# Imaging Spectroscopy of a Type II solar radio burst observed by LOFAR

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The Broad Impact of Low Frequency Observing
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# Talk Outline

- **What are Coronal Mass Ejections and Type II solar radio bursts?**
- **Why is it important to study solar processes?**
- **How to obtain information from Type II burst observations**

  **- Using the dynamic spectrum morphology to extract the local coronal magnetic field**

  **- Imaging of the emission source**

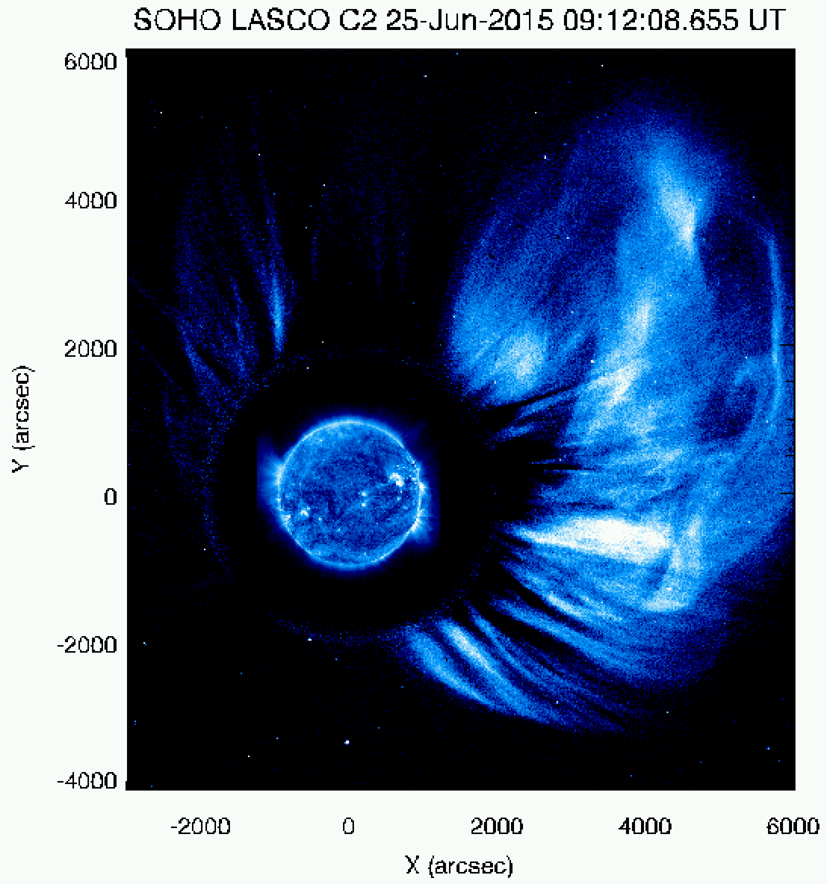
- **Overview of obtained results**

# Coronal Mass Ejections (CMEs)

- **Sporadic violent solar eruptions of massive plasma and magnetic structures into the interplanetary space.**

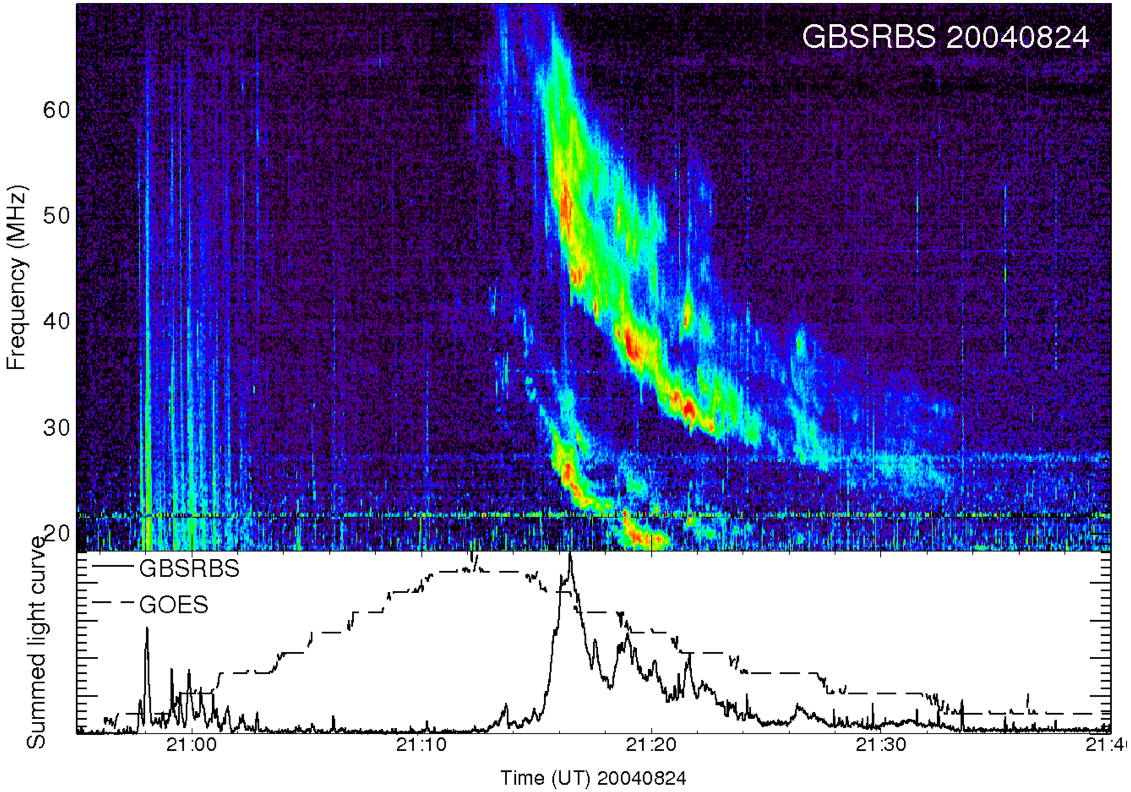
- **The rapid expulsion of particles by the CME forms abrupt discontinuities in density, pressure, and temperature producing a shock wave.**

- **A "bump-in-tail" instability in the electron beam distribution will result in Landau resonance and produce Langmuir waves.  This process is referred to as the Plasma Emission mechanism.**



# Type II radio bursts

- **Electrons excited by shock waves manifest as Type II radio bursts and radiate through the plasma emission mechanism**
- **Emission at fundamental (f) and second-harmonic (2f) of local plasma frequency can be observed (Mclean & Labrum, 1985)**
- **Each of the Fundamental (F) and Harmonic (H) bands can experience splitting into two thinner lanes, a phenomenon known as "band-splitting"**




**Characteristic Type II morphology due to the slow drift from high to low frequencies**

**Splitting of both F and H bands is visible**

Figure courtesy of White (2007).

