Solar radio observations and space weather

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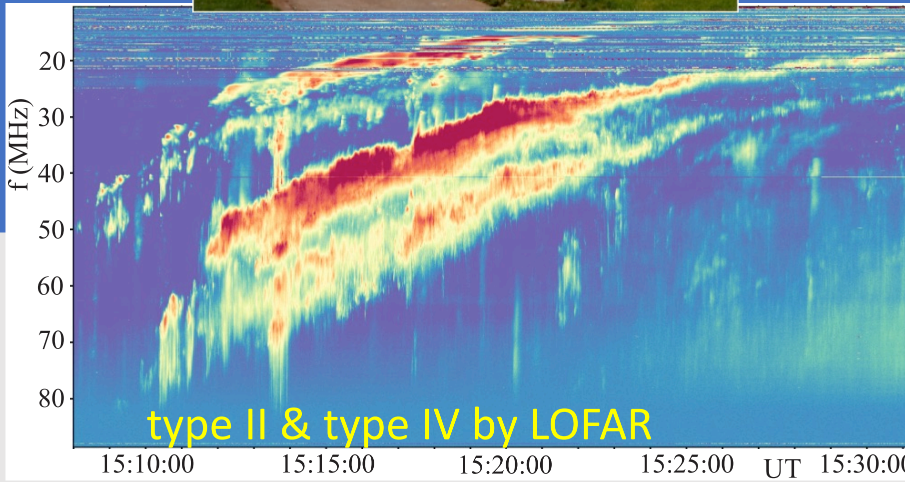
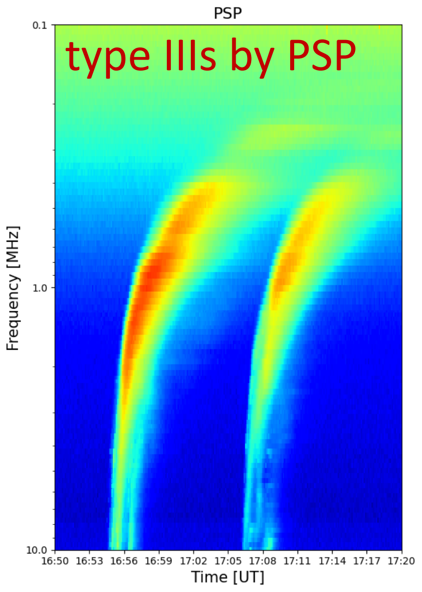
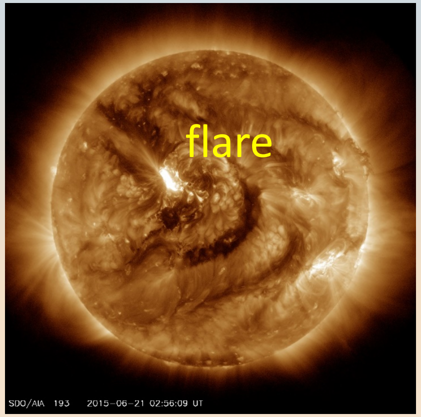
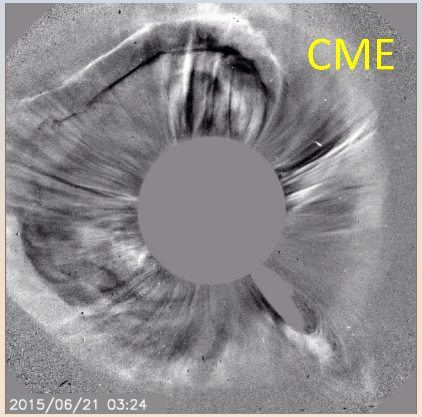




What is space weather and why is it important?

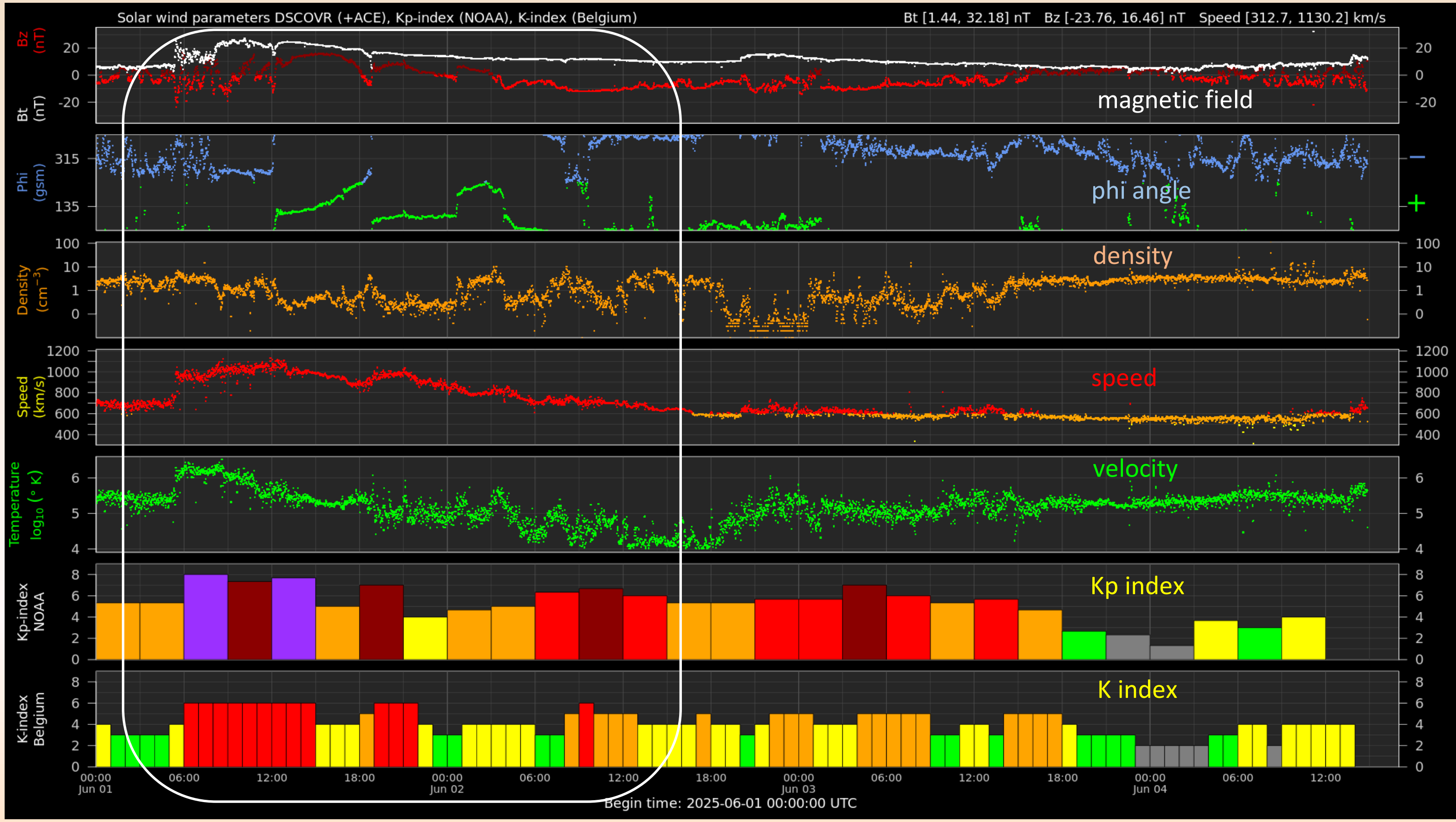




Eruptive processes: flare/CME (coronal mass ejection) events

heating of corona, plasma motion, waves & shocks
(white light, in situ & radio), particle acceleration.

The eruptive phenomena on the Sun and fast solar wind can impact the Earth's magnetosphere and induce geomagnetic storms.

