Incoherent emissions from CMEs: the three part structure

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This lecture will cover only the near-meter wavelength range. There is nonetheless important imaging work done on microwave emissions from the Sun, namely from Nobeyama. The relevant emission mechanisms where covered in previous lectures:

- thermal free-free emission
- thermal gyro-ressonance emission
- non-thermal gyro-synchrotron emission

Already covered were also the valuable insights these observation provide into:

- flare geometry
- flare dynamics
- CME phenomena (filament eruptions)

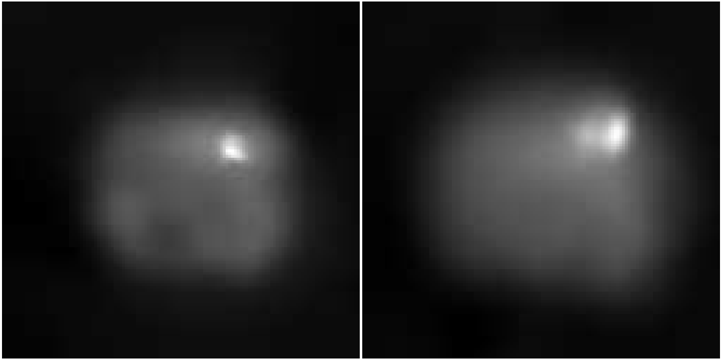
Outline

Incoherent emissions from CMEs: the three part structure

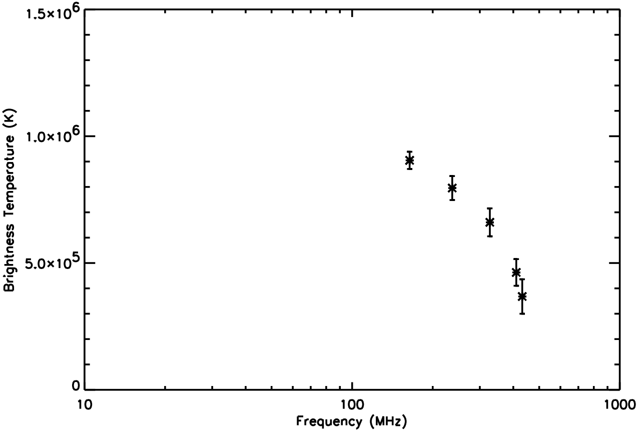
- Thermal free-free emission from the quiet Sun.
- Prominence/bright core, both in quiescent state and erupting in decimeter wavelength range (thermal emission "extinction features")
- Thermal emission from the leading edge of CMEs.
- Gyrosynchroton emission from CME loops.

The emphasis is on imaging observations.

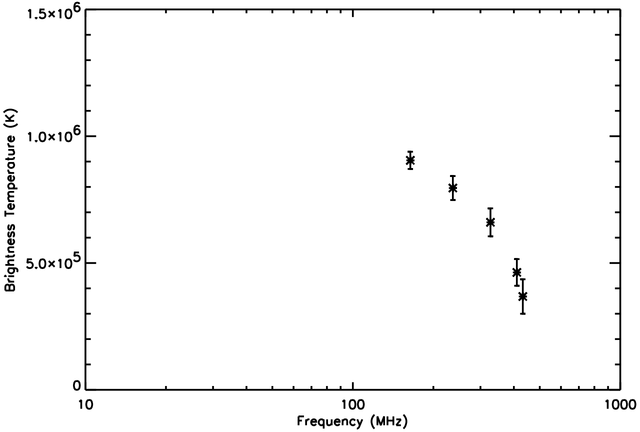
Thermal free-free emission from the quiet Sun



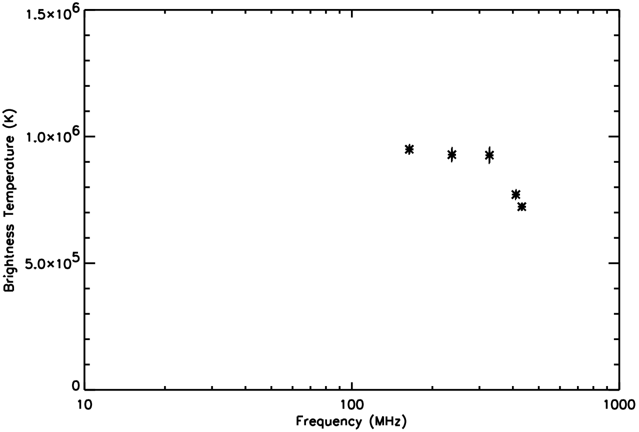
Images from Nançay Radioheliograph on 1998 April 20, in 327 MHz (left) and 164 MHz (right). The smooth disk corresponds to the thermal emission, with weak bright non-thermal noise storms also seen.



