Lecture 7: Radio Observations of Coronal Mass Ejections I

Hale COLLAborative Graduate Education (COLLAGE) Course 2017

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Lectures 7-8 outline

- Radio astronomy preliminaries
  - Radiative transfer
  - Relevant emission mechanisms
  - Types of solar radio bursts   *This Lecture*
- Radio observations of CMEs
  - CME body
    - Thermal CME
    - Gyrosynchrotron CME
    - Type IV radio bursts
  - CME-driven shocks
    - White light/EUV imaging, UV spectroscopy, and in situ signatures
    - type II radio bursts

Preliminaries

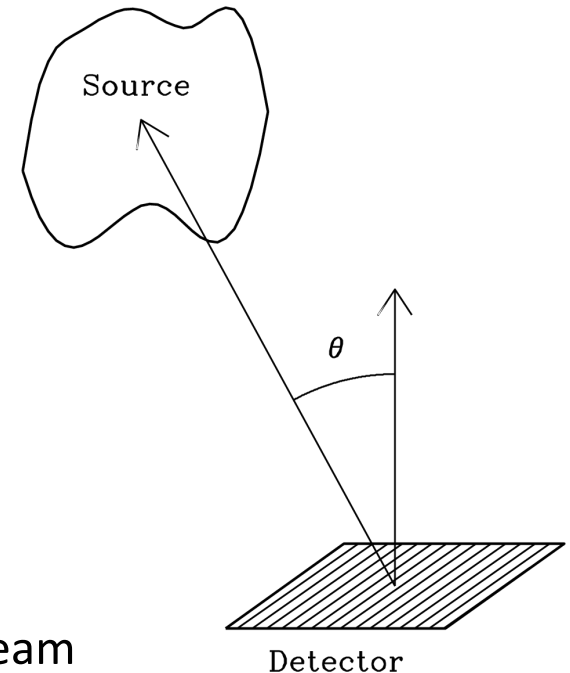- Specific intensity

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

- 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

Source

θ

Detector

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:
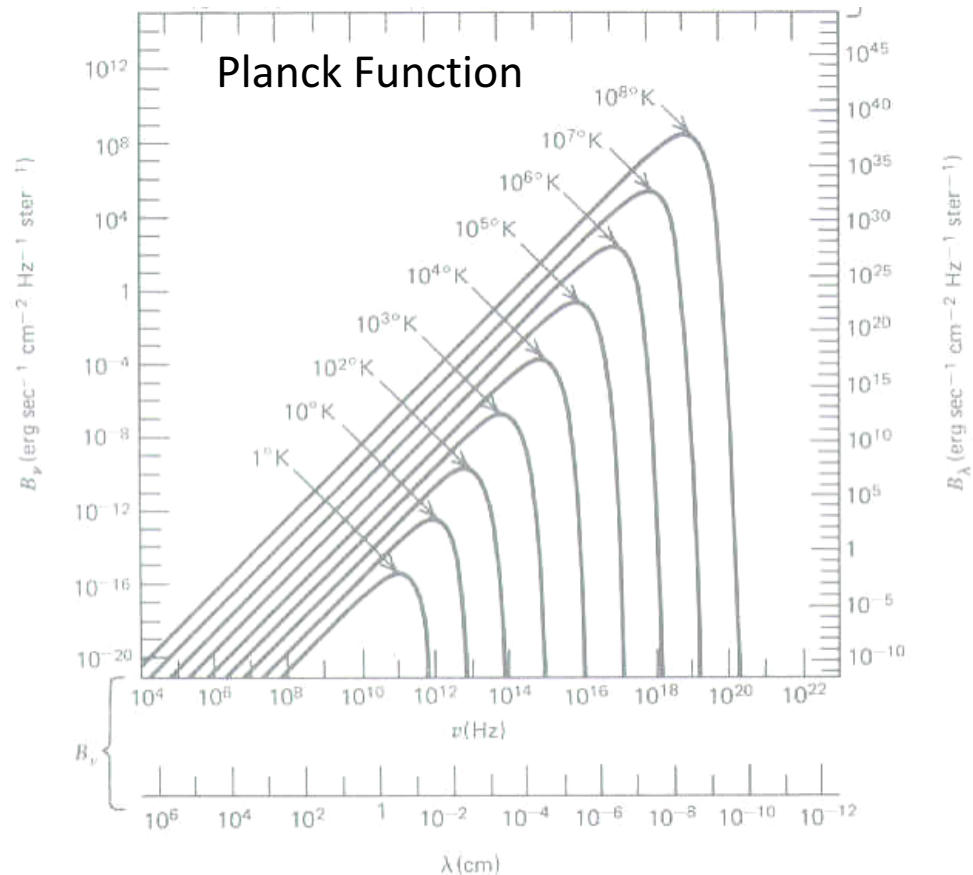
$$\frac{dI_\nu}{d\tau_\nu} = S_\nu - I_\nu$$

- 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

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

The Planckian then simplifies to the Rayleigh-Jeans Law.

$$B_v(T) = \frac{2hv^3}{c^2} \frac{1}{e^{hv/kT} - 1} \approx \frac{2v^2}{c^2} kT$$

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

$$I_v = B_v(T_B) = \frac{2v^2}{c^2} kT_B$$

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, $\tau_\nu \ll 1$, $T_B \approx \tau_\nu T_{eff}$
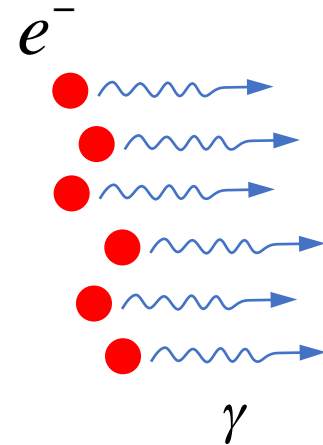
Relevant Radio Emission Mechanisms: An Introduction

Bremsstrahlung

e^-

γ

Nucleus

Gyromagnetic Radiation

e^-

γ

B

Plasma Radiation

e^-

γ
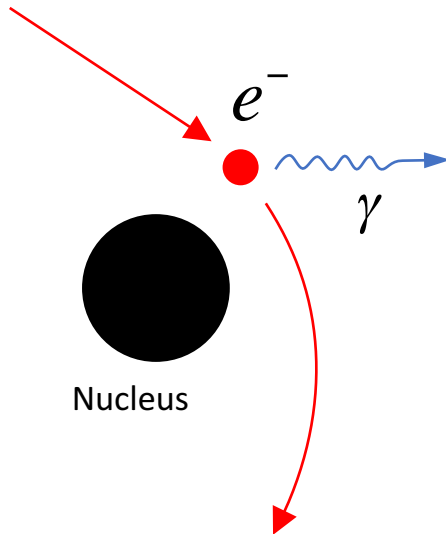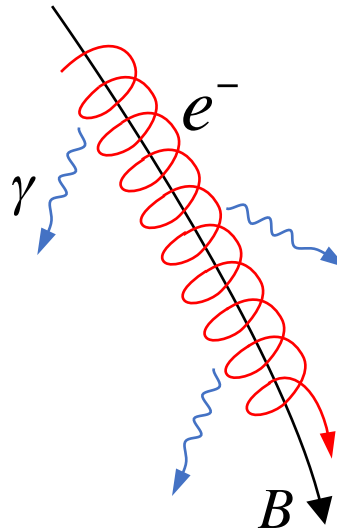
Bremsstrahlung Radiation

- 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

e^-

γ

Nucleus
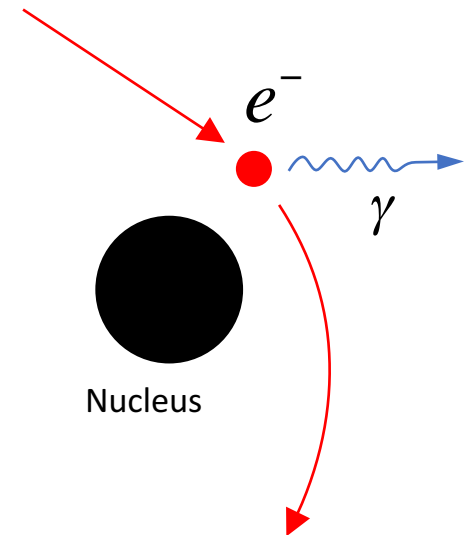
Gyromagnetic radiation

- 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

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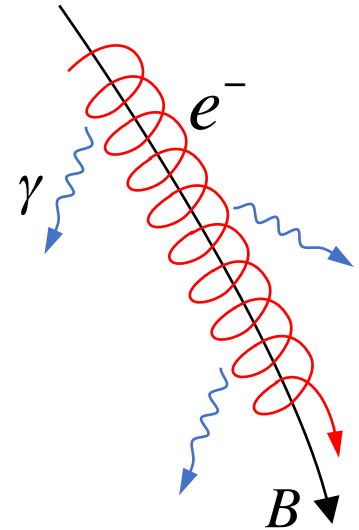
Plasma Radiation

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

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

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

let's do some derivation...
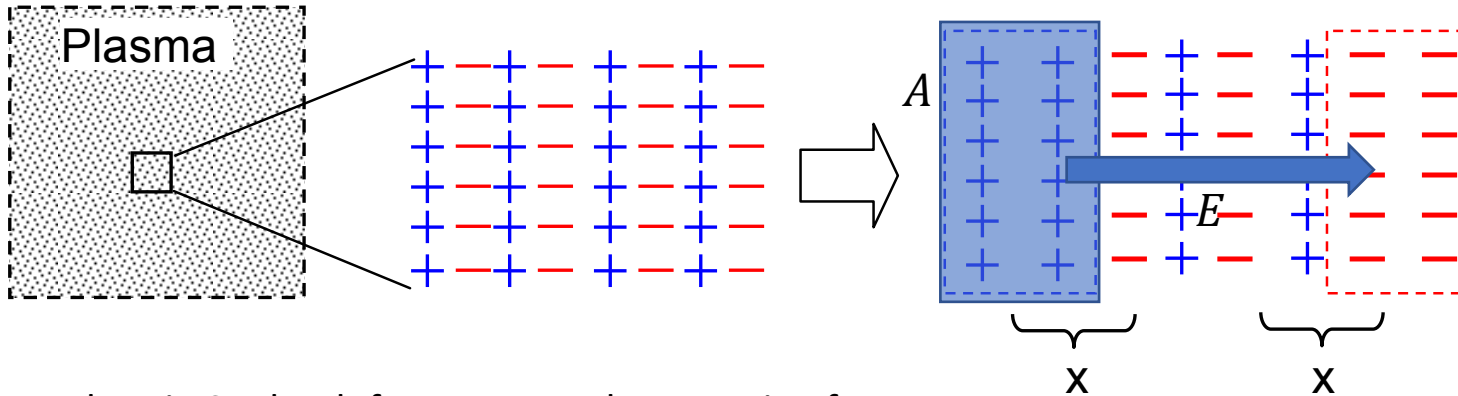
- Electric Coulomb force acts as the restoring force

- 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: $m_e \frac{d^2 x}{dt^2} = -eE = -4\pi n_e e^2 x$, 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

