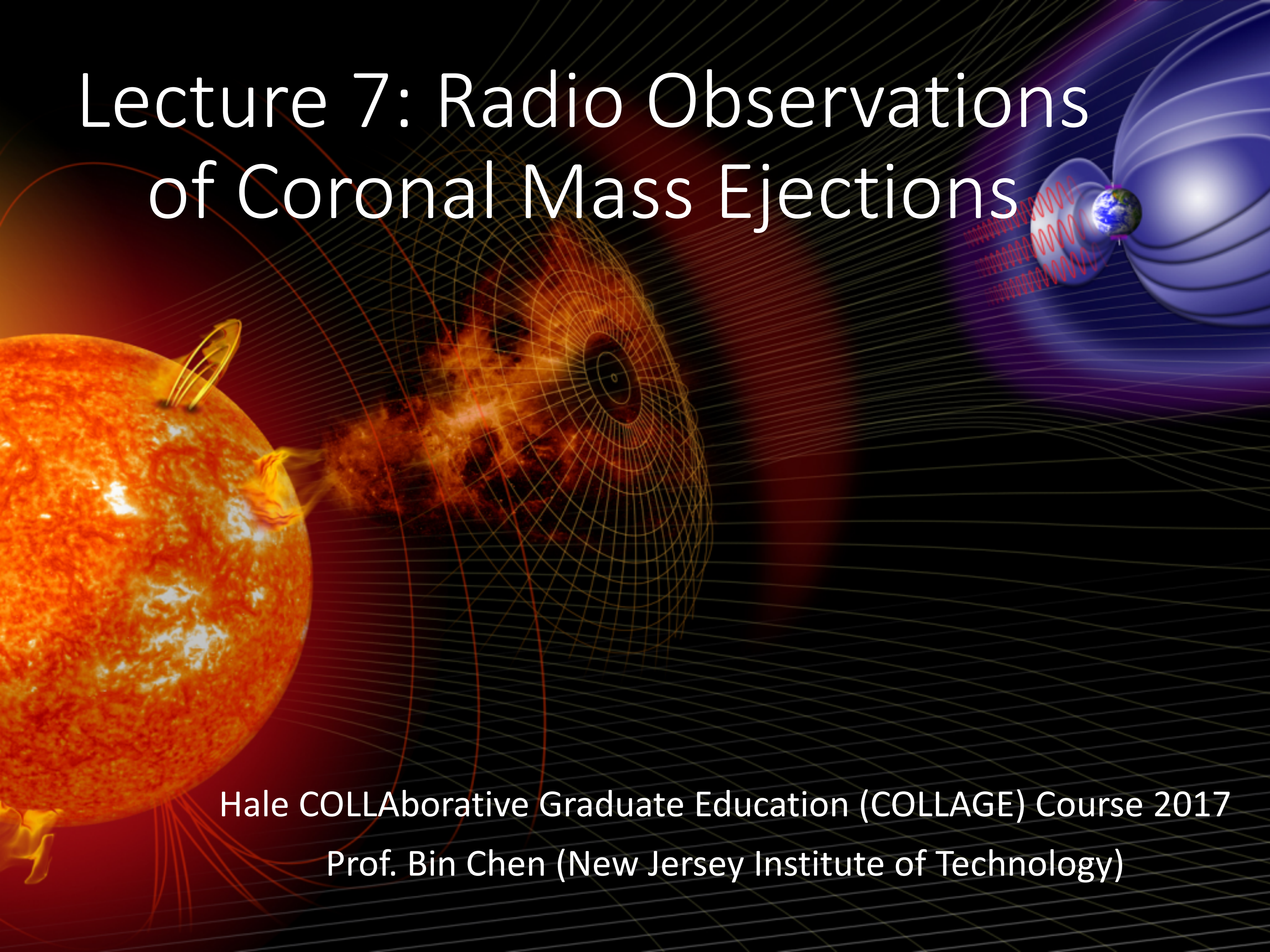


Lecture 7: Radio Observations of Coronal Mass Ejections

Hale COLLAborative Graduate Education (COLLAGE) Course 2017

Prof. Bin Chen (New Jersey Institute of Technology)

Lectures 7-8 outline

- Radio astronomy preliminaries
  - Radiative transfer
  - Relevant emission mechanisms
  - Types of solar radio bursts
- Radio observations of CMEs
  - Thermal CME
  - Gyrosynchrotron CME
  - Type IV(m) radio bursts
  - CME-driven shocks: type II radio burst and in situ signatures
  - (Time permitting) IPS, dispersion measure, Faraday rotation

Preliminaries

- Specific intensity

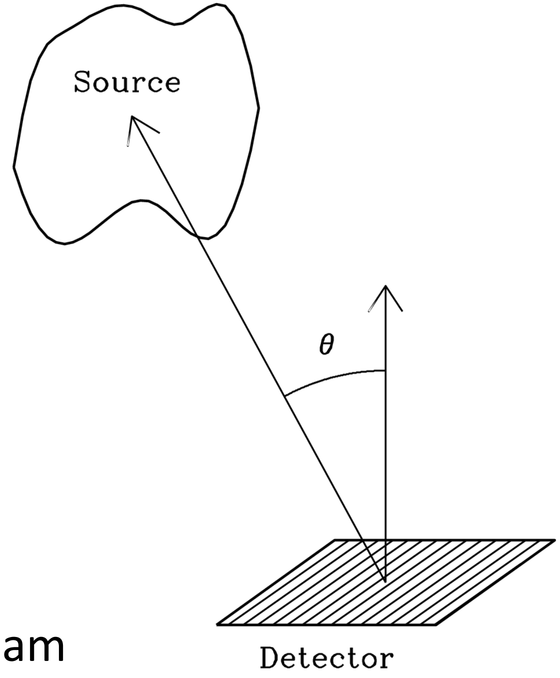
$$dE = I_\nu \cos\theta \, d\sigma \, d\Omega \, dt \, d\nu$$

- Flux density

$$S_\nu \equiv \int_{\text{source}} I_\nu(\theta,\phi)\cos\theta \, d\Omega$$

- Units
  - Flux density S_ν: ergs cm^{-2} s^{-1} Hz^{-1}
    - 1 Jy = 10^{-26} ergs cm^{-2} s^{-1} Hz^{-1}
    - 1 solar flux unit (sfu) = 10^{4} Jy
  - Specific intensity I_ν: ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1}
    - Sometimes radio images have units of Jy/beam
  - Total flux: ergs cm^{-2} s^{-1}

*CGS unit throughout this lecture



Radiative Transfer

- In the absence of emission, absorption, or scattering (the "free space"), the specific intensity I_ν along a ray does not change.
- However, if emission and absorption occurs, we use the radiative transfer equation

$$\frac{dI_\nu}{ds} = -\kappa_\nu I_\nu + j_\nu$$

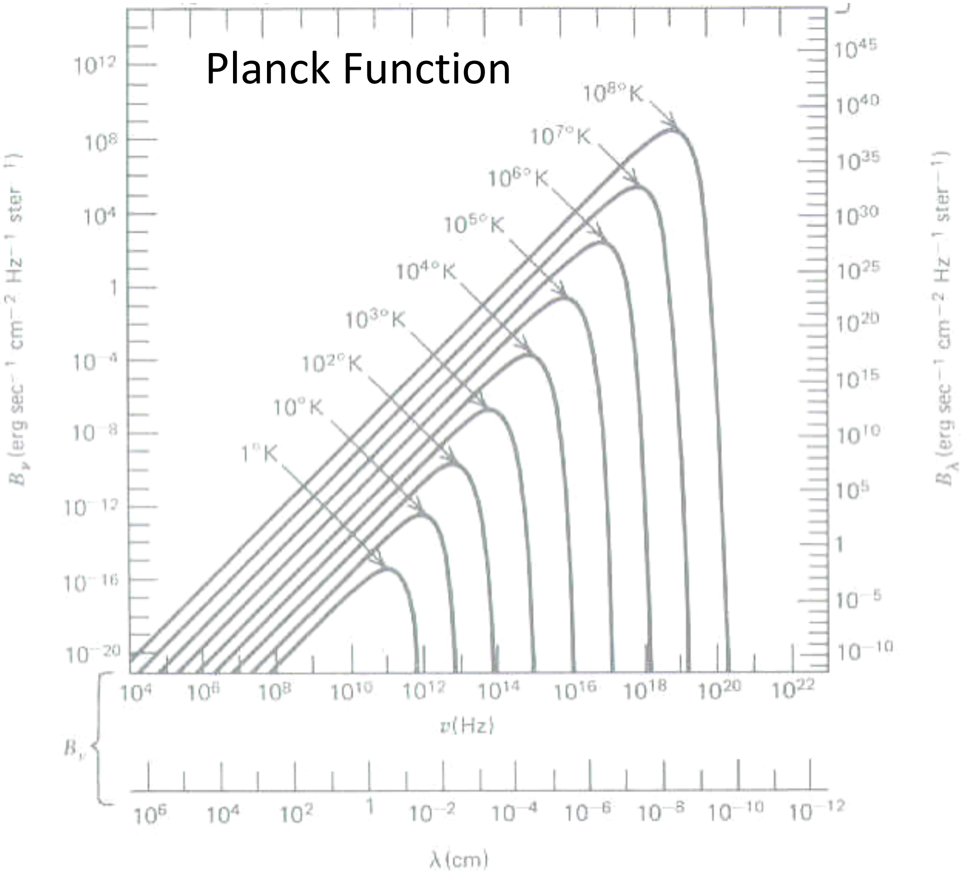
where κ_ν is the absorption coefficient (units cm^{-1}) and j_ν is the emission coefficient (units ergs cm^{-3} s^{-1} Hz^{-1} sr^{-1}).

Radiative Transfer

- Defining the optical depth $\tau_\nu = \kappa_\nu ds$ (no unit) and the source function $S_\nu = j_\nu / \kappa_\nu$ the transfer equation can be written as:
$$\frac{dI_\nu}{d\tau_\nu} = S_\nu - I_\nu$$
- For an isolated and homogeneous source the solution is
$$I_\nu(\tau_\nu) = S_\nu(1 - e^{-\tau_\nu})$$
  - When $\tau_\nu \gg 1$, the source is optically thick and $I_\nu \approx S_\nu$
  - When $\tau_\nu \ll 1$, the source is optically thin and $I_\nu \approx \tau_\nu S_\nu$

Brightness Temperature

- While specific intensity can be expressed in units of Jy/beam or SFU/beam, a simple and intuitive alternative is brightness temperature, which has units of Kelvin.



Planck Function

Brightness Temperature

Note that at radio wavelengths

$$h\nu / kT << 1 \;\rightarrow\; e^{h\nu/kT} - 1 \approx 1 + \frac{h\nu}{kT} - 1 = \frac{h\nu}{kT}$$

The Planckian then simplifies to the Rayleigh-Jeans Law.

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT} - 1} \approx \frac{2\nu^2}{c^2}kT$$

It is useful to now introduce the concept of brightness temperature T_B, which is defined by

$$I_\nu = B_\nu(T_B) = \frac{2\nu^2}{c^2}kT_B$$

Rewriting the Radiative Transfer Equation

- Similarly, we define the effective temperature as

$$S_\nu = \frac{2\nu^2}{c^2} k T_{eff}$$

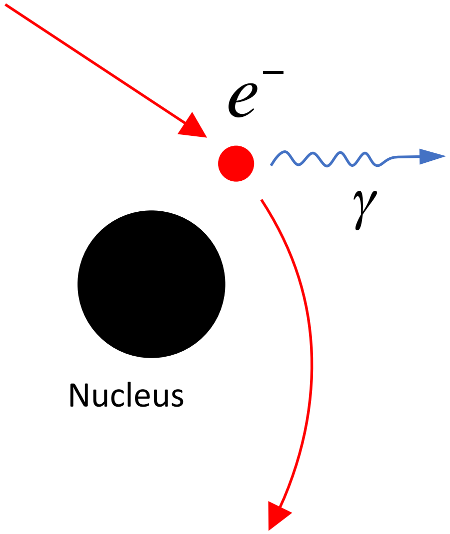
- Using our definitions of brightness temperature and effective temperature, the transfer equation can be rewritten

$$\frac{dT_B}{d\tau_\nu} = -T_B + T_{eff}$$

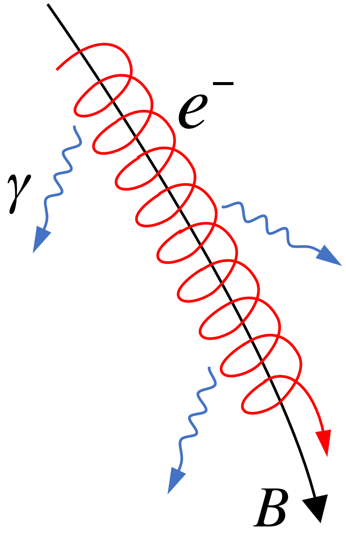
  - Optically thick source, $\tau_\nu \gg 1, T_B \approx T_{eff}$
  - Optically thin source, $\tau_\nu \ll 1, T_B \approx \tau_\nu T_{eff}$

Relevant Radio Emission Mechanisms: An Introduction

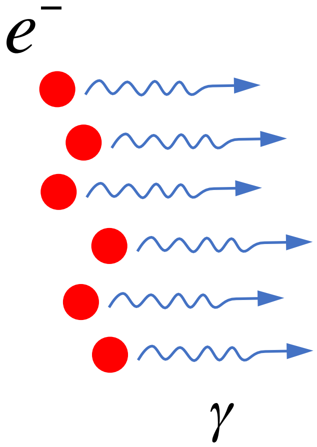
Bremsstrahlung



Gyromagnetic Radiation

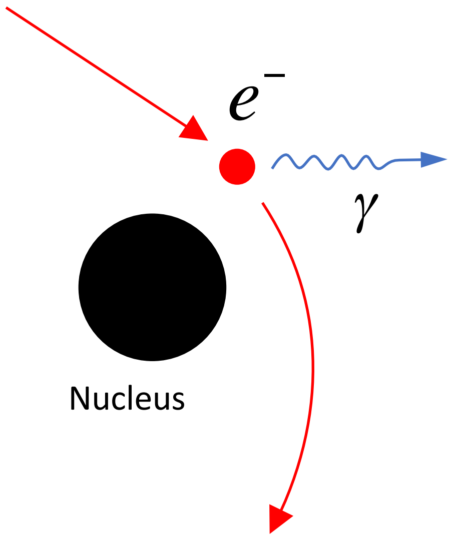


Plasma Radiation



Bremsstrahlung Radiation

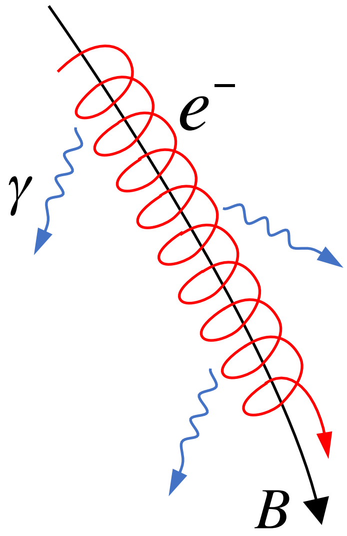
- Acceleration experienced in the Coulomb field
- At radio wavelengths, thermal bremsstrahlung radiation is from virtually everywhere: quiet Sun, active regions, flares, and CMEs
- Nonthermal bremsstrahlung is relevant to X-ray and gamma-ray emission from flares