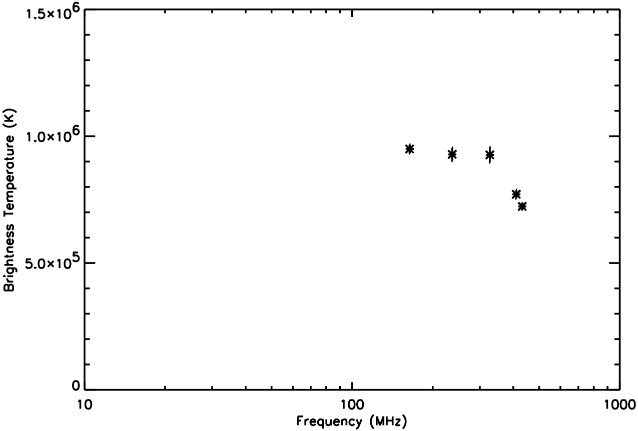
Center of the disk brightness temperature for 1998 April 20. Note the near-coronal temperature at 164 MHz, and the sharp drop at the higher frequencies.



Center of the disk brightness temperature for 1998 April 20. Note the near-coronal temperature at 164 MHz, and the sharp drop at the higher frequencies.



Center of the disk brightness temperature for 2001 April 15. Note the near-coronal temperature from 164 MHz to 327 MHz, and the sharp drop at the higher frequencies.



Center of the disk brightness temperature for 2001 April 15. Note the near-coronal temperature from 164 MHz to 327 MHz, and the sharp drop at the higher frequencies.

One needs to go back to the equations presented in previous talks.

The absorption coefficient α for free-free for coronal plasmas is:

$$\alpha = \frac{\varepsilon}{f^2} \frac{N^2}{T^{3/2}} \frac{1}{n}$$

with $\varepsilon \approx 0.20$ in the corona, and n is the refraction index.

The optical depth is the integral of this coefficient along the line of sight

$$\tau(x) = \int_x^\infty \alpha dx$$

Assuming constant temperature:

$$\tau(x) = \frac{\varepsilon}{f^2 T^{3/3}} \int_x^\infty \frac{N^2}{n} dx$$

The f dependence explains the sharp drop at higher frequencies. But, things are more complex, due to the effects related to the refraction index.

The important quantity is the local plasma frequency:

$$w_p = \sqrt{\frac{e^2 n_e}{\epsilon_0 m_e}} = 2\pi\ 90 \sqrt{\frac{n_2}{10^8 \mathrm{cm}^{-3}}}\ [\mathrm{MHz}]$$

(notice the 2π).

In a plasma with no ambient magnetic field:

$$n^2 = 1 - \frac{w_p^2}{w^2}$$

This implies that at each level in the corona the local plasma frequency acts like a cuttoff frequency.

Why? Because if $w < w_p$ then $n^2 < 0$, so transverse waves can not exist.

There are several effects associated with a varying refraction index, and they need to be considered when using ray tracing techniques in the solar corona at meter wavelengths.

Frequencies higher than w_p at the base of the corona can sample the whole corona and into the chromosphere.

Ray-tracing is relatively easy in this case.

The ray "emerges" from the cromosphere (optically thick) with the chromospheric temperature and the coronal contribution can be computed just by integrating the square of the density to the observer.

$$\tau(x) = \frac{\varepsilon}{f^2 T^{3/3}} \int_x^{\infty} N^2 dx$$

At frequencies high enough $n \approx 1$ and the integral does not depend on frequency, so optical depth goes with f^{-2}.

The corona becomes "transparent" at sufficiently high frequencies. At microwaves one sees the chromosphere, not the corona.