Voyager 1 Plasma Wave Science
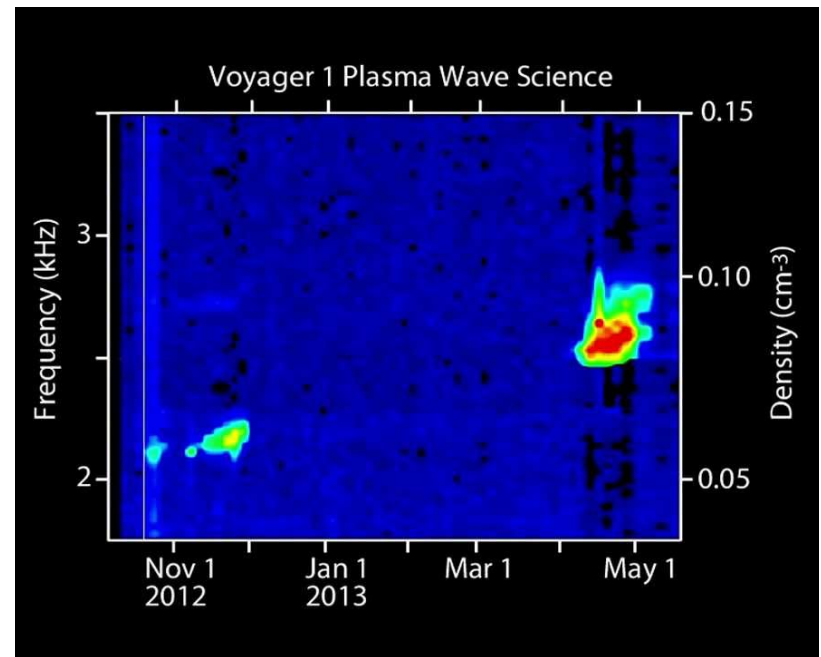
Radio Observations in General

- Emission Mechanisms

Thermal
Non-Thermal

- Range of Observations

Chromosphere (~100 GHz)
Aurora (KHz)

- Types of radio data
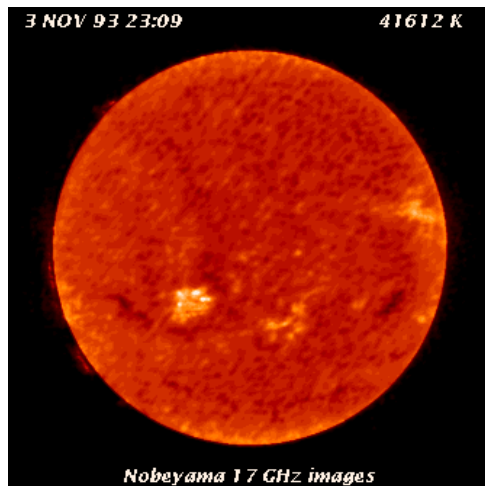
Nobeyama Radioheliograph 17 GHz

+
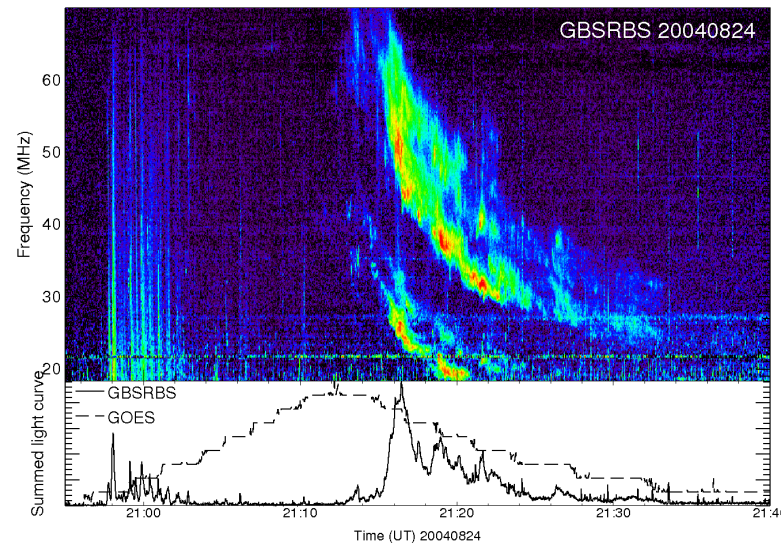
Solar radio bursts types from 1960s
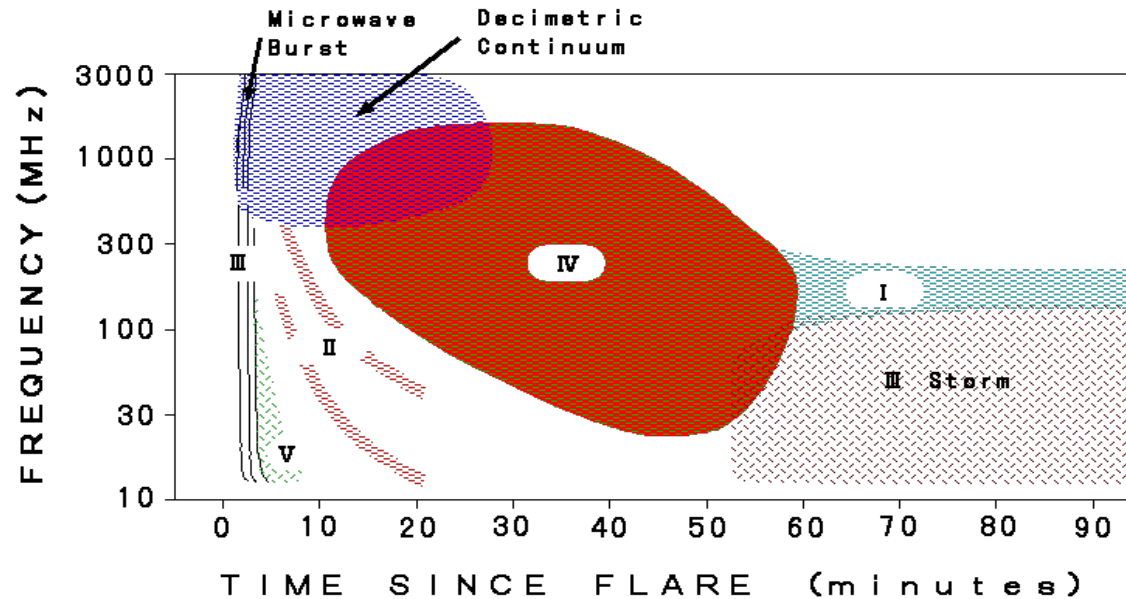
- Type I: short duration, narrow band, non-drifting bursts. Origin unknown.
- Type II: CME-driven shock (~1000 km/s)
- Type III: fast electron beams (~0.3c), rapid frequency drift
- Type IV: close magnetic structure -- CME body, post-CME reconfiguration
- Type V: extended phase of type III

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)

