Coherent emission

Don Melrose

School of Physics
University of Sydney

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Outline of talk:

1. Nature of coherent emission
2. Plasma emission
3. Electron cyclotron emission
4. Triggering & fine structure
5. Helliwell's model
6. Crab giant bursts
7. Summary

Nature of coherent emission

Three generic types

- Plasma emission (solar radio bursts, planetary bow shocks)
- Electron cyclotron maser emission (planes, Sun, flare stars)
- Pulsar radio emission (not understood)

Three "coherent" mechanisms Ginzburg & Zheleznyakov (1975)

- Emission by bunches (localization in $\mathbf{x}$ & $\mathbf{p}$)
- Reactive instability (localization in $\mathbf{p}$)
- Maser growth = negative absorption

Back reaction (BR) to coherent emission

- Bunches: BR disperses the bunch in $\mathbf{x}$-space FASTEST
- Reactive: BR broadens beam in $\mathbf{p}$-space NEXT FASTEST
- Maser: BR = quasilinear relaxation STILL FAST
- BR => suppression of instability
- Astrophysics: relaxation to marginal stability DEFAULT

Plasma emission

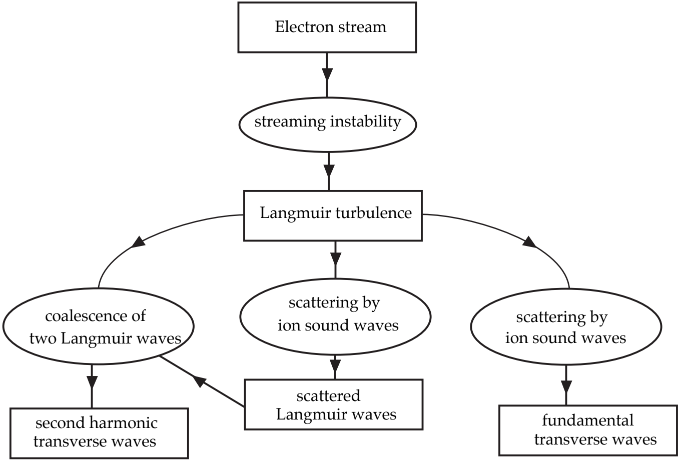


Figure: Schematic of processes leading to F & H plasma emission

Quasilinear relaxation

Beam instability

- Resonance $\omega - \mathbf{k} \cdot \mathbf{v} = 0 => v > \omega/k = v_\phi$
- Instability for $dF(v)/dv > 0$ at $v = v_\phi$
- Driver ("pump"): faster electrons outpacing slower electrons
- Quasilinear relaxation decreases $dF(v)/dv > 0$

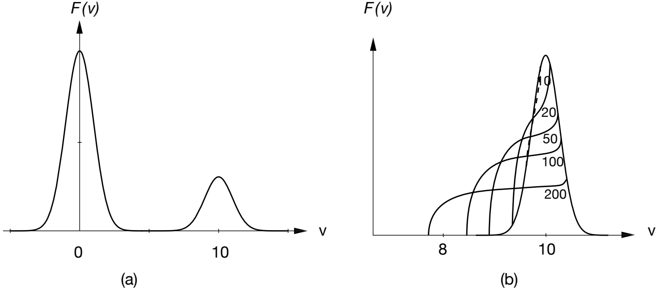


Figure: Evolutions of beam distribution: (a) initial distribution; (b) distribution after number of growth times indicated.

Plasma instabilities: marginal stability

Dilemma

- Plasma instabilities grow rapidly
- Exhaust free energy in few hundred growth times

Marginal stability

- System must relax to marginally stable state
- Balance: very slow driver ("pump")
- & large number of localized, transient bursts of growth

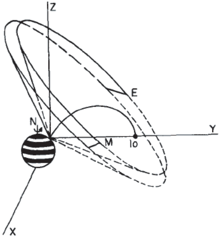
Observational evidence

- Langmuir waves in IPM in highly localized "clumps"
- Log-normal statistics for E in clumps
- Consistent with "stochastic growth theory" (SGT):
  - random localized bursts of growth, $E = e^G E_0$
  - growth factor G random variable
  - => E log-normal in bursts Robinson 1992; Cairns & Robinson 1997

Electron cyclotron maser emission (ECME)

Jupiter's DAM

- Bursts at $< 40\,\mathrm{MHz}$
- Emitted at Ω_e
- Bizarre radiation pattern
- Confirmed by spacecraft



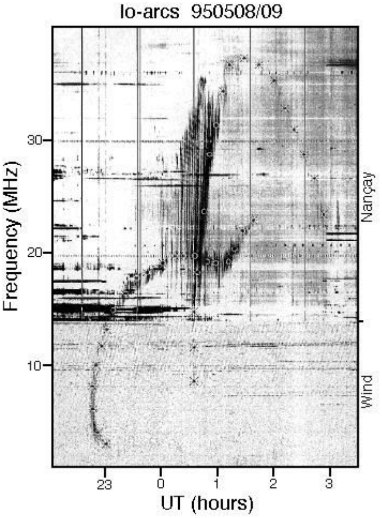
Dulk 1967

Io effect

- Correlation with moon Io discovered in 1962
- Io drags flux tube through corotating magnetosphere
- $=>$ EMF $\approx 2\,\mathrm{MV}$; explains $\approx 2\,\mathrm{MeV}$ electrons