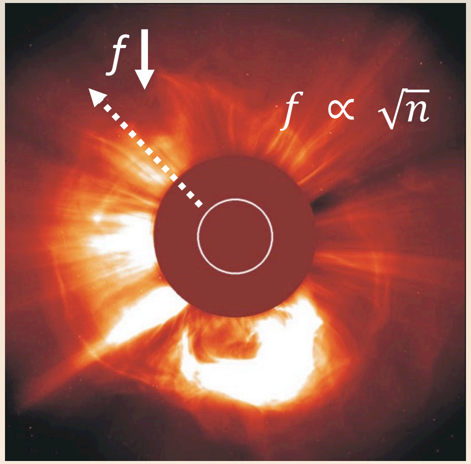


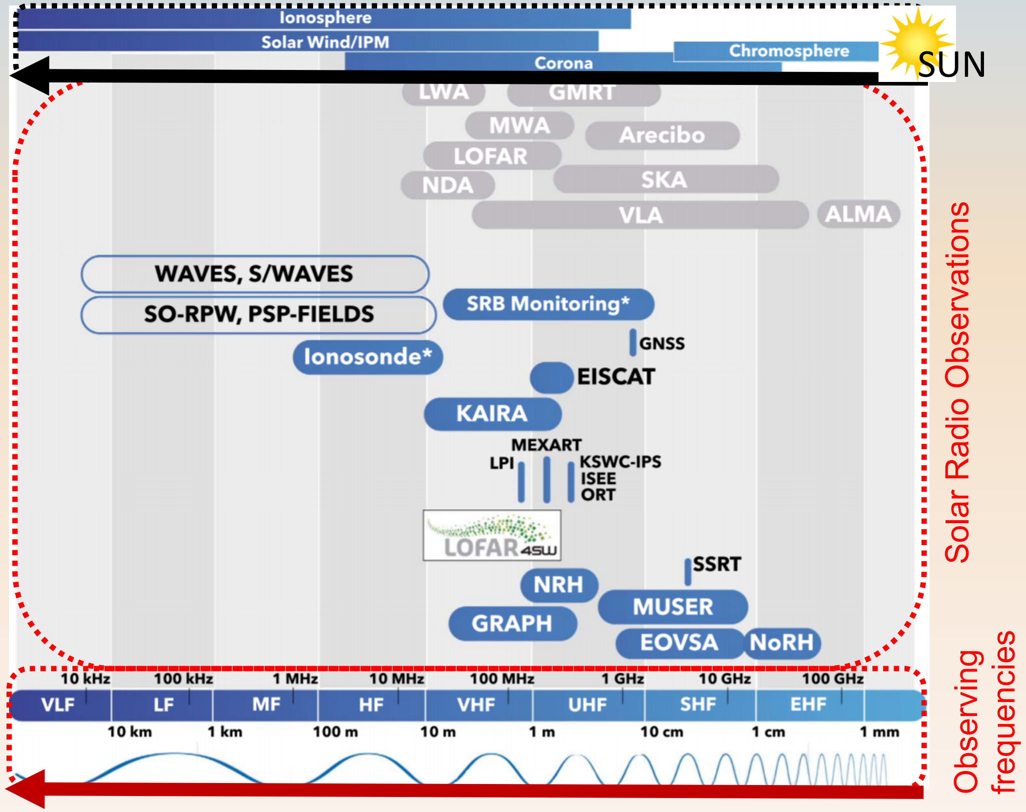
Space Weather research are efforts to study generation and propagation of the solar phenomena – solar storms & their impact to the Earth with the aim to understand and forecast the phenomena.

How does radio emission contribute to space weather?

Radio observations map the plasma processes all the way from the Sun to Earth!

- Solar radio bursts
- Interplanetary scintillations (IPS)





Adapted from Carley at al., 2020

Radio observations can provide information:

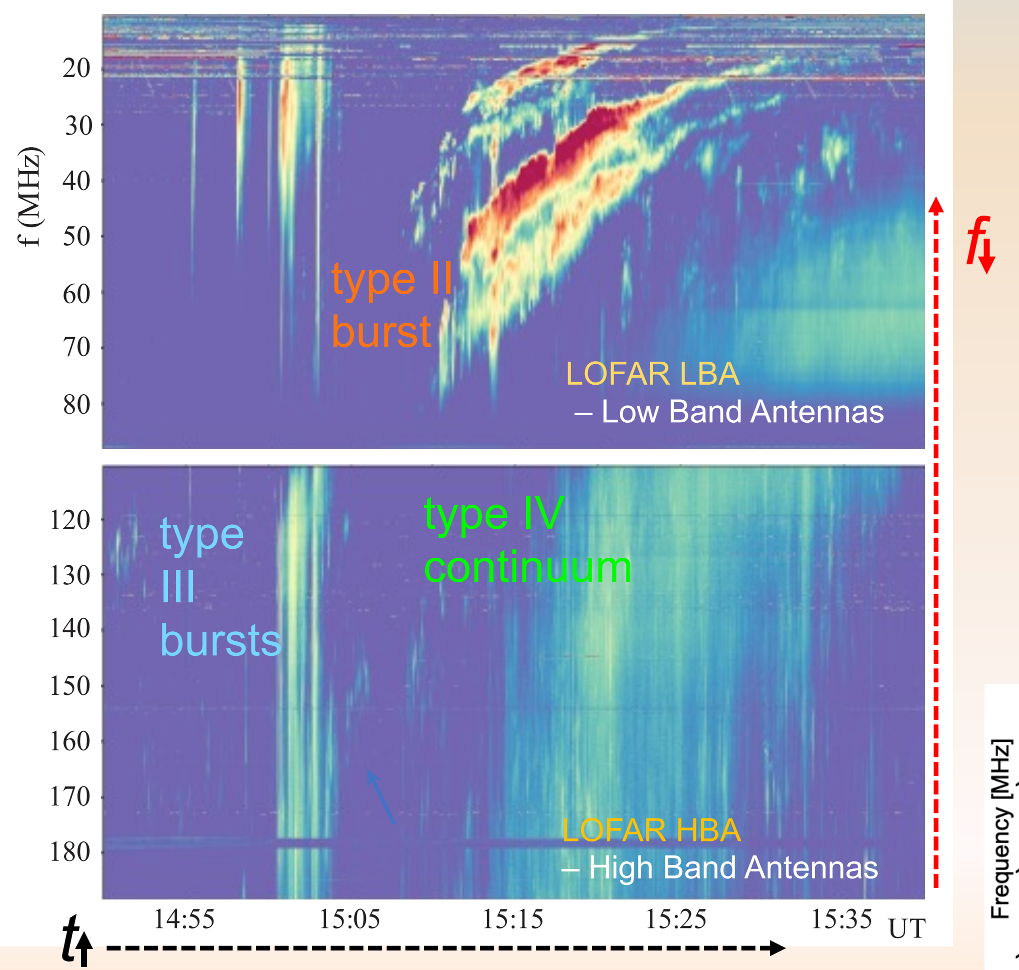
a) on the ambient plasma characteristics (density, Alfvén Mach number, Alfvén velocity, magnetic field) along the propagation path of the associated driver (e.g. electron beams, shocks).

b) about the associated eruptive processes, general magnetic field topology & solar wind characteristics.

c) on tracking of the shock waves and forecasting arrival of the shock wave & its driver to Earth.

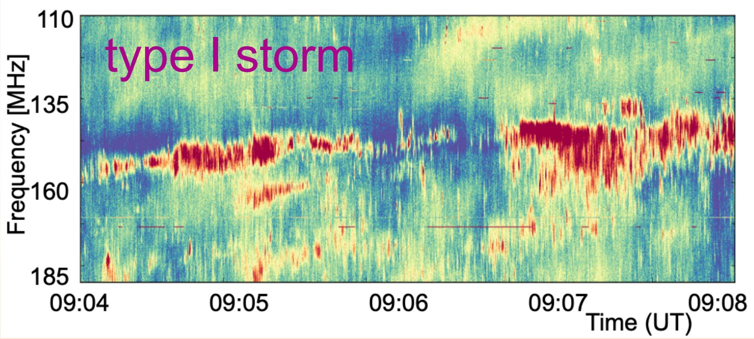
Radio observations for Space Weather: Solar radio bursts

We have five main types of radio bursts, classified in the m-wavelength range, and they are all providing different information, relevant for space weather.