GBSRBS 20040824
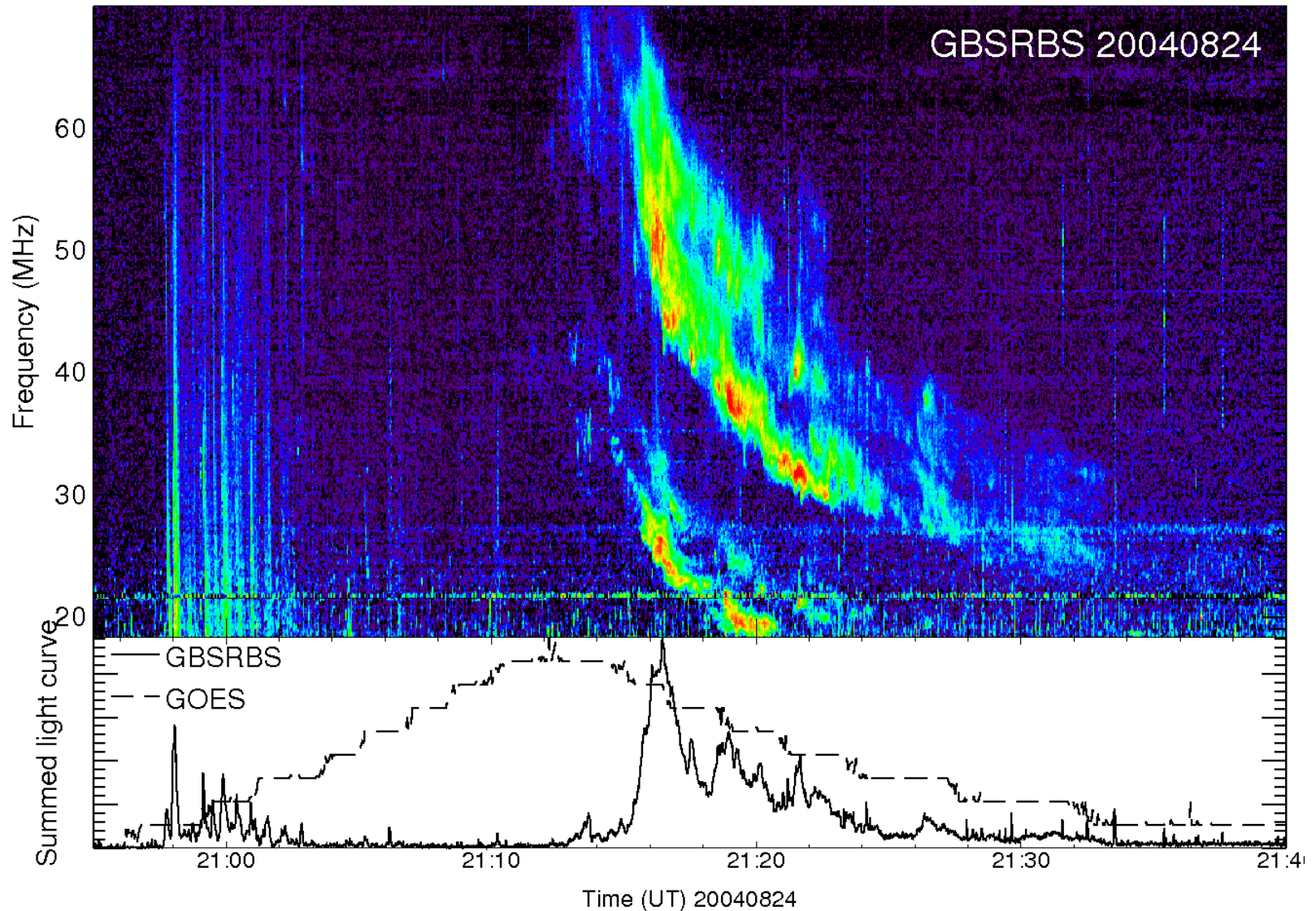
Type III burst: fast-drift electron beam (4 mins)
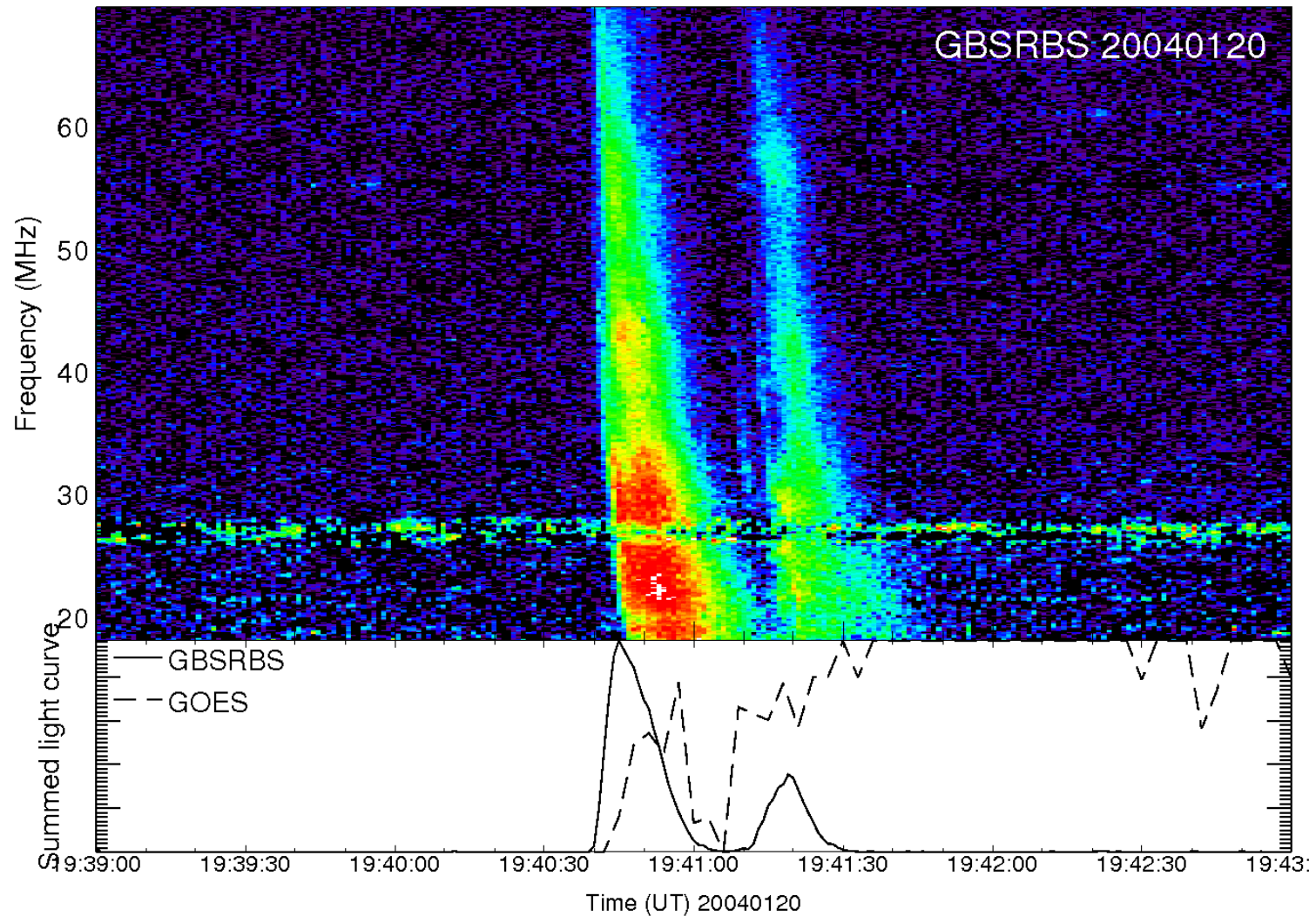
Type II followed by Type IV (2 hours)
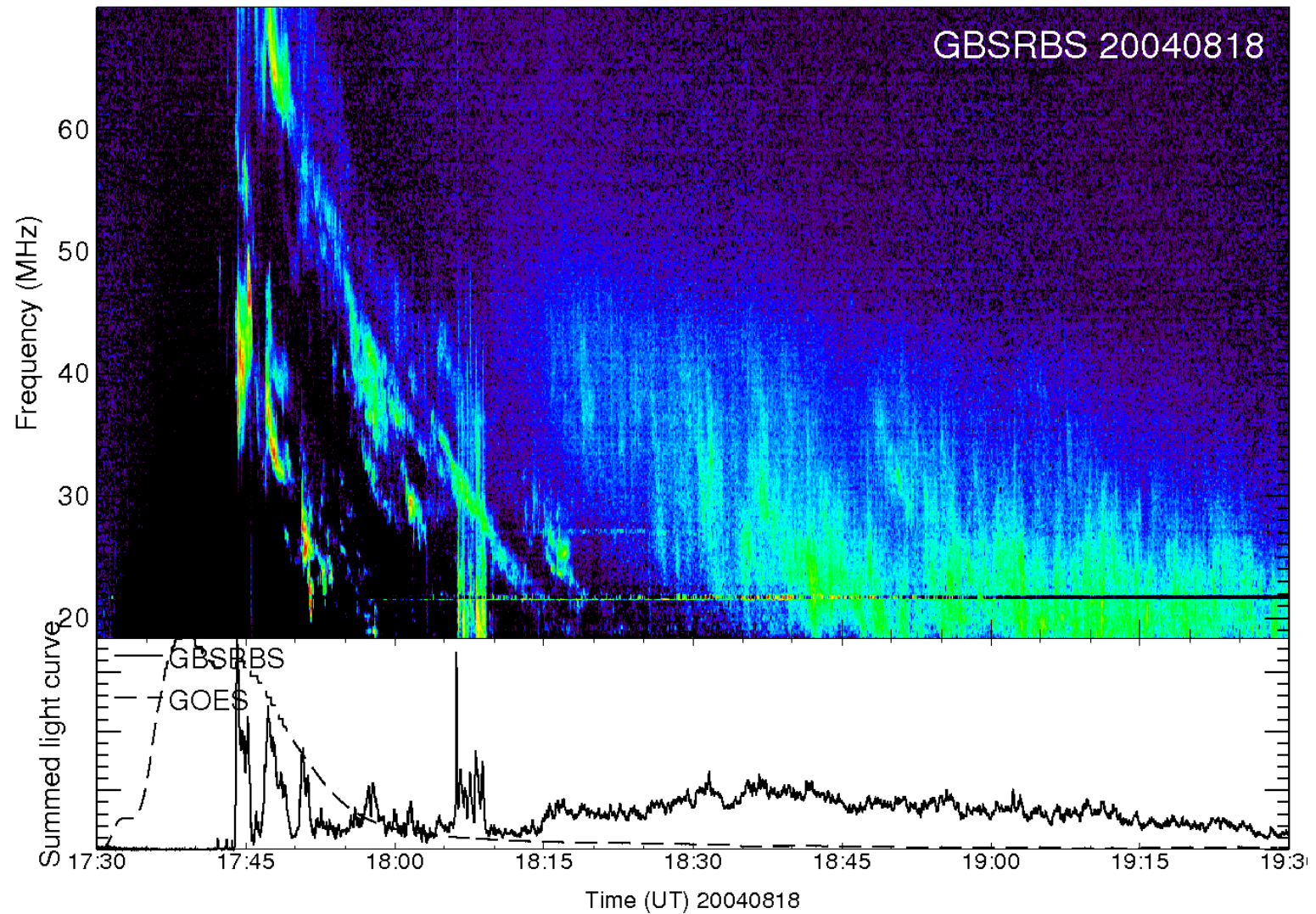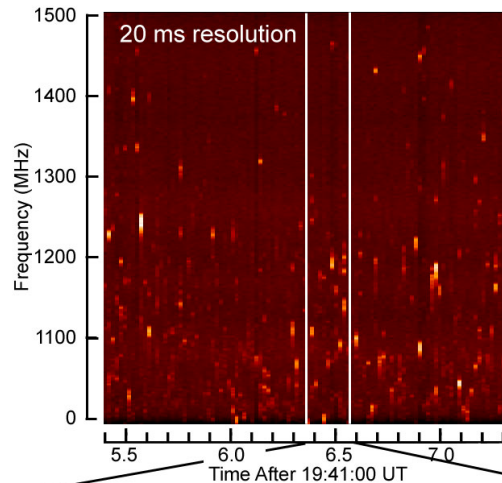
Type V: extended phase of Type III (6 mins)

GBSRBS 20050607

Type I bursts (3 hours)