Gyromagnetic radiation

- Acceleration experienced in the magnetic field
- Gyroresonance radiation from thermal electrons. Relevant in places with strong B field: e.g., active regions
- Gyrosynchrotron radiation from relativistic electrons. Relevant when high energy electrons are present: e.g., flares and CMEs
- Electron gyrofrequency: one "natural frequency" of the solar corona

$$f_{ce} = \frac{eB}{2\pi m_e c} \approx 2.8B \text{ MHz}$$



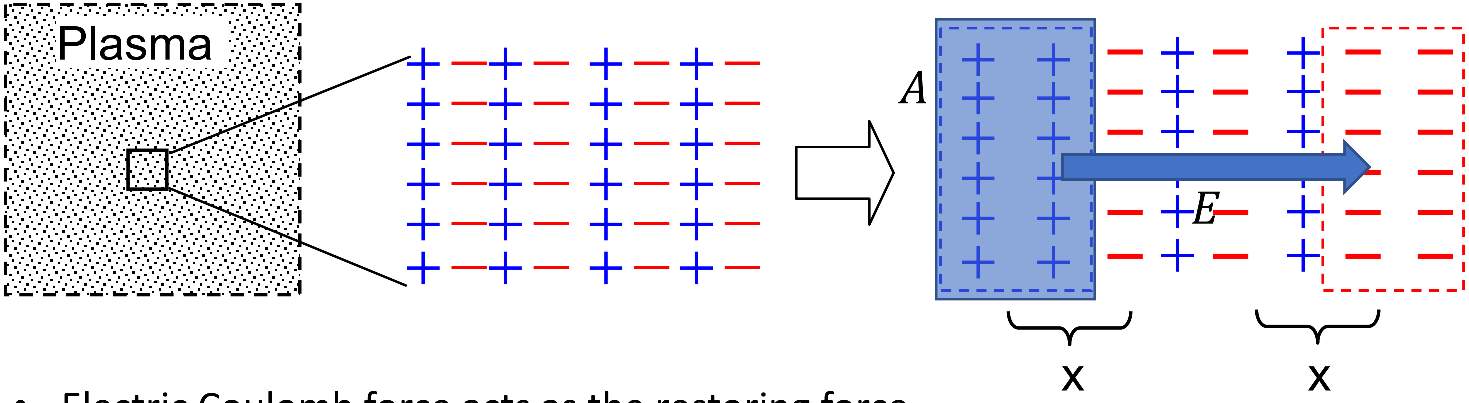
Plasma Radiation

- Plasma oscillation, also known as "Langmuir wave", occurs near the plasma frequency, another important natural frequency in the solar corona

$$f_{pe} = \sqrt{\frac{n_e e^2}{\pi m_e}} \approx 8980\sqrt{n_e}\ \mathrm{Hz}$$

- Plasma radiation arises when Langmuir waves are converted to (transverse) electromagnetic waves via wave-wave interactions.

let’s do some derivation…



- Electric Coulomb force acts as the restoring force
- Gauss’s Law: $\nabla \cdot E = 4\pi\rho$. Integral form $\oiint E \cdot \hat{n} ds = 4\pi Q$
- So $E = \frac{4\pi Q}{A} = \frac{4\pi\rho A x}{A} = 4\pi e n_e x$
- Newton’s 2nd law: $m_e \frac{d^2x}{dt^2} = -eE = -4\pi n_e e^2 x$, which has the form of a simple harmonic oscillator:

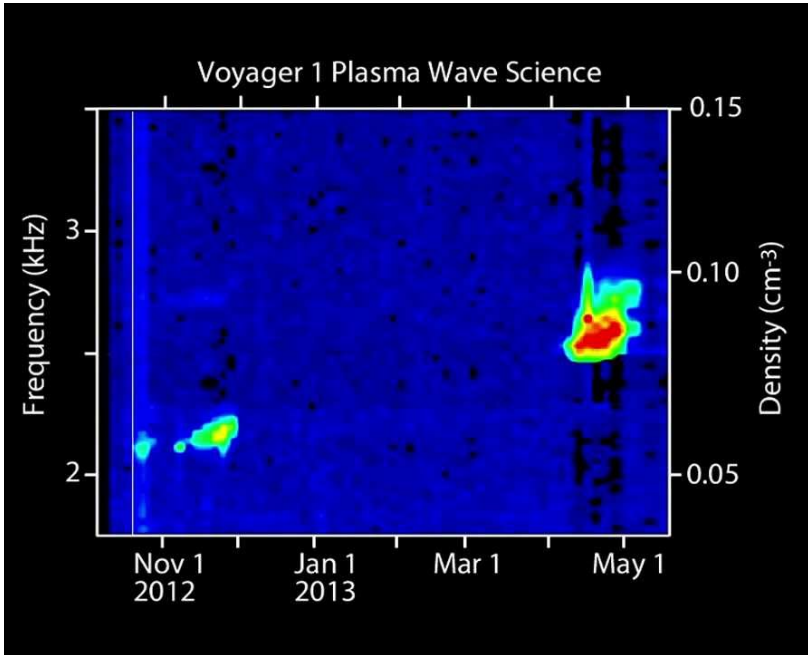
$$\ddot{x} + \omega_{pe}^2 x = 0,$$

where $\omega_{pe} = \sqrt{\frac{4\pi n_e e^2}{m_e}} = 2\pi f_{pe}$ is the plasma frequency

Plasma frequency: typical values

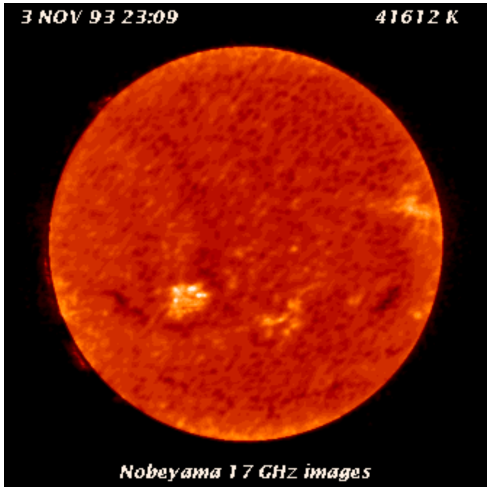
Plasma Environment	n_e **(cm^{-3})**	f_{pe} **(MHz)**
ISM	0.05	0.003
Ionosphere	10^5	3
Low corona	10^{10}	900
Copper	10^{23}	2.8×10^9

[Listen to plasma oscillations when Voyager enters the local ISM]



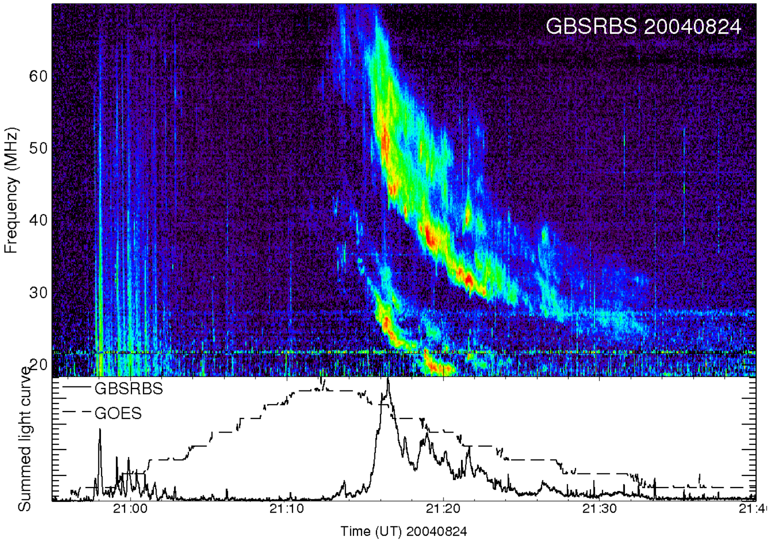
Radio Observations in General

- Emission Mechanisms
  - Thermal
  - Non-Thermal
- Range of Observations
  - Chromosphere (~100 GHz)
  - Aurora (KHz)
- Types of radio data

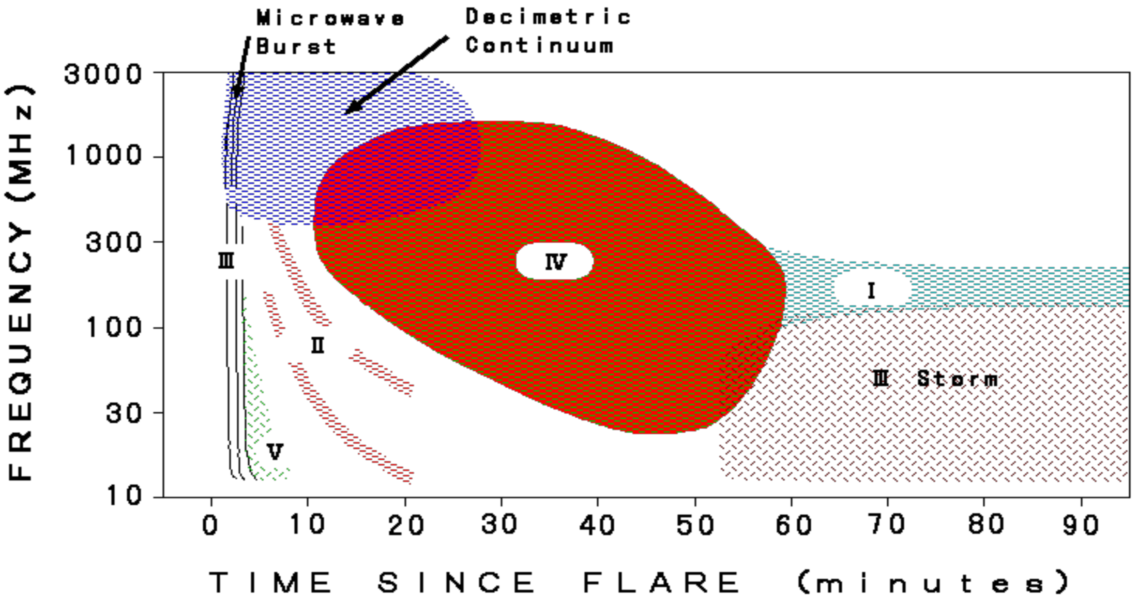


Nobeyama Radioheliograph 17 GHz

+



Solar radio bursts types from 1960s



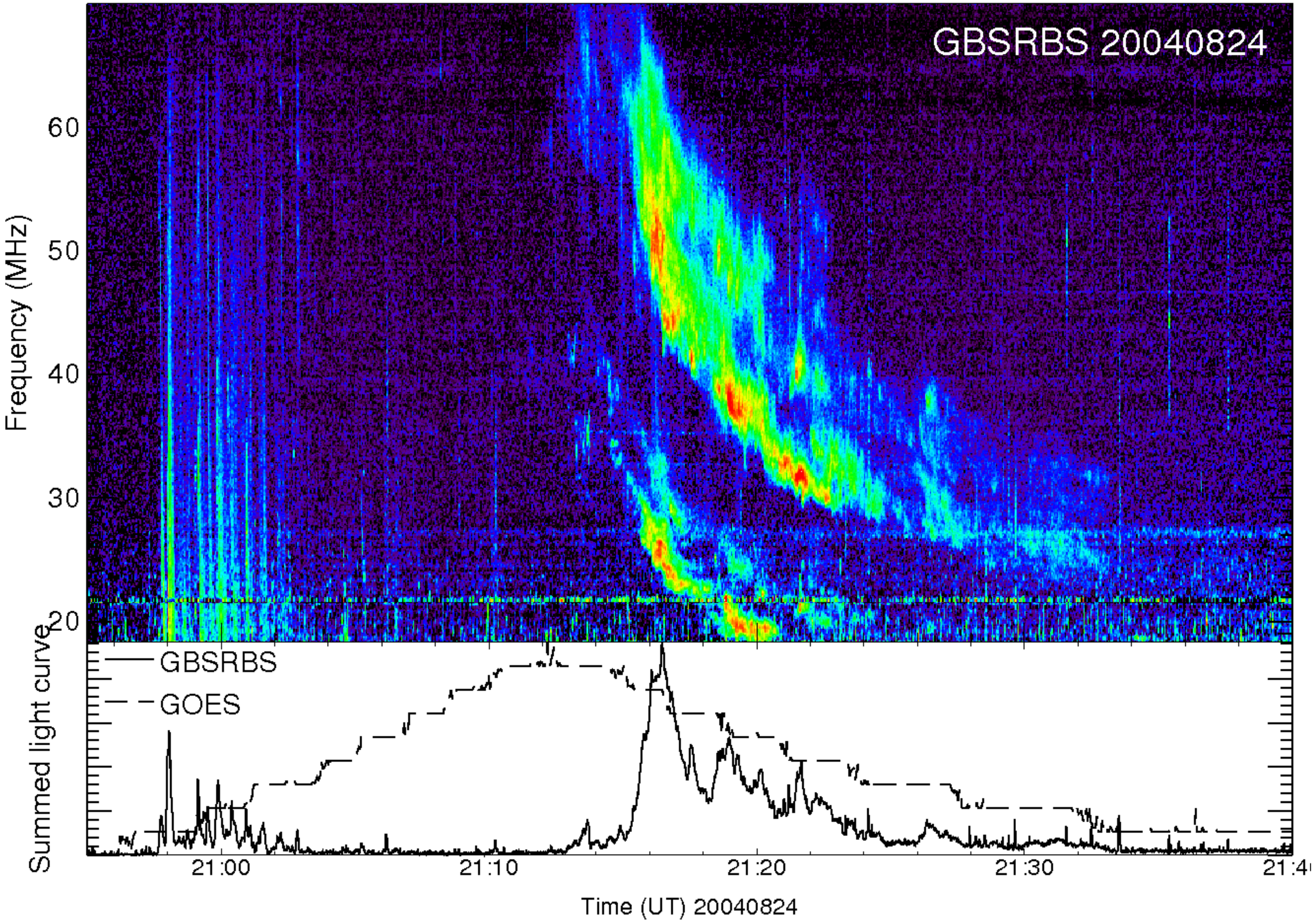
- Type I: short duration, narrow band, non-drifting bursts. Origin unknown.
- Type II: CME-driven shock (~1000 km/s)
- Type III: fast electron beams (~0.3c), rapid frequency drift
- Type IV: close magnetic structure -- CME body, post-CME reconfiguration
- Type V: extended phase of type III

