Coherent emission in astrophysical plasmas

Don Melrose

School of Physics
University of Sydney

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Introductory remarks

Low-frequency radio astronomy

- New era of low-frequency radio astronomy: LOFAR, MWA, ...
- Earlier era (in Australia): 1945 to circa 1980
- Nonthermal emission at higher frequencies:
  incoherent synchrotron radiation
- Bright bursty emission at lower frequencies:
  'coherent' = non-incoherent
- Since $\sim$ 1980 coherent emission $\rightarrow$ space physics
- Exception: radio emission from pulsars
- Many unsolved problems remain

Sources of ‘coherent’ emission

Four established examples of coherent emission

- Plasma emission, notably solar radio bursts
- Electron cyclotron maser emission (ECME):
  planets (DAM & AKR) & stars (Sun, flare stars, ...)
- Pulsar radio emission
- Radio emission by cosmic ray showers in air

Coherent emission mechanism

- Solar radio bursts: growth of Langmuir waves
  due to ‘bump-in-tail’ electrons distribution
- ECME: driven by anisotropic electron distribution
- Pulsar emission mechanism is unknown
- Extensive air showers (EASs)
  N particles radiating N^2 times power per particle

Type III solar radio bursts

Ruby Payne-Scott (1912–1981)

Making Waves *The Story of Ruby Payne-Scott: Australian Pioneer Radio Astronomer*

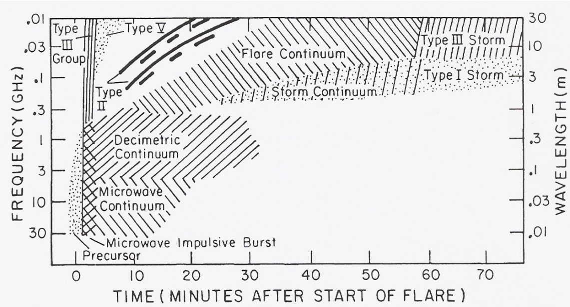
W.M. Goss, Springer, 2013

- Co-discoverer (with Joe Pawsey) of solar type III bursts

  Pawsey, Payne-Scott & McCreadie, *Nature*, **157**, 158 (1946)

- Payne-Scott called them 'unpolarized' (fast-drift) bursts
- Provided interpretation: exciting agency emitting at f_p
- Estimated speed: $\approx 0.2\,c$

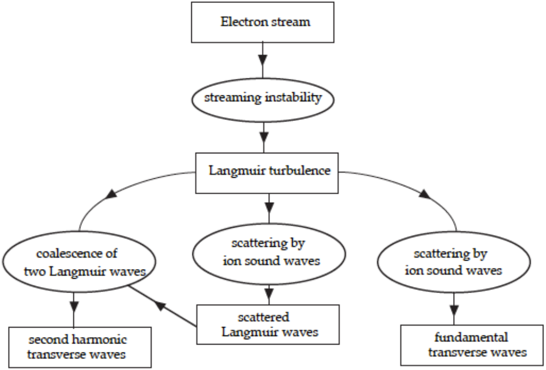
Type I, II & III bursts (Wild 1950)



- Types I: storm bursts, 1–20 s, Δf = few MHz
- Types II: slow drift $\approx -0.25\,\mathrm{MHz\,s^{-1}}$
- Types III: fast drift $\approx -20\,\mathrm{MHz\,s^{-1}}$
- Fundamental (F) & second harmonic (H) emission identified

Wild, Murray & Rowe, *Nature* **172**, 533 (1953)

First Theory for Plasma Emission



- Ginzburg & Zheleznyakov theory; highly innovative

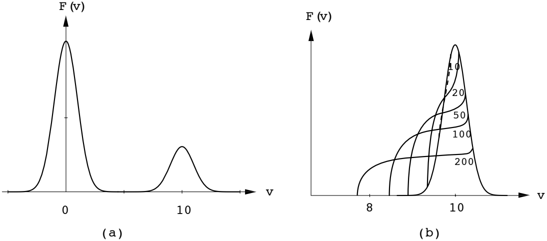
  Ginzburg & Zheleznyakov, (*A Zh* 1958); *Sov. Astr. AJ* **2**, 653 (1959)

