mathrm{sfu} = 10^4\,\mathrm{Jy}$; solar-minimum level, order of magnitude).

$$S_\nu(10\,\mathrm{pc}) = 7 \times 10^5\,\mathrm{Jy} \times \left(\frac{1\,\mathrm{AU}}{10\,\mathrm{pc}}\right)^2 \approx 0.2\,\mu\mathrm{Jy}$$

- $L_\nu^\odot \approx 2 \times 10^{10}\,\mathrm{erg\,s^{-1}\,Hz^{-1}}$ (cgs, as in the stellar literature).
- An active M dwarf detected at $1\,\mathrm{mJy}$ at 10 pc has $L_\nu \approx 1.2 \times 10^{14}\,\mathrm{erg\,s^{-1}\,Hz^{-1}}$: $\sim 10^4$ times the quiet Sun.
- Detected stars are therefore a biased sample: magnetically active, young, rapidly rotating, binary, or evolved with dense winds.

Lesson from the radio Sun

Solar-like flares on other stars are not resolved: we see only $S_\nu(\nu, t)$ and polarization, never the formation height directly.

A radio Hertzsprung–Russell diagram in one table

Class	Main radio processes	Observational signature
Solar-type, old	thermal corona/chromosphere; rare flares	$\lesssim \mu$Jy at 10 pc; usually undetected
Young/active solar-type, RS CVn	gyrosynchrotron; coherent bursts	quiescent mJy; flares; moderate circular pol.
Active M dwarfs	gyrosynchrotron; plasma emission and ECM bursts	flares; up to $\sim 100\%$ circular pol.; low-frequency coherent emission
Ultracool dwarfs (late M, L, T)	ECM aurorae	periodic, $\sim 100\%$ circular pulses; quiescent gyrosynchrotron
Hot massive stars	free-free from ionized winds	$\alpha \approx +0.6$; steady
AGB stars, red giants	thermal radio photosphere	$\alpha \approx +2$; $T_\mathrm{b} \sim 10^3$ K

Review: Güdel (2002), doi:10.1146/annurev.astro.40.060401.093806.

Active coronae: gyrosynchrotron and the Güdel–Benz relation

- Gyrosynchrotron (L9): 10 keV–few MeV electrons in 10^2–10^3 G fields, $s \sim 10$–100; thick below a peak at a few to tens of GHz.
- Incoherent: $T_\mathrm{b} \lesssim 10^9$–$10^{10}$ K in practice; circular polarization tens of percent at most.
- Quiescent emission persists between flares: a population of non-thermal electrons is maintained continuously.

An empirical correlation

For many classes of active stars and Solar flares,

$$L_\mathrm{X}/L_\nu \approx 10^{15.5}\,\mathrm{Hz}$$

(Güdel & Benz 1993, doi:10.1086/186766).

- Interpretation: coronal heating and particle acceleration are linked.
- Empirical fit; ultracool dwarfs violate it strongly.

Worked example: incoherent or coherent stellar burst?

Burst: $S_\nu = 10\,\mathrm{mJy}$ at 1.4 GHz, M dwarf at $D = 5\,\mathrm{pc}$, $R_* = 0.3 R_\odot$ (illustrative). Source no larger than the disc: $\Omega_\mathrm{s} \le \pi R_*^2 / D^2$.

$$\Omega_\mathrm{s} \le \pi \left(\frac{2.1 \times 10^8\,\mathrm{m}}{1.54 \times 10^{17}\,\mathrm{m}} \right)^2 = 5.8 \times 10^{-18}\,\mathrm{sr}$$

$$T_\mathrm{b} \ge \frac{c^2 S_\nu}{2 k_\mathrm{B} \nu^2 \Omega_\mathrm{s}} = \frac{(3 \times 10^8)^2 (10^{-28})}{2(1.38 \times 10^{-23})(1.4 \times 10^9)^2 (5.8 \times 10^{-18})} \approx 3 \times 10^{10}\,\mathrm{K}$$

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- Above typical gyrosynchrotron values even for a source as large as the whole star (Solar flare sources are much smaller).
- Add high circular polarization and narrow bandwidth: coherent emission (plasma or ECM).
- A source of radius $3R_*$ still gives $T_\mathrm{b} \ge 3 \times 10^9\,\mathrm{K}$.

Coherent stellar emission: plasma emission or ECM?

Plasma emission (earlier in this lecture)

- $\nu \approx \nu_{\rm p}$ or $2\nu_{\rm p}$: density; drifts as the source moves (Solar Type II/III analogues).
- Moderate circular polarization (fundamental can be high).

ECM (L9)

- $\nu \approx s\,\nu_{\rm c}$: $|B|$; needs $\nu_{\rm p} \ll \nu_{\rm c}$.
- Nearly 100% circular polarization; beamed; often periodic.

- Decisive evidence: periodicity at the rotation period, polarization degree and sense, bandwidth and drift, and whether $\nu_{\rm p} < \nu_{\rm c}$ is plausible for the coronal model.
- Stellar coronal mass ejections should produce Type II-like drifting bursts; clear stellar analogues remain scarce: an open question.

Summary

- Methanol masers. Class I are collisionally pumped and trace shocks, offset from protostars; Class II are radiatively pumped and sit on massive protostars.
- Quiet Sun. Thermal free-free: $T_\mathrm{b} \sim 10^6\,\mathrm{K}$ from the corona at metre wavelengths, $\sim 10^4\,\mathrm{K}$ from the chromosphere at millimetre wavelengths; lower frequency forms higher up.
- Active Sun. Gyroresonance above sunspots and gyrosynchrotron from flares raise the flux, most near a few GHz.
- Coherent bursts. Plasma emission at ν_p or $2\nu_\mathrm{p}$ gives density; the drift rate gives the exciter speed.
- Stars. The Sun would be undetectable as a radio star; active stars follow the Güdel–Benz relation, and coherent flares are plasma emission or ECM, told apart by polarization, periodicity and bandwidth.

Further reading

- **Solar and stellar radio:** Dulk 1985, ARA&A 23, 169; Bastian, Benz & Gary 1998 (doi:10.1146/annurev.astro.36.1.131); Güdel 2002 (doi:10.1146/annurev.astro.40.060401.093806).
- **Coronal density:** Newkirk 1961 (doi:10.1086/147104).
- **Methanol masers:** Menten 1991, ApJ 380, L75.