Examples from the Green Bank Solar Radio Burst Spectrometer (GBSRBS)

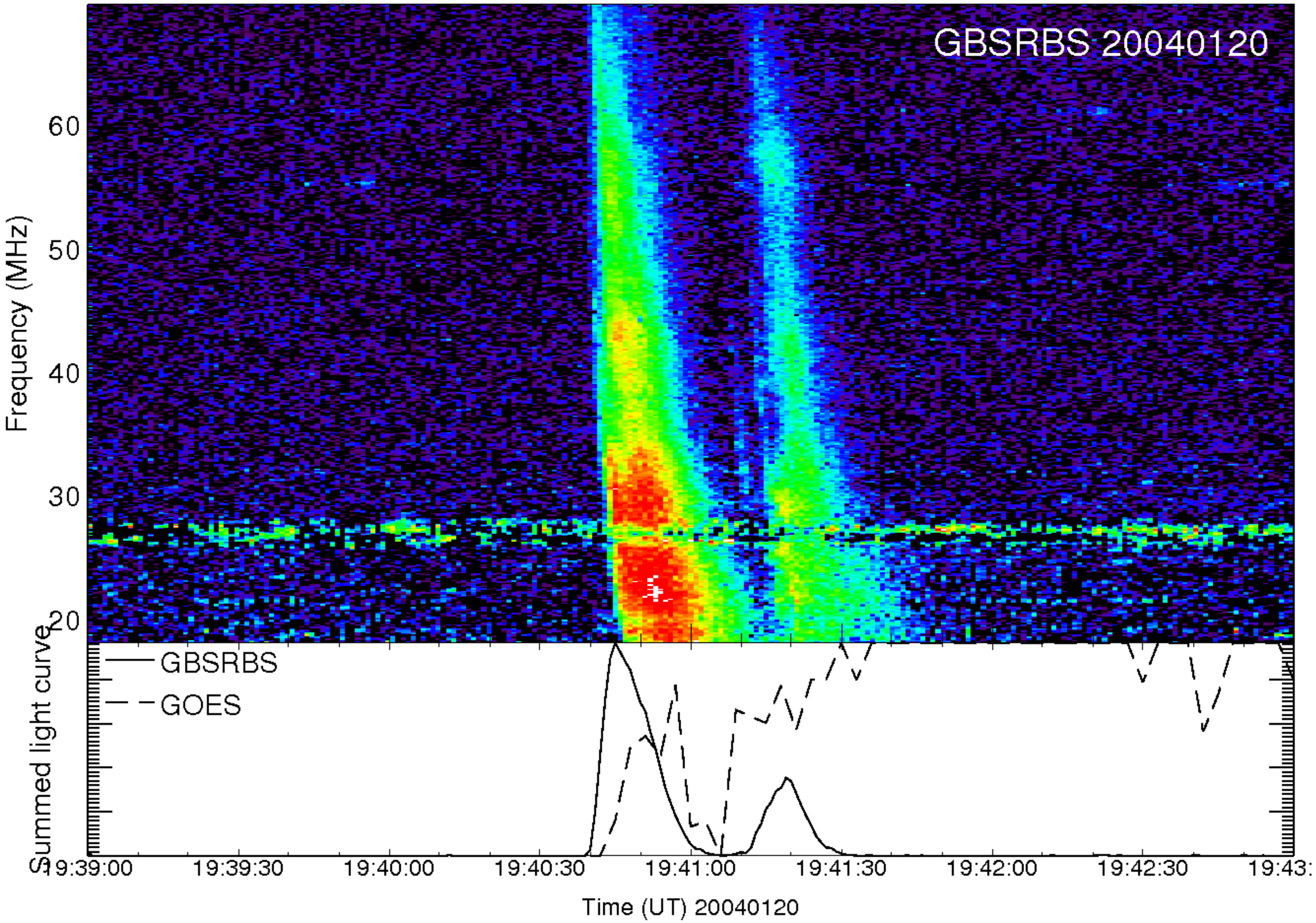
- http://www.astro.umd.edu/~white/gb/
- Located in the Green Bank Radio Quiet Zone, operating in 18-70 MHz, 70-300 MHz, 300-1000 MHz

Credit of following images: Stephen White

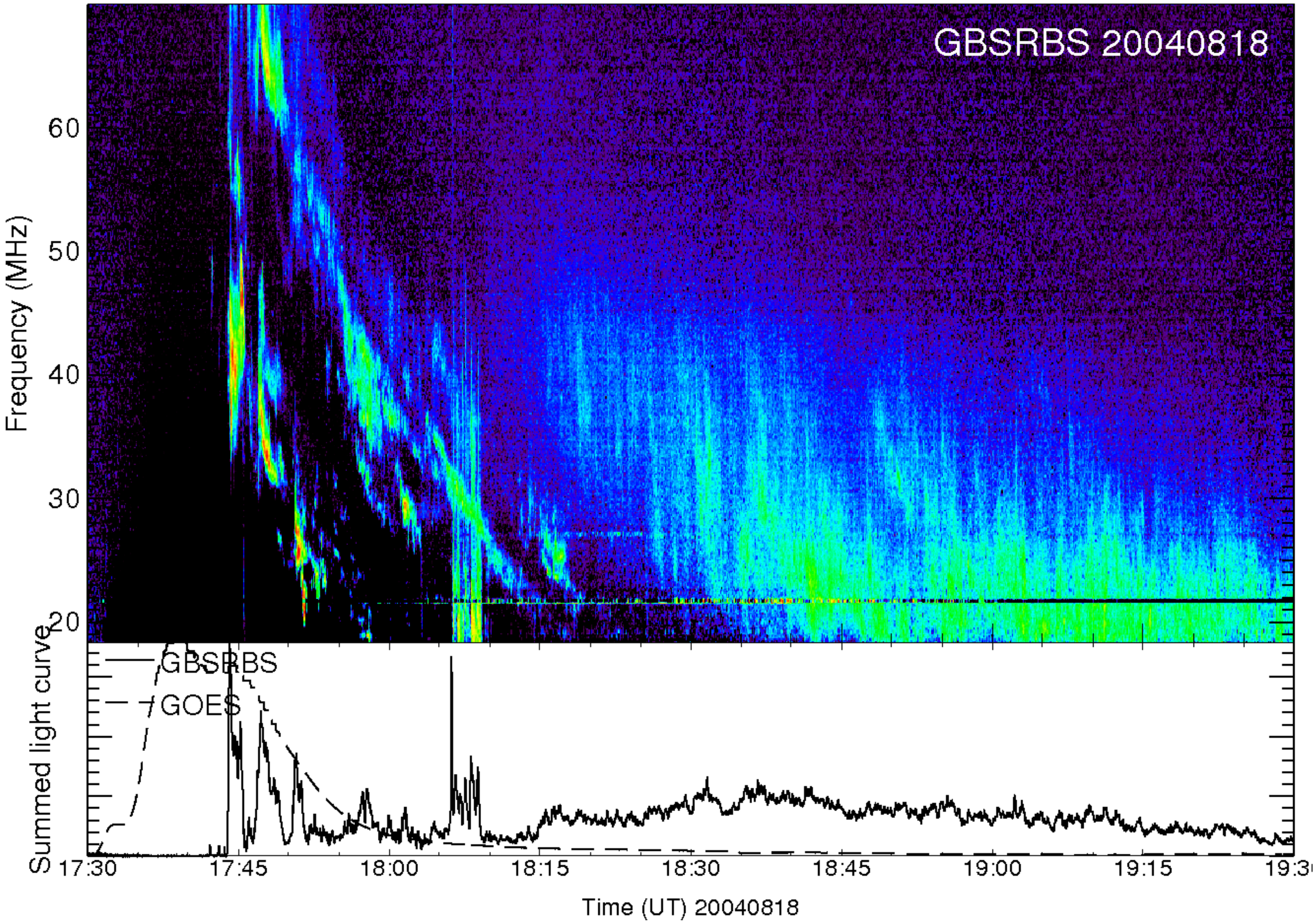
Type III’s followed by Type II (45 mins)



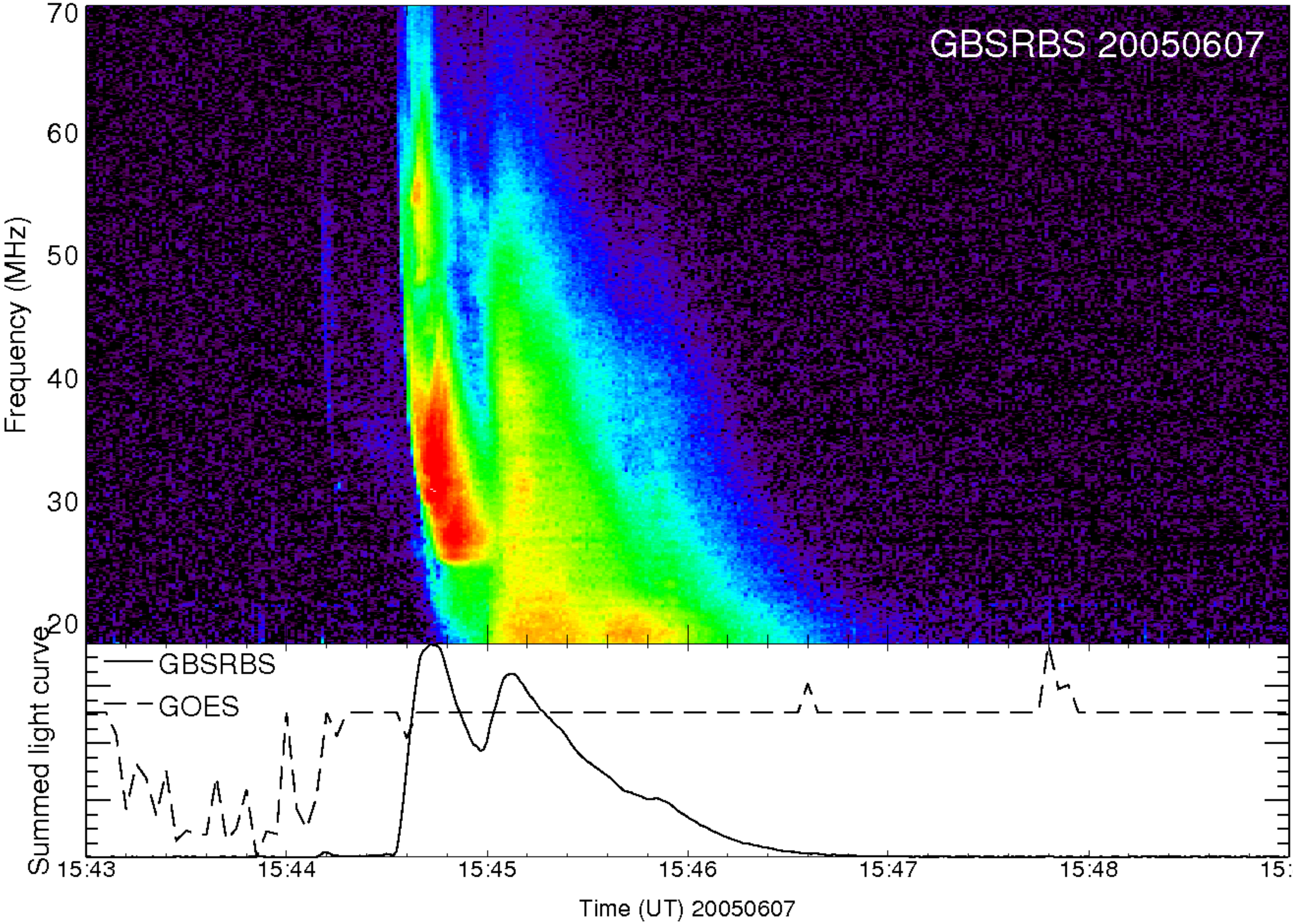
Type III burst: fast-drift electron beam (4 mins)



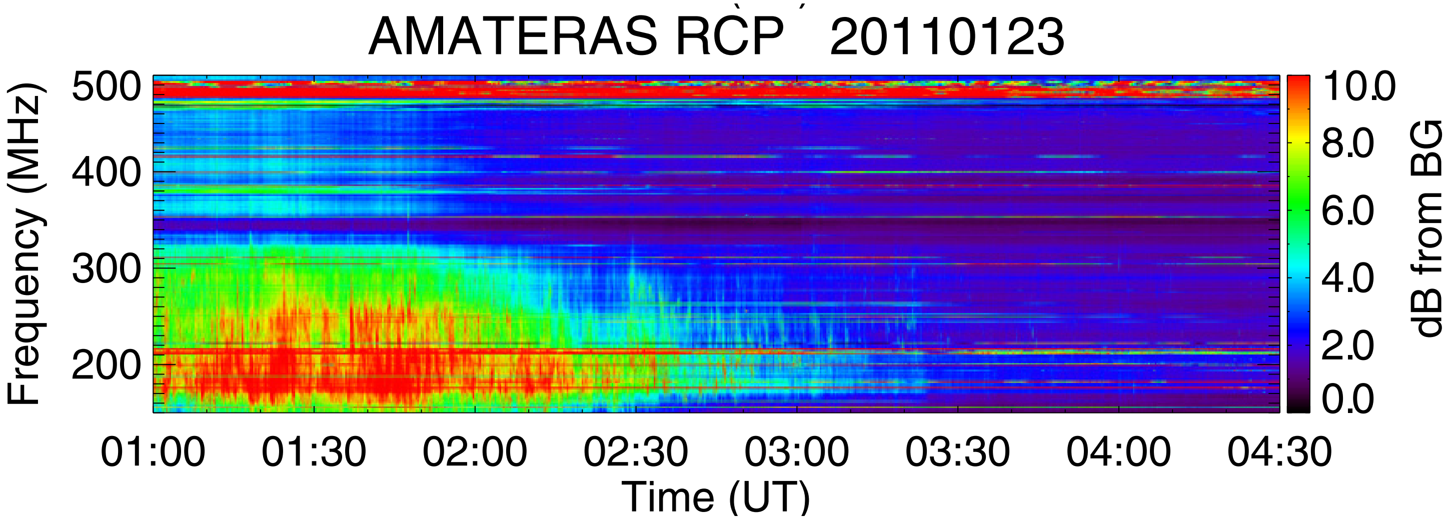
Type II followed by Type IV (2 hours)