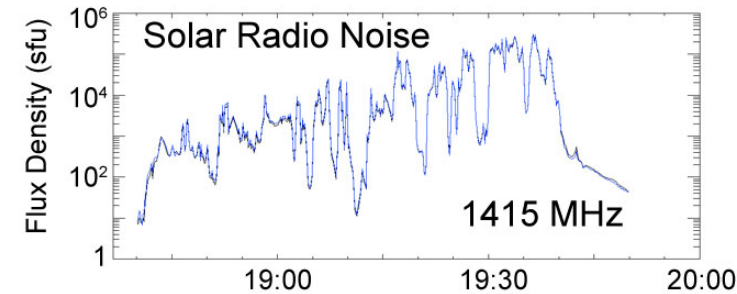AMATERAS RCP 20110123

< 1s

AMATERAS Solar Radio Spectra
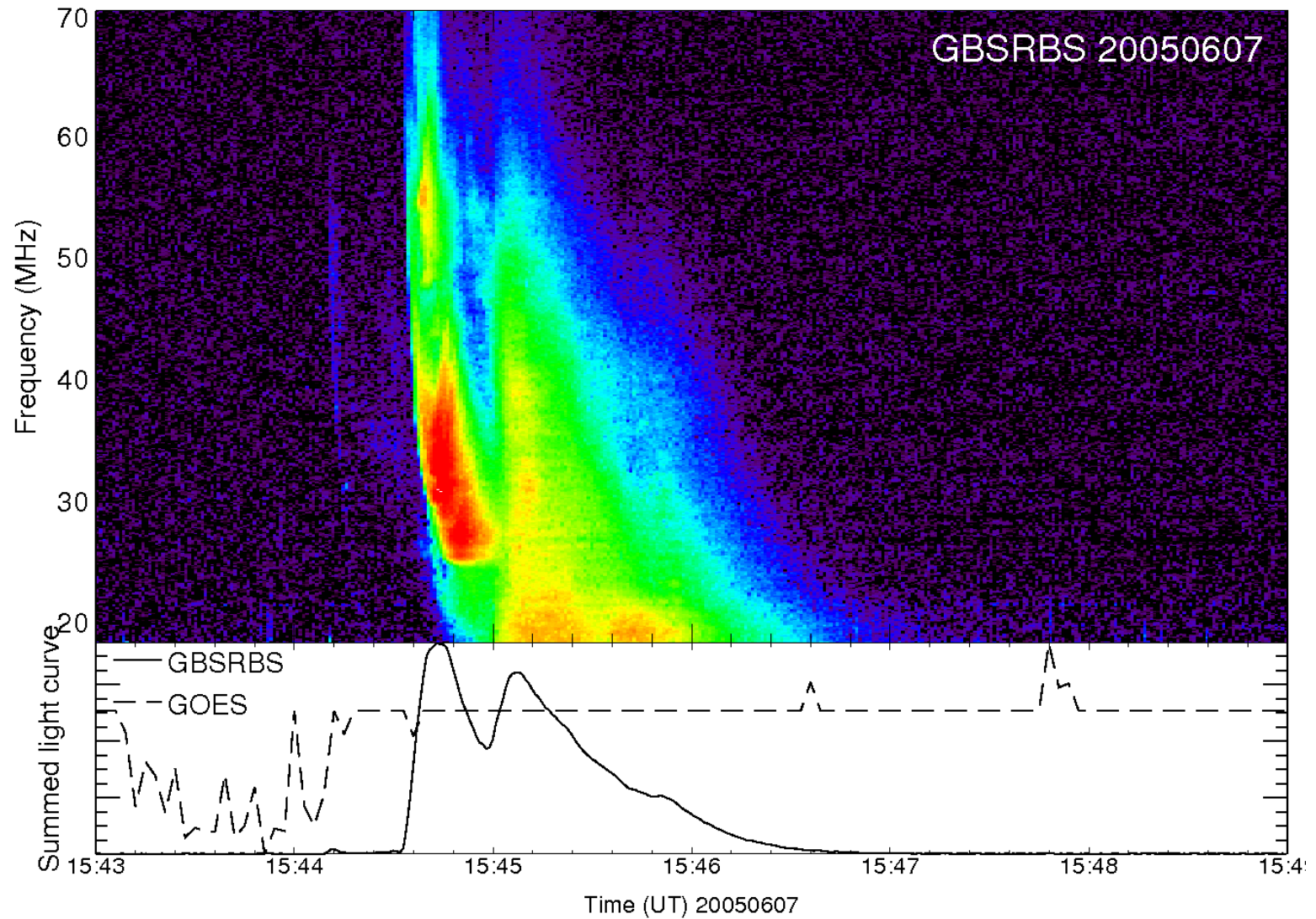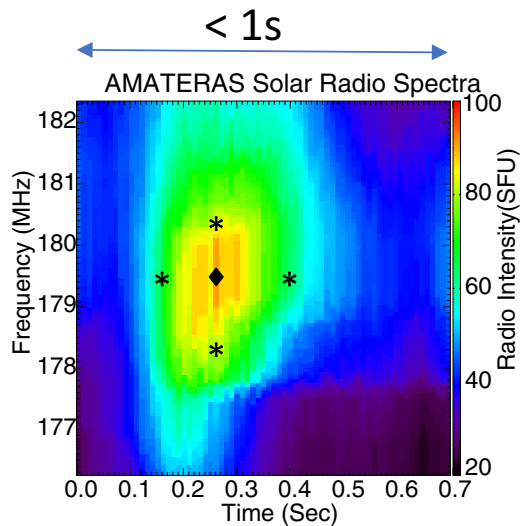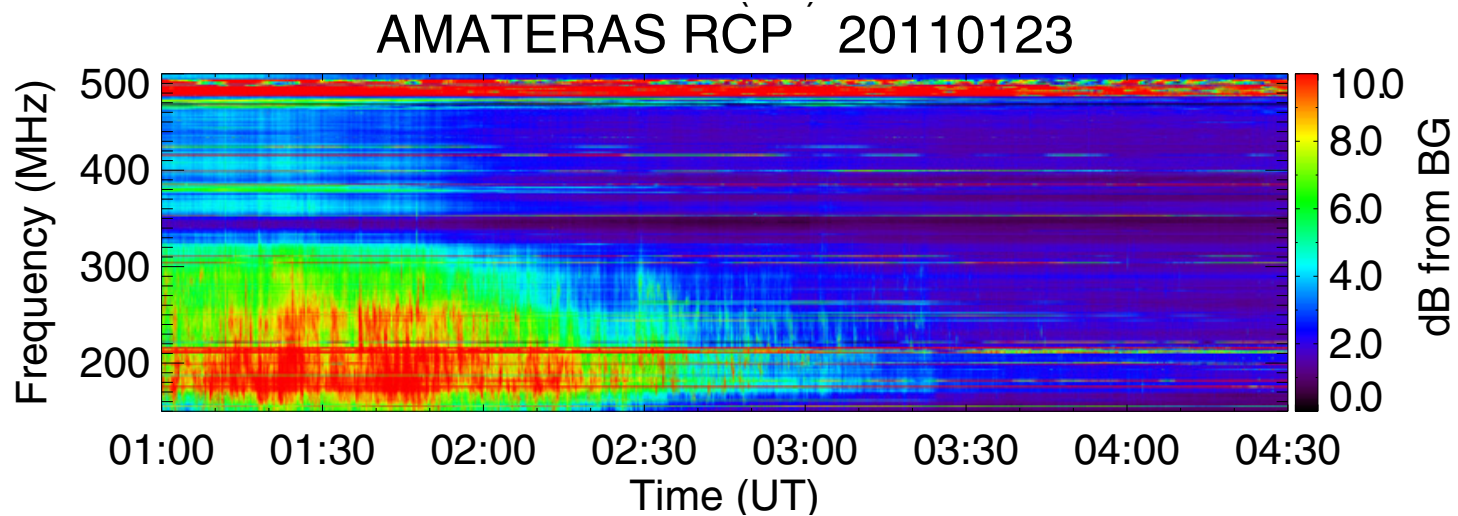
Iwai et al. 2014

Other complex types

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

20 ms resolution

Full (1 μs) resolution

100 μs

20 ms gaps

From Dale Gary

FST Dynamic Spectrum

Solar Radio Noise

1415 MHz

Quiet
061206

GPS Receiver Noise

ZHU1-WAAS L2
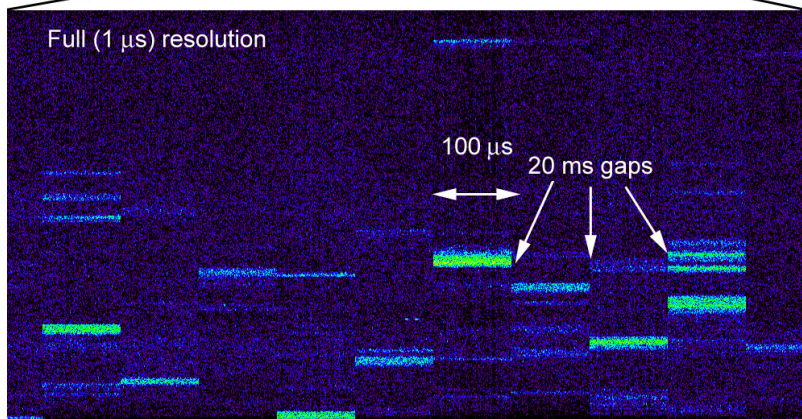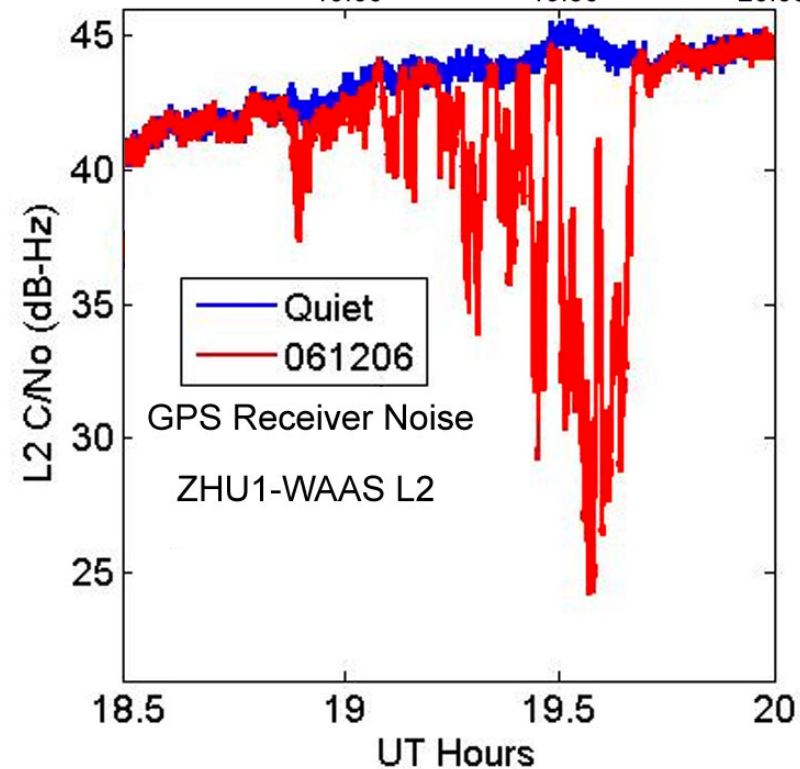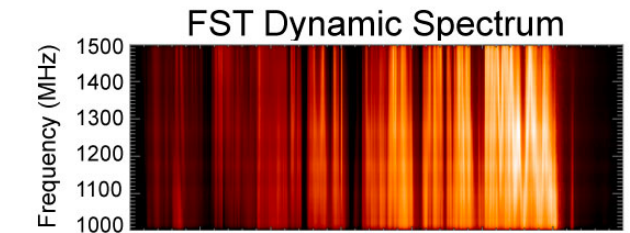
Decimetric radio bursts associated with flare termination shock
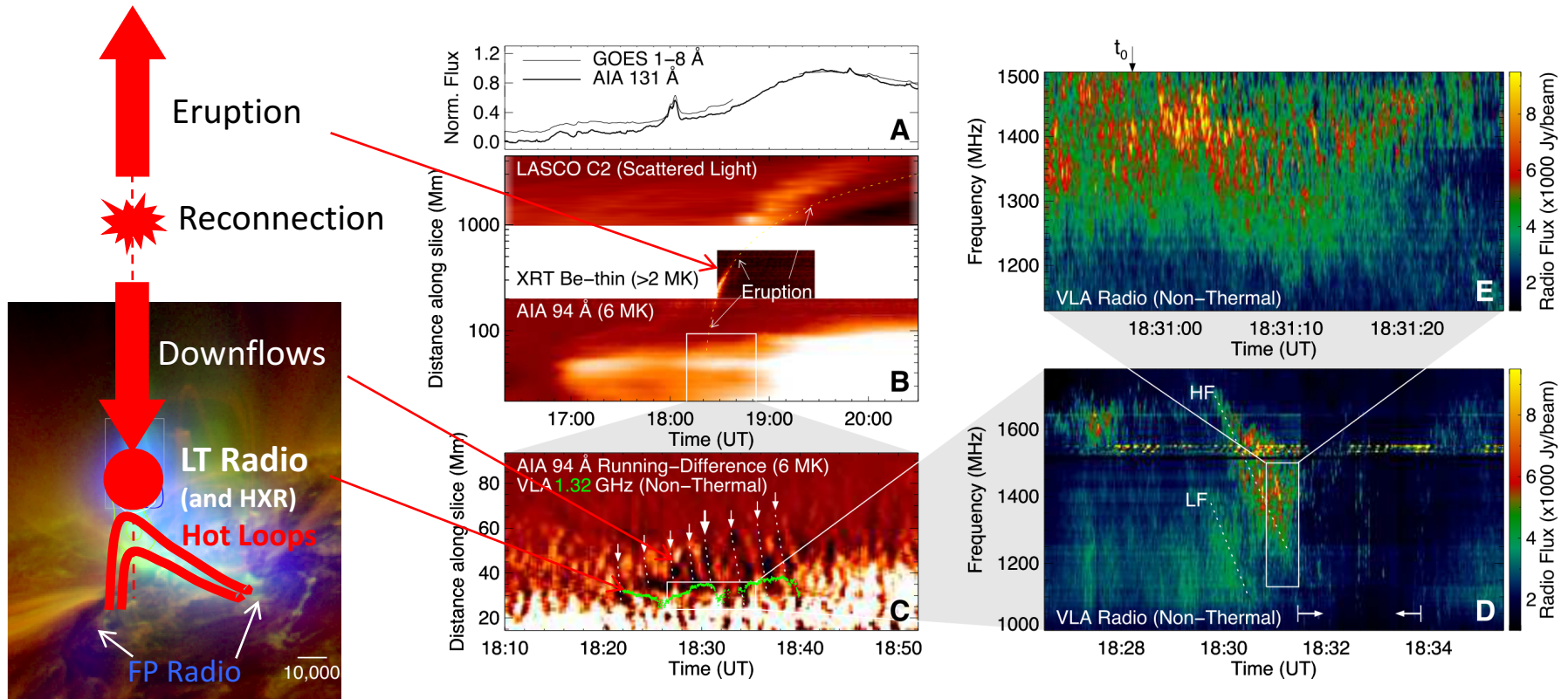
Chen et al. 2015, *Science*

