Leibniz-Institut für Astrophysik Potsdam

Tracking of an Electron Beam Through the Corona with LOFAR

G. Mann, F. Breitling, C. Vocks, H. Aurass, and K.G. Strassmeier

Leibniz-Institut für Astrophysik Potsdam (AIP)

An der Sternwarte 16, D-14482 Potsdam, Germany

e-mail: GMann@aip.de

Leibniz Gemeinschaft

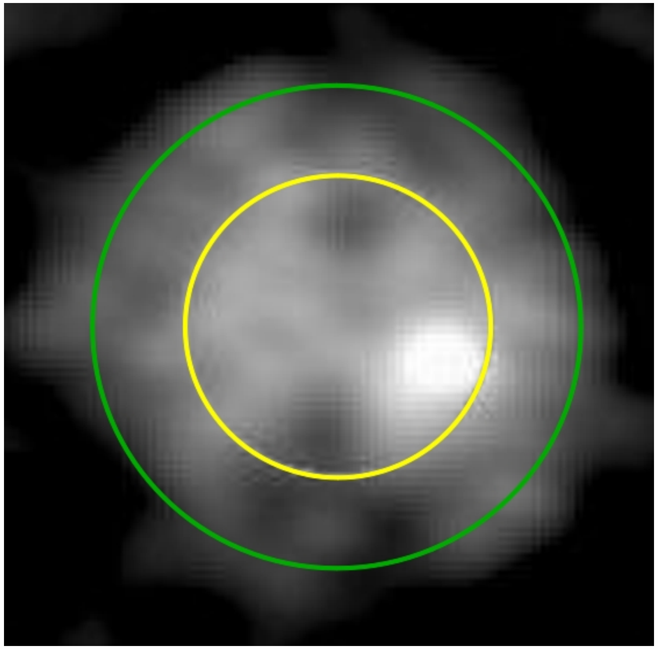
EUROPÄISCHE UNION
Investition in unsere Zukunft
Europäischer Fonds
für regionale Entwicklung

LAND BRANDENBURG

Bundesministerium
für Bildung
und Forschung

LOFAR's First Observation of the Sun

commissioning phase: June 9, 2010



at 135 MHz

The Sun is an intense radio source.

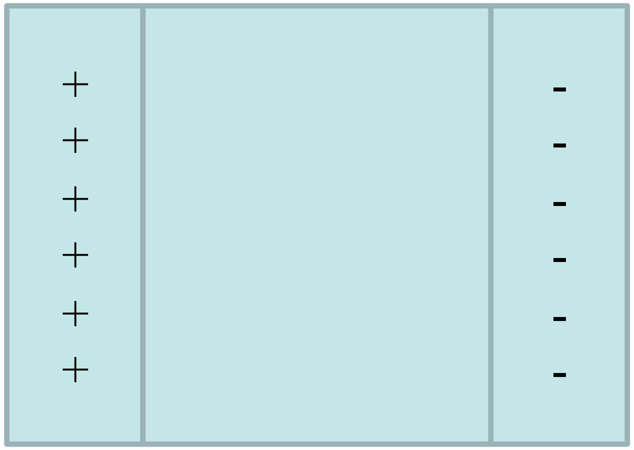
The radio radiation comes from the corona.
(→ plasma emission)

LOFAR can work as a dynamic radio imager of the Sun

→ ***tracking active processes on the Sun with LOFAR***

Plasma Emission

corona – fully ionized plasma



local charge separation
→ Langmuir waves

fundamental emission:

$$\omega_R = \omega_L + \omega_{LF}$$

radio = Langmuir w. + LF plasma waves

harmonic emission:

$$\omega_R = \omega_L + \omega_L$$

radio = Langmuir w.