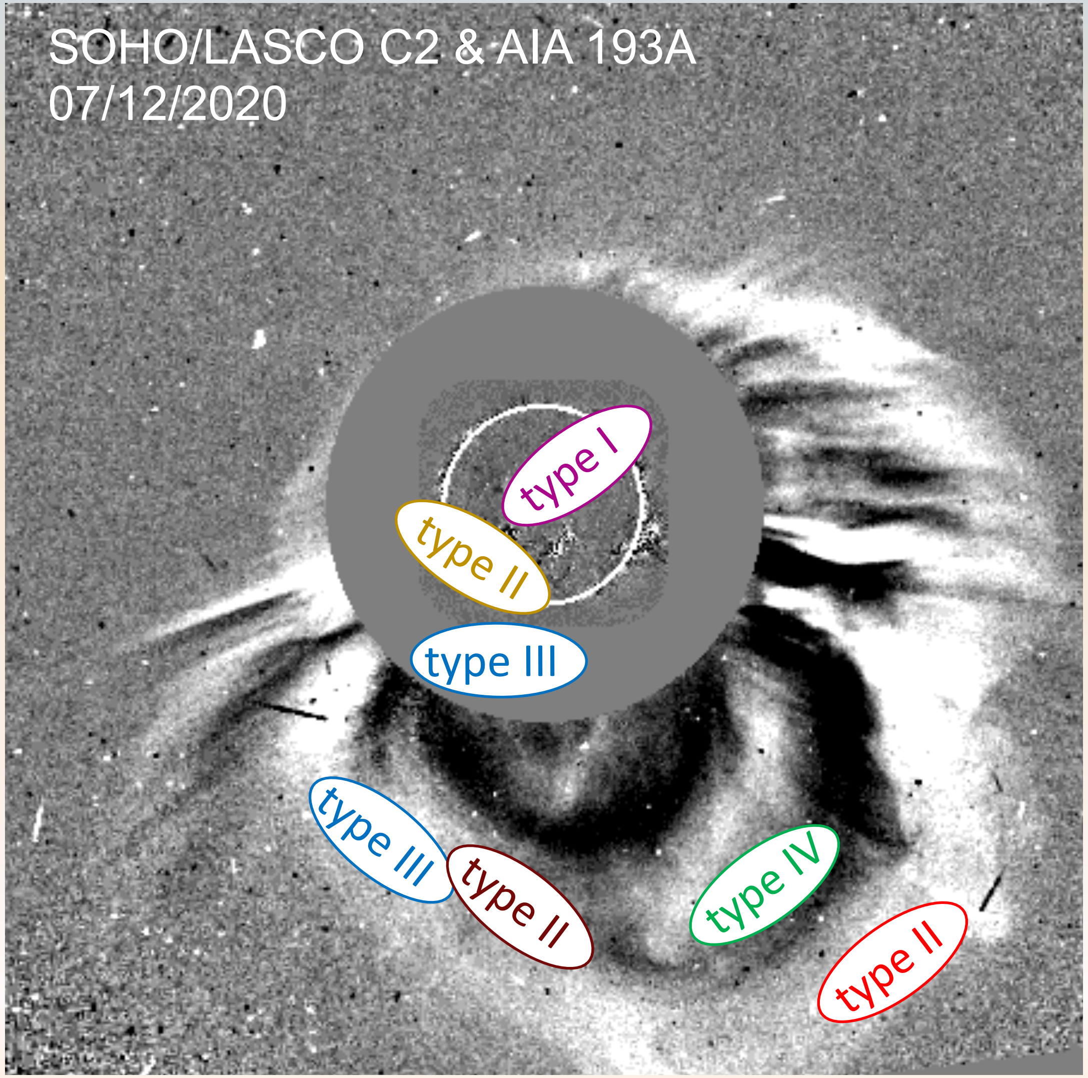


Magdalenić et al., 2020

- Type I radio bursts – associated with reconnection above the complex active regions.
- Type II radio bursts – signatures of the electron beams accelerated at the shock wave front.
- Type III radio bursts – signatures of the fast electron beams, $v \approx c/3$, propagating along open or quasi-open field lines.
- Type IV continuum – considered to be due to electrons accelerated within the CME.



Solar radio observations & solar eruptions



- **Type I bursts**

influenced by the CME
(e.g. Iwai et al., 2012)

- **Type II radio bursts**

a) flare blast wave
b) CME leading edge OR CME flanks
c) combination

(e.g Magdalenic et al., 2010; Morosan et al., 2023, Jebaraj et al., 2020, 2021; review by Vrsnak & Cliver, 2008)

- **Type III radio bursts**

due to reconnection

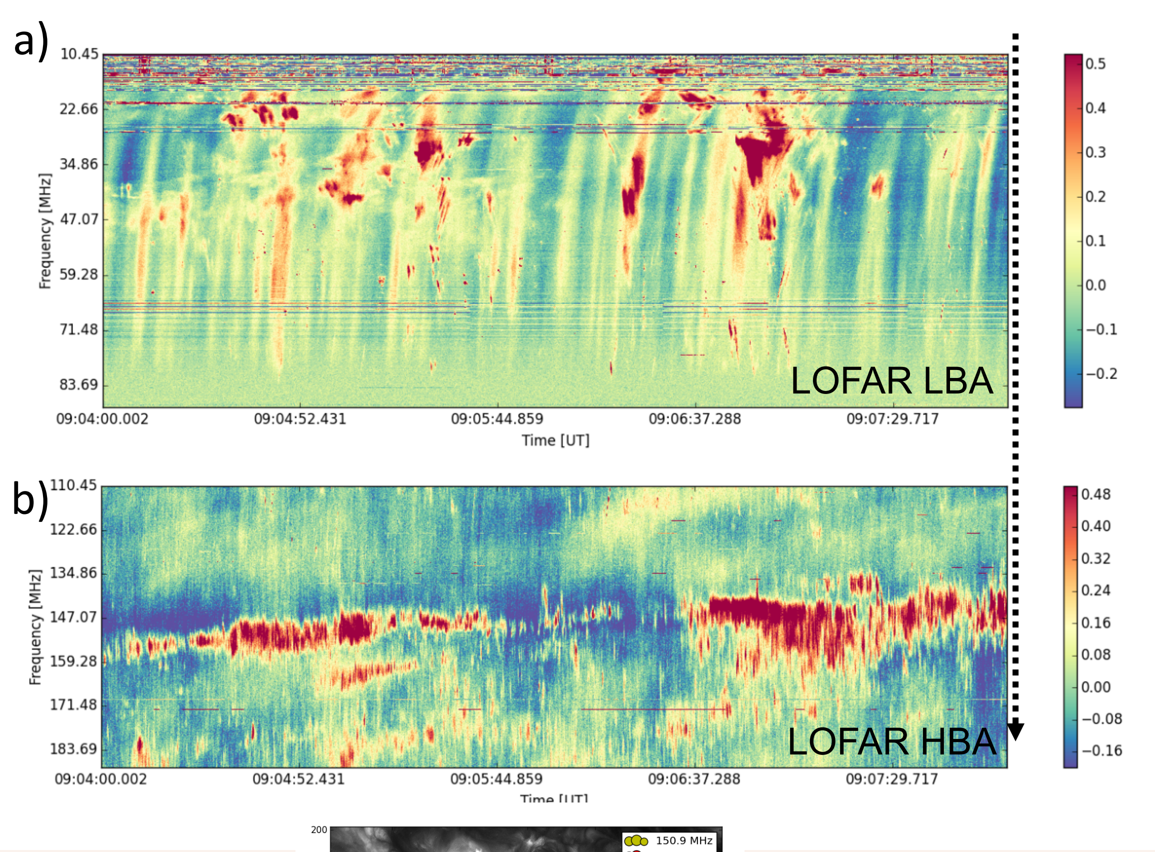
a) at close to the flare site
b) close to the CME flanks
c) higher up in corona

(e.g. review by Reid & Ratcliffe 2014; Pick et al, 2016; Magdalenic et al, 2014; Jebaraj et al, 2020, 2021: Wang et al. 2023; Gerekos et al, 2024)

- Type IV continuum

emission from within the CME
(e.g. Carley et al., 2017; Liu et al., 2018; Morosan et al. 2018, review by Carley et al. 2020)