# Motivation

- **CMEs can reach Earth and cause geomagnetic storms that can be very damaging.**

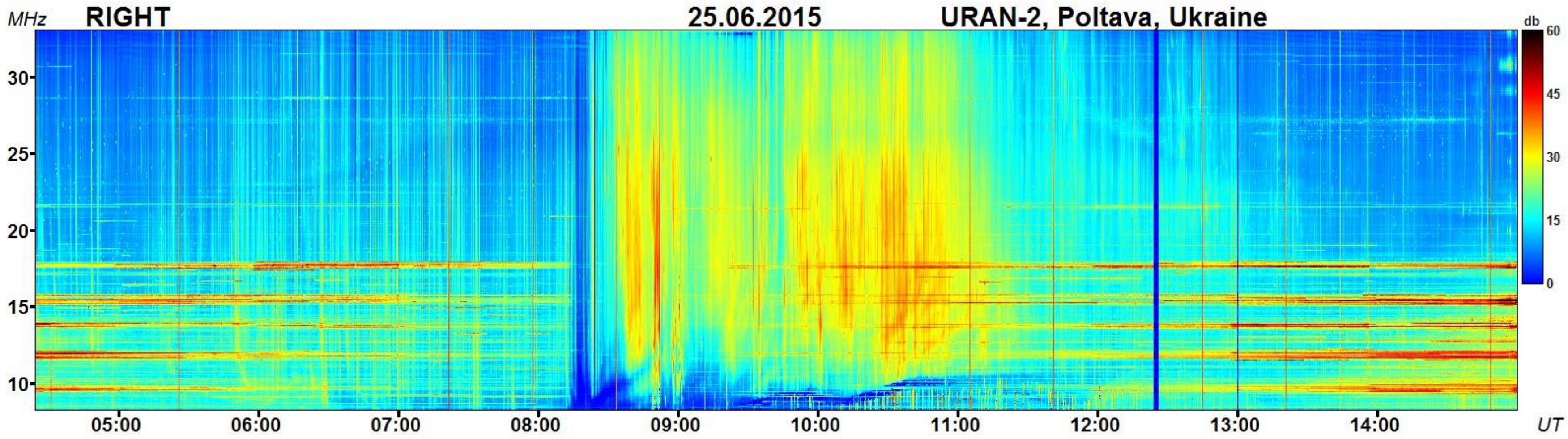
- **Type II bursts trace outward propagating shock waves and can thus be used as a diagnostic tool for shock wave parameters and local coronal conditions at each point in space.**

- **Advantage of Radio Observations: Ability to extract information from solar eruptions at distances close to the solar surface that cannot be probed in-situ or imaged at higher wavelengths.**

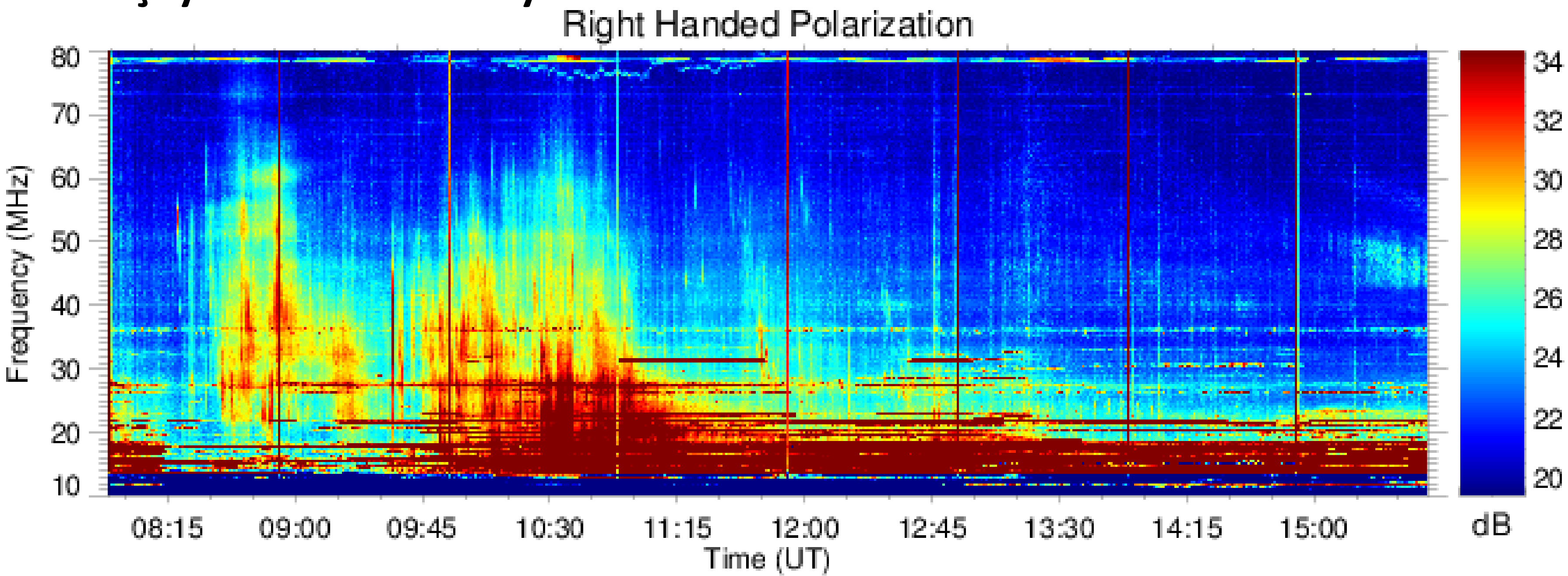
- **Observe the detailed structure of Type II bursts at previously largely unexplored frequencies with a telescope of unprecedented capabilities.**