Radio bursts associated with propagating wave packets

(a) 1530 MHz

(b) 1307 MHz

(c) 1198 MHz

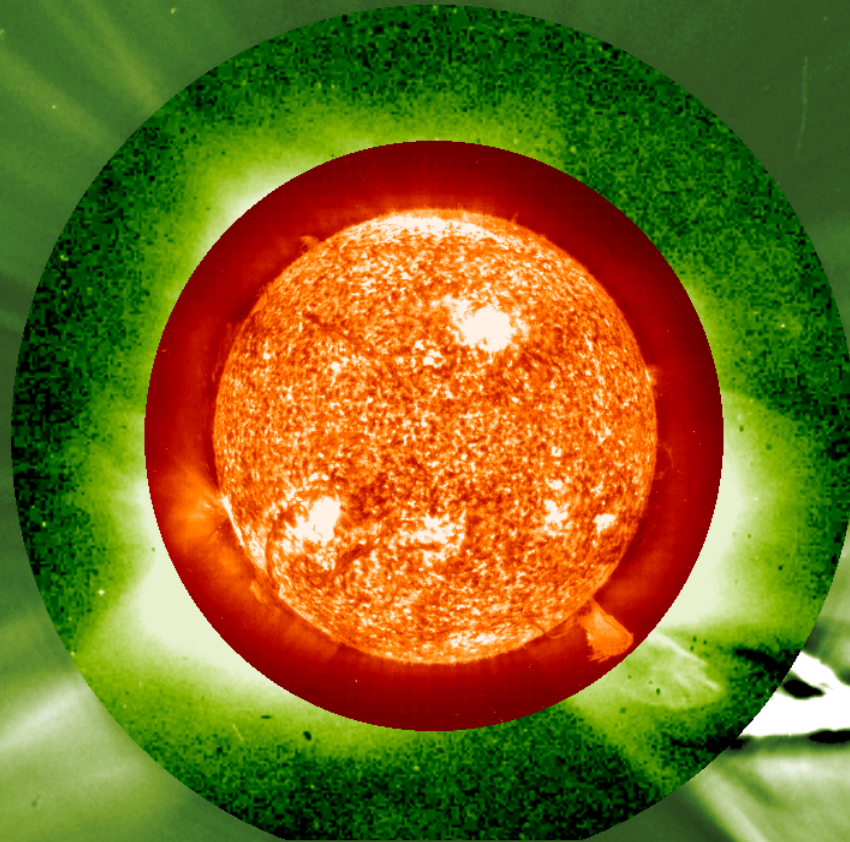(d) Start Time 18:49:04 UT
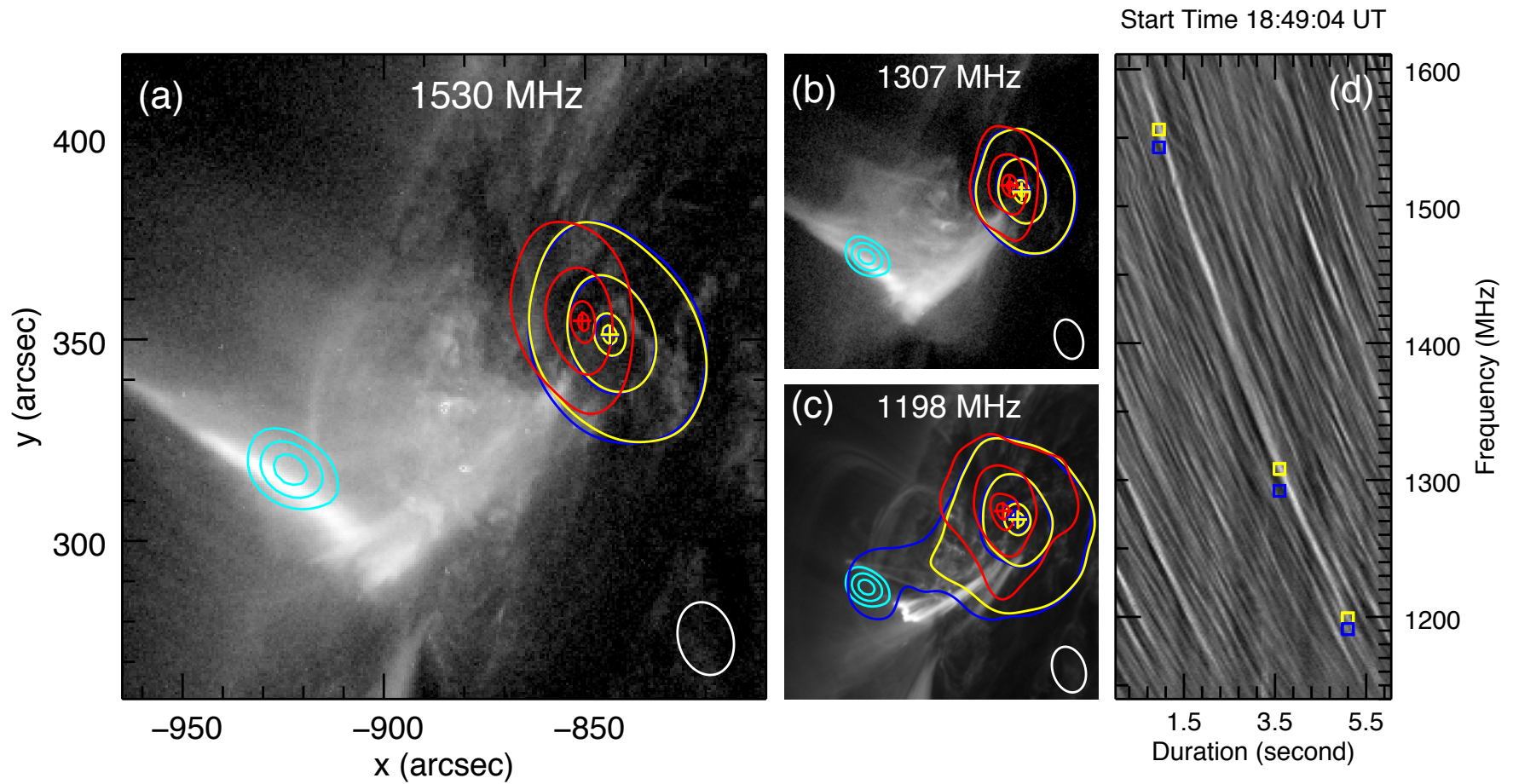
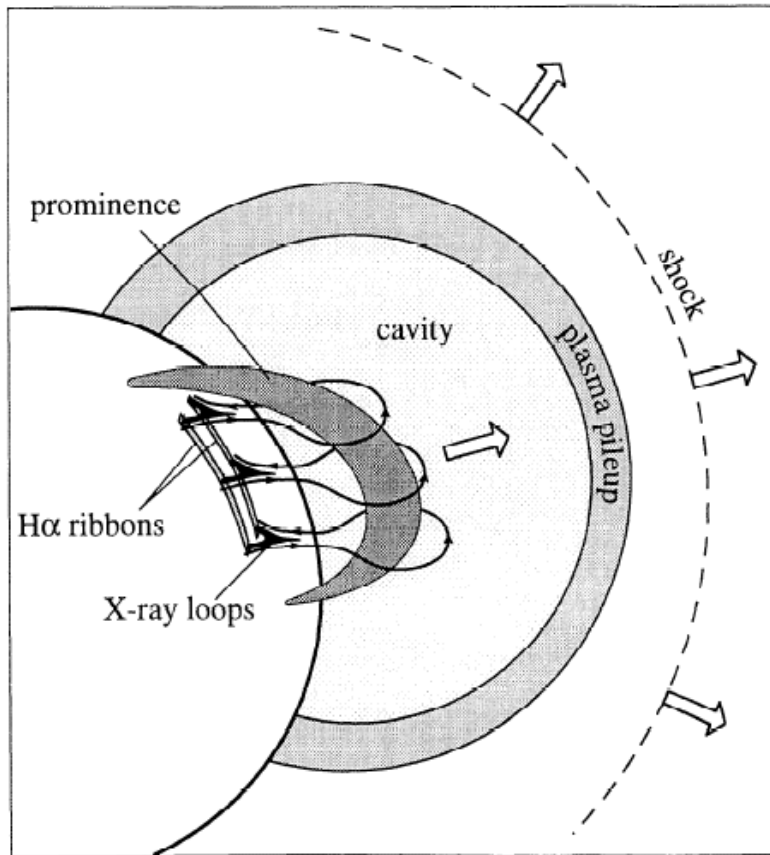Wang, Chen & Gary 2017

A nice illustration of solar radio emission
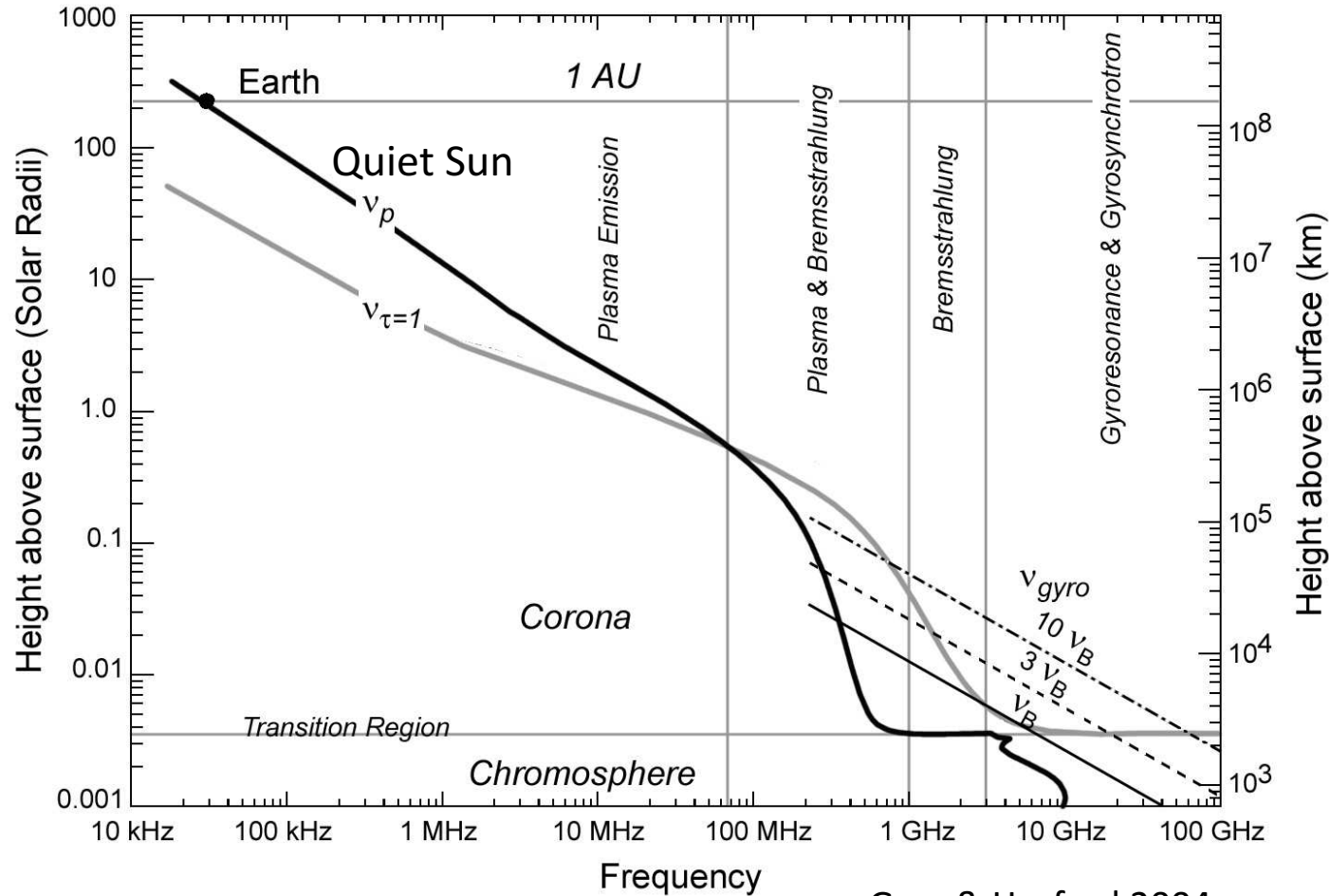
Gary & Hurford 2004