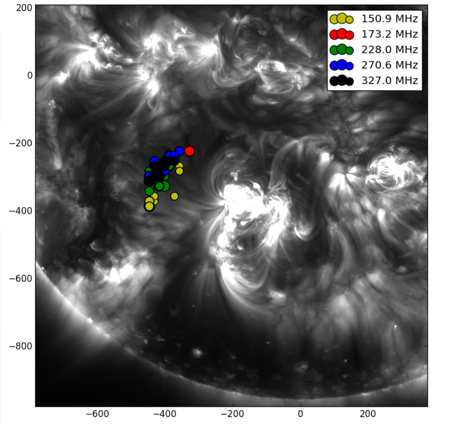
Radio observations for Space Weather: Type I radio bursts



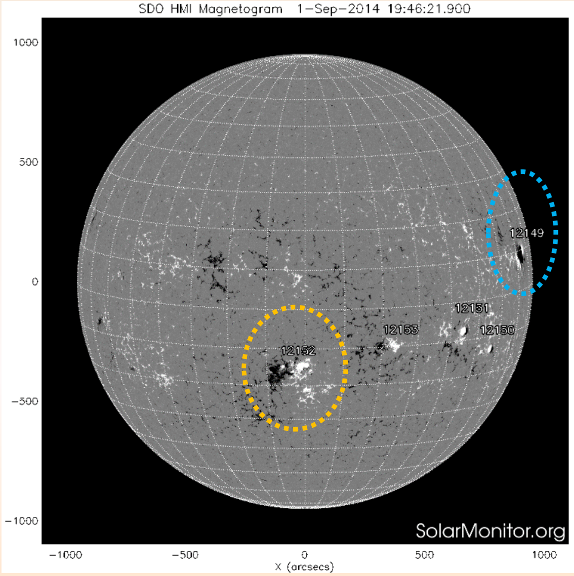
- narrowband, short duration bursts,
- often combined in chains, i. e., so-called noise-storms.

➢ Presence of a complex active region on the visible side of the solar disc,

➢ Large probability of C-class and stronger flares.



Noise storm was associated with NOAA AR 2152 (Marqué et al., in preparation).



Observed:

- Two complex active regions (NOAA ARs 2152 & 2149).
- Number of C-class flares & M-class flare.

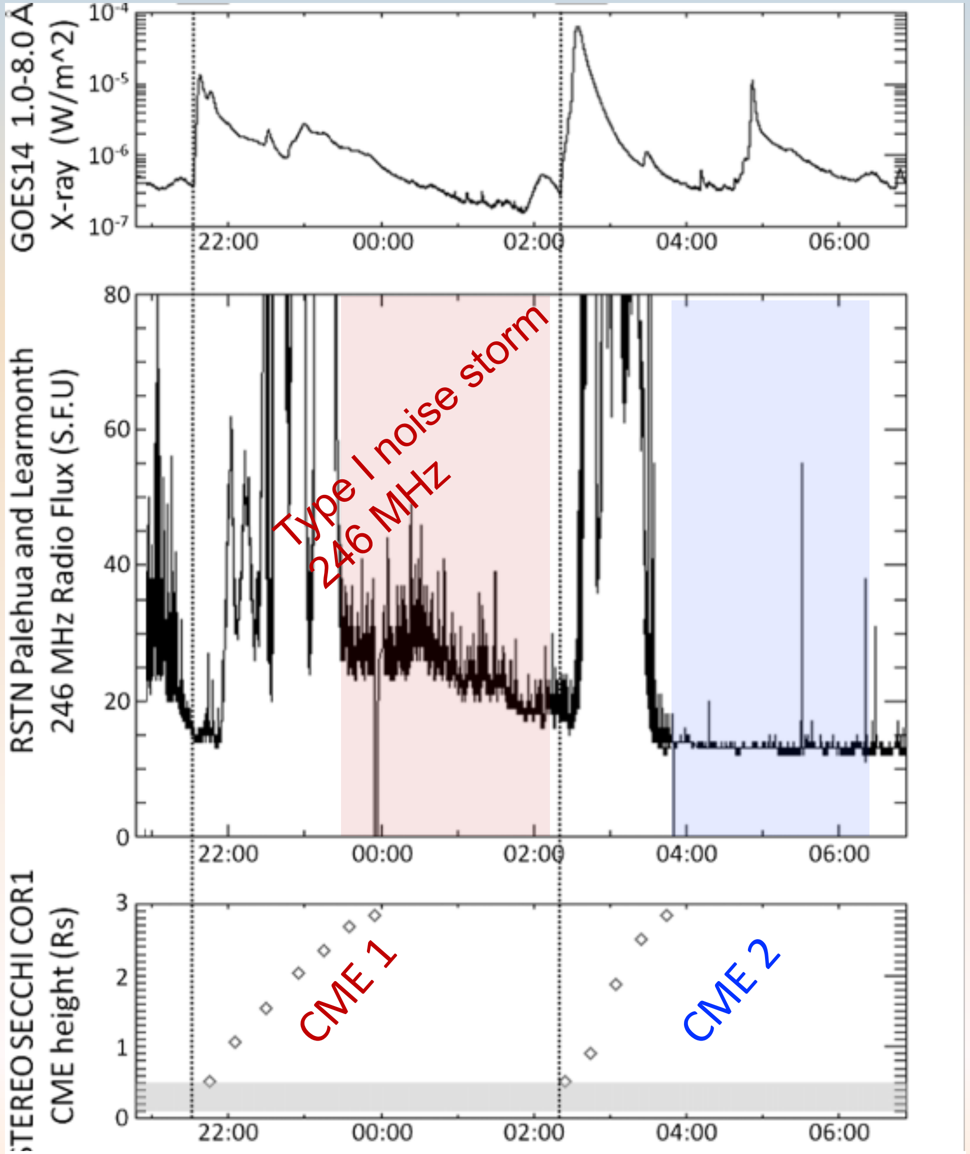
Type I radio bursts & CMEs

- Change of the type I noise storm intensity might indicate presence of a CME (Iwai et al., 2012; Kumari et al, in prep).

The type-I noise storm was activated at a side-lobe reconnection region that was formed after eruption of the 1st CME