If W than w_p at the base of the corona one “misses” part of the corona. This needs to be accounted in ray-tracing techniques. Each aspect is related to one of the terms in the optical depth equation:

$$\tau(x) = \frac{\varepsilon}{f^2 T^{3/3}} \int_x^\infty \frac{N^2}{n} dx$$

The index of refraction goes to zero at the density level whose corresponding plasma frequency to the observing frequency. This enhances the integral.

The frequency dependency compensates in part the loss of corona.

A ray coming from ∞ is reflected and sent to the observer (doubling of coronal contribution when compared with the frequencies entering the chromosphere.

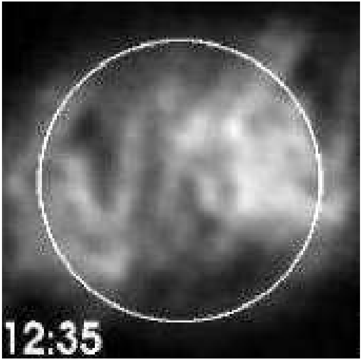
Far from the Sun center, at meter frequencies, ray tracing procedures need to account for another effect. Since n is varying this leads to bending of rays at angles with the density gradient. These will be reflected back without reaching the plasma frequency.

Meter frequencies are highly sensitive to depletions in density near the base of the corona, thus they can image cavities and track their progression. They are also sensitive to density enhancements (streamers, CME fronts?).

Exercise: find what happens for observing frequencies between 30 and 300 MHz, assuming $T = 10^6$ K, and that the density at the base of the corona corresponds to an observing frequency of 200 MHz.

Radio CMEs: thermal free-free emission and the precursor to CME cavity.

Radio imaging of the precursor to CME cavity.

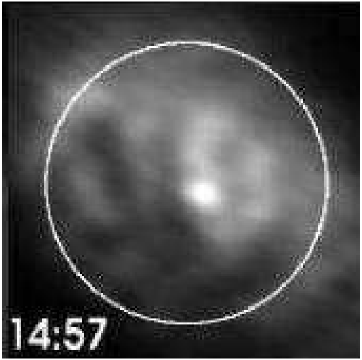


Nançay RH image

- note coronal holes
- dark region near center overlying filament corridor
- These regions can be explained by assuming a drop from 25 to 75% in electron density.
- The filament alone can not explain drop in brightness.

Ref: Marqué et al (2002;2004).

Radio imaging of the precursor to CME cavity.

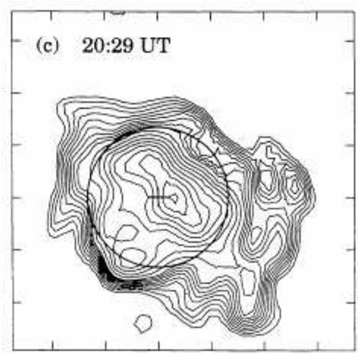


Nançay RH image

- note coronal holes
- dark region near center overlying filament corridor
- These regions can be explained by assuming a drop from 25 to 75% in electron density.
- The filament alone can not explain drop in brightness.

The precursor to the white-light CME cavity can be imaged on disk and its development followed with high cadence.

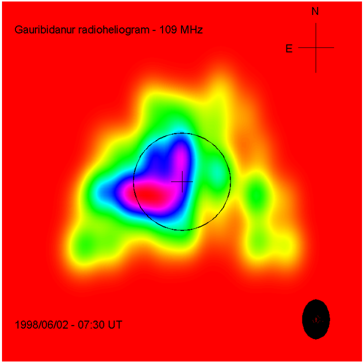
Radio CMEs: thermal free-free emission from CMEs.



Clark Lake image 1986 February 16

- bremsstrahlung emission from “quiet-Sun”
- note dense streamers
- excess emission, thermal emission from CME?

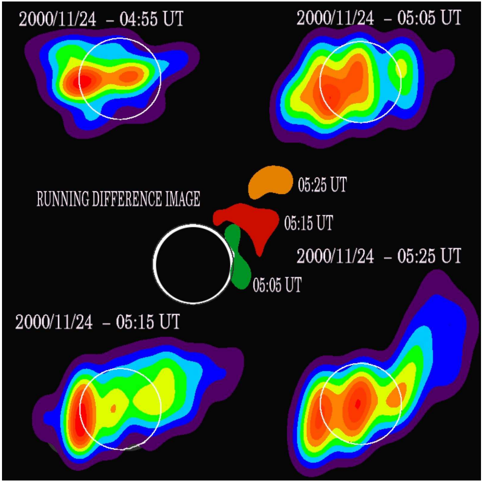
Ref. Gopalswamy and Kundu (1992). ApJ 390, L37-L39.