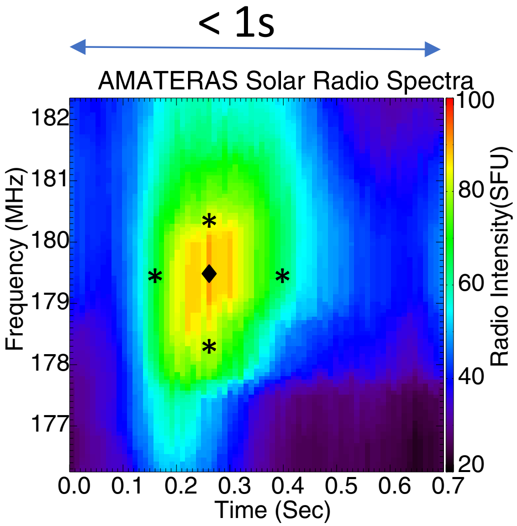


Type V: extended phase of Type III (6 mins)



Type I bursts (3 hours)

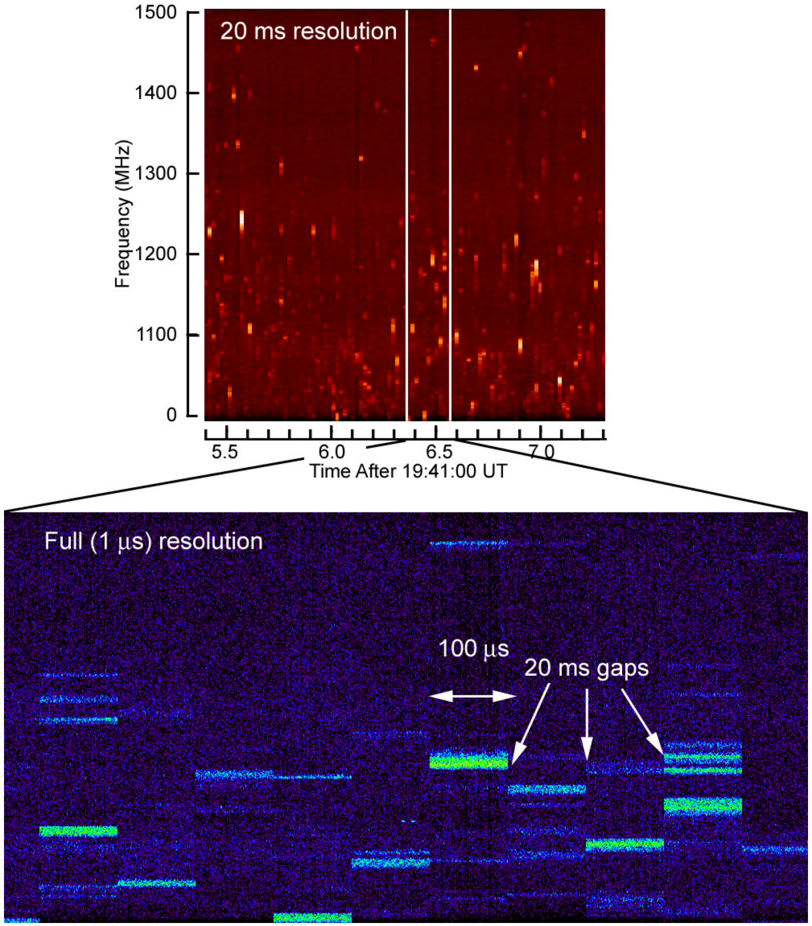




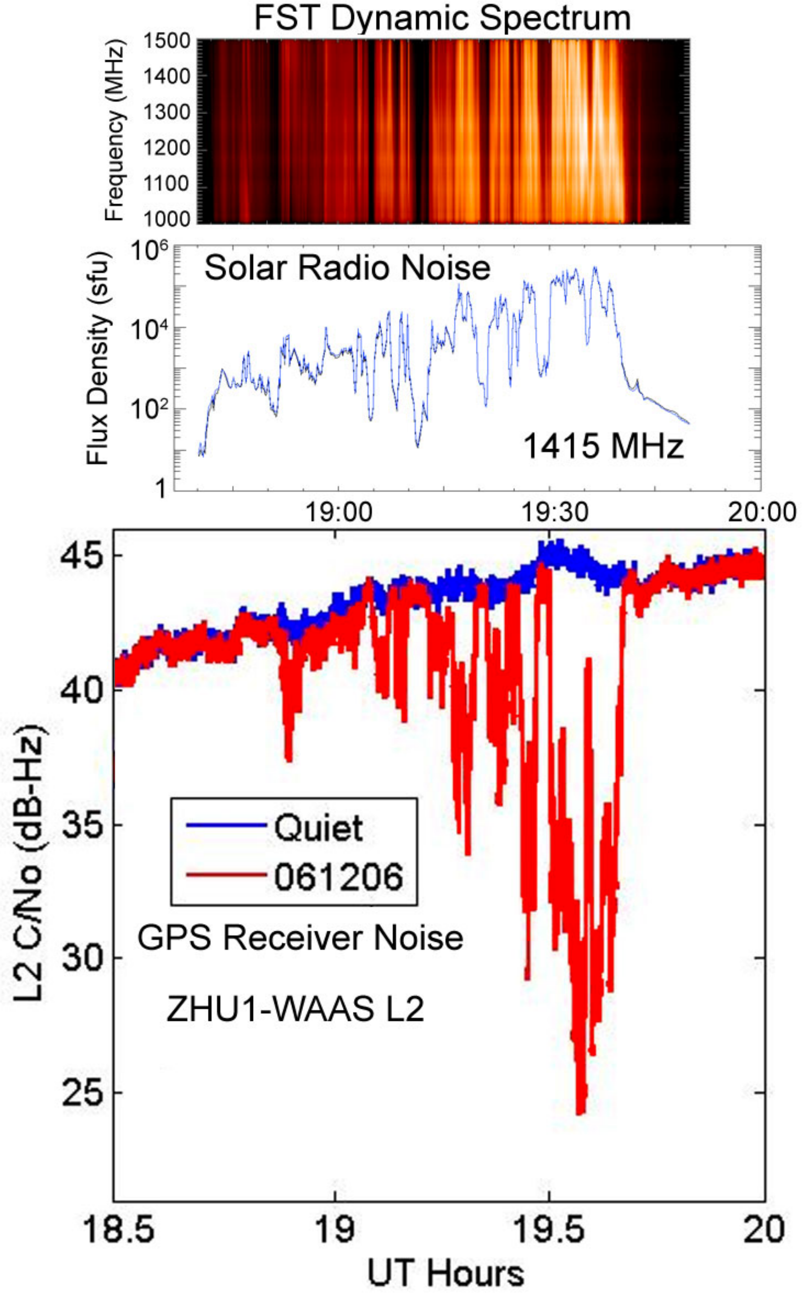
Iwai et al. 2014

Other complex types

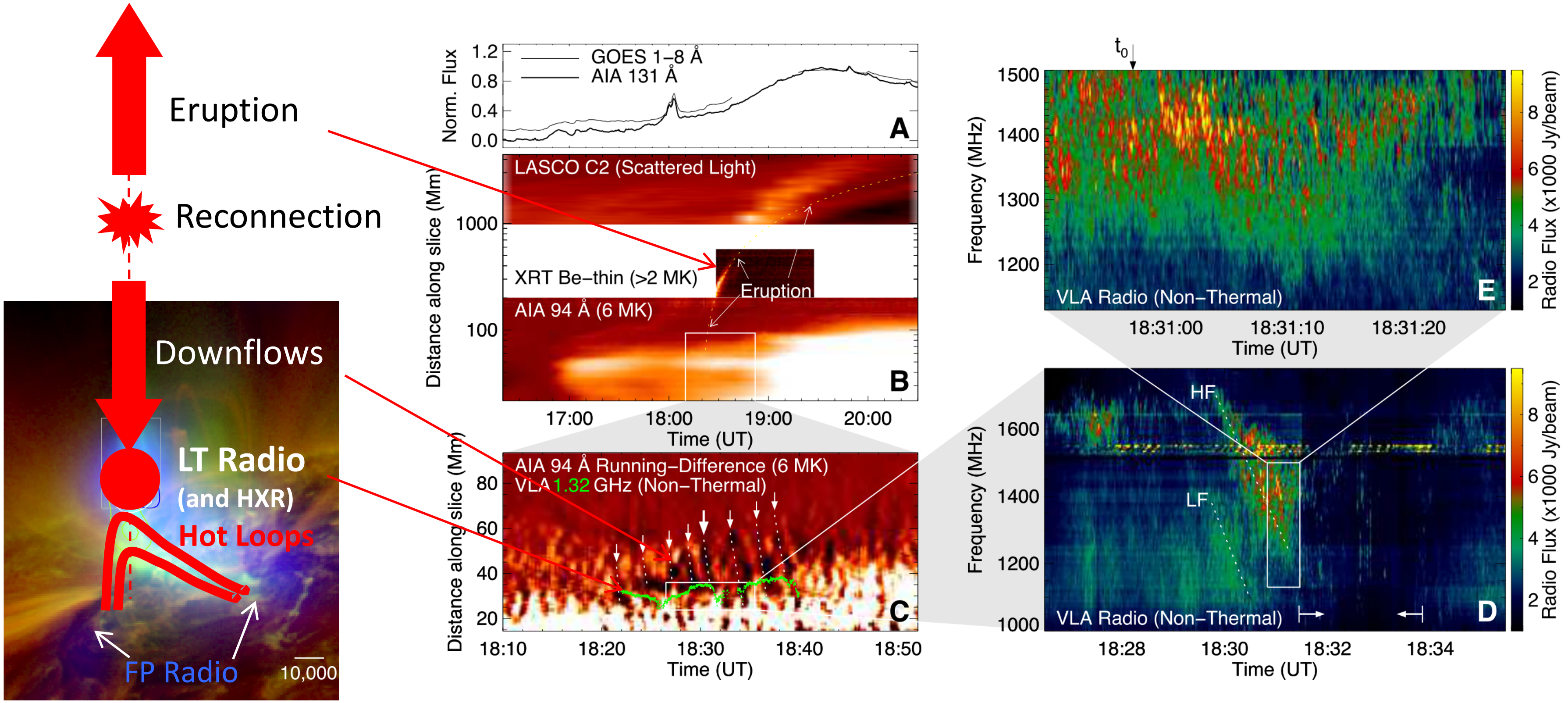
Strongest solar radio burst ever recorded, > 1 million sfu at ~1 GHz