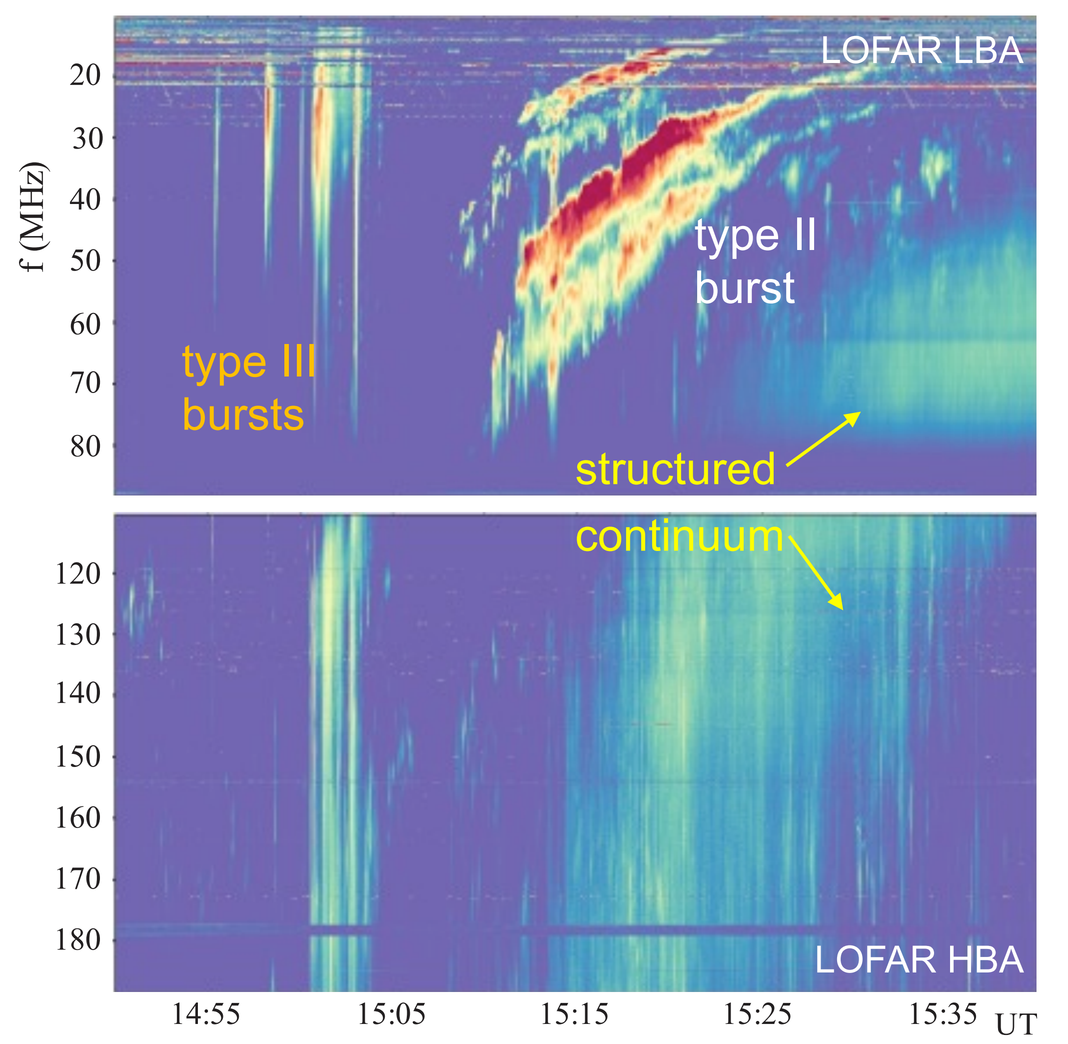
&

suppressed by the eruption of the following, 2nd CME which strongly change the magnetic field configuration.



Iwai et al., 2012

Complex radio events: type II, III, IV radio bursts

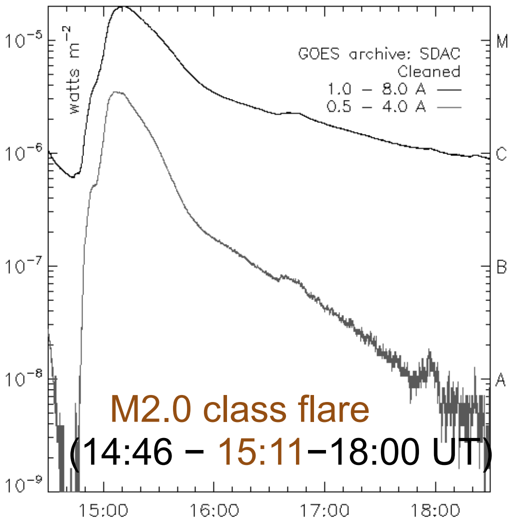


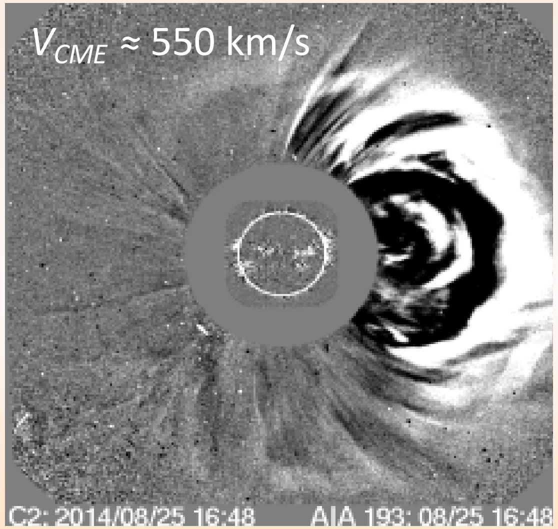
- Radio event starts with type III bursts followed by the type II burst and almost simultaneously the broadband type IV emission.

➢ Strong, long-duration flare, with the impulsive phase around the time of first type III bursts

➢ Associated coronal shock wave ($v_{type\ II}$ ~ 800 km/s)

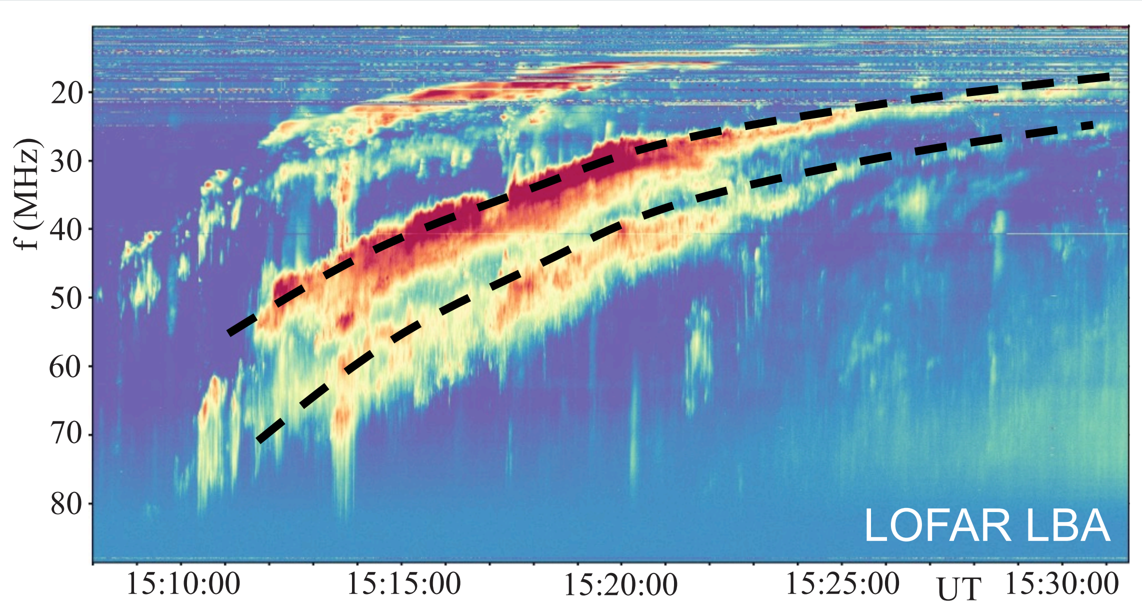
➢ Wide & strong CME (presence of type IV emission).

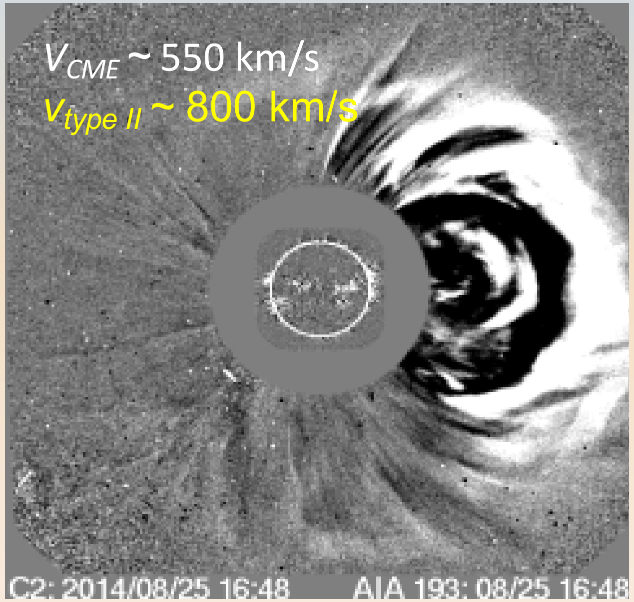




Magdalenić et al., 2020

Radio observations for Space Weather: type II radio bursts





1. Type II drift rate is a good indicator of **the shock wave speed.**

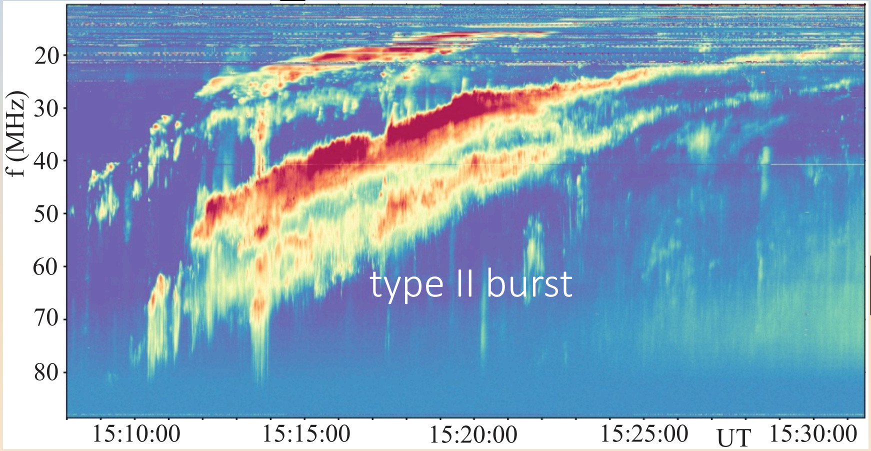
Frequency drift $D_f(t) = |df/dt|$ & coronal electron density model (e.g. Saito et al,1970; Leblanc et al,1998, Vrsnak et al, 2004) ⇨ Type II speed / shock wave speed ⇨ Forecasting shock / CME arrival to 1 AU.