# 25th June 2015 observations

- **URAN-2**




- **Nançay Decameter Array**



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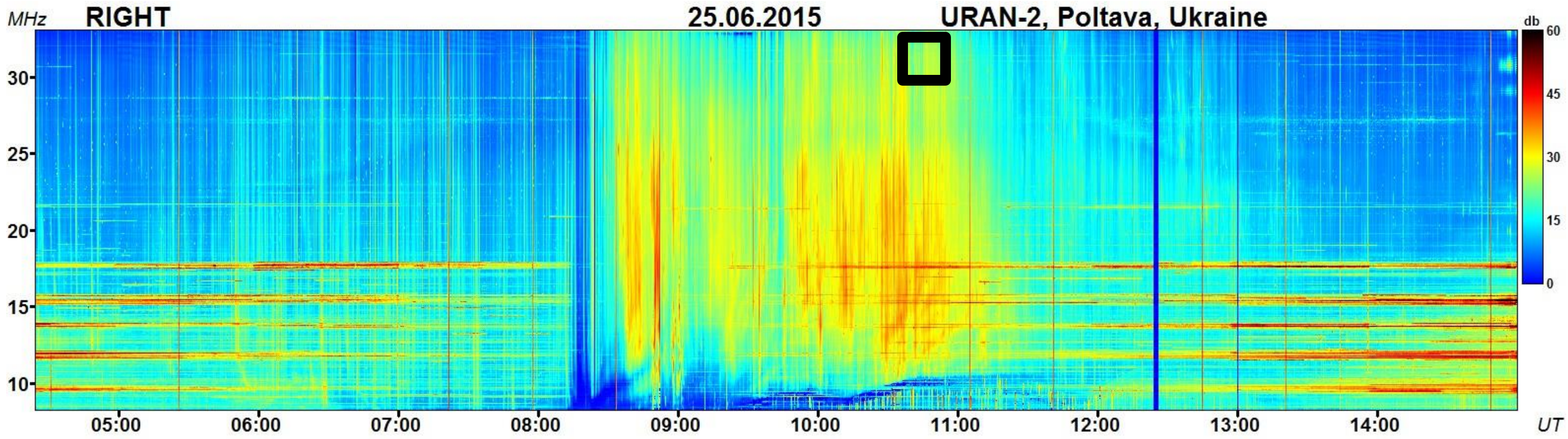
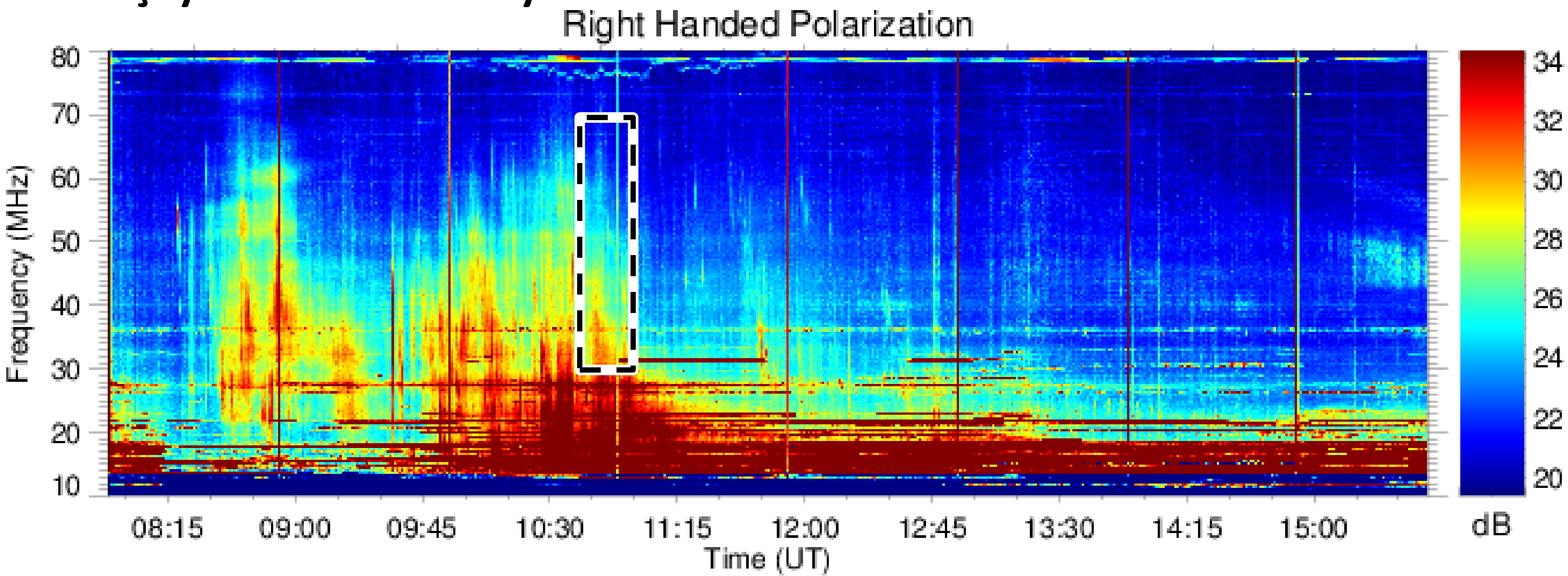
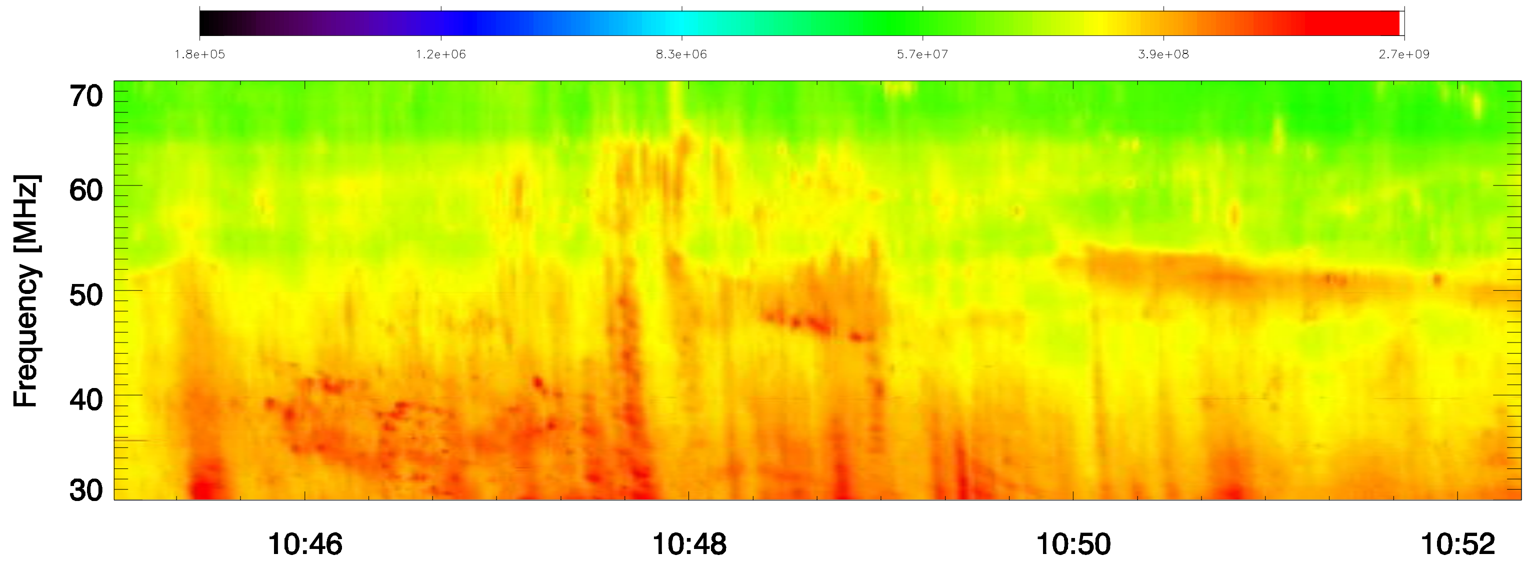


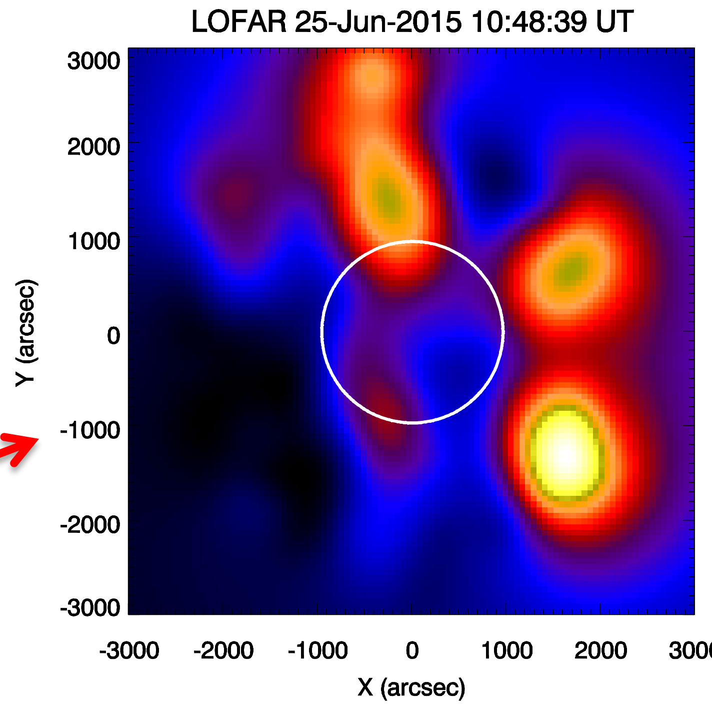

- **Nançay Decameter Array**



# 25th June 2015 LOFAR observation




- **Used LOFAR's LBA core stations with Coherent Stokes beam-formed mode**
- **Band-splitting visible between 10:46:00 and 10:47:40 UT**
- **Radio emission at 10:46:28 UT at about 39 MHz with respect to the solar limb (white circle)**