- Multistage process: all stages updated by later authors

  Melrose, *Aust. J. Phys.* **23**, 871 & 885 (1970); Zhelznyakov & Zaitsev, *Sov. Ast. AJ* **14**, 47 & 250 (1970)

Maser instability in type III bursts

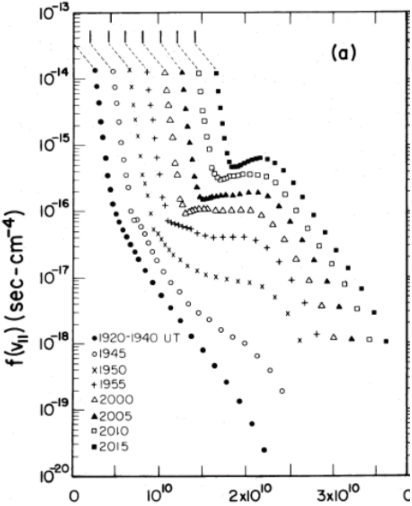
Evolution of bump-in-tail instability



Grognard, in McLean & Labrum (eds), *Solar Radiophysics*, CUP (1985)

- Langmuir waves with phase speed $v_\phi = v$
  grow whenever $\partial f(v)/\partial v > 0$ satisfied
- Homogeneous beam model: energy losses are catastrophic:
  beam stops in $\approx 100/f_p$
- Driver: faster e^-s outpace slower e^-s
  $=> \partial f(v)/\partial v > 0$ continuously redevelops

Confirmation of weak-beam model



Lin, Potter, Gurnett & Scarf, ApJ **251**, 364 (1981)

Clumpy Langmuir waves in IPM

Where are the Langmuir waves?

- Spacecraft passing through type III source
  failed to identify Langmuir waves (over few years)
- Plasma emission without Langmuir waves?
  Lin, Potter, Gurnett & Scarf, ApJ **251**, 364 (1981)
- Recognition that Langmuir waves are in isolated clumps

Coherent emission processes are extremely intermittent

- Instability operates near marginal stability
- Slow driver towards instability
  (faster e^{-}s outpacing slower e^{-}s in this case)
- Balanced by localized bursts of wave growth
  backreaction tends to relax unstable distribution
- Explanation for highly localized growth still debated
  likely associated with local inhomogeneities

Type I emission

Type I emission not understood

- What is exciting agency for bursts?
- Why F but no H?
- Does type I continuum have structure?
- How is continuum generated?

Type I–III boundary

- Type I burst & continuum at higher frequencies
  type III emission at lower frequencies
- What defines the boundary?
  Interface between closed and open **B**?
- Ongoing reconnection probably drives the storm
  but what drives ongoing reconnection?

Extreme inhomogeneities

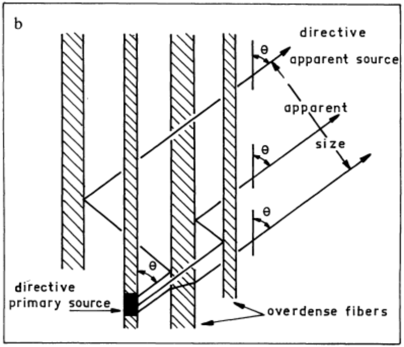
Solar corona must be highly structured

- Directivity of type I bursts
- Ducting of type III bursts
- Depolarization of F emission

Scattering by inhomogeneities

- Snell's law $n \sin\theta =$ const. $n \sim 10^{-2}$ at F source
  $=>$ $\theta \sim 10^{-2}$ for $n \to 1$
  $=>$ sources should be seen only at CMP
- Monte Carlo models for scattering
  $=>$ apparent size and angular range both increase
- WRONG: violates Poincaré invariant ('generalized étendue')

Directivity of type I



Bougeret & Steinberg, *A&A*, **61**, 77 (1977)

Fibrous conona needed to explain Type I

- Reflection through large angles off 'fibers'
- Emission in low-density region surrounded by overdense fibers