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

Standard Flare-CME Model
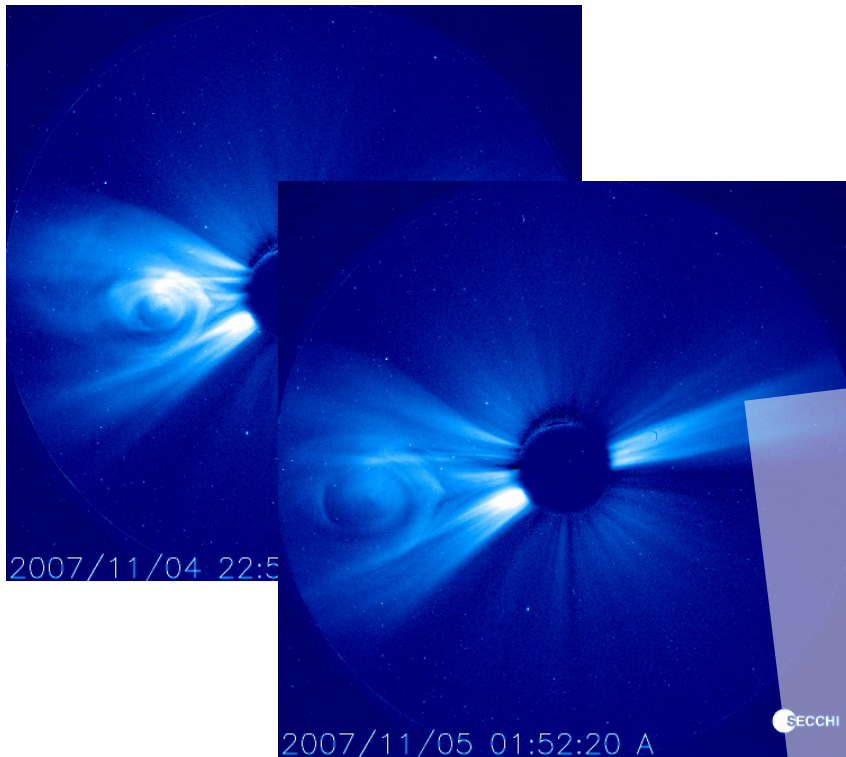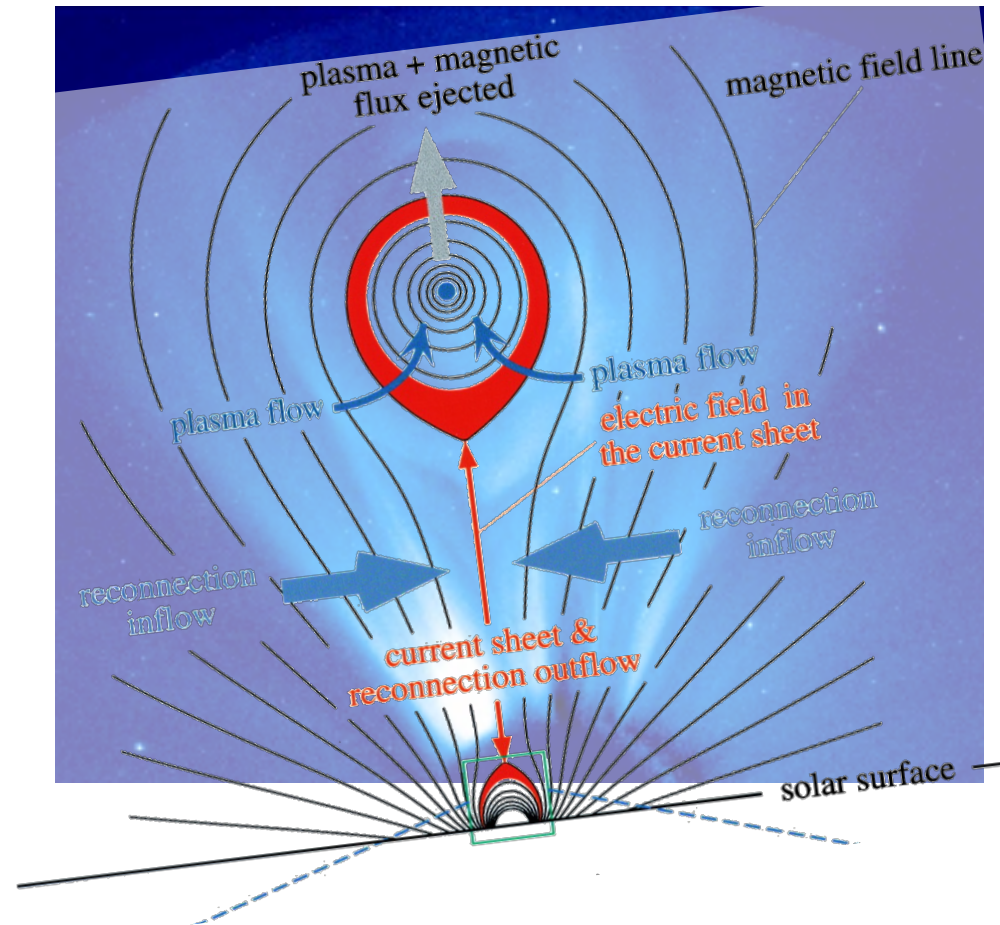

Forbes-Lin model

From Lecture 5 (Prof. Jiong Qiu)
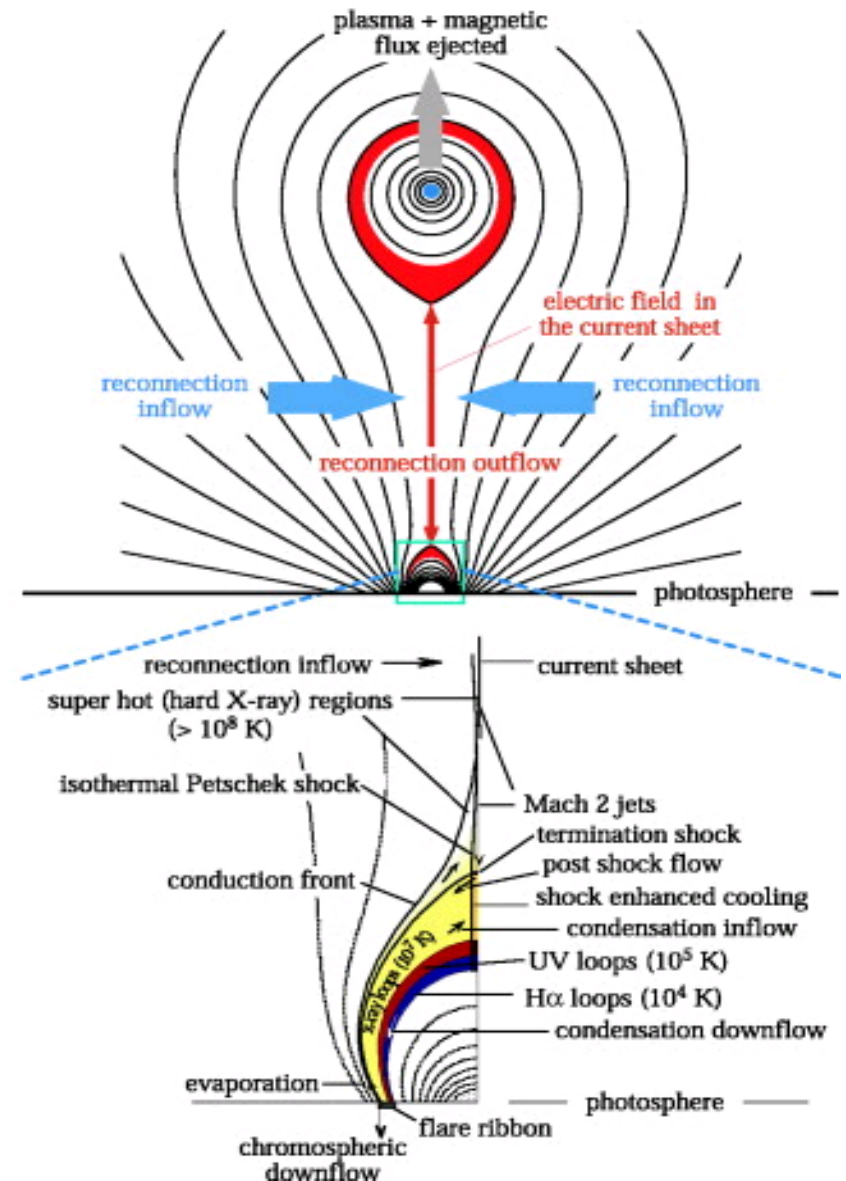
CMEs in white light

From Angelos Vourlidas

From Lecture 5 (Prof. Jiong Qiu)

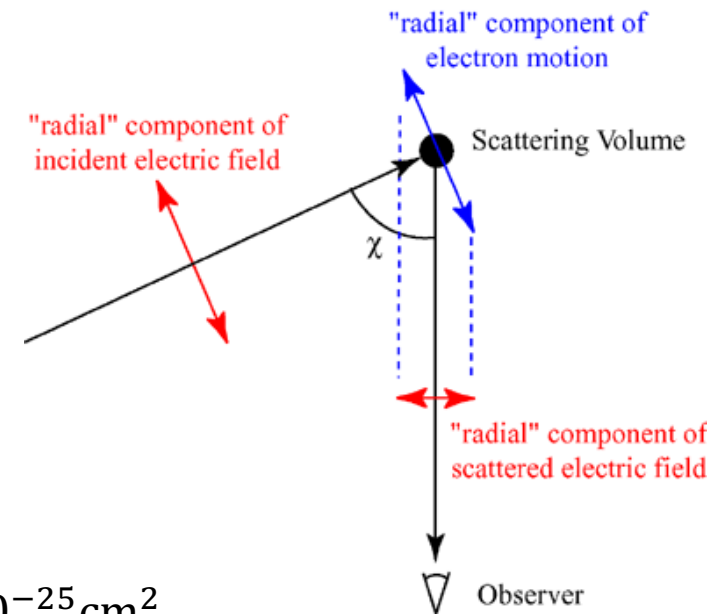# White light emission: Thomson scattering