Io-related arcs

Arc pattern confirmed bizarre angular distribution



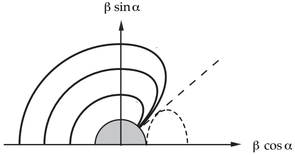
Requirements for ECME

Resonance condition

- Cyclotron resonance condition $\omega - \Omega_e/\gamma - k_z v_z = 0$
- Instability driven by $\partial f/\partial p_\perp > 0$
- Escape of radiation requires $\Omega_e \gg \omega_p$

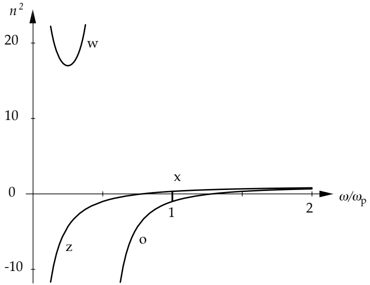
Loss-cone driven ECME

- $\partial f/\partial p_\perp > 0$ in loss-cone
- Driver: forced precipitation $p_\perp^2/B =$ const.
- Loss cone after mirroring



Explains bizarre radiation pattern for DAM

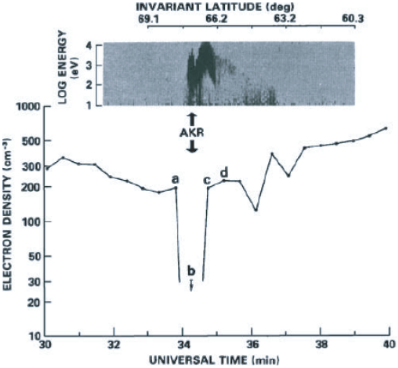
Escape of ECME



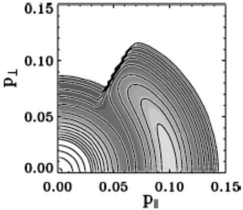
- Curves on the left for $\omega_p \gg \Omega_e$
- Cyclotron maser in whistler mode (cannot escape)
- Curves on right for $\omega_p \ll \Omega_e$
- ECME in x mode can escape provided Doppler shifted to above cutoff frequency

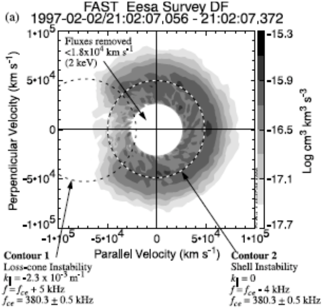
Earth's AKR

- Analogous radiation from the Earth at $< 0.5\,\mathrm{MHz}$
- Correlates with inverted-V precipitating electrons
- Emitted in low density cavity Benson & Calvert 1979



Recent developments





Faster growth for shell distribution

BUT: ECME cannot escape in presence of cold plasma

Astrophysical applications

- ECME favored for solar spike bursts
- ECME accepted for flare stars
- Also applied to blazars Begelman, M.E., Ergun, R.E., Rees, M.J. 2005, ApJ 625, 51

Triggering and fine structure

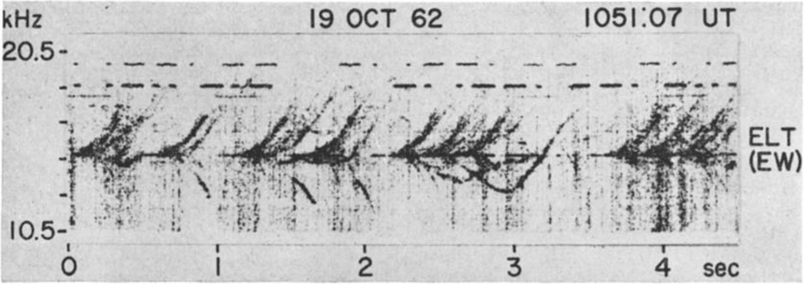
Triggers

- What triggers the localized bursts of growth?
  - Enhance local growth rate
  - Reduce local loss rate
  - Enhance local background
- SGT suggests random triggers
- Exceptional (non log-normal) events?

Fine structures: extreme events

- Exceptional events common but not random
  - Triggered VLF emissions
  - Triggering of ECME by type III bursts
- Extremely narrow bandwidth events
  - Fine structures in DAM
  - Giant bursts in pulsars
- Maser theory requires RPA: bandwidth $>$ growth rate

VLF emissions



Triggered VLF

- Whistlers triggered by Morse code dashes
- Emissions drift in frequency

Driver for VLF emissions

Free energy for VLF emissions

- Electrons in radiation belts in steady state
- Drift in from solar wind
- Sets up $\partial f(v_\perp)/\partial v_\perp > 0$