$$f_R = n f_{pe}$$

n=1: fundamental emission
n=2: 1st harmonic emission

$$f_{pe} = \frac{1}{2\pi}\sqrt{\frac{e^2 N_e}{\varepsilon_0 m_e}}$$

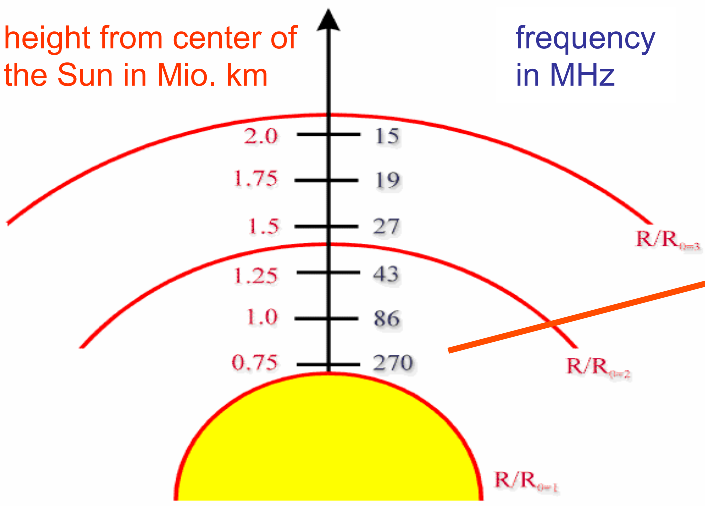
plasma frequency

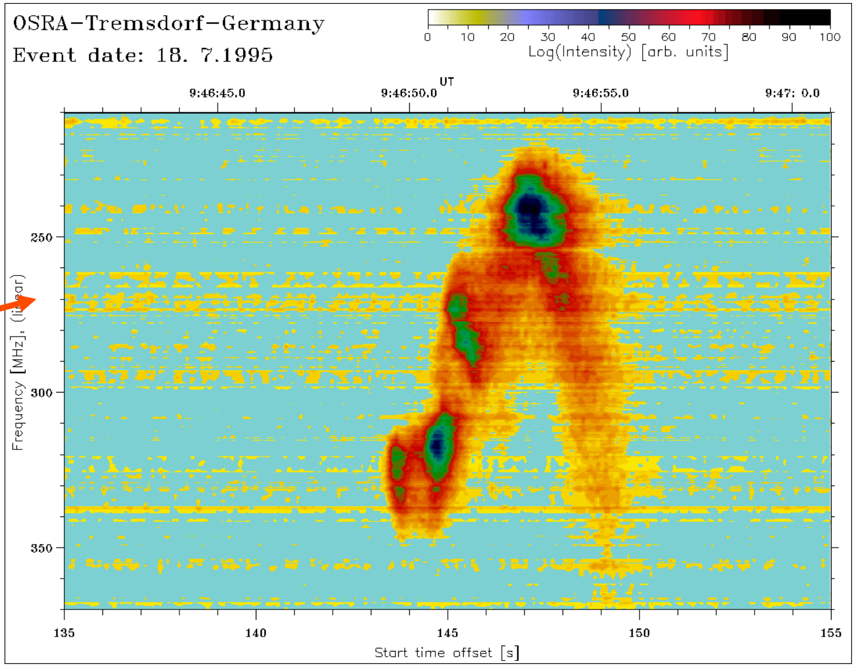
Interpretation of Dynamic Radio Spectra?

Radio wave emission → plasma emission

$$f \approx n \cdot \sqrt{e^2 N_e / \pi m_e} \quad \rightarrow \quad \text{drift rate:} \quad D_f = \frac{df}{dt} = \frac{f}{2}\frac{1}{N}\frac{dN}{dr} V_{source}$$

heliospheric density model (*Mann et al., A&A, 1999*)