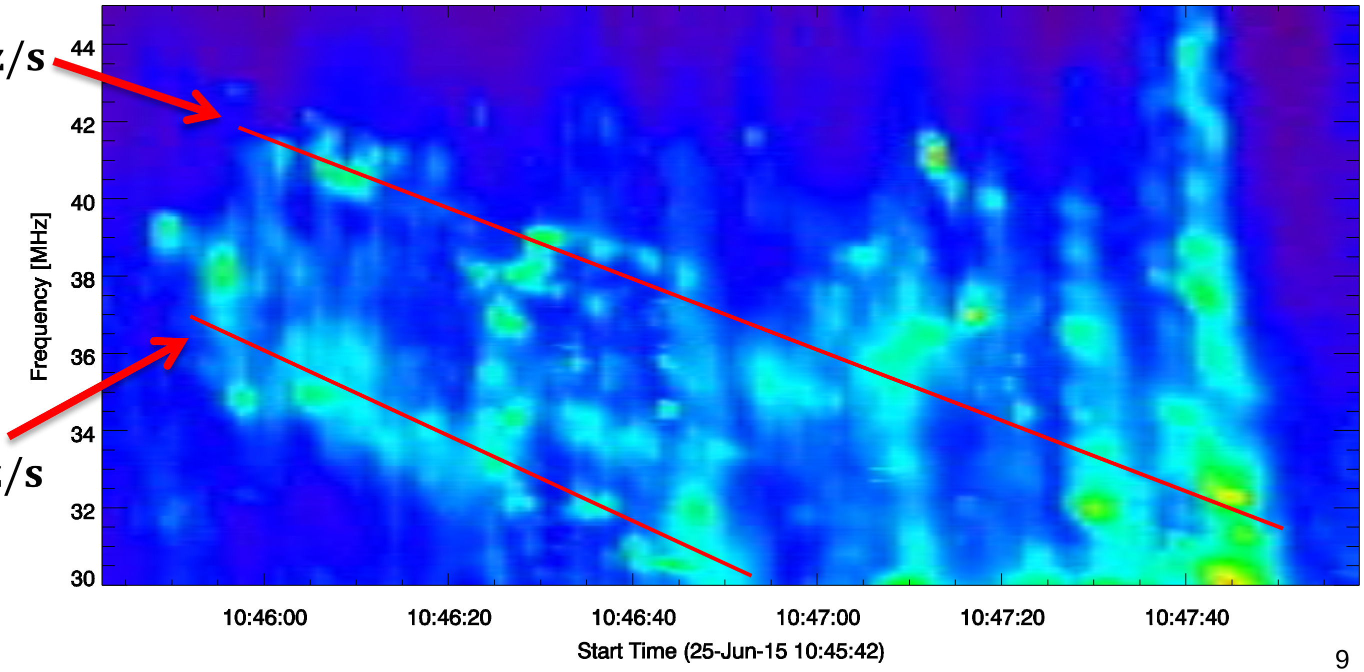


# Frequency Drift Rate

- **Linear fit considering the highest intensities**
- **Since the band is split, a fit was applied on each of the upper and lower band parts**
- **Frequency drift rate given by gradient of line**
- **Decrease in frequency with time corresponds to decrease in densities encountered as shock propagates away from the Sun**

$$\left(\frac{df}{dt}\right)_{upper} = -0.092\ \mathrm{MHz/s}$$

$$\left(\frac{df}{dt}\right)_{lower} = -0.110\ \mathrm{MHz/s}$$



# Coronal Density Model

- **Assume fundamental emission,**

$$f_{pe} = 8.98 \times 10^3 \sqrt{n_e} \quad \text{[Hz]}$$

where: $n_e$ is in $\text{cm}^{-3}$

- **Take the 1xNewkirk coronal density model (1961):**

$$n_e = N \times n_0 \times 10^{4.32/R} \quad [\text{cm}^{-3}]$$

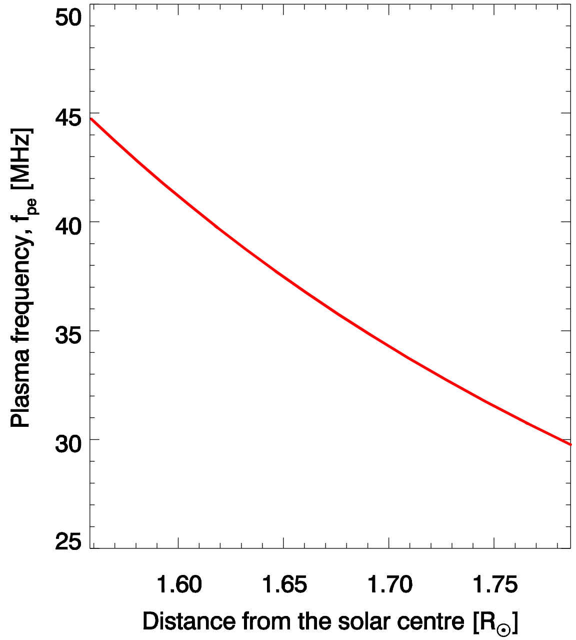
where: $n_0 = 4.2 \times 10^{10}\ \text{cm}^{-3}$

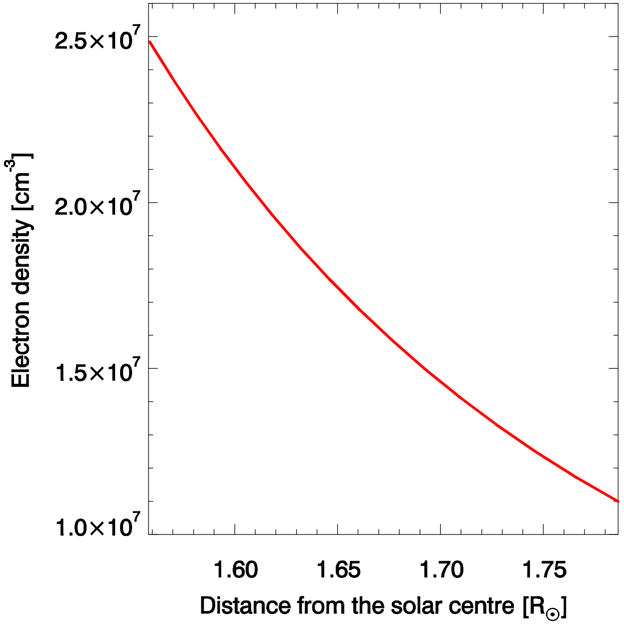
N = 1 for 1×Newkirk

R = distance from solar centre $[\text{R}_\odot]$

- **Can estimate the source's distance from the solar centre (R)**

- **R was estimated to be between 1.56-1.79 $\text{R}_\odot$**



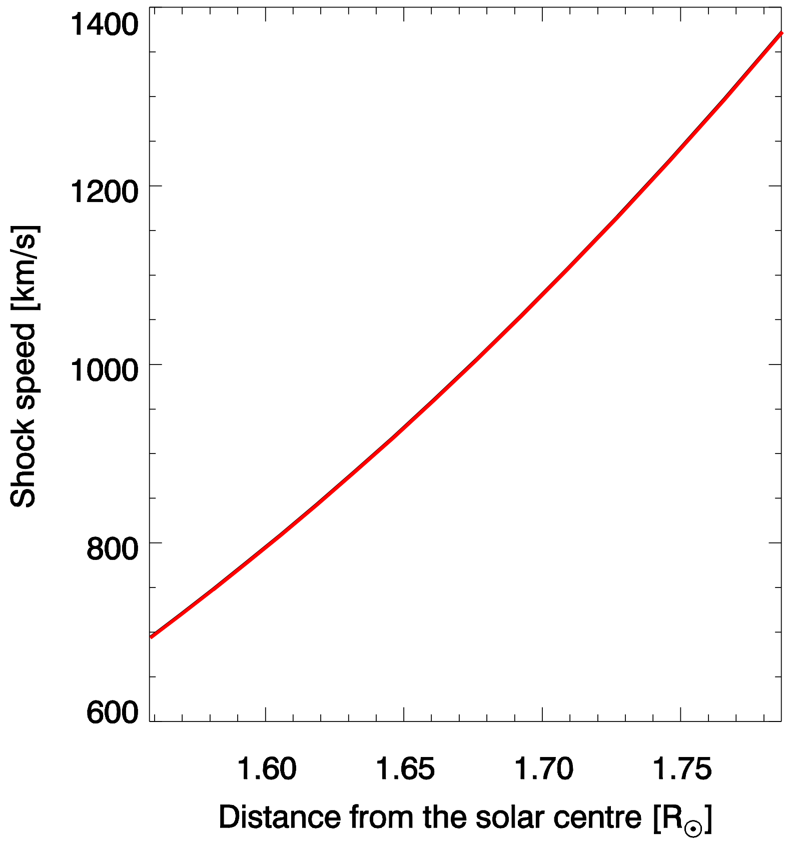



# Shock Speed

- **Following calculations consider Upper Band frequency drift rate only**

- **The (radial) shock speed is calculated through:**

$$V_{shock} = \frac{df_{pe}}{dt} \times \frac{2R_{\odot}n_e}{f_{pe}} \times \left(\frac{dn_e}{dR}\right)^{-1} \quad [\mathrm{kms}^{-1}]$$