Depolarization of F emission

Depolarization of type I

- Type I emission (only F, no H) is highly circularly polarized

  Payne-Scott, *Aust. J. Sci. Res. A* **2**, 214 (1949); Payne-Scott & Little, *ibid* **4**, 508 (1951)
- Polarization decreases systematically as storm approaches limb

  Zlobec, *Sol. Phys.*, **43**, 453 (1975); Wentzel, Zlobec & Messerotti, *A&A*, **159**, 40 (1986)
- => increasing depolarization with increasing deflection angle

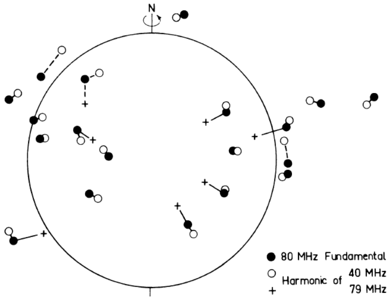
Depolarization of type III

- Type III never 100% polarized (F$<$ 70%, H $<$ 20%, o mode)

  Dulk, Suzuki & Sheridan, *A&A*, **130**, 39 (1984)
- Theory => F emission should be 100% o-mode
- Depolarization due to reflection of sharp boundaries

  Melrose, ApJ **637**, 1113 (2006)

Ducting of type III emission



Duncan, *Sol. Phys.* **63**, 398 (1979)

Apparent sources are scatter images

- Height of apparent source $\gg$ actual source
- At given f, F & H sources roughly coincide

  F source at f always much higher than H source at $2f$

Structures required for ducting

Field-aligned inhomogeneities

- Radio emission generated in underdense regions
- Reflected off walls of duct => strong ducting along **B**
- F emission ducted to beyond H layer => density ratio $\gtrsim 10$
- Depolarization => extremely sharp boundaries
- Summary: type III also requires fibrous corona

How could MWA help?

- Suppose apparent source $= 10\times$ actual source
- => ducted radiation fills only $10^{-1}\times$ actual source
- Made up of small or large, thin or fat, long or short patches?
- Scale depends on details of ducts
- Can scale be identified by MWA?

Pulsar radio emission

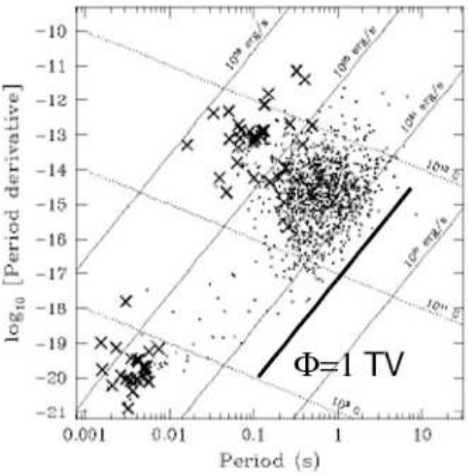
Radio pulsars

- Discovered in 1967; over 2000 now known
- Neutron stars, mass $\approx 1.4\,M_\odot$
- Rotational periods, $P \approx 10^{-3}$–$10\,\mathrm{s}$
- Extremely good clocks, $\dot{P} \approx 10^{-15}$
- Super-strong magnetic fields, $B \approx 10^6$–$10^{12}\,\mathrm{T}$

Radio emission process (not known)

- Due to highly relativistic electrons (or positrons) in ground Landau state ($p_\perp = 0$)
- Several suggested emission mechanisms
  - Curvature emission (CE)
  - Plasma-like emission (PE)
  - Anomalous-cyclotron emission (ACE)
  - Linear-acceleration maser (LAE)

The P–$\dot{P}$ diagram

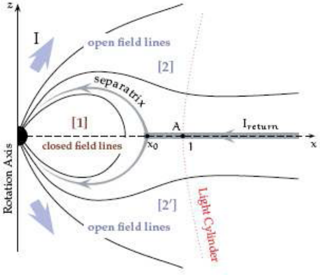


X marks a pulsar with P, $\dot{P}$ measured from X-rays as well as radio observatons. Pulsars have $\Phi > 10^{12}\,\mathrm{V}$. (Arons 2007)