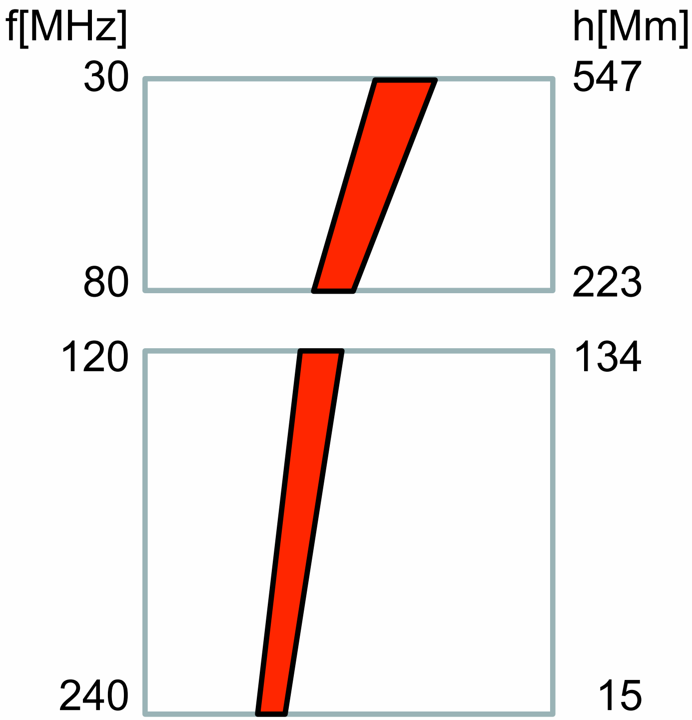


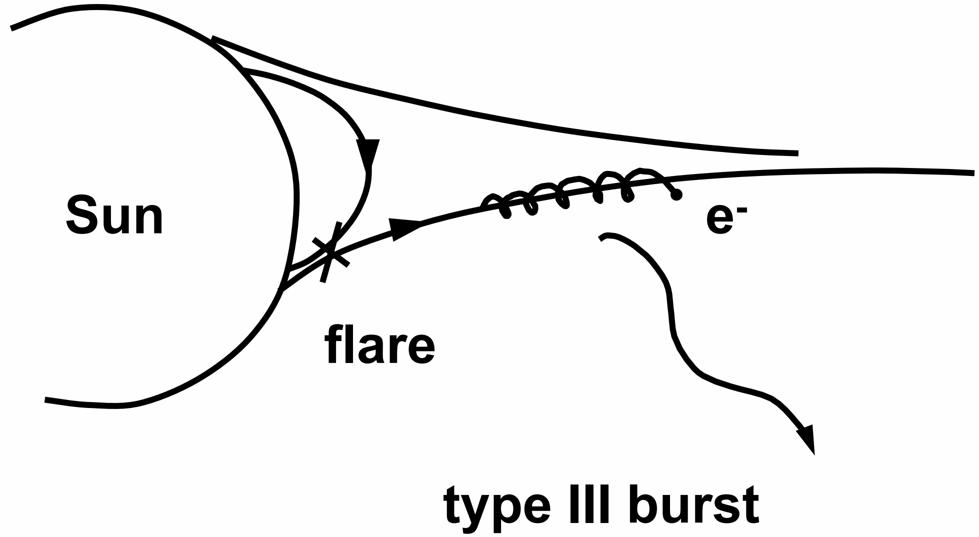
height ≙ frequency

velocity ≙ drift rate

dynamic radio spectrogram ↔ height-time diagram