- 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 $\sigma_T = \frac{8\pi}{3} r_e^2 \approx 6.65 \times 10^{-25} \text{cm}^2$

❖ Source function S_ν is related to the incident intensity from the photosphere and the viewing angle
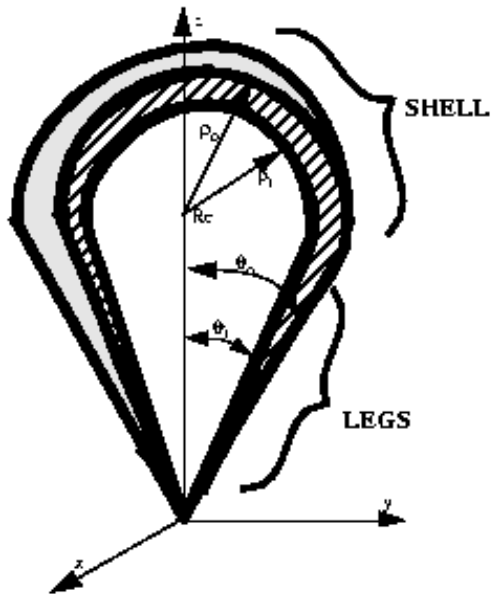
See Prof. Steven Cranmer's lecture 6 of COLLAGE 2016 for more details

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
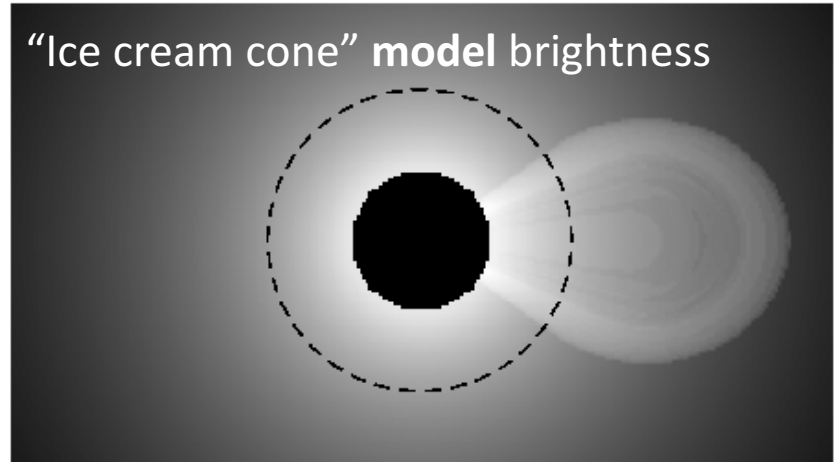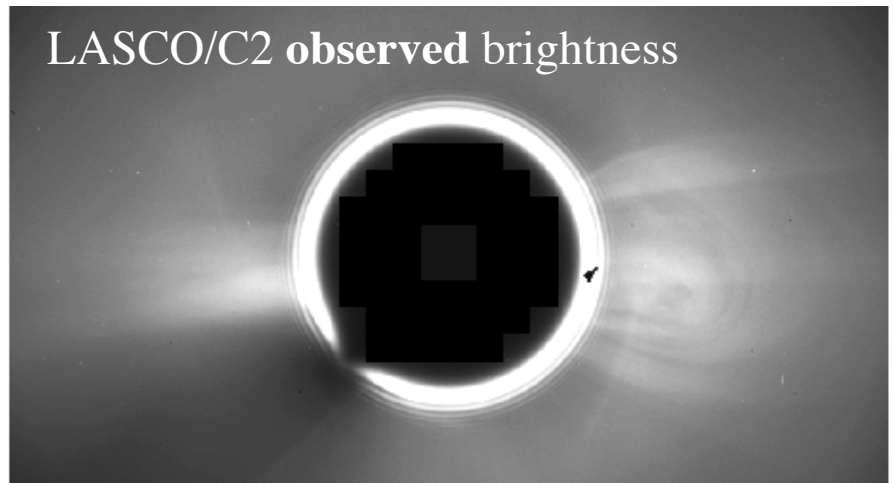 - It is close to the plane of maximum scattering
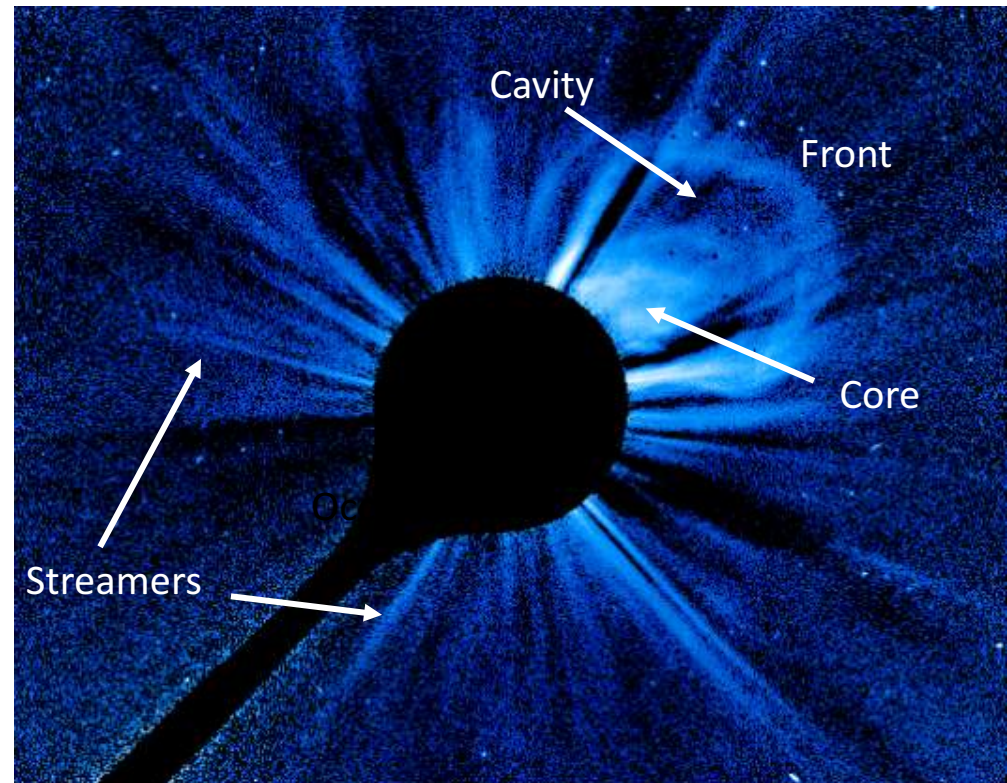
White Light CME

"Ice cream cone" **model** brightness

LASCO/C2 **observed** brightness

The "ice cream cone" model

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)
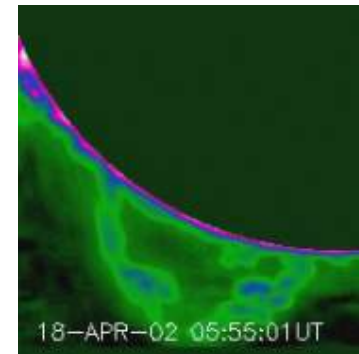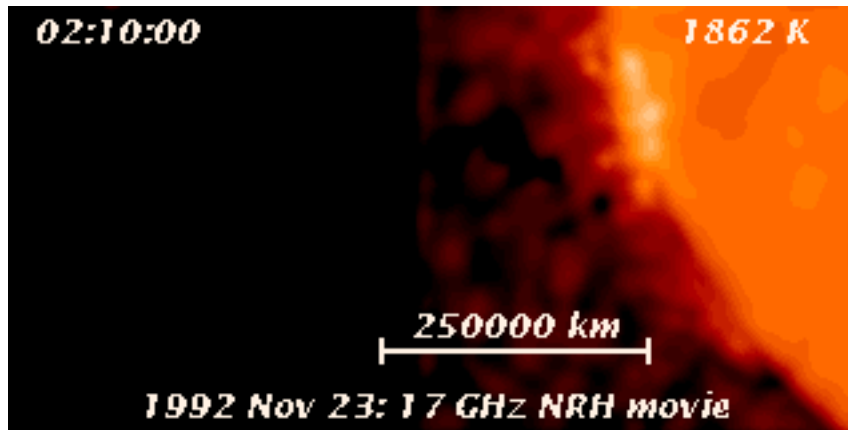
e^-

γ

Nucleus
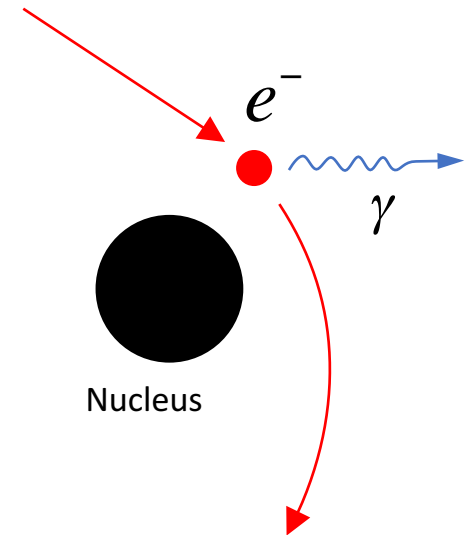
Detectability of thermal radio CME