Pulsar electrodynamics

Incompatible models

- Vacuum dipole model
  no plasma
- Corotating magnetosphere
  neglects inductive **E**
- Force-free models
  invert cause & effect



(Timokhin 2006)

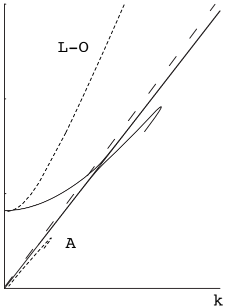
'Catch 22'

- Models not useful in predicting radio emission
- Need radio observations to constrain models
- Enormous body of data, but
  every phenomenological 'rule' has exceptions
- Do we ignore exceptions?
  or look for 'Rosetta stone'?

Wave dispersion in pulsar plasma

Pulsar plasma: ω–k plot

- Parallel L-O & A modes (solid)
- Oblique L-O & A modes (dashed)
- Light line (long dashed)
- (X-mode not shown)



Features of the four emission mechanisms

- PE & ACE require refractive index > 1
  possible for L-O over small range of angles
  & range of frequencies above $\approx f_p \langle\gamma\rangle^{1/2}$
- LAE also only generates L-O mode ($n > 1$ not needed)
- Only CE allows X-mode

Polarization of pulsar radio emission

Rich variety of polarization features

- General sweep of linear polarization
  rotating vector model?
- Jumps between orthogonal polarizations
- High circular polarization (sometimes) in single pulses
  low circular polarization in mean pulse profile

Simple theory => emission in O mode

- Observed polarization imposed as propagation effect
- Ducting model like type III bursts?
- Requires extreme cross-field inhomeogeneities

Polarization data has not helped identify emission mechanism

How can we make progress?

Widely accepted assumptions

- Pulsar magentosphere populated through pair creation
- All particles in 1D motion along field lines
- Emission beamed into forward cone $\sim 1/\gamma$
- Magnetic field approximated by $B \propto (P\dot{P})^{1/2}/r^3$ for $r \ll r_L$
- Emission confined to polar-cap field lines
  polar-cap angle $\theta_{\rm PC} \approx (r/L_L)^{1/2} \ll 1$
- Number density $\approx M(\varepsilon_0 ec)B/P$
  multiplicity $M \gg 1$ needed to explain wind

Possible additional assumptions

- Only one emission mechanism for all pulsars
- Emission site at $r/r_L \approx 0.1$–$0.2 => r \propto P$
  (probability of seeing emission $\approx r/r_L$)

Frequency range similar for all pulsars

- Radio emission peaks at $\sim 100\,\mathrm{MHz}$, extends to $\gtrsim 10\,\mathrm{GHz}$
- Free parameters: Lorentz factor, γ, $\langle\gamma\rangle$, M

Problems with suggested emission mechanisms

Curvature emission (CE)

- Frequency $\approx (c/R_c)\gamma^3$ is too low for plausible γ
- Frequency $\propto 1/P$ cannot work for all pulsars
- Maser emission requires exceptional conditions
- 'Coherent' CE often assumed without justification

Plasma-like emission (PE)

- Frequency $\propto (\dot{P}P)^{1/4}/P^2$ times $(M^{1/2}\langle\gamma\rangle^{1/4})\gamma$
- Maser driven by $\partial f(\gamma)/\partial\gamma > 0$

  can apply only below peak in $f(\gamma)$, $\gamma \approx \langle\gamma\rangle$

Anomalous-cyclotron emission (ACE)

- Frequency $\propto (\dot{P}P)/P^5$ times $\gamma^3/(M\langle\gamma\rangle^{1/2})$
- Maser driven by 1D anisotropy

Linear acceleration emission (LAE) (Melrose 1978)

- Frequency determined by maximum growth rate
- Maser driven by driven by $\partial f(\gamma)/\partial\gamma > 0$

No mechanism is obviously preferred

Fine structures in coherent emission

Fine structures identified as specific phenomena

- S bursts in DAM, giant bursts in pulsars, ...
- narrow $\Delta\omega$, short Δt, exceptionally high T_B
- Is maser theory consistent with fine structures?
- Is it consistent to assume
  $$(\text{growth rate}) < (\text{bandwidth of growing waves} = \Delta\omega)?$$

Can fine structures arise as propagation effect?