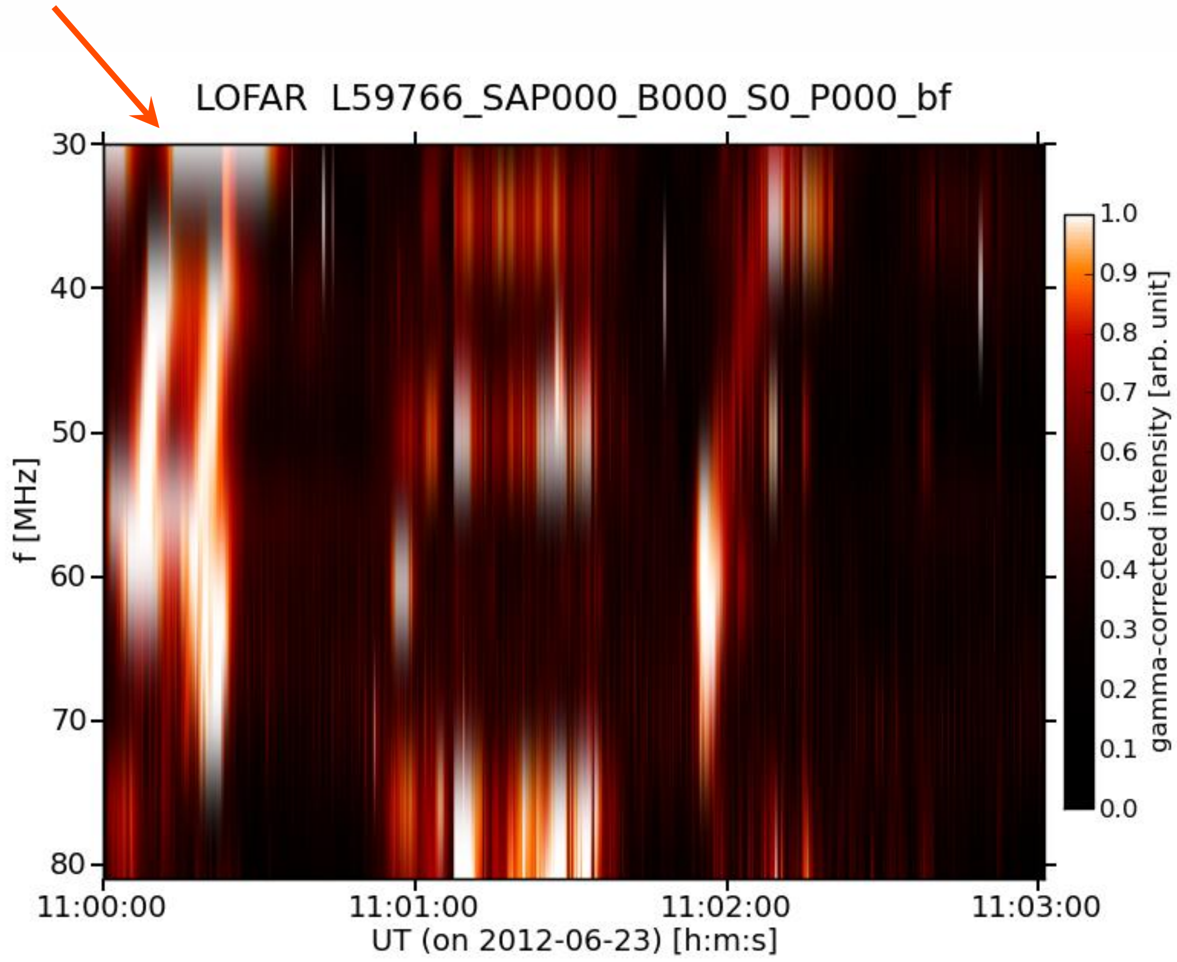
Solar Type III Radio Bursts



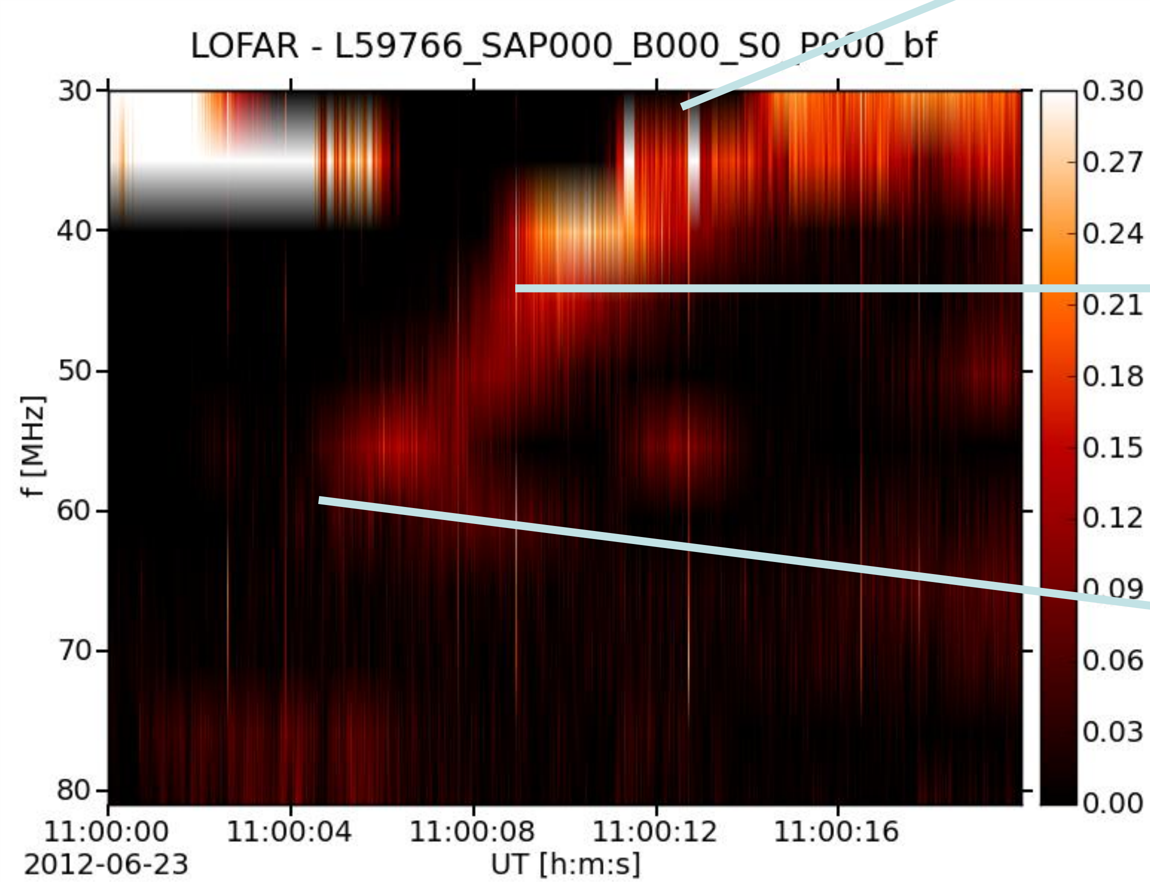


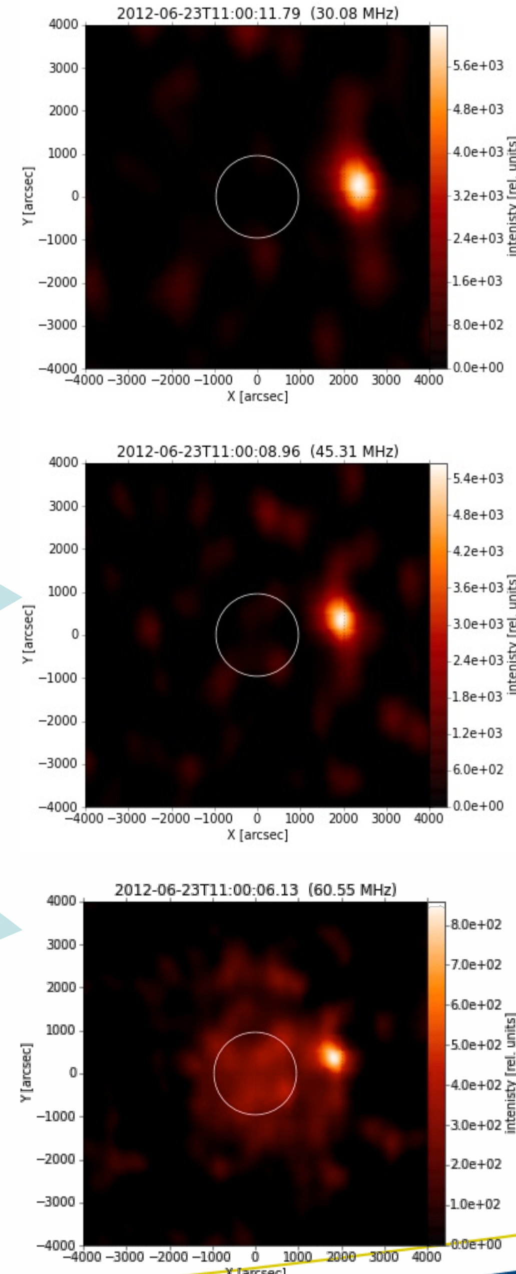
A type III burst is a radio signature of an electron beam initially generated at a flare.
It travels along magnetic field lines through the corona and emits radio waves.
(Wild et al., 1952)