From Dale Gary

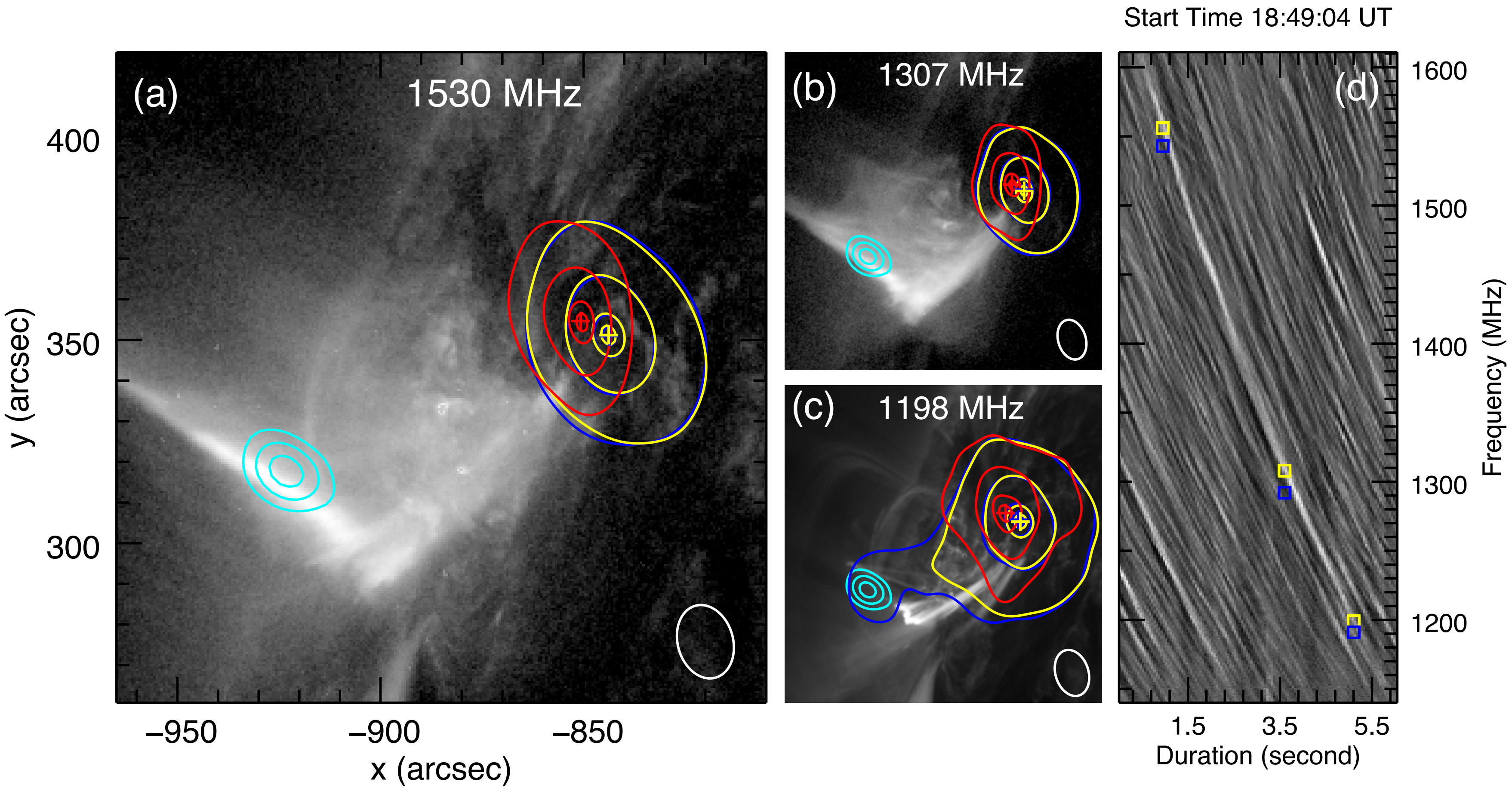


Decimetric radio bursts associated with flare termination shock



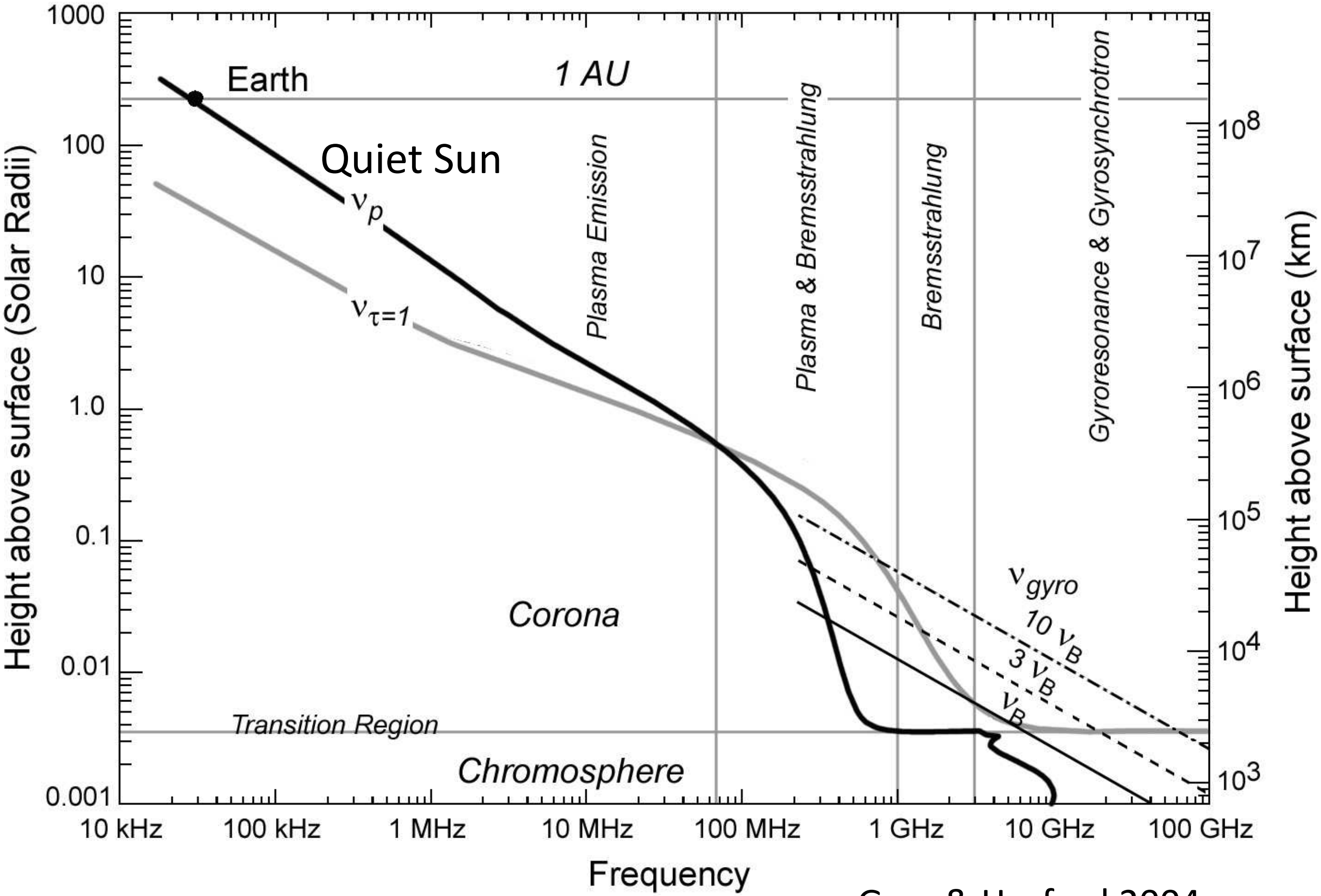
Chen et al. 2015, *Science*

Radio bursts associated with propagating wave packets



Wang, Chen & Gary 2017

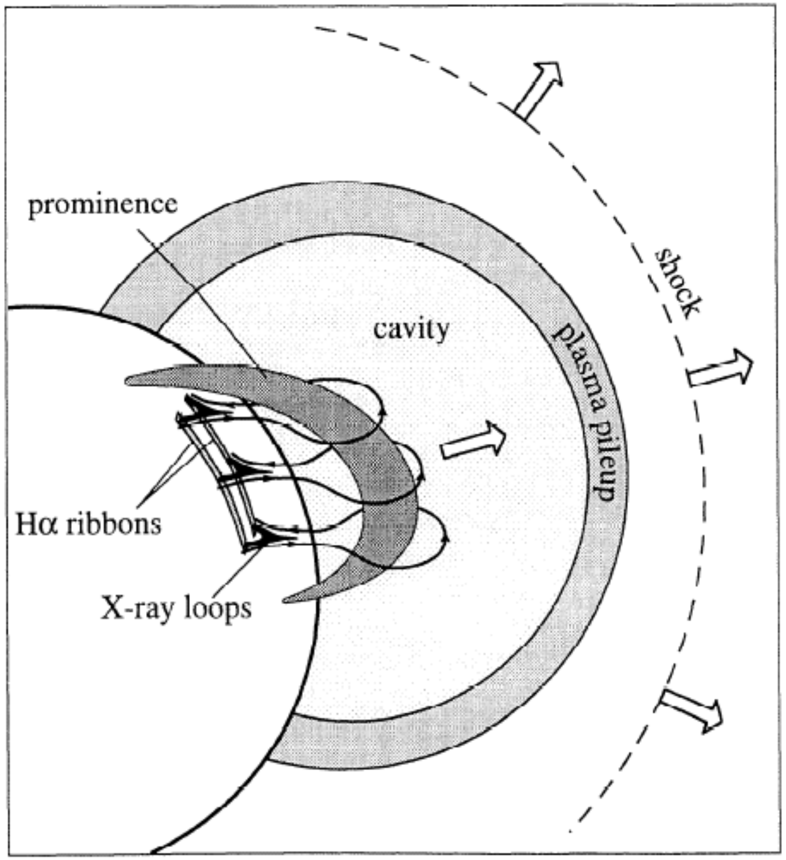
A nice illustration of solar radio emission



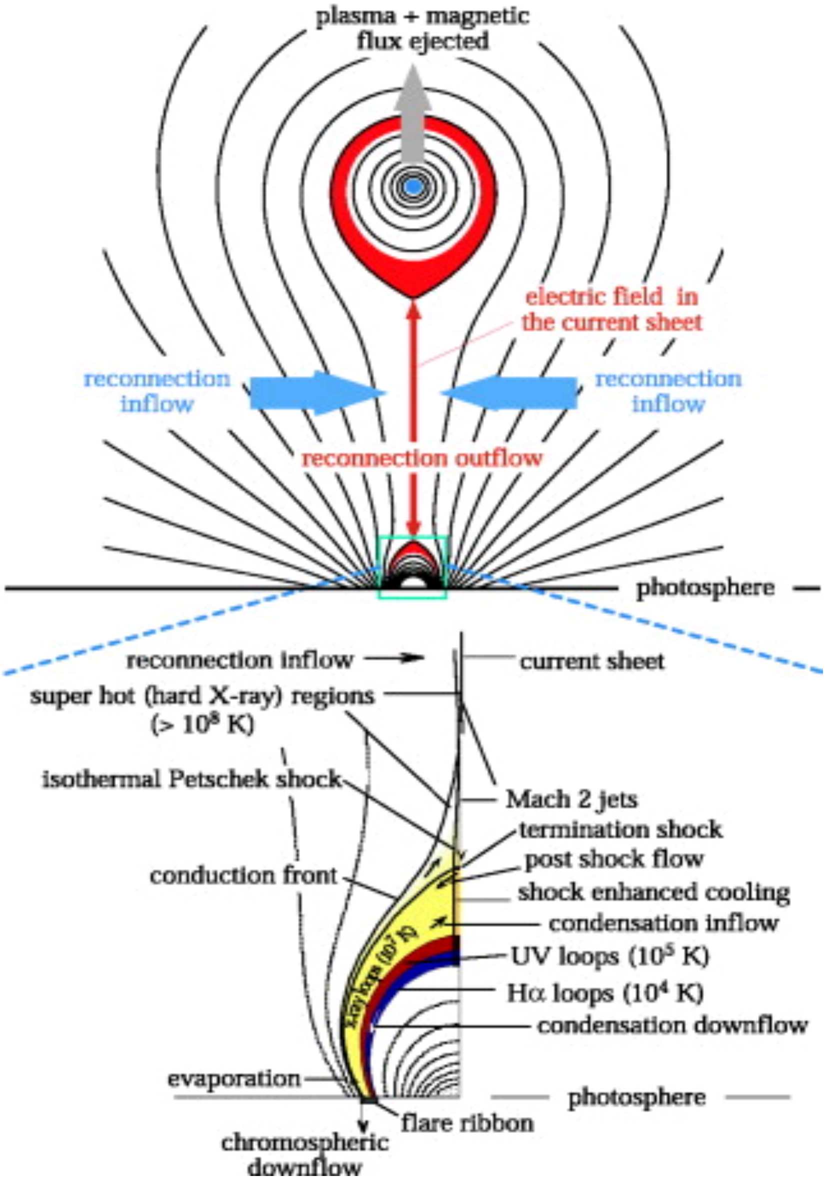
Gary & Hurford 2004

Okay, let’s apply these to coronal mass ejections!

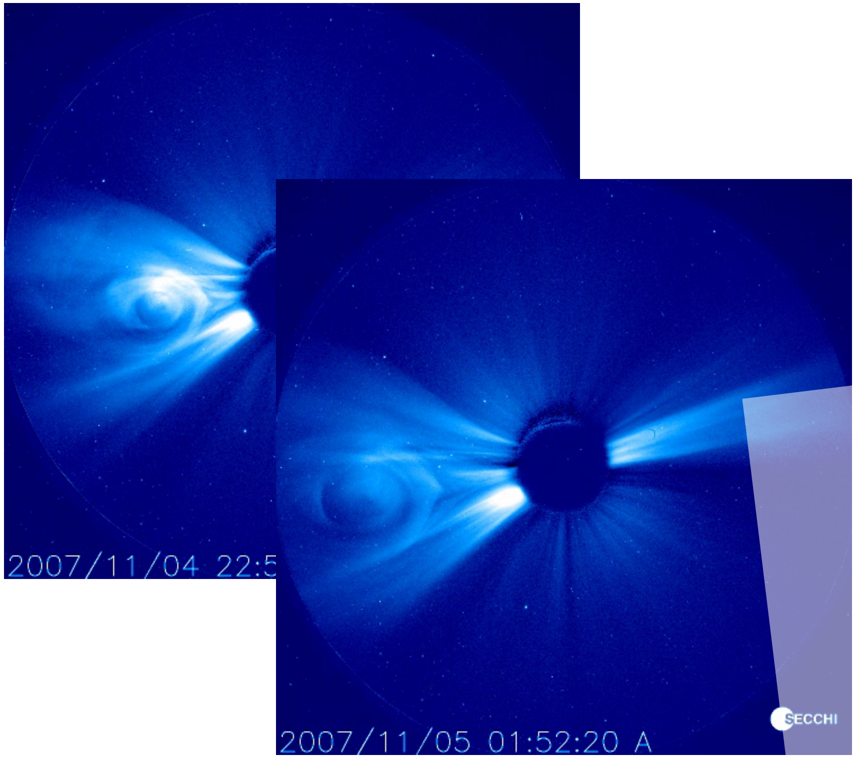
Standard Flare-CME Model

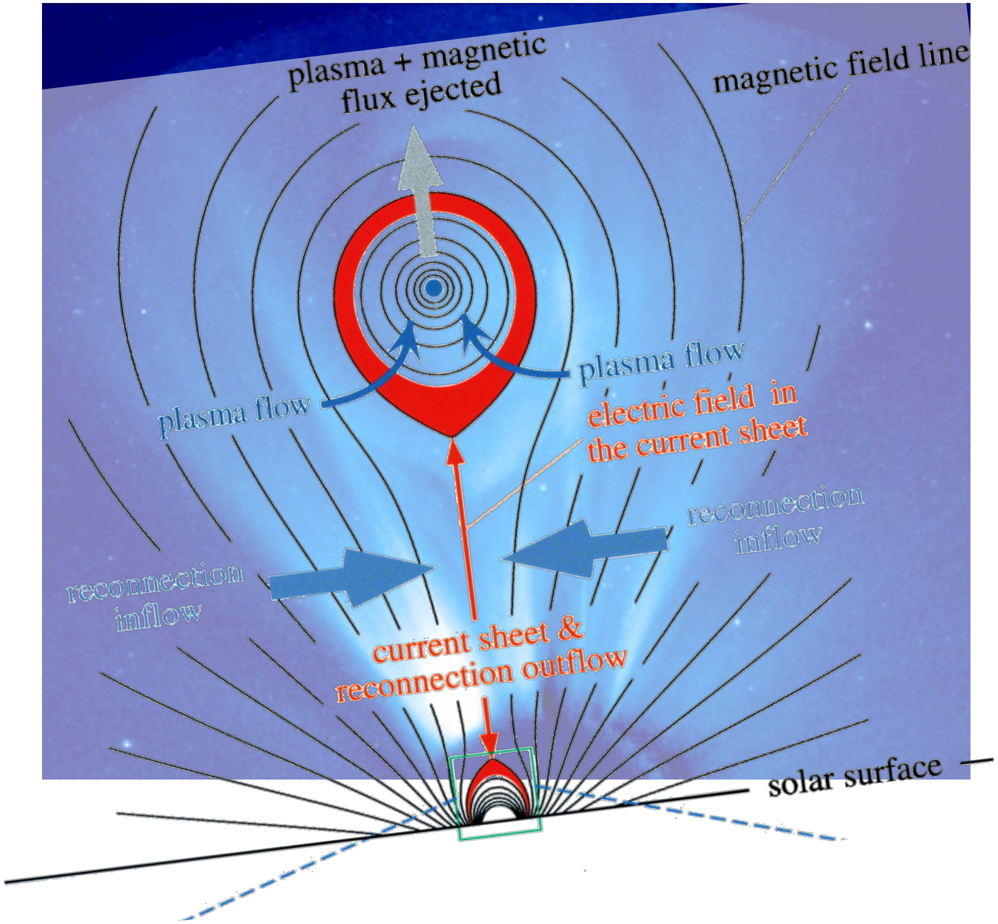


Forbes-Lin model



From Lecture 5 (Prof. Jiong Qiu)





CMEs in white light

From Angelos Vourlidas

From Lecture 5 (Prof. Jiong Qiu)