2. Type II band split (assuming upstream-downstream hypothesis by Smerd et al, 1974, 1975, & Vrsnak et al., 2000, 2001, 2002 etc.) provides **estimate of the Alfven Mach number, Alfven speed, shock wave amplitude.**

→ important for validation of the solar wind and CME models such as EUHFORIA (Pomoell & Poedts, 2018) or ENLIL (Odstrcil, 1996) used in space weather.

e.g. Magdalenić et al, 2008, 2014; Zucca et al, 2018; Jebaraj et al, 2020; Morosan et al, 2023

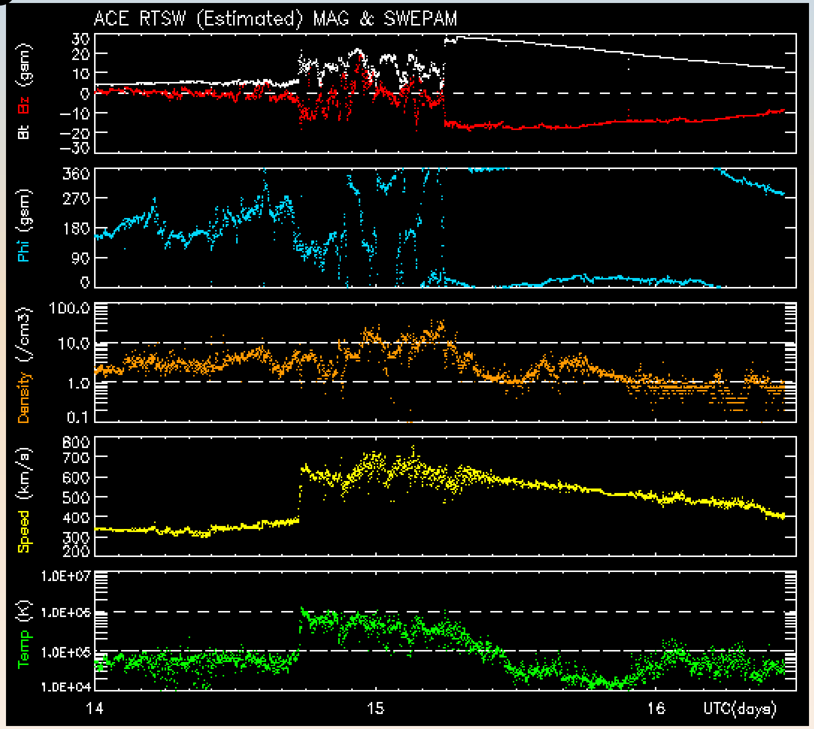
Tracking CME-driven shock waves using radio observations



v_{SHOCK}

prediction 1

Prediction of shock arrival to 1 AU

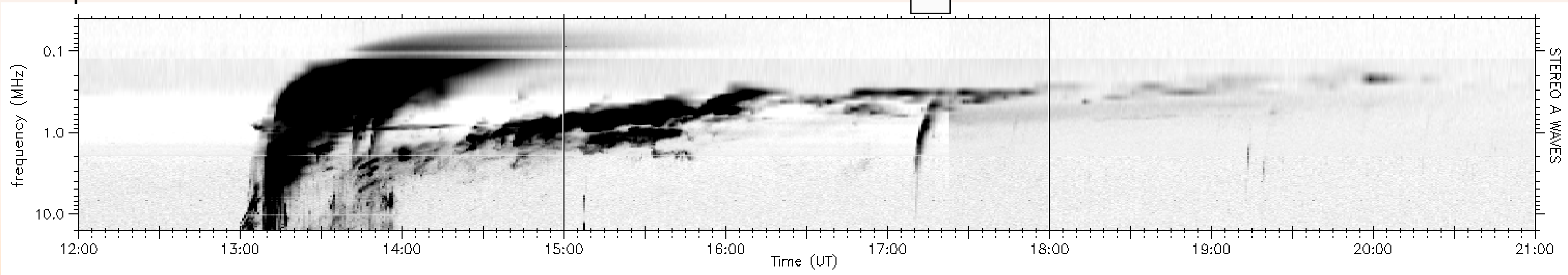


- Low corona: metric to decametric type II bursts.
- Ground based observations.

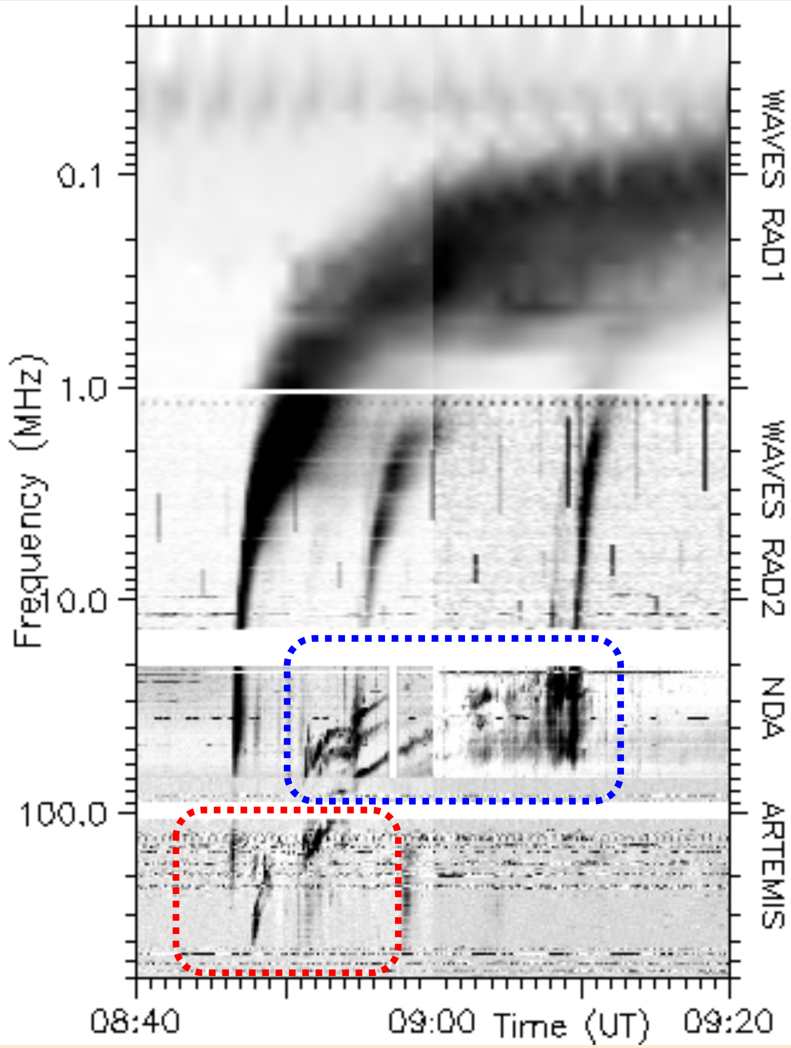
- High corona to interplanetary space: hectometric to kilometric type II bursts.
- Space based observations.