where: $n_e$ = electron density [$cm^{-3}$]

f = frequency [MHz]

R = distance from solar centre [km]

# Band-Splitting

- **A band-splitting interpretation proposed by Smerd et al. (1974; 1975) attributes the splitting to *simultaneous emission from the upstream and downstream parts* of a shock front**
- **Relates band-splitting to the *Rankine-Hugoniot jump conditions* across the shock**
- **Relative bandwidth (BWD) related to density jump across the shock (Priest, 2014):**

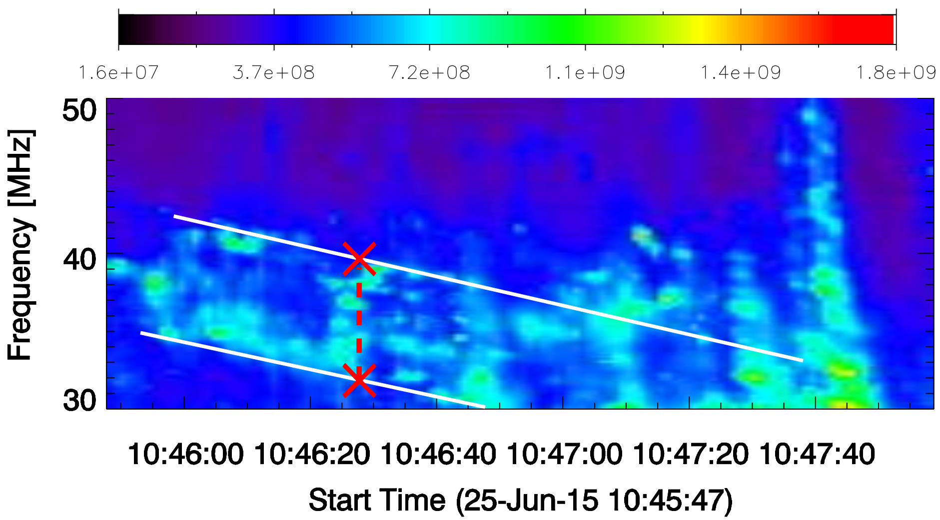
$$BWD = \frac{f_U - f_L}{f_L}$$

$$X \equiv \frac{n_2}{n_1} = \left(\frac{f_U}{f_L}\right)^2 = (BWD + 1)^2$$

where:

U = upper band (higher frequency)

L = lower band (lower frequency)




- **Estimated (average) density jump, X = 1.40**

# Alfvén Speed

- **<u>Assume:</u> (i) plasma beta, β = 0.5**

  **(ii) adiabatic index, γ = 5/3**

  **(iii) angle between shock normal and upstream B-field, θ = 90°.**

**So, the Alfvén Mach Number, $\mathbf{M_A}$ (Vršnak et al., 2002):**

$$M_A = \sqrt{\left(\frac{X(X+5+5\beta)}{2(4-X)}\right)}$$

$$= 1.55$$

**And the Alfvén Speed, $V_A$:**

$$V_A = \frac{V_{shock}}{M_A} \qquad [km s^{-1}]$$

# Magnetic Field

**Since**

$$V_A = \frac{B}{\sqrt{\mu_0 \rho}} = \frac{B}{\sqrt{4\pi \times 10^{-7} m_i n_i}} \quad [\mathrm{ms^{-1}}]$$

Taking: $n_i = n_e$ and $m_i = m_{proton}$

**The magnetic field is estimated using:**

$$B_{est} = 5.1 \times 10^{-5} \times V_A \times f_{pe} \quad \text{[Gauss]}$$

where: $V_A$ is in $kms^{-1}$

$f_{pe}$ is in $MHz$

**Compare to the magnetic field model e.g., Dulk and Mclean (1978):**

$$B_{model} = 0.5(R-1)^{-1.5} \quad \text{[Gauss]}$$

where: R = distance in $R_\odot$

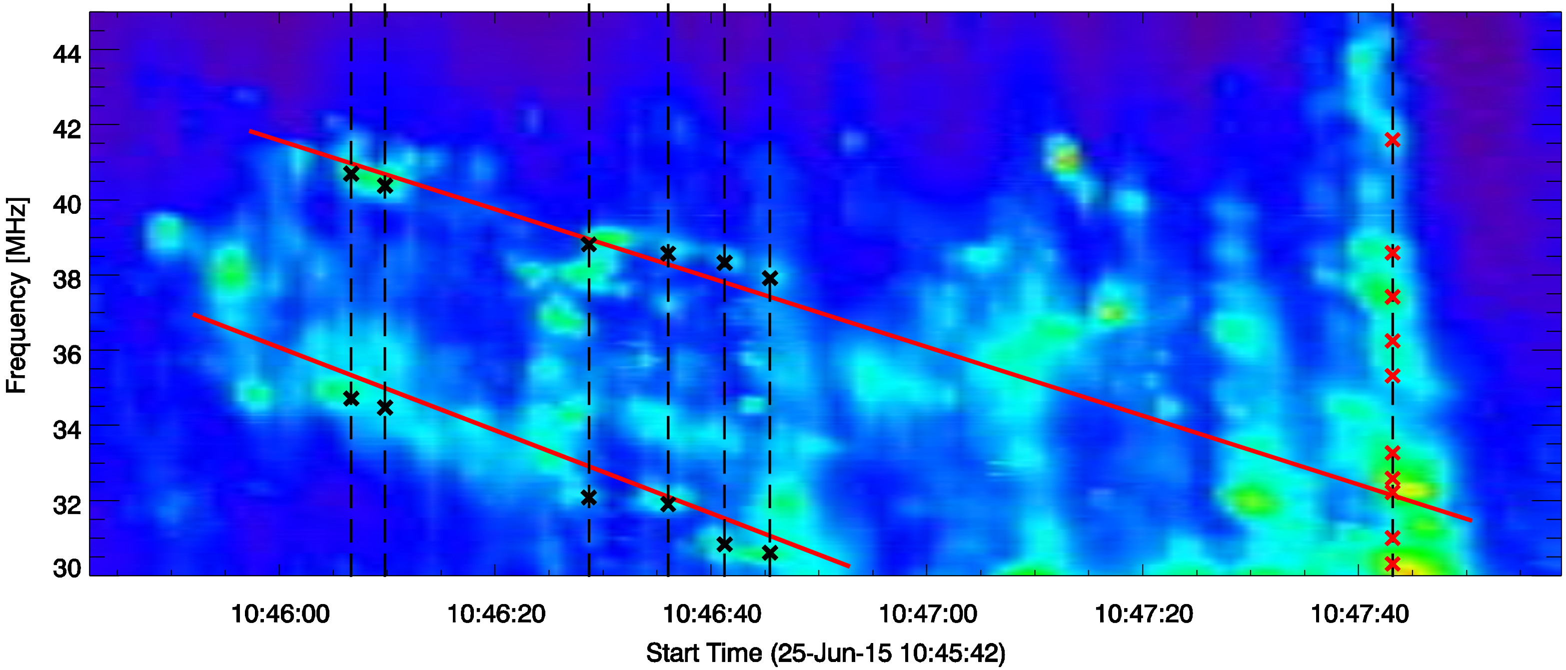
# Source Motion

- **Imaging a specific moment in time and frequency enables the examination of the motion of the emission source during the observation**
- **Selected points in time and frequency for:**