- Inhomogeneities lead to scattering and diffraction
- Caustics can arise naturally as propagation effects
- Most fine structures may be due to caustics

Measuring coherence

Intensity interferometry

- Hanbury Brown-Twiss effect: radio concept $\to$ optics
- Photon counting: correlations related to coherence
- Photon count rate $\propto$ intensity I
- Consider statistical average $\langle I^N \rangle$, $N = 1, 2, \ldots$
- Ideal coherence => $\langle I^N \rangle = \langle I \rangle^N$
- Random phases => $\langle I^N \rangle = N! \langle I \rangle^N$

Measurable quantities in radio astronomy

- Correlators give I; also Stokes parameters Q, U, V
- Set of measurable quantities $\langle I^N \rangle / \langle I \rangle^N$
  similar quantities involving I, Q, U, V
- What do learn by measuring $1 \le \langle I^2 \rangle / \langle I \rangle^2 \le 2$?

Summary & Conclusions

Renewed interest in low-frequency radio astronomy

- New telescopes with high time & space resolution (MWA)
- Renewed interest in solar radio bursts
- ECME from brown dwarfs, extra-terrestrial planets, ...

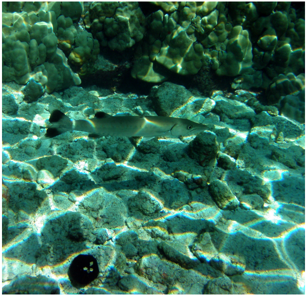
We still do not understand pulsar radio emission

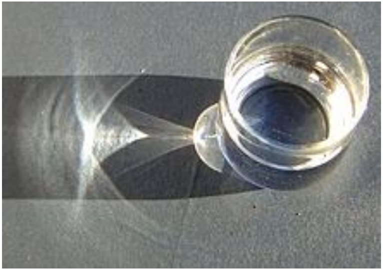
- Pulsar electrodynamics requires a major rethink
  existing models are unhelpful and technically incorrect
- Radio emission mechanism should to related to pair creation
- Is there more than one radio emission mechanism?
- New ideas/approaches needed

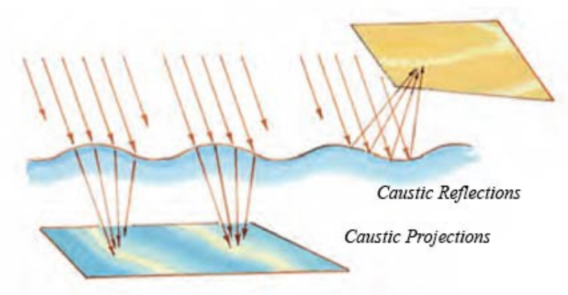
Are fine structures distinct phenomena or are they caustics?

- If giant bursts are caustics
  why are they observed only in particular pulsars?
- If they are not caustics, what are they?