v_{SHOCK}

prediction 2

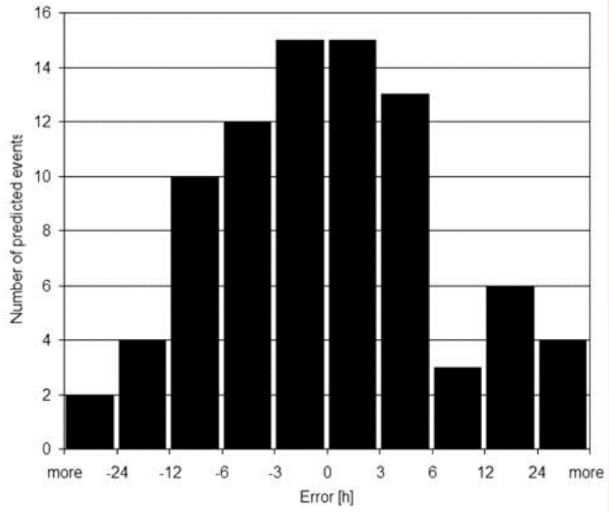


Accuracy of estimates of the CME-driven shock wave arrival time at Earth using type II bursts



- Numerous studies of shock & CME arrival using metric and/or decametric to kilometric type II radio bursts

  (e.g. Dryer and Smart, 1984; Smith and Dryer, 1995; Fry et al., 2001; Reiner et al., 1998; Dulk et al., 1999; Leblanc et al., 2001; Cremades et al., 2007, 2015)

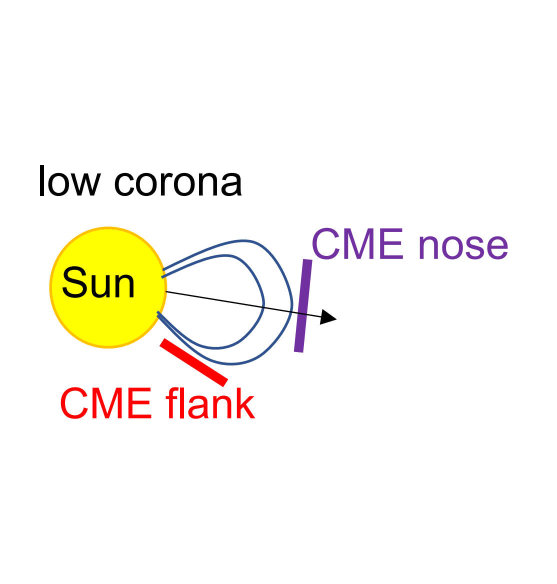


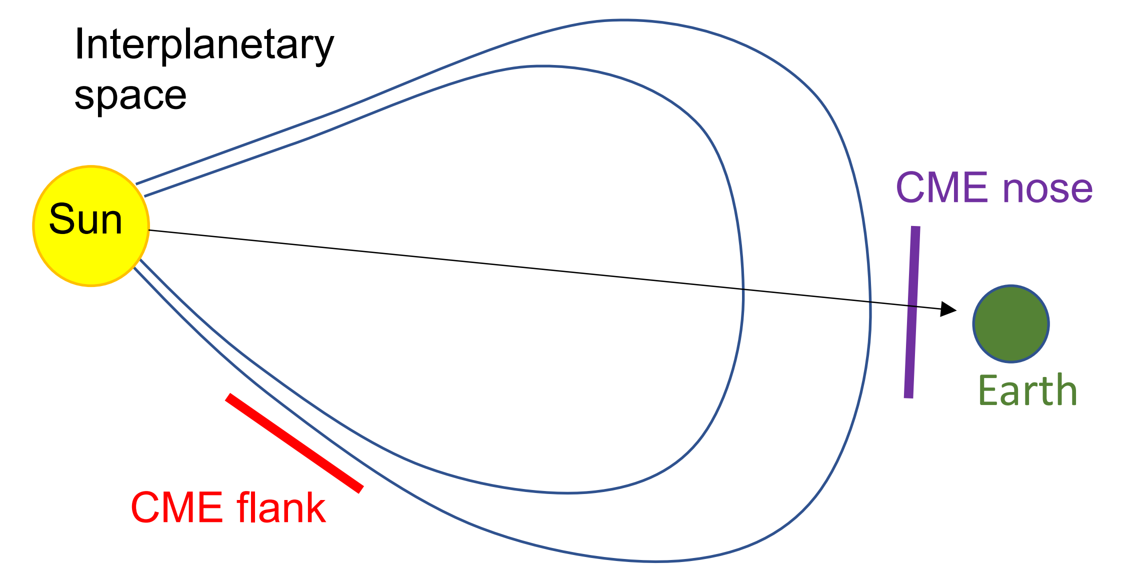
From Cremades et al., 2007

- Average error of the prediction of the shock arrival to Earth is about 11h.
- Results are somewhat better when metric type II bursts are employed.

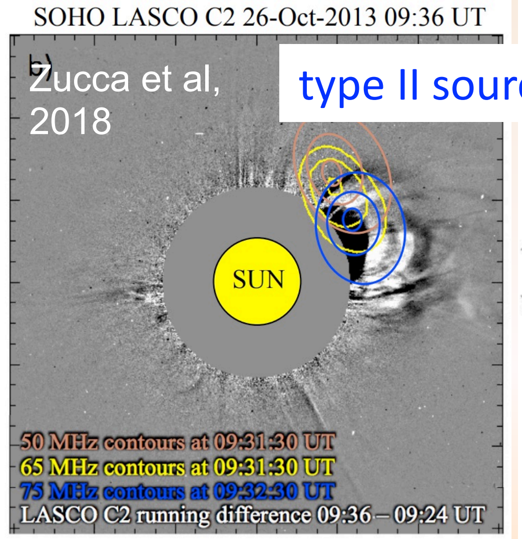
Why don’t we have better estimation of the shock arrival time?

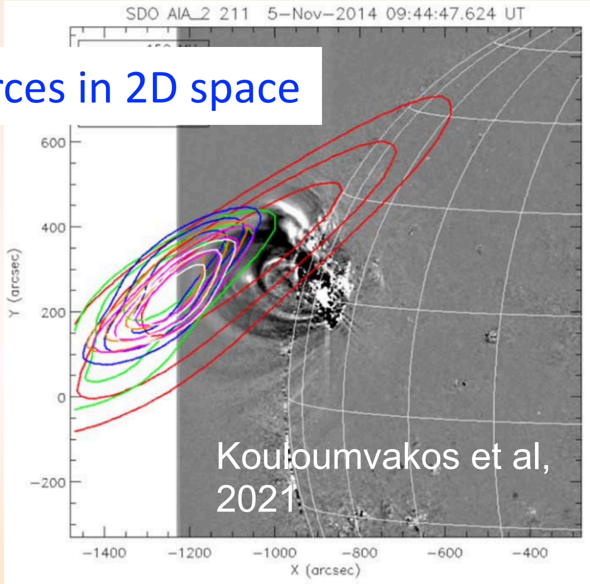
- Are type II source regions preferably at the CME flanks or the CME nose?