Solar Type III Radio Burst Observed with LOFAR I

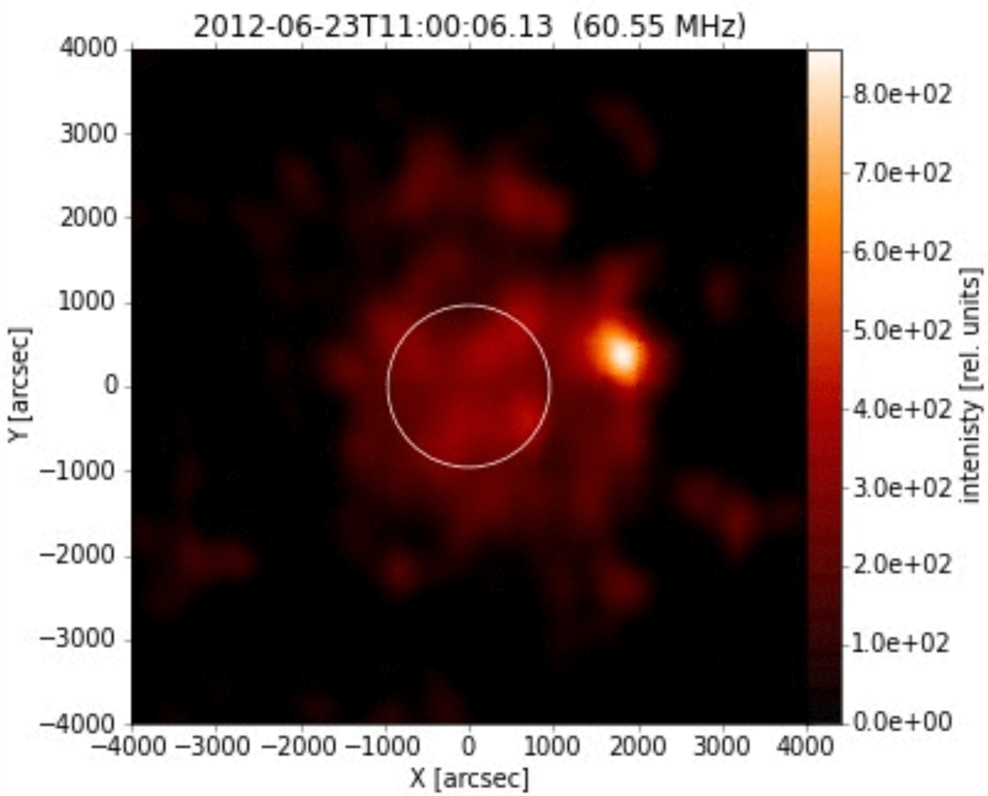


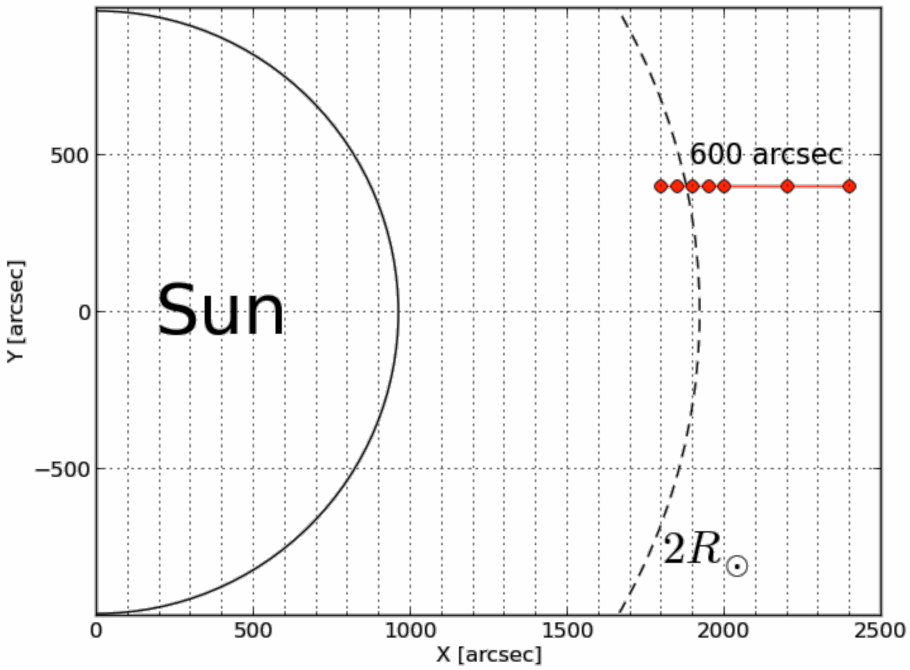
Type III Burst II





Tracking of an Electron Beam Through the Corona with LOFAR I

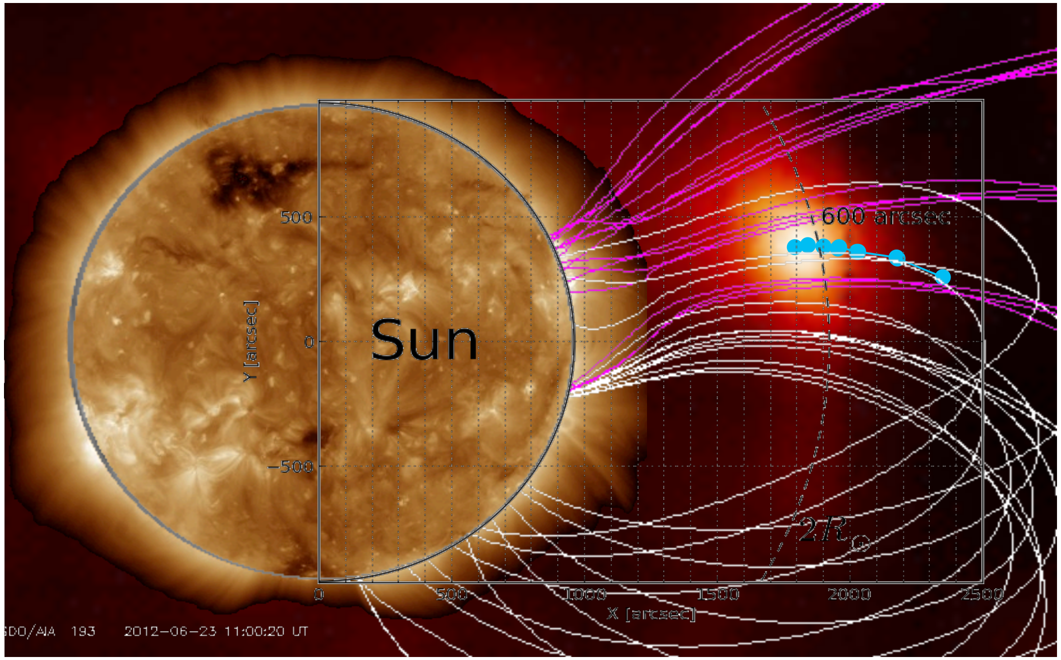




Δx = 600'' = 436,200 km (→ 1'' = 727 km at the Sun)

→ radial velocity V_r = 600''/5.5 s = 79,300 km/s = 0.264 c (18.8 keV)

Tracking of an Electron Beam Through the Corona with LOFAR II



The photospheric magnetic field was extrapolated using the Potential-Field Source-Surface (PFSS) method provided by the SolarSoft program package. *(Schrijver & De Rosa, 2003)*

LOFAR confirms that type III bursts are generated by electron beams propagating along (closed) magnetic field lines.

Interpretation I

localization: 60 MHz: (1800'', 400'') → (1309 Mm, 291 Mm)
30 MHz: (2400'', 400'') → (1745 Mm, 29 Mm)