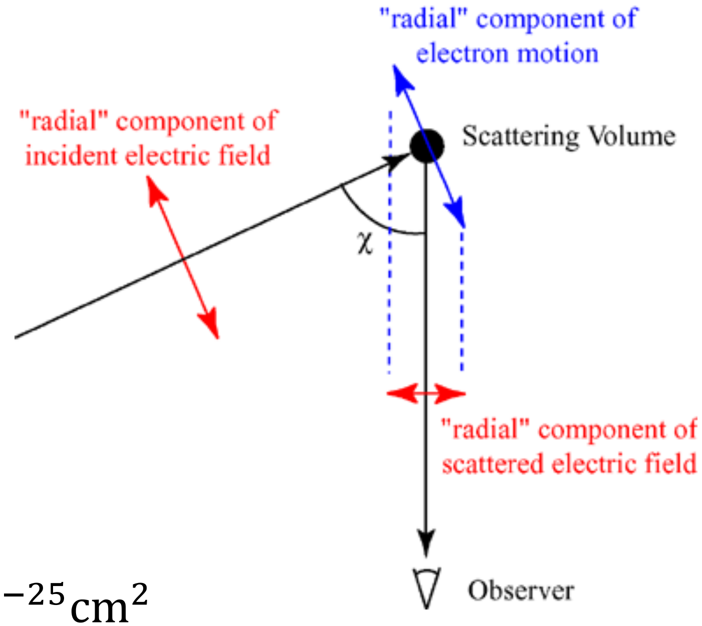
White light emission: Thomson scattering

- Not too far away from the solar disk, white light emission is dominated by Thomson scattering off free electrons (“K-corona”)
- The corona is extremely optically thin, the white light brightness is

$$I_\nu \approx \int S_\nu d\tau_\nu = \int_{-\infty}^{+\infty} \sigma_T S_\nu n_e dl$$

❖ Thomson cross-section $\sigma_T = \frac{8\pi}{3} r_e^2 \approx 6.65\times10^{-25}\mathrm{cm}^2$

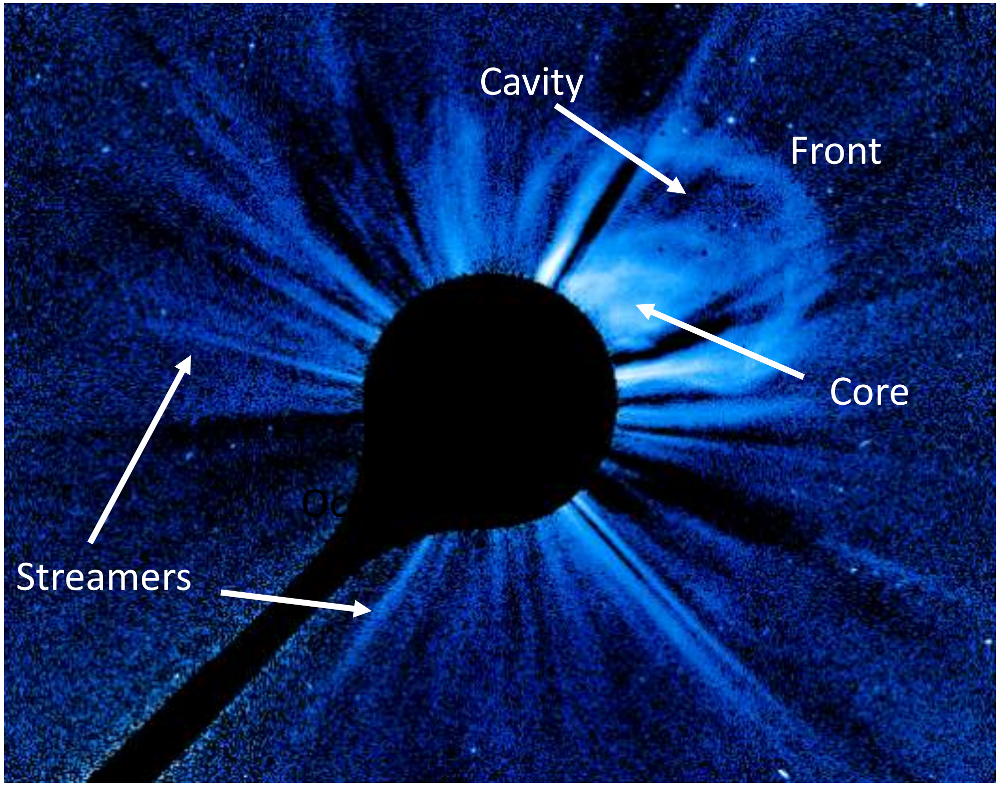
❖ Source function S_ν is related to the incident intensity from the photosphere and the viewing angle



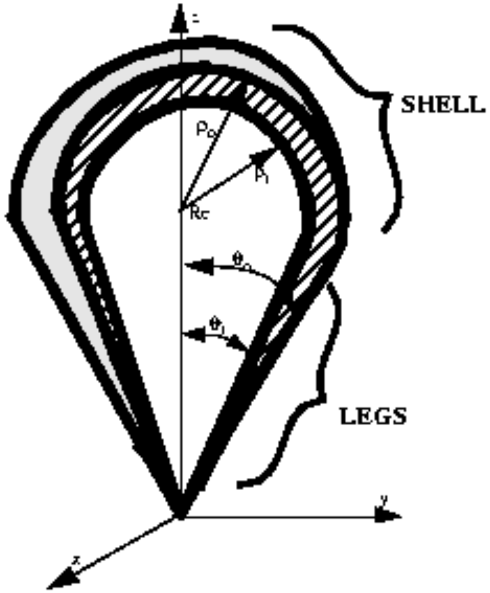
See [Prof. Steven Cranmer’s lecture 6](#) of COLLAGE 2016 for more details

Review of CME White Light Observation

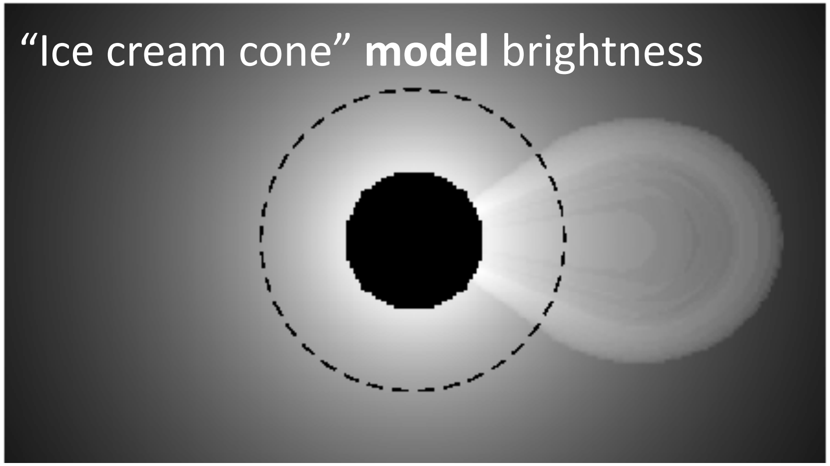
- White light emission is due to Thomson scattering, which goes as $n_e dl$
- We can see a bright WL emission because:
  - It has more mass than the ambient
  - It is extended *along* the LOS
  - It is close to the plane of maximum scattering

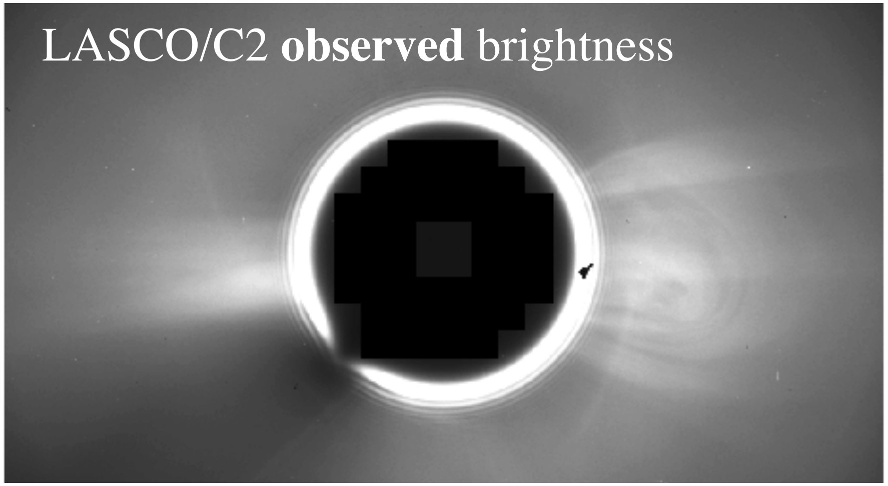


White Light CME



The “ice cream cone” model

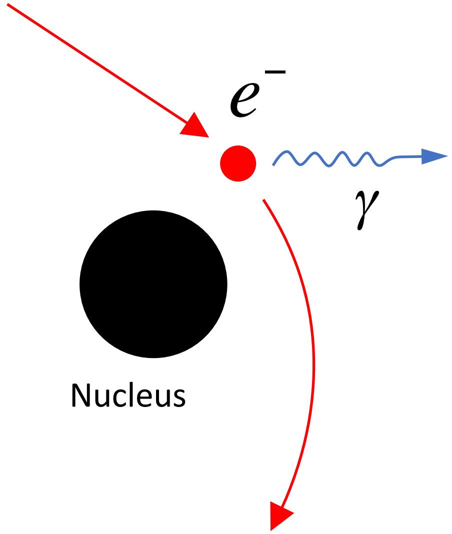

“Ice cream cone” **model** brightness


LASCO/C2 **observed** brightness

From Sarah Gibson

Thermal radio emission from CME

- CME body also produces thermal bremsstrahlung radio emission
  - Coulomb "collisions" involve both ions and electrons
  - Radio intensity $I_\nu \propto \int n_e n_p dl \propto n_e^2 l$, known as "emission measure"
- Radio intensity weakens much faster at larger distance, however relatively more straightforward for modeling
- Possible to see thermal radio CMEs against the disk (no occulter)



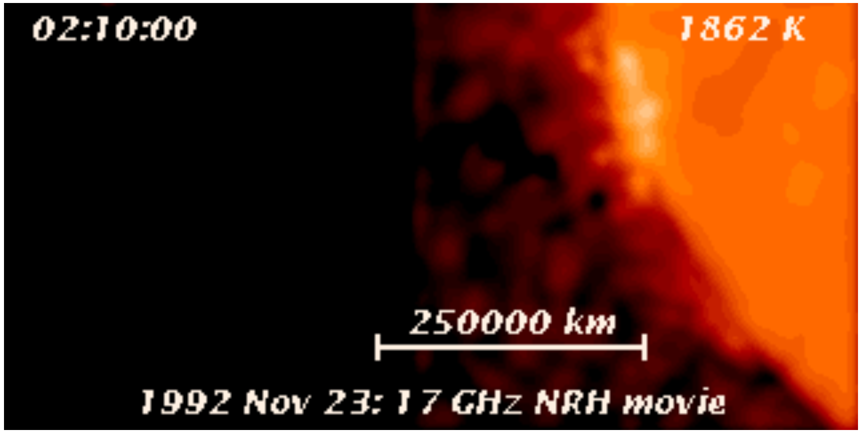
Detectability of thermal radio CME

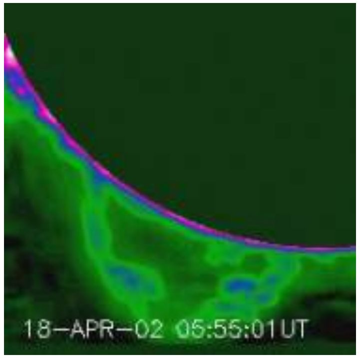
- Well, no problem for dense and cool prominences