Recent event.

Gauribidanur image 1998 June 2

- bremsstrahlung emission from "quiet-Sun"
- excess emission related to CME progression


2000/11/24 – 04:55 UT
2000/11/24 – 05:05 UT
RUNNING DIFFERENCE IMAGE
05:25 UT
05:15 UT
05:05 UT
2000/11/24 – 05:25 UT
2000/11/24 – 05:15 UT

What about the mass?

$$M_{cme} = 2 \times 10^{-24}(5L{-}1T_bT^{1/2}f^2)^2V$$

- L, thickness of CME along the line of sight
- Tb, excess brightness temperature
- T, coronal temperature
- f, observed frequency
- V, CME volume

Mass estimate consistent with white-light estimates.
Also magnetic field ≈ 0.86 G at 2.7 $R_\odot$ consistent with other estimates.

R

G K (1992). A J 390, L37-L39.
R K , C . V. S (2003). A J 591:L166-L166.

Radio CMEs: gyrosynchrotron emission from CMEs.

Nançay Radioheliograph image. 164 MHz, field of view: 12 solar radii. Image scaled from -50,000 K to 2.5 million K, then multiplied by radial filter.

Time of image 10:00 UT.

Nançay Radioheliograph image. 164 MHz, field of view: 12 solar radii. Image scaled from -50,000 K to 2.5 million K, then multiplied by radial filter.

Time of image 10:12 UT.

Nançay Radioheliograph image. 164 MHz, field of view: 12 solar radii. Image scaled from -50,000 K to 2.5 million K, then multiplied by radial filter.

Time of image 10:24 UT.

Nançay Radioheliograph image. 164 MHz, field of view: 12 solar radii. Image scaled from -50,000 K to 2.5 million K, then multiplied by radial filter.

Time of image 10:12 UT.

Gyrosynchrotron emission, from electrons in the ~ 100s keV to few MeV, inside a magnetic loop from a few tenth to a few Gauss.

Ref: Bastian et al. (2001), ApJ 558:L65-L69.

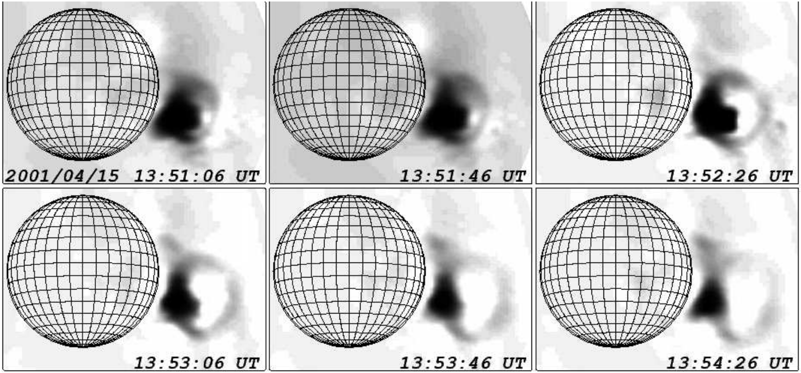
This is simply a particular case of moving type IV emission.

Soon after their discovery, radio type IV bursts were explained as being due to synchrotron emission from relativistic electrons. (Boischot & Denisse 1957).

Type IV bursts were later shown to be subdivided into various classes, with distinct emission mechanisms.

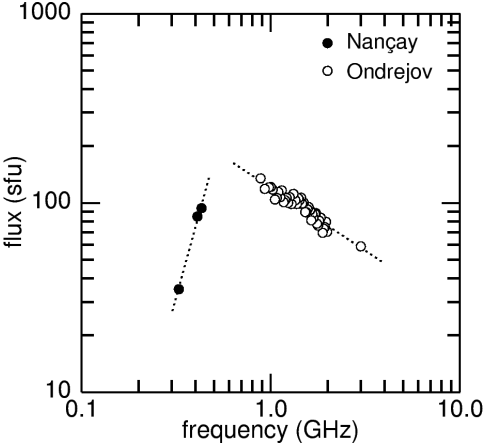
In this event the size of the emitting region argues against plasma emission, and the brightness at different frequencies suggest it is not thermal.