  ***Type II* upper and lower bands (shown in black crosses)**

  ***Type III* burst at 10:47:43 UT (shown in red crosses)**

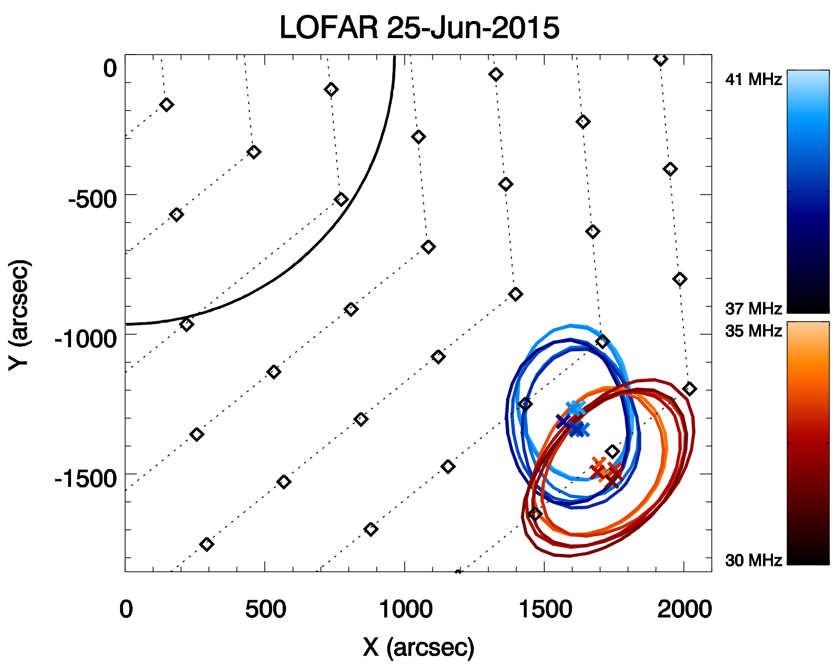
- **For the *Type II*: an UPPER band point and a LOWER band point is selected for each moment in time**
- **For the *Type III*: selected points across frequencies for a single moment in time**

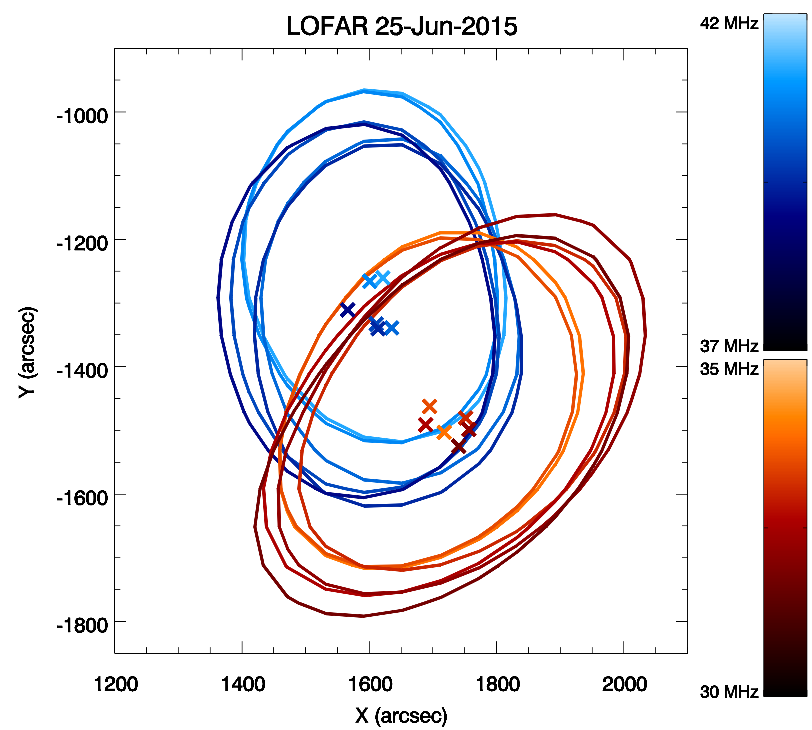


# Source Motion

**Type II:**

- **(left) Centroid locations plotted along with 90% maximum intensity contours for the Type II burst. The black diamonds represent individual beams and collectively the Field of View of LOFAR during the observation.**
- **(right) A magnification into the Type II sources and associated centroids**
- **Blue colour scheme used for upper band sources and red for the lower band.**