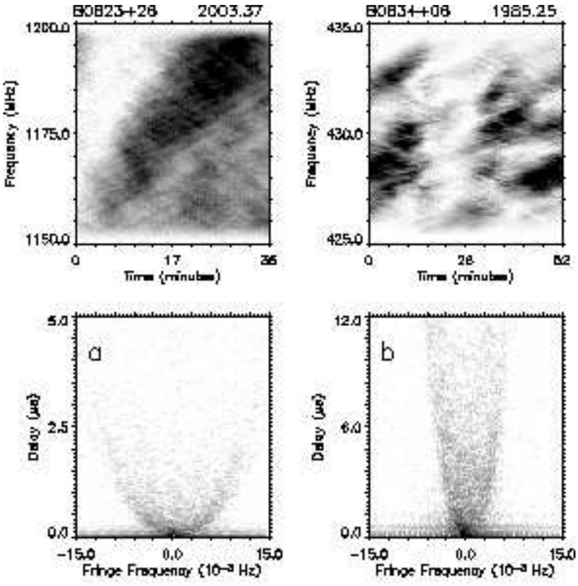
Caustics



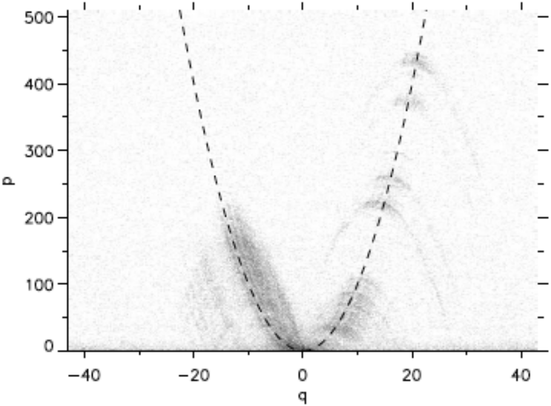




Scintillation of radio pulsars



Parabolic arcs



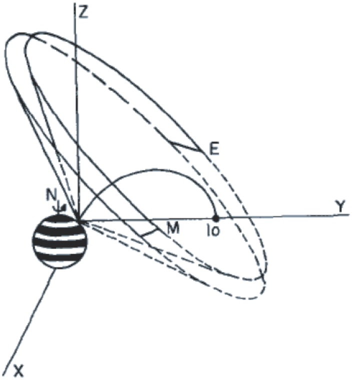
Parabola: frequency delay $\propto (\delta\theta)^2$, time delay $\propto (\delta\theta)$

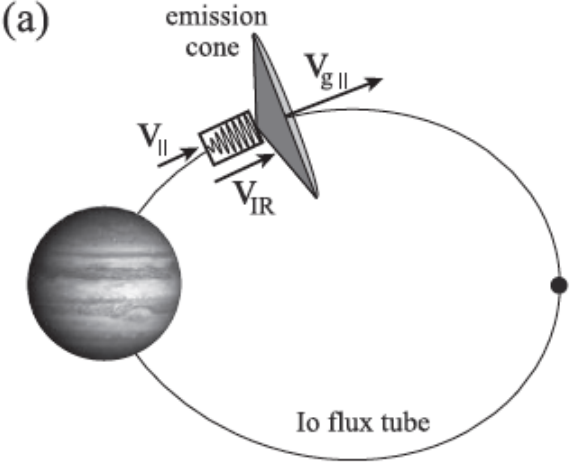
Shape of prabola depends on distance to scattering screen

Only single screen involved! (Walker *et al.* MNRAS **354**, 43, 2004)

Jupiter's decametric radio bursts (DAM)

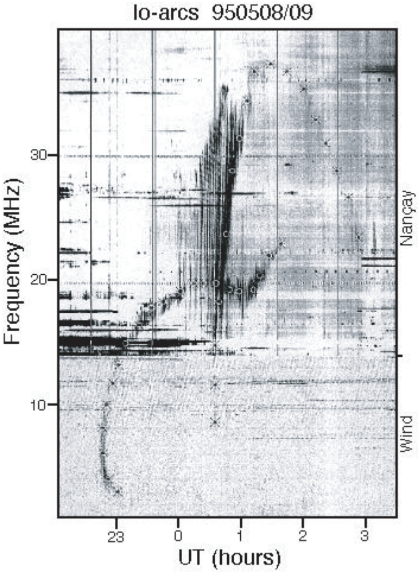
- DAM discovered at 22.2 MHz (Burke & Franklin 1955)
- Upper cutoff at 39.5 MHz
  = electron cyclotron frequency near N pole
- Correlation with Io (Bigg 1962)
- Bizarre radiation pattern (Dulk 1967)
  on thin surface $\approx 1^\circ$ of wide-angled cone