This particular emission allows for diagnostics of magnetic field, spectral index of electrons, high energy cutoff electrons, energetic electron density. For that one needs spectra at each position in the loop.



2001 April 15, Nançay observations at 410 MHz. Gyrosynchrotron emission from expanding CME loops.

Ref: Maia et al (2007). ApJ 660:874-881.


1000
100
10
flux (sfu)
0.1
1.0
10.0
frequency (GHz)
Nançay
Ondrejov

It is obvious that the low-frequency part of the 2001 April 15 event has been suppressed or absorbed.

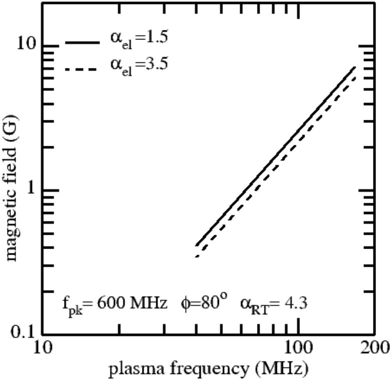
This could be due to a variety of mechanisms: the Razin effect, free-free absorption, self-absorption, cyclotron resonance absorption, or a combination of these.

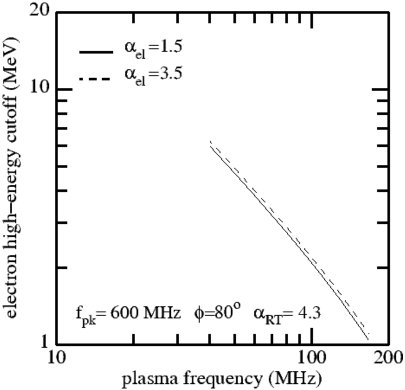
The observed spectral index in this part of the spectrum is a strong indicator that the cutoff mechanism is most likely Razin-Tsytovich suppression (emission in a plasma, not in vacuum).

Razin-Tsytovich suppression gives a cutoff at a frequency about

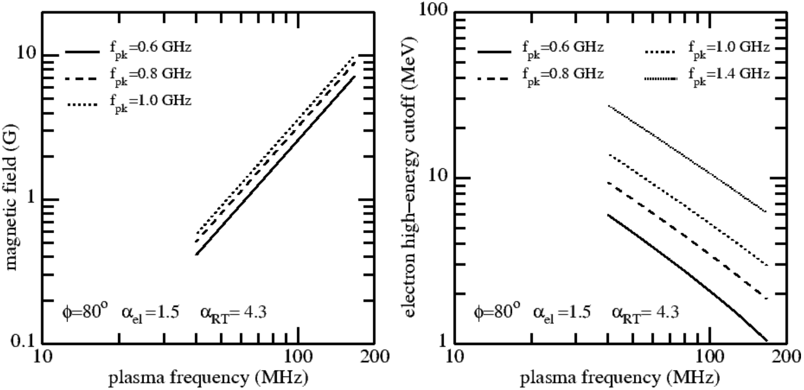
$$f_{RT} = \frac{2}{3} \frac{f_p^2}{f_B \sin \phi}$$

where f_B is the electron cyclotron frequency.





Model results for the Nançay observations, at 2 Rs from Sun center, 11:54 UT, assuming Razin suppresion peak at 600 MHz for two distinct electron spectral indexes.



Model results for the Nançay observations, at 2 Rs from Sun center, 11:54 UT, assuming for the possible range Razin suppresion peaks. Ref. Ramaty (1995).

The radio CME phenomenon:

The cavity, core, typical of white light CMEs can be imaged in a radio CME. High cadence of radio instruments permits to study early phases in detail.

- Filaments can be imaged in microwaves.
- The optimal wavelength range to see cavities is the dm.
- Thermal emission from CME leading edge is seen at “coronal” frequencies
- The optimal wavelength range to see gyrosynchrotron emission from radio-loops depends on the height of the CME at the time of the electron injection:
  - below 2 solar radii: full loops seen at hundreds MHz to 1GHz (FASR).
  - above 3 solar radii: full loops seen at meter wavelengths. NRH, GRH