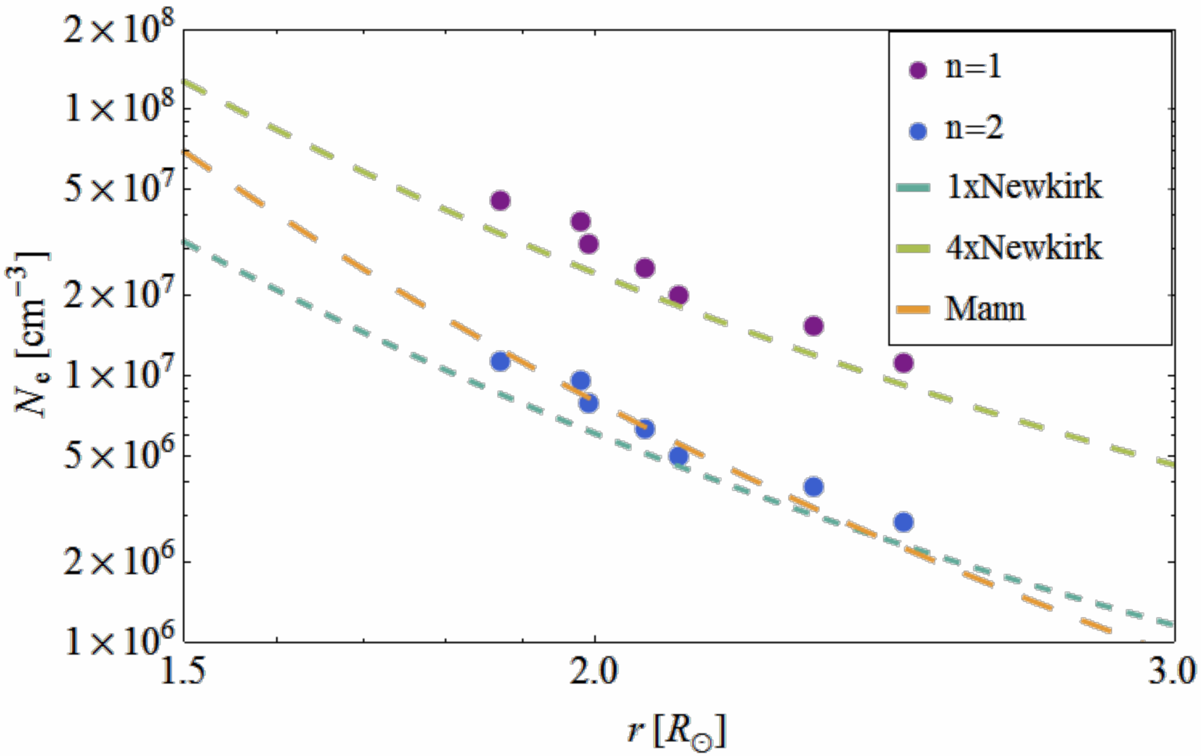
f (MHz)	r/R_S	N_e (cm^{-3}) F	N_e (cm^{-3}) H
60	1.916	$4.466 \cdot 10^7$	$1.116 \cdot 10^7$
30	2.527	$1.116 \cdot 10^7$	$2.791 \cdot 10^6$

density model: $N_e(r) = N_S \, e^{\lambda [(R_S/r)-1]}$

$$\rightarrow \quad \frac{N_{60\,MHz}}{N_{30\,MHz}} = 4.00 = \frac{e^{-0.4781\lambda}}{e^{-0.6043\,\lambda}} \quad \rightarrow \quad \lambda = 11$$

because of $\lambda = 13.83 \left(\frac{T_0}{T} \right)$ with $T_0 = 1\,MK \quad \rightarrow \quad T = 1.26\ MK$

Interpretation II



- The radial density profile as measured with LOFAR agrees with the Newkirk (1961) model, if harmonic emission is assumed.
- The model by Mann et al. (1999) results from a special solution of Parker's (1958) wind equation.

Conclusions

In the framework of LOFAR's commissioning phase, we demonstrated:

- The solar imaging pipeline (→ *Breitling*) works well.
- LOFAR can really work as a ***dynamic spectroscopic radio imager*** of the Sun
  (→ LOFAR opens a new window, indeed.)
- For the first time, LOFAR confirms, that solar type III radio bursts are really generated by beams of energetic electrons travelling along magnetic field lines.
- With LOFAR, the density can be measured in coronal regions previously not accessible to observations.

Thank you for your attention!

This work was done
in collaboration
with the solar KSP and
LOFAR/ASTRON team

Solar Radio Emission I

- fundamental rad.:

$\omega_R = \omega_{pe} + \omega_{LF}$ $\qquad$ $\omega_{LF} \leq \omega_{Whistler} \leq 0.1\,\omega_{ce}$

$\omega_R \leq 1.01\,\omega_{pe}$ $\qquad$ because of $\omega_{pe} / \omega_{ce} > 10$ in the corona

- harmonic emission:

$\omega_R = 2\,\omega_{pe}$

index of refraction at the emission site

$$n = \frac{k^2c^2}{\omega^2} = 1 - \frac{\omega_{pe}^2}{\omega^2} \quad \rightarrow \quad \frac{v_G}{c} = \sqrt{1 - \frac{\omega_{pe}^2}{\omega^2}}$$

at the emission site: $\qquad$ for F: $v_G = 0.12$ c

for H: $v_G = 0.87$ c

The harmonic radiation can easier leave the emission site than the fundamental one.