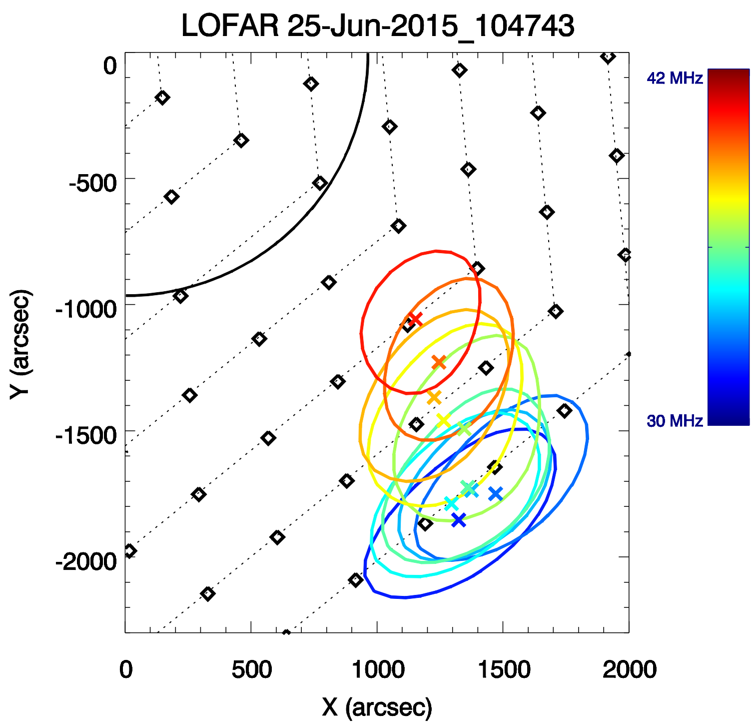


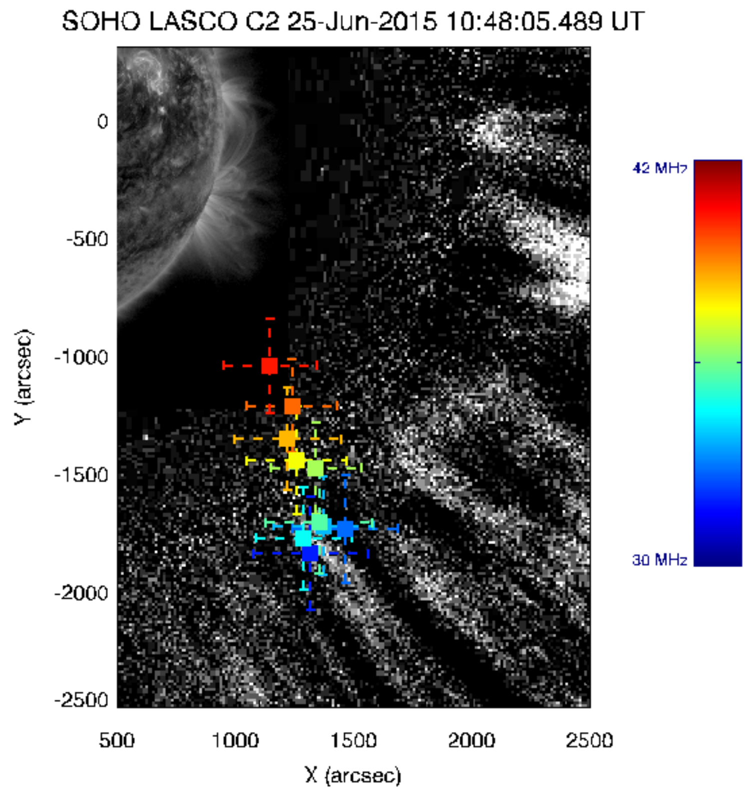



# Source Motion

**Type III**:

- **(left) Centroid locations plotted along with 90% maximum intensity contours for the Type III burst. The black diamonds represent individual beams and collectively the Field of View of LOFAR during the observation.**
- **(right) Error bars assigned to Gaussian estimations of the Type III centroids**



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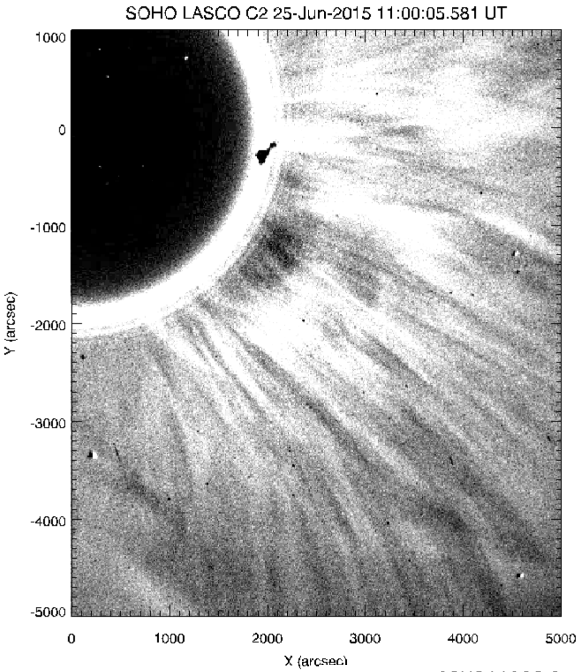
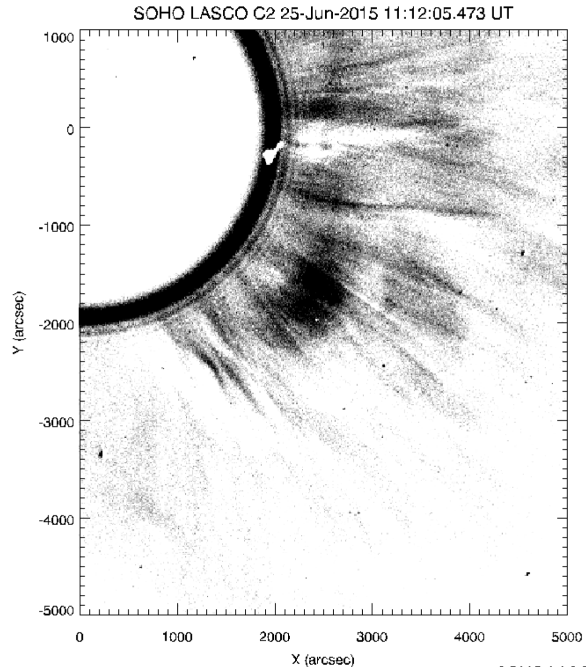
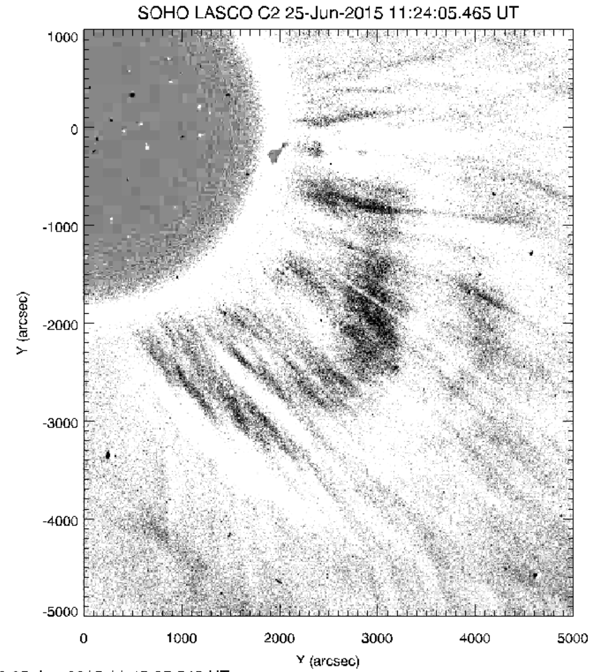
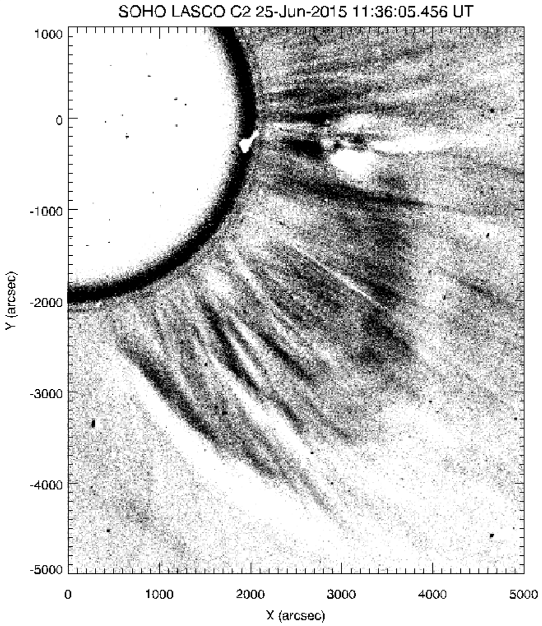
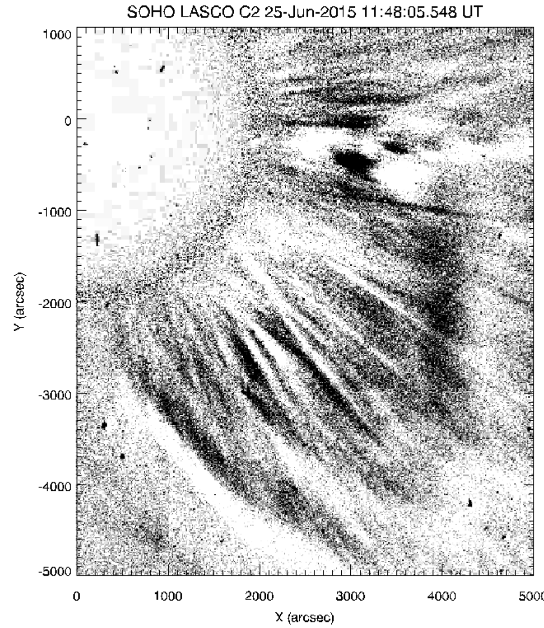
# Eruption starting at 10:48 UT



# Source Motion

- **Combination of:**
  - **- SDO/AIA image showing solar surface near Type II occurrence time**
  - **- SOHO/LASCO (C2) running difference image near Type II start time**
  - **- Centroid locations obtained using LOFAR data**