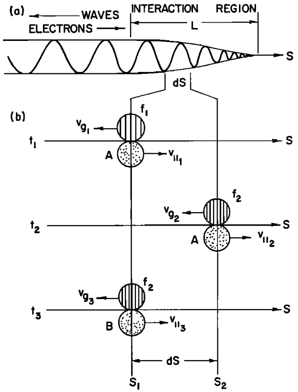
Loss of electrons

- Scattering into loss cone by whistlers
- $=>$ steady average auroral electron precipitation
- Actual precipitation very bursty
- Fine structures in bursts and whistlers correlate

Helliwell's model

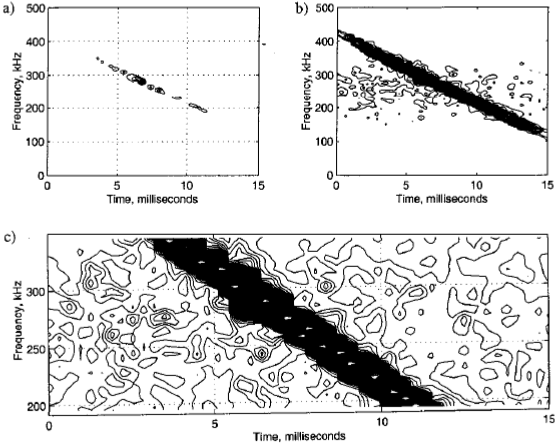
Phenomenological model

- Resonance satisfied
  $\omega - \Omega_e - k_z v_z = 0$
- Waves grow in interaction region (IR)
- Resonance also satisfies
  $d[\omega - \Omega_e - k_z v_z]/dt = 0$
- Frequency drift due to motion of IR



Helliwell, R.A. 1967 JGR **72**, 4773

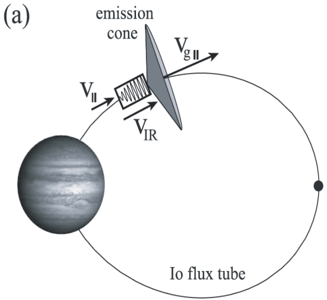
Fine structures in Jovian S bursts



Phase coherence Carr, T.D. 2001

- Phase-coherent bursts
- Background Galactic noise level changes
- Amplification before S-burst suppressed after S-burst

ECME form of Helliwell's model



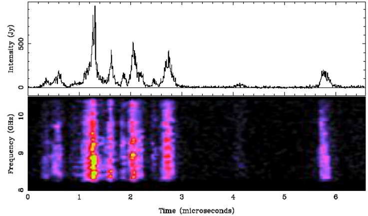
Coherent fine structures

- Resonance satisfied: $\omega - \Omega_e/\gamma - k_z v_z = 0$
- Helliwell's condition satisfied: $d[\omega - \Omega_e/\gamma - k_z v_z]/dt = 0$
- Applied to x mode for $\Omega_e \gg \omega_p$
- Can explain observed drifts Willes, A. 2002

Crab giant bursts

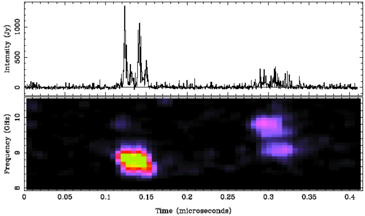
Giant bursts in Main Pulse

- several microbursts



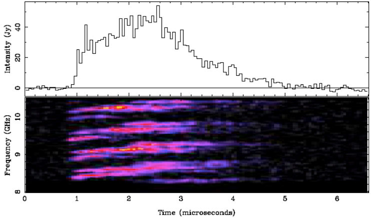
Giant bursts in Main Pulse

- nanoshots



Giant bursts in Interpulse

- Bands



Summary

- Plasma emission & ECME relatively well understood
- Masers operate near marginal stability
- Actual source the envelope of statistically large number of localized, transient bursts of wave growth
- Triggering & fine structure outside the scope of simple theory
- Helliwell's (1967) phenomenological model plausible basis
- Pulsar radio emission & giant bursts poorly understood

Why don't we understand pulsar radio emission?

Pulsar electrodynamics

- Pulsar electrodynamics inadequately understood
- Ideas developed for aligned model
- Ignores central role of displacement current
- Precludes predicting emission from first principles

Location of apparent source

- Emission from polar-cap regions
- Aberration & geometry plausibly => source height
- Seemingly unrelated to acceleration site

Polarization

- Observed polarization imposed as propagation effect
- Suggests apparent source is not actual source
- => further uncertainty on source location

'Rosetta-stone' approach

- Look for definitive signature of emission mechanism
- Many suggestions but no consensus

Pulsar radio emission mechanisms

Plasma-like-emission

- Ouflowing relativistic particles => beam instability
- $n_O^2 > 1$ in small range
- Dispersion curve allow escape
- Interesting variant in oscillating model

Curvature emission

- Synchrotron-like emission
- Maser possible for $df(\gamma)/d\gamma > 0$
- Maser emission only for one polarization

Linear acceleration emission

- Due to acceleration by $E_{||}$
- Maser possible for $df(\gamma)/d\gamma > 0$

Anomalous cyclotron emission

- $\omega - s\Omega - k_{||}v_{||} = 0$, $s = -1$
- Requires mode with $n^2 > 1$
- Applies only in weak-B region

Pulsar wave modes