Solar Radio Emission II

law of refraction

$$\frac{\sin \vartheta_i}{\sin \vartheta_r} = n \quad \rightarrow \quad \vartheta_r = \arcsin\left(\frac{\sin \vartheta_i}{n}\right)$$

$\rightarrow$ because of total reflection:

$\vartheta_i \leq 8°$ for fundamental emission

$\vartheta_i \leq 60°$ for fundamental emission

influence at local density fluctuations (turbulence)

$$n^2 = 1 - \frac{\omega_{p0}^2 (1 + \delta N / N_0)}{\omega_F^2}$$

$$\rightarrow \quad n = \sqrt{0.02 - 0.98 \frac{\delta N}{N_0}} \qquad \text{damping if :} \quad 0.02 \leq \delta N / N_0$$

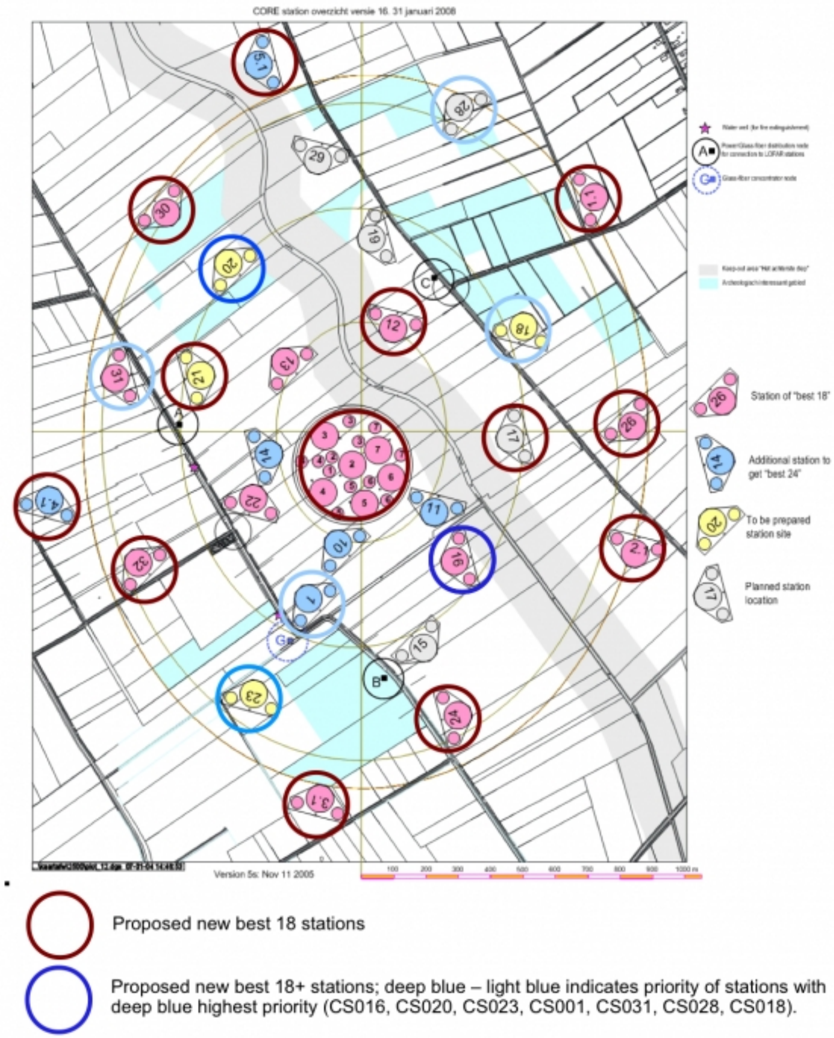
Density fluctuations influence strongly the propagation of radio waves in the corona.

Solar Radio Emission III

In the solar corona radio waves are emitted by plasma emission.

Due to density fluctuations in the corona, the spatial resolution is reduced to few 10”.

LOFAR’s core stations and first ring of remote stations are sufficient for solar observations.



Coronal Density Model I

- spherical symmetry: $0 = -\frac{dp}{dr} - \rho g$ with $g = \gamma_G \frac{M_s}{r^2}$; $p = N k_B T$; $\rho = \mu m p N$

  $\mu = 0.6$ – mean molecular weight

- the integration provides

$$N(R) = N_s \exp\left(\lambda\left[\frac{R_s}{r} - 1\right]\right)$$

with $\lambda = \lambda_0 \left(\frac{T_0}{T}\right)$ and $\lambda_0 = \frac{\mu \gamma_G m p M_s}{k_B T_0 R_S} = 13.83$ for $T_0 = 10^6 K$

$$N_e = 0.521 N$$

AIP

Coronal Density Model II

Comparison with observations: *(Newkirk 1961, Koutchmy 1994)*

- coronal density model: $N_e(r) = \alpha N_0 10^{4.32(R_S/r)}$ $N_0 = 4.2 \cdot 10^2 cm^{-3}$ *(Newkirk, 1961)*

  α=1: quiet equatorial regions

  α=4: dense coronal loops

- corresponds to a barometric density model with a temperature

  T = 1.4 MK *(see Mann et al., 1999)*

  $N_S = 1.687 x 10^9 cm^{-3}$

  $f_{pe} = \alpha^{1/2}$ 266 MHz (at $r = R_s$)

f [MHz]	n=1 r/R_S	n=2 r/R_S
240	1.021	1.191
180	1.085	1.279
120	1.191	1.427
80	1.318	1.615
30	1.782	2.370