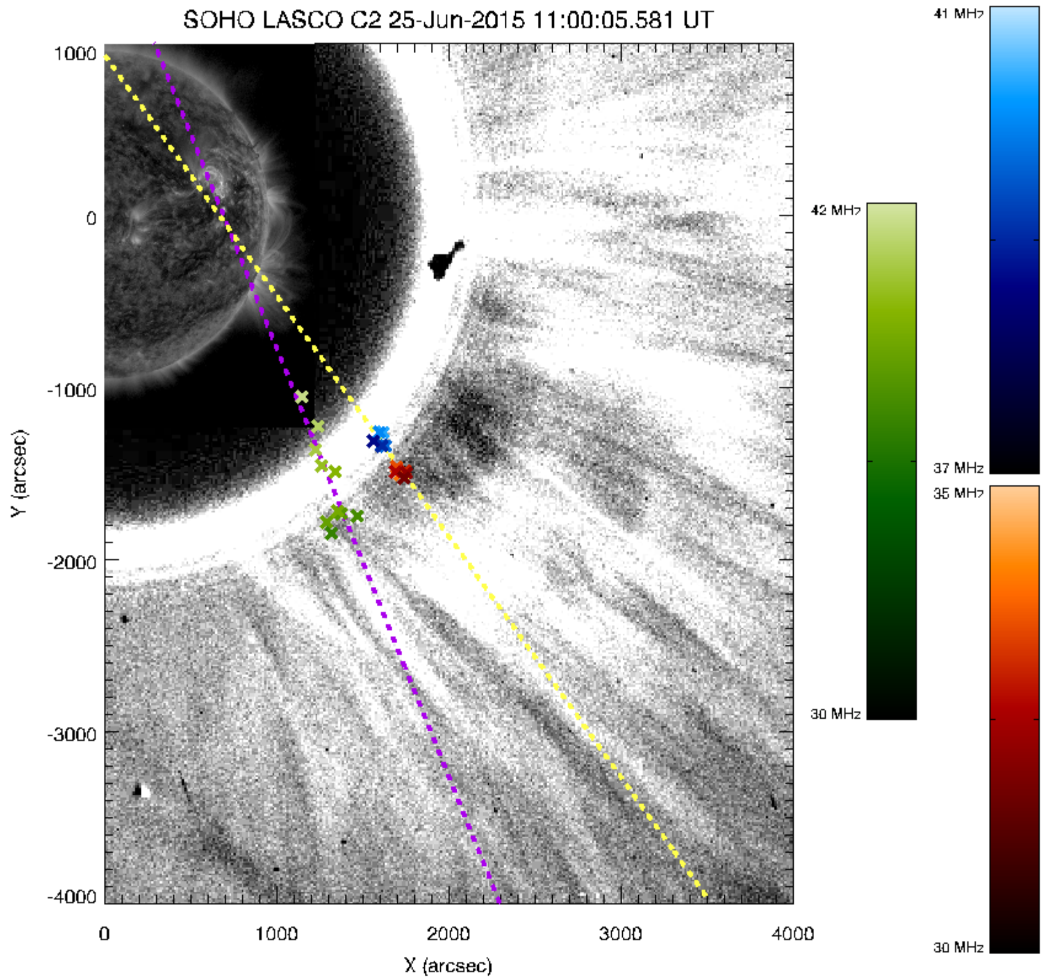
- **Crosses represent:**

  **Type II upper band centroids**

  **Type II lower band centroids**

  **Type III centroids**

- **Fitted lines through both Type II (yellow) and Type III (purple) centroids point towards active region from which a CME at around 9:00 UT originated, but their location and timing coincides with the eruption at around 10:48 UT**



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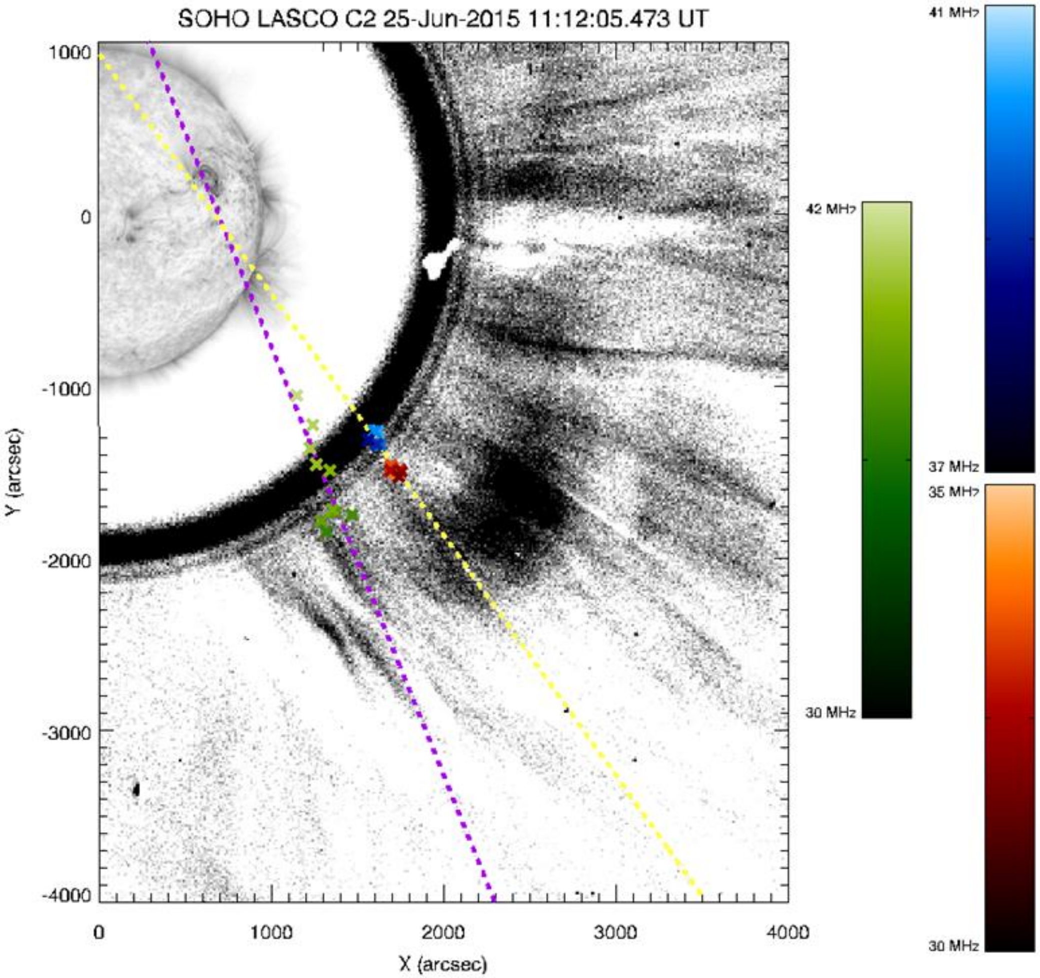

# Overview of Analysis

1. **Relation of the morphological characteristics of dynamic spectra to parameters describing the local coronal environment and the shock wave properties, e.g.:**
   - **Shock speed**
   - **Alfvén speed**
   - **Magnetic Field**

2. **Study of the Emission Source Motion**
   - **Compared position of Type II upper and lower band sources**
   - **Compared position of Type II sources and Type III**
   - **Illustrated direction of propagation with respect to solar surface**
   - **Illustrated emission source locations with respect to solar eruptions**

3. **Objective: Compare observational results against band-splitting models (see e.g. Zimovets et al., 2012)**

# THANK YOU

# ANY QUESTIONS?


References:

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