Bremsstrahlung radiation

$$I_\nu \propto \int n_e n_p dl \propto n_e^2 l$$

$$\kappa_\nu \propto T_e^{-1/2}$$



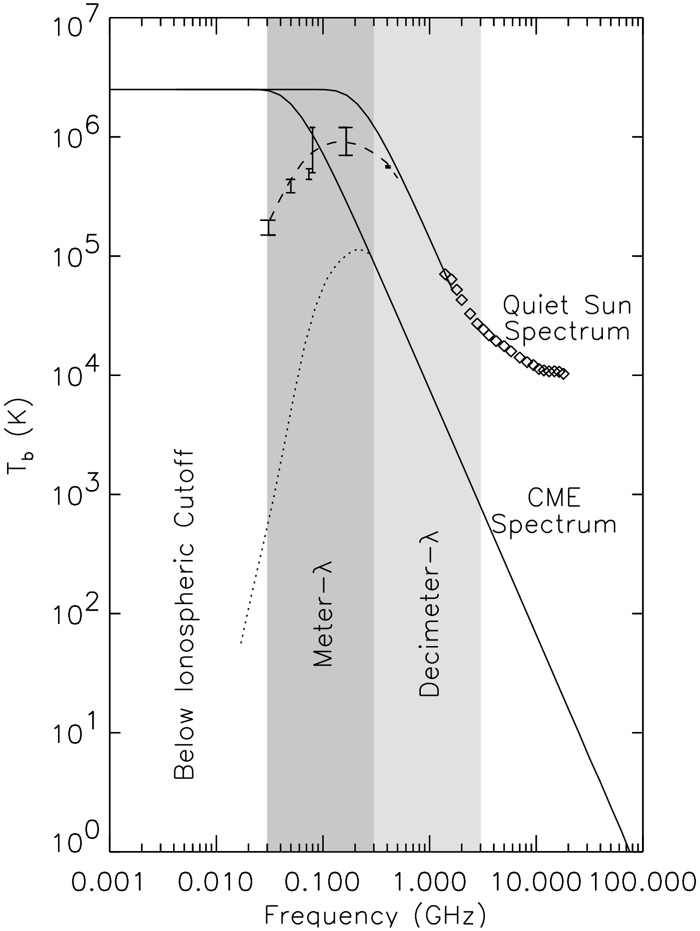


NoRH 17 GHz

Thermal radio detectability of CME body

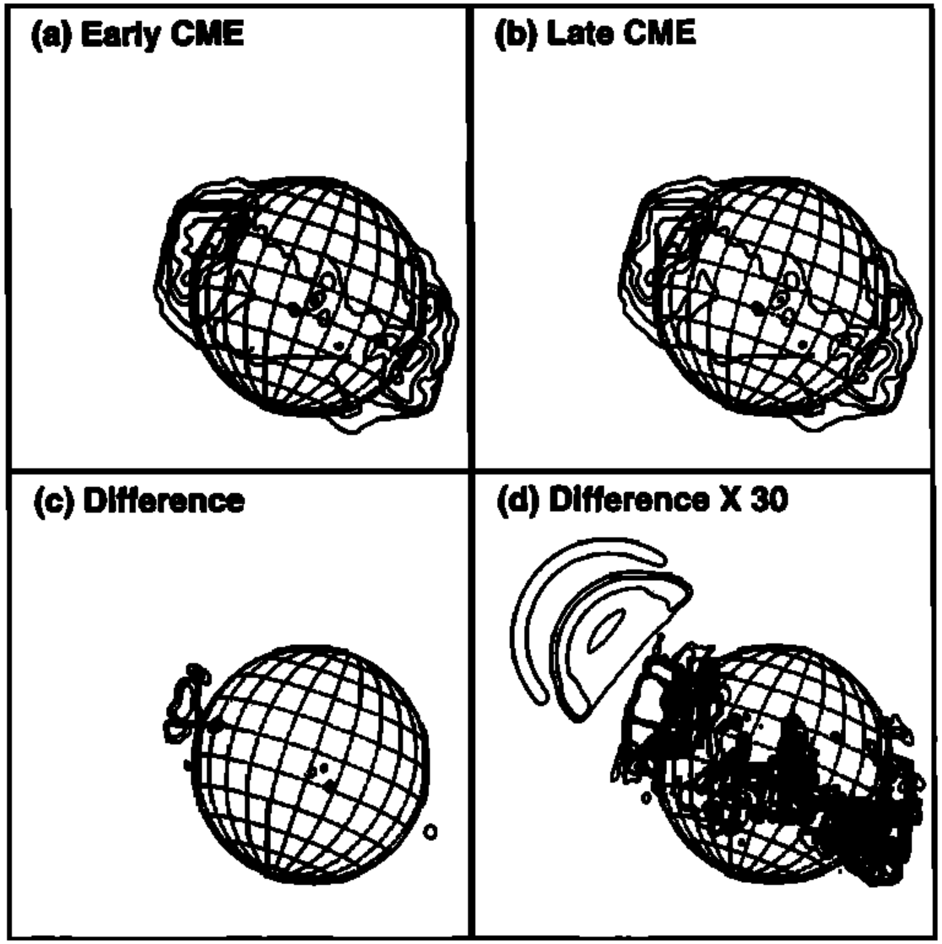
- Contrast of CME/QS ~ 1:10 in meter & dm range, but much smaller at higher frequencies
- Susceptible to be ”blinded out” by intense plasma radiation and/or nonthermal gyrosynchrotron radiation
- Possible to detect with an instrument with large FoV and sufficient dynamic range

Simulated free-free radio spectra



From Bastian & Gary 1997

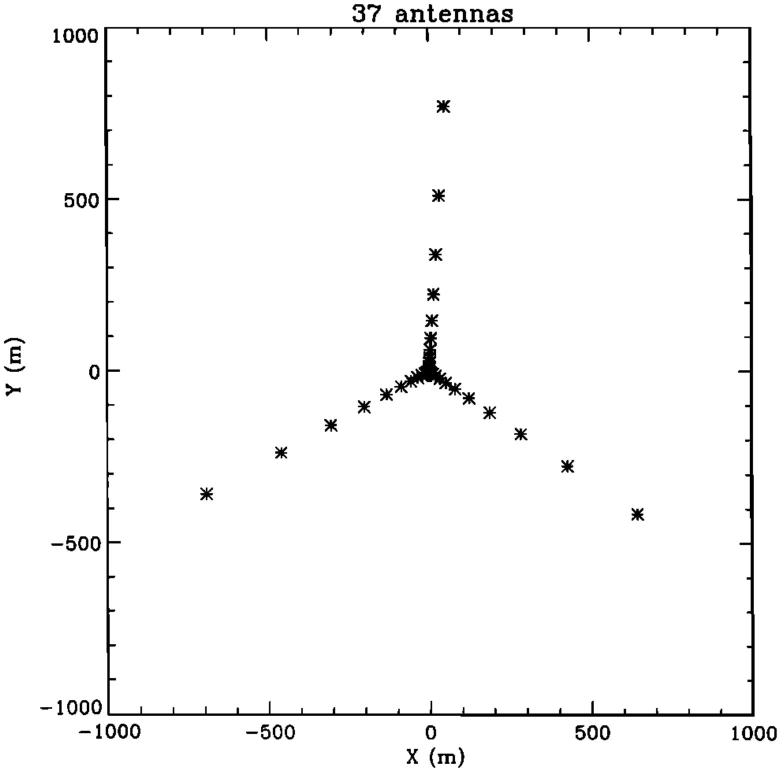
Simulation from a toy CME model



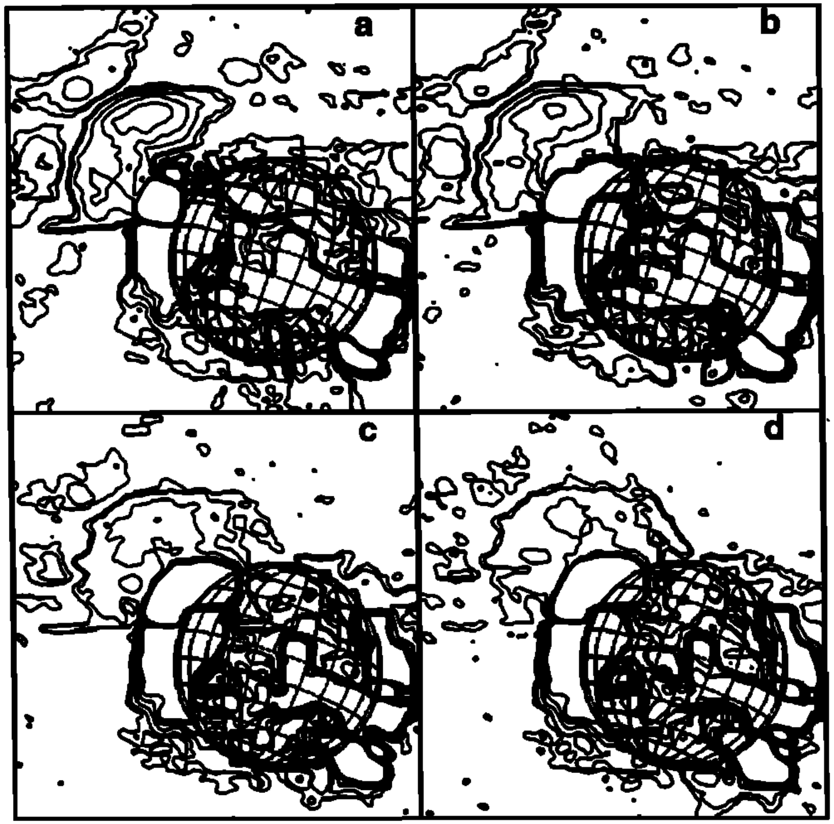
From Bastian & Gary 1997

- This is from an ideal radio telescope
- In reality, detection using this difference imaging technique would inevitably suffer from confusion due to uncleaned sidelobes

A close-to-reality case



A hypothetical 37-element Y-shaped array



dt = 5 min

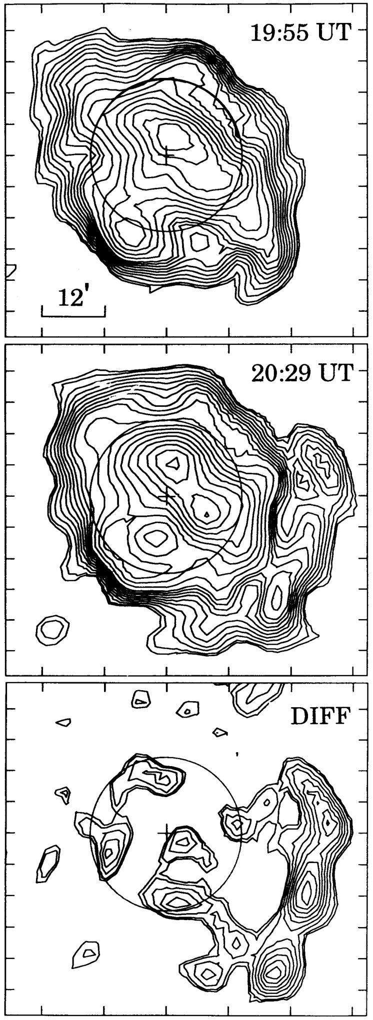
dt = 10 min

dt = 20 min

dt = 30 min

Simulated difference imaging results at 960 MHz

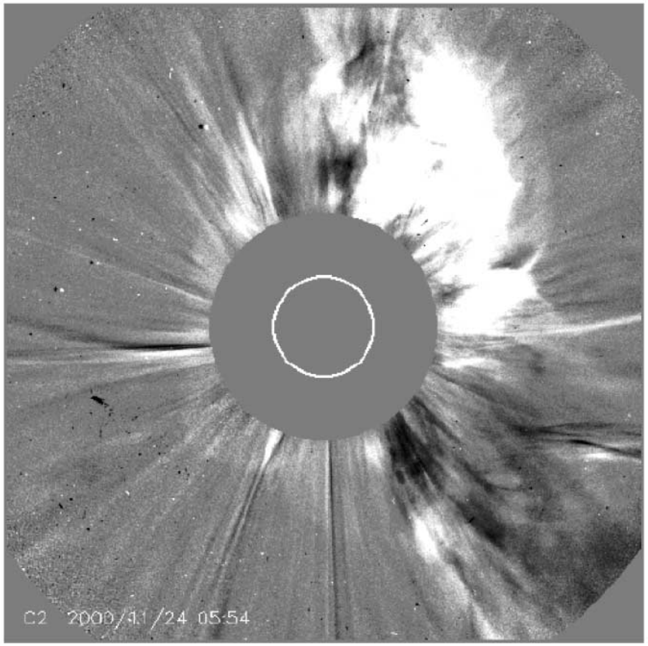
Some (rare) examples of thermal radio CMEs



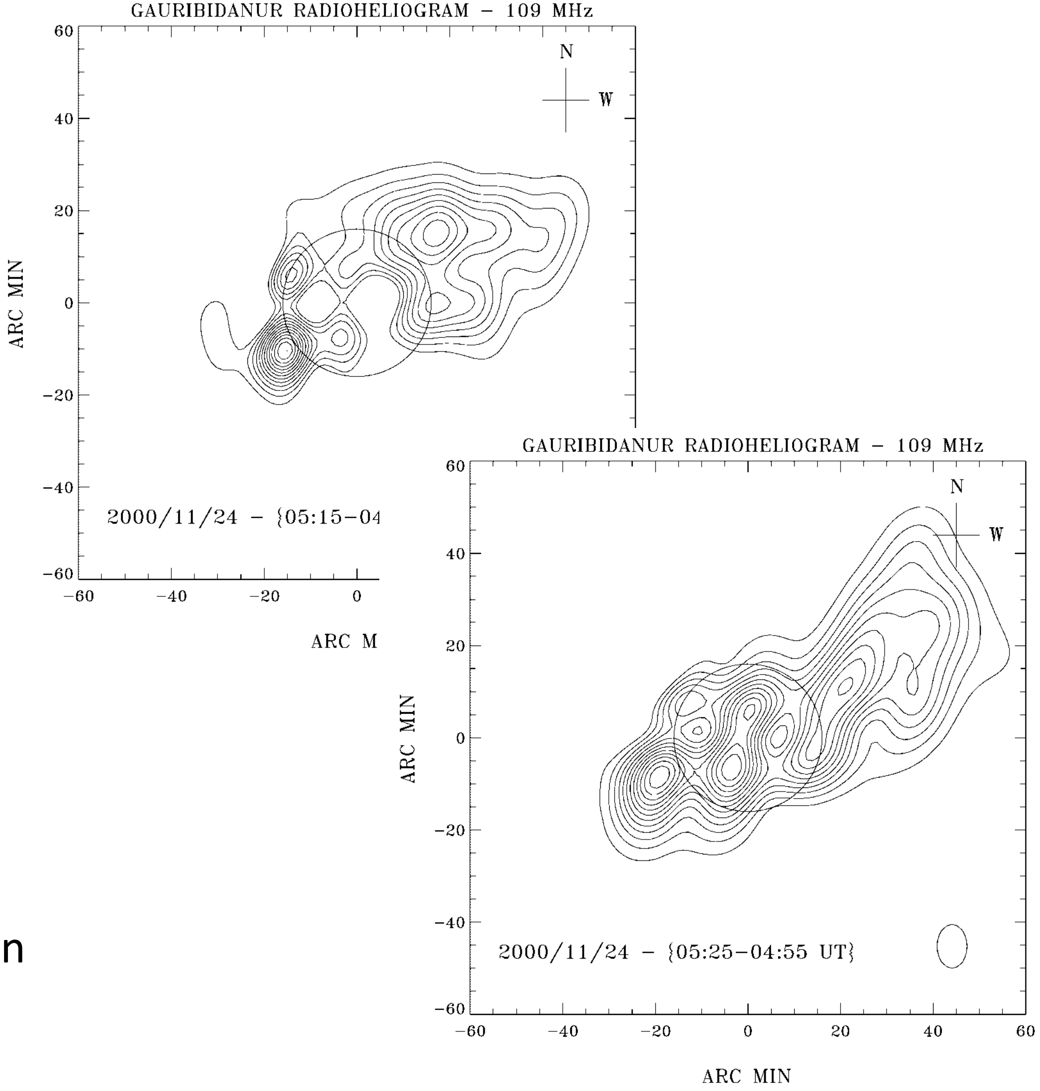
- Gopalswamy & Kundu 1992. Observation made in 1986 using Clark Lake Radioheliograph at 73.8 MHz.
    - ❖ $T_{B\_CME} \approx 1{\times}10^5$ K
    - ❖ $n_e \approx 9.5 \times 10^6\ \mathrm{cm}^{-3}$
    - ❖ $M_{CME} \approx 2.7 \times 10^{15}$ g