- Well, no problem for dense and cool prominences

Bremsstrahlung radiation

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

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

02:10:00 1862 K
250000 km
1992 Nov 23: 17 GHz NRH movie

18-APR-02 05:55:01UT

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
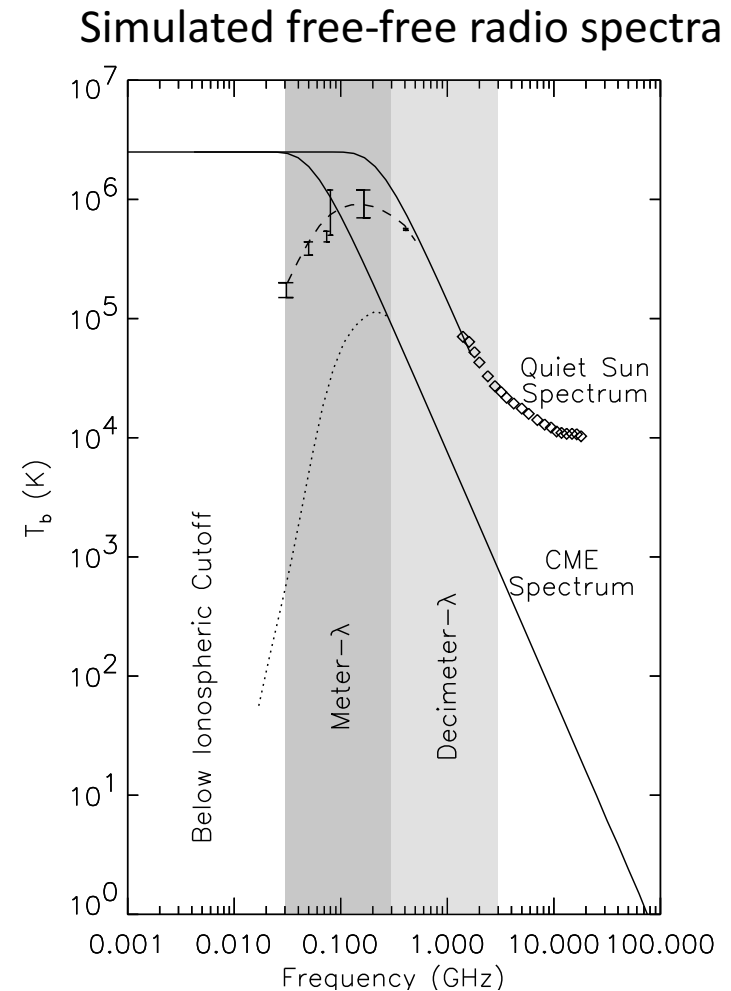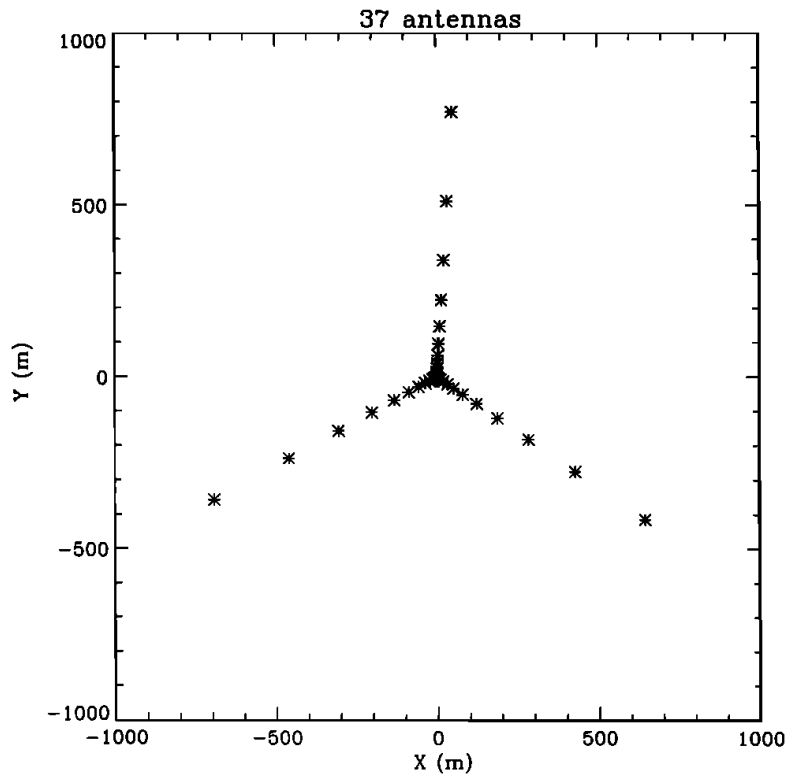

From Bastian & Gary 1997
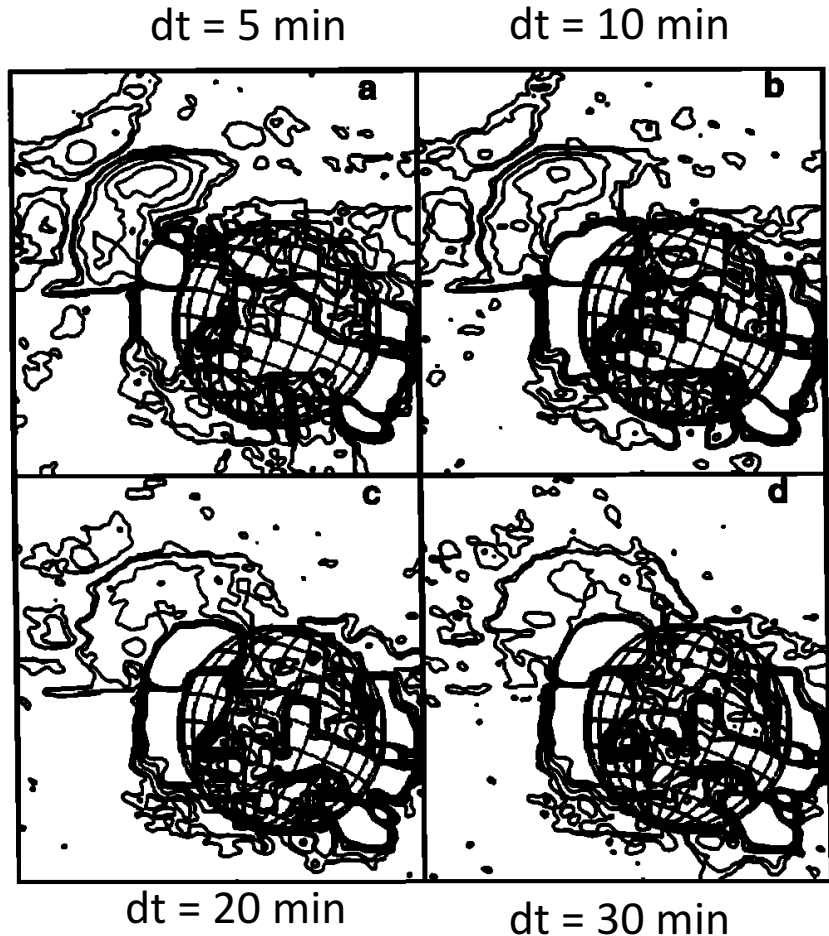
Simulation from a toy CME model
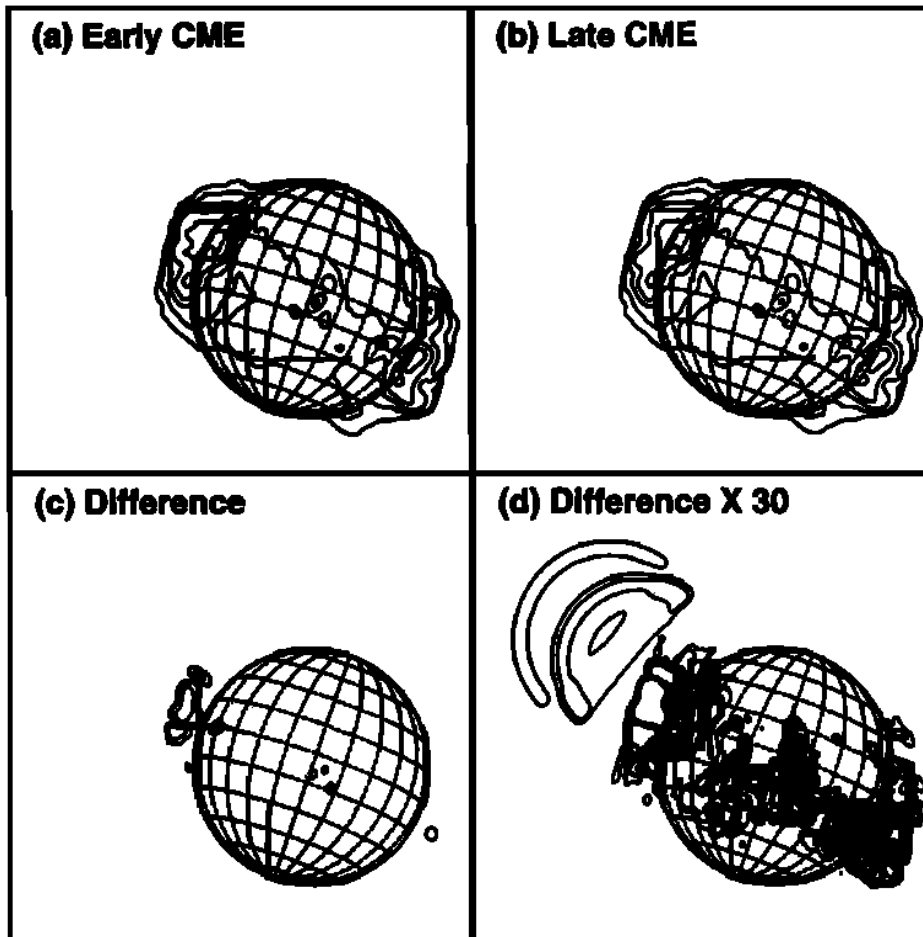
- This is from an ideal radio telescope
- In reality, detection using this difference imaging technique would inevitably suffer from confusion due to uncleaned sidelobes
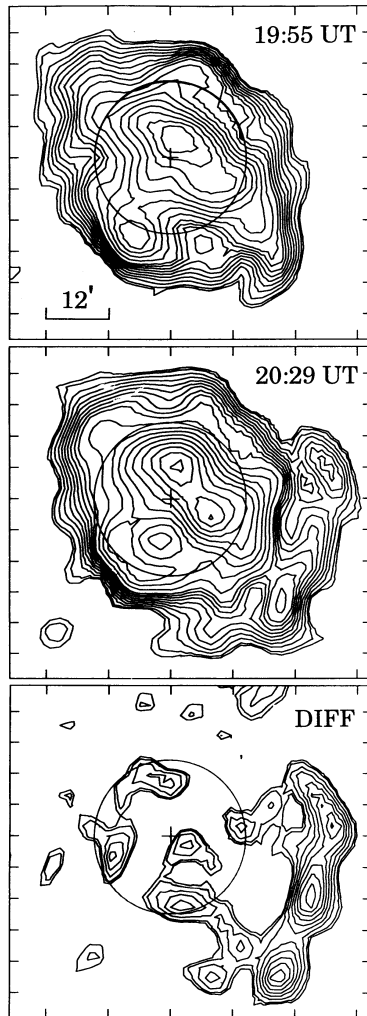
From Bastian & Gary 1997

A close-to-reality case

37 antennas

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.
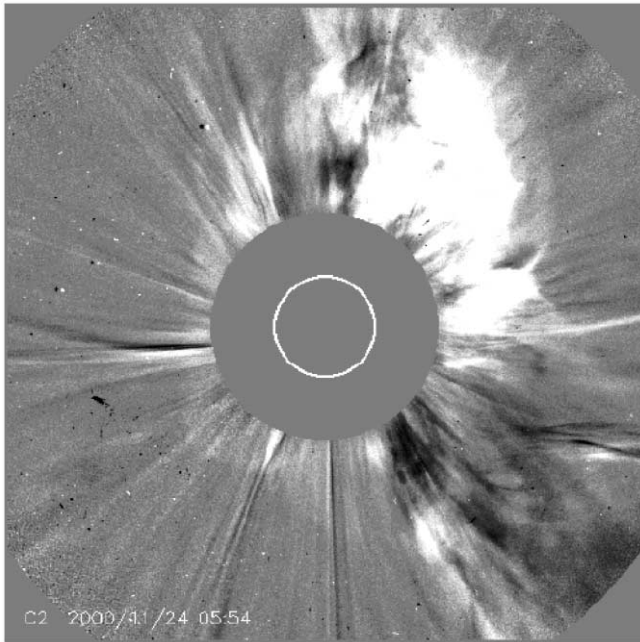 - ❖ $T_{B\_CME} \approx 1 \times 10^5$ K
  - ❖ $n_e \approx 9.5 \times 10^6$ cm^{-3}
  - ❖ $M_{CME} \approx 2.7 \times 10^{15}$ g

Another example

- White light CME

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