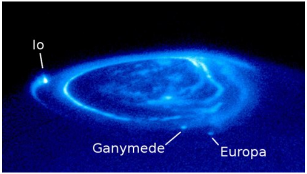
Willes 2002, JGR **107**, 1061

Evidence for Io's influence

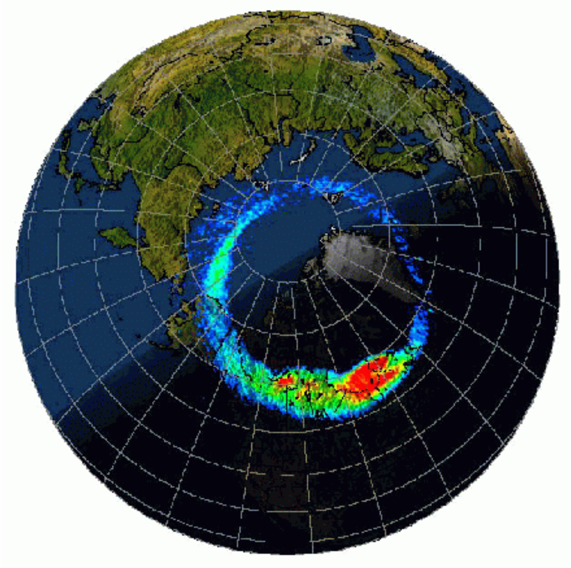


Left: Io-controlled DAM forms arcs

Below: auroral UV



The Earth's auroral oval from space



Auroral kilometric radiation (AKR)

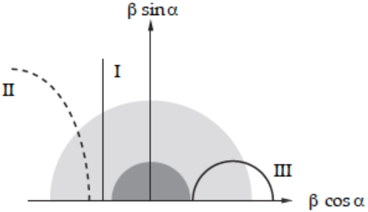
The Earth is a spectacular radio source

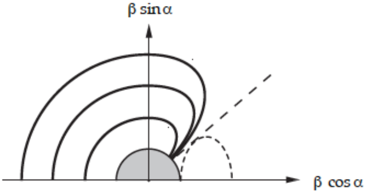
- AKR discovered as ‘Earth noise’ by spacecraft in 1960s
- Correlates with ‘inverted V’ auroral electrons
- Emission at local electron cyclotron frequency (< 500 kHz)

Coherent cyclotron emission

- Coherence DAM initially attributed to “electron bunches”
- N electrons radiate N^2 times the power per electron
- Electron cyclotron maser emission (ECME) developed in 1970s
- ECME applied to AKR (Melrose 1976; Wu & Lee 1979)
  compared with *in situ* data on electrons for AKR
- applied to solar spike bursts & to flare stars (Melrose & Dulk 1982)
- ECME widely accepted; opinions differ over details

ECME





Resonance condition

$\omega - s\Omega_e/\gamma - k_{\|} v_{\|} = 0, \qquad \Omega_e = eB/m$

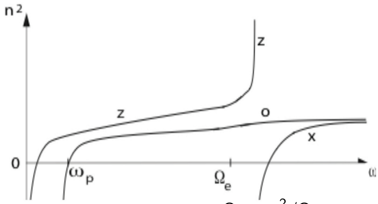
Resonance ellipse

- Resonant particles lie on an ellipse in $v_\perp$–$v_{\|}$ space
  $v_\perp = \beta c \sin\alpha$, $v_{\|} = \beta c \cos\alpha$ in figure
- Instability driven by $\partial f/\partial p_\perp > 0$

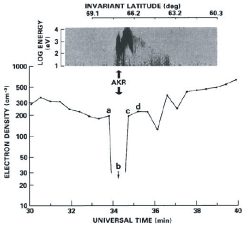
Loss-cone driven ECME

- $\partial f/\partial p_\perp > 0$ in loss-cone, $\alpha = \alpha_c$
- Driver: forced precipitation, only $\alpha > \alpha_c$ reflected
- => emission on narrow surface of wide cone

Very low densities required



$\omega_x \approx \Omega_e + \omega_p^2/\Omega_e$



Doppler shift to $> \omega_x$ required for ECME

- x-mode exists at $\omega > \omega_x$
- reflected electrons => positive Doppler shift
- requires $\omega_p \ll \Omega_e$
- auroral cavity discovered, consistent with theory

Data on electron distribution

- Early data supported loss-cone model
- Later data suggested different driver