Another example

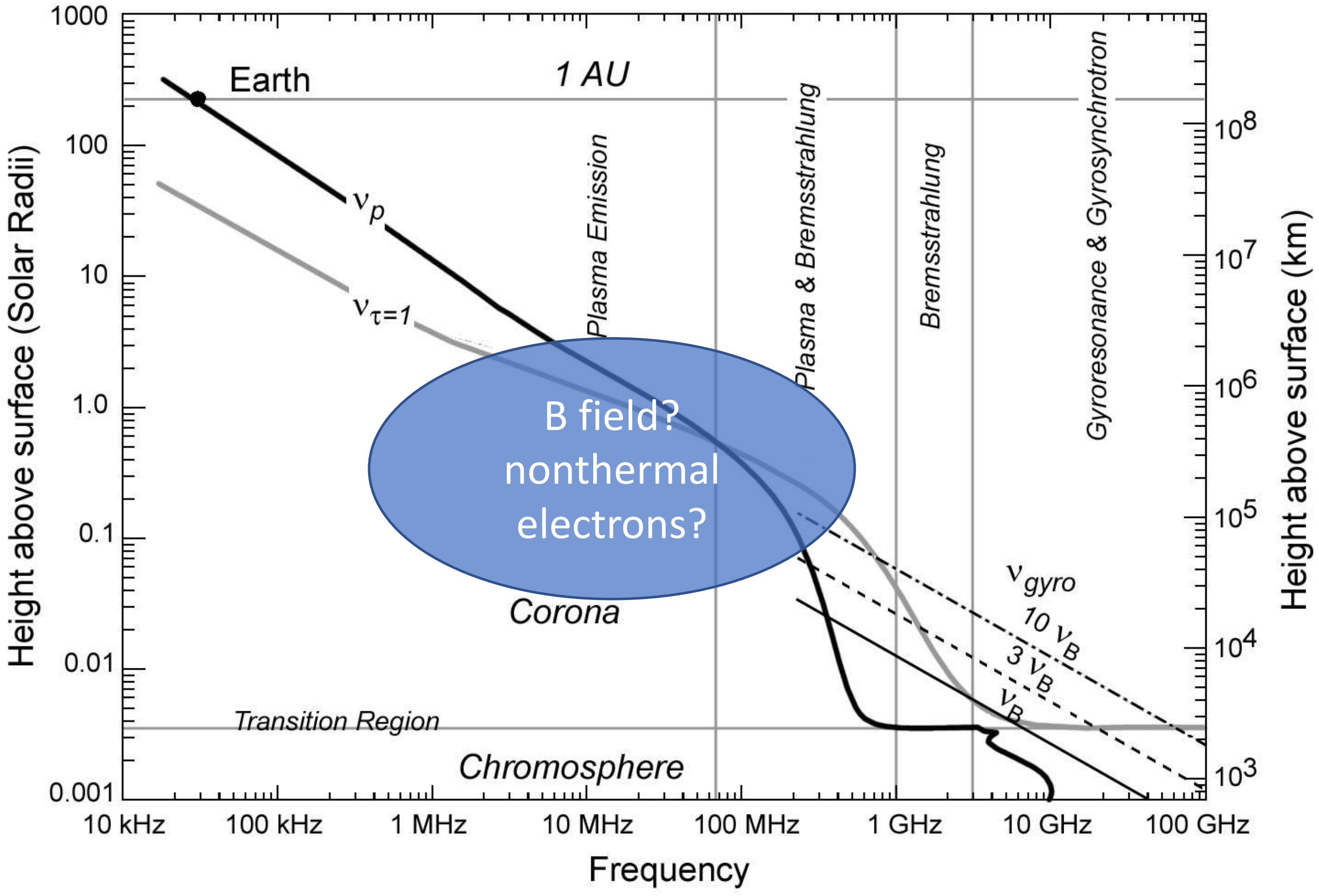
- Wl CME



Ramesh, Kathiravan & Sastry 2003, from Gauribidanur Radioheliograph in India at 109 MHz

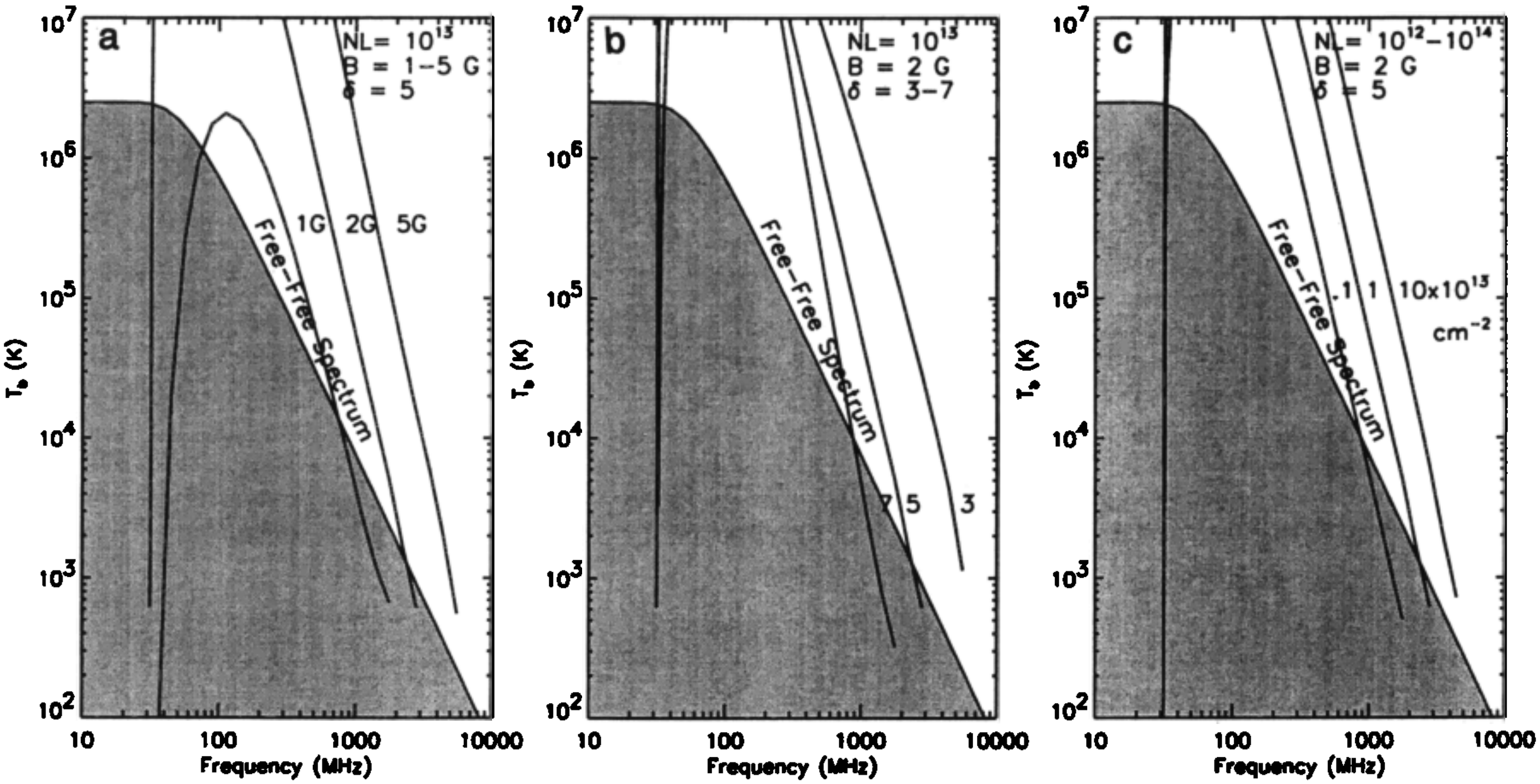


How about gyrosynchrotron emission?



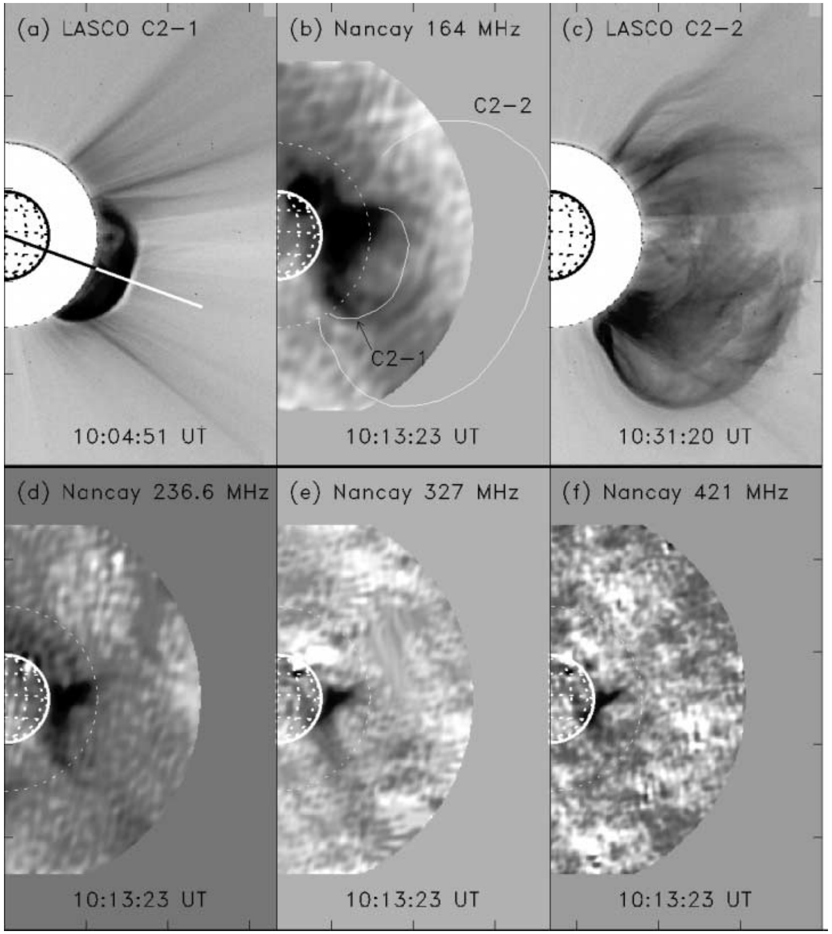
B field?
nonthermal
electrons?

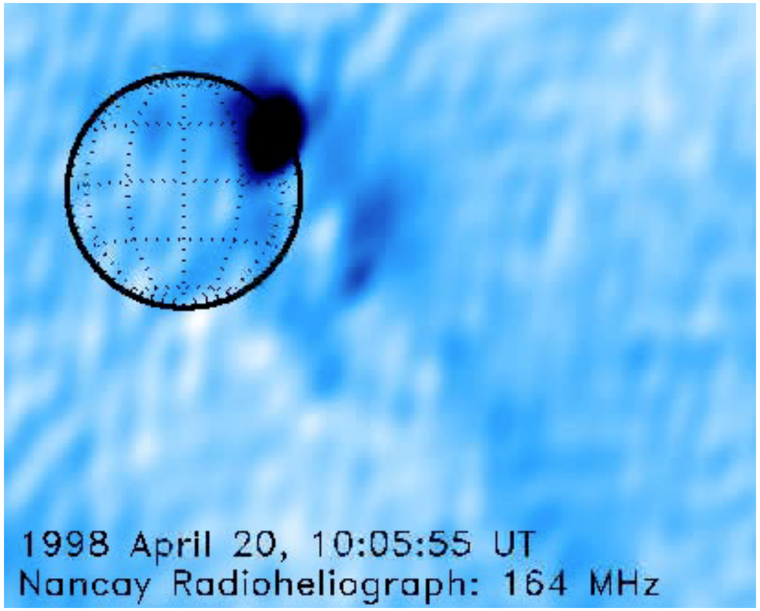
Gyrosynchrotron vs. thermal: from a toy model



From Bastian & Gary 1997

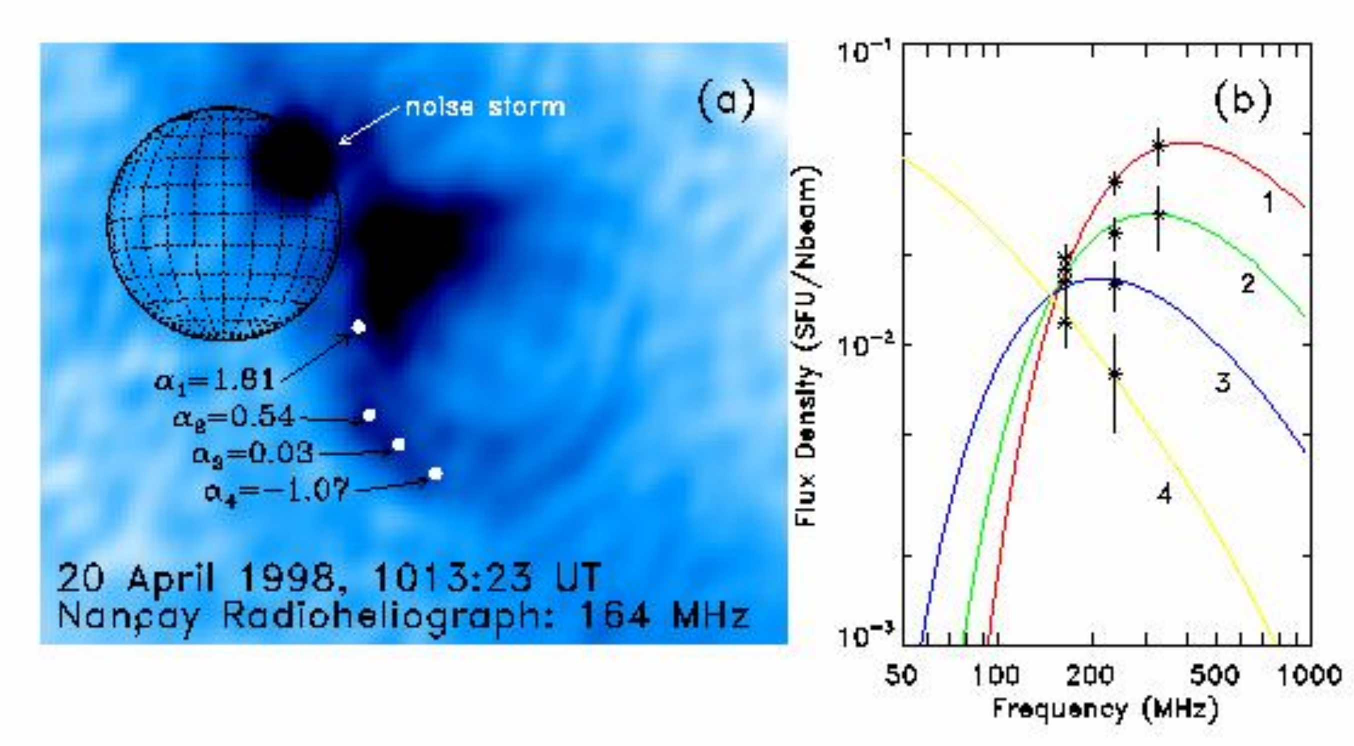
First observation of an expanding CME loop





Bastian et al. 2001

CME B field and thermal/nonthermal electron properties



- B_{CME} ~ 0.1 – few G
- E_e ~ 0.5 – 5 MeV
- n_{th} ~ few x 107 cm-3