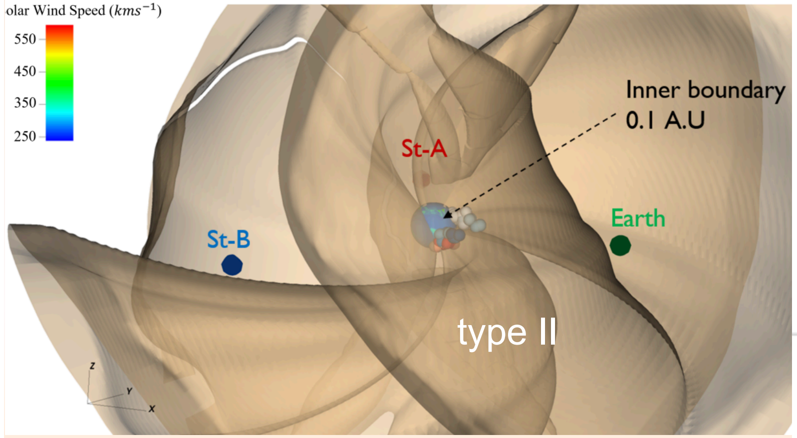


type II sources in 2D space

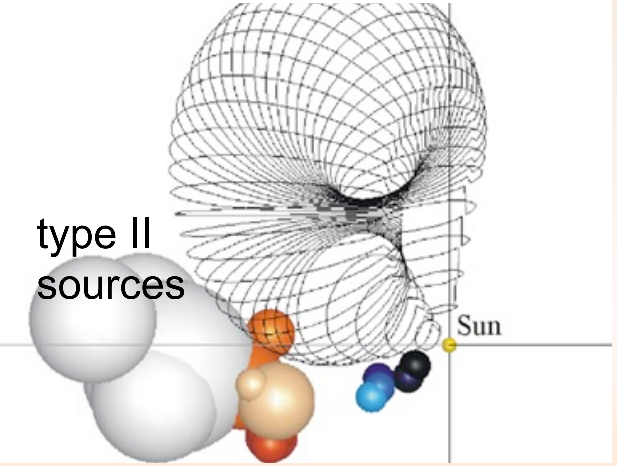




type II sources in 3D space obtained using radio triangulation



Jebaraj et al, 2021

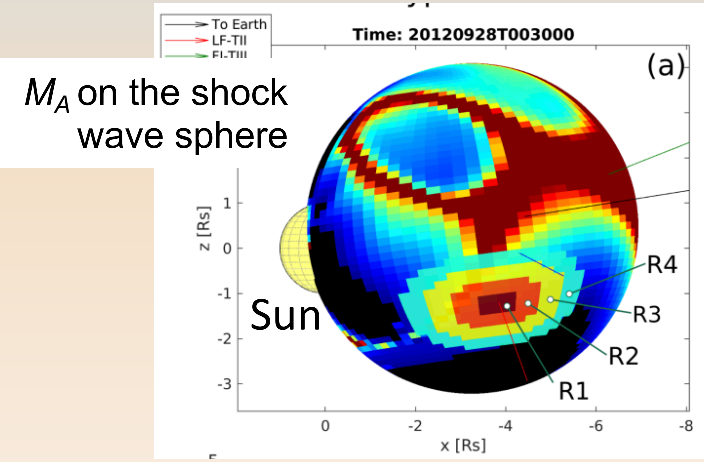


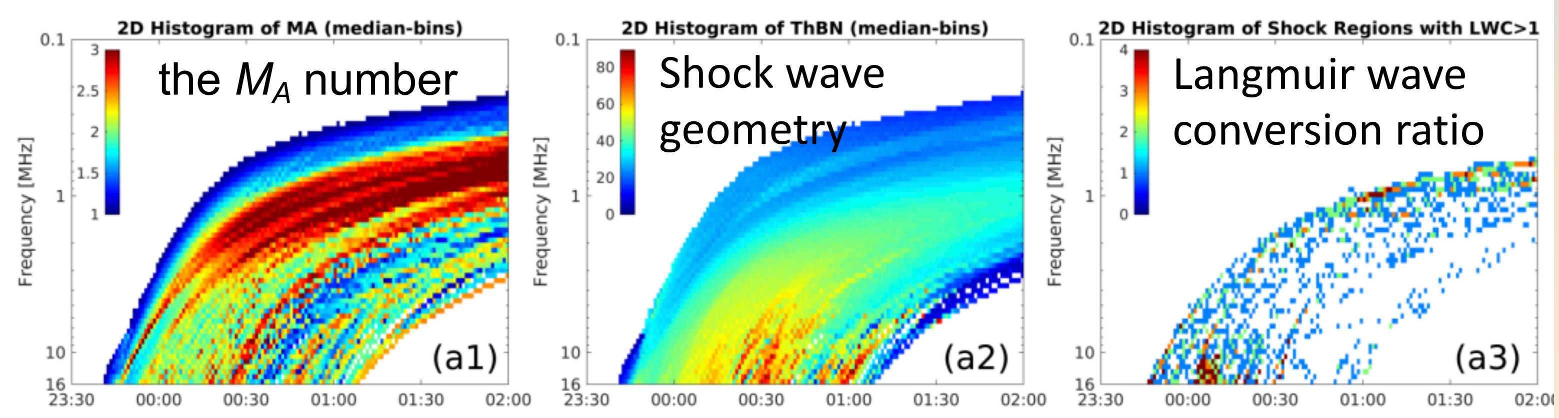
Magdalenić et al, 2014

How to proceed further?

- Combining shock wave/CME modeling & the type II source positions in the 3D space.
- Modelling of the radio emission processes.

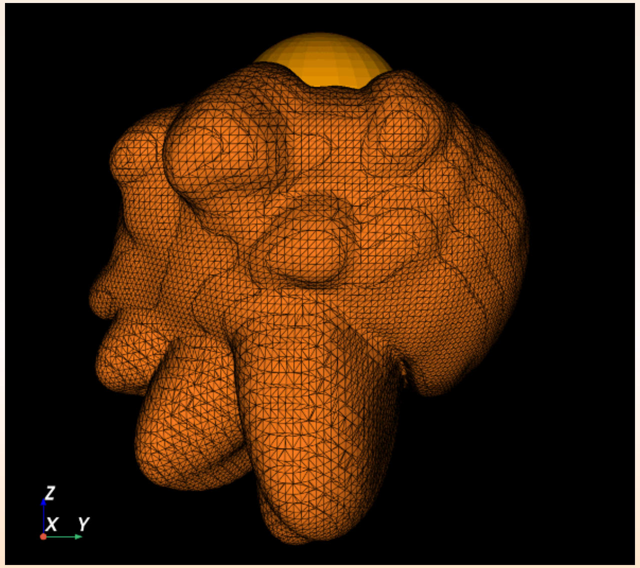
Jebaraj et al, 2021 & Kouloumvakos et al., 2021





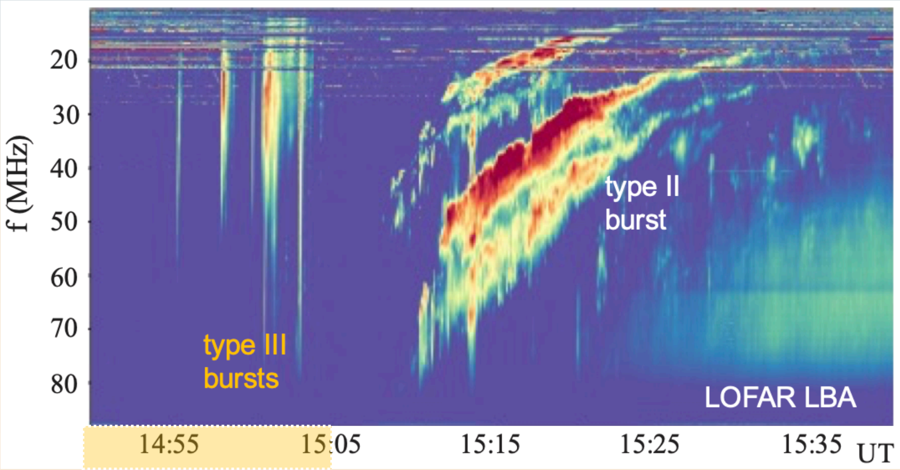
a) Importance of the CME's main propagation direction of and its angle with the Sun-Earth line (Valentino & Magdalenic, 2024)

b) Importance of the CME & shock distortion due to interaction with the solar wind
(Valentino, Niemela & Magdalenic, in preparation)



Distortion of the modelled CME/shock front.

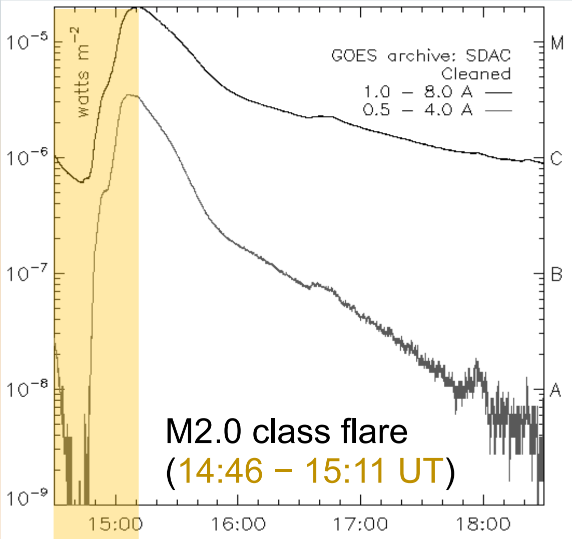
Radio observations for Space Weather: type III radio bursts



- The fast electron beams generate type III bursts observed during the flare-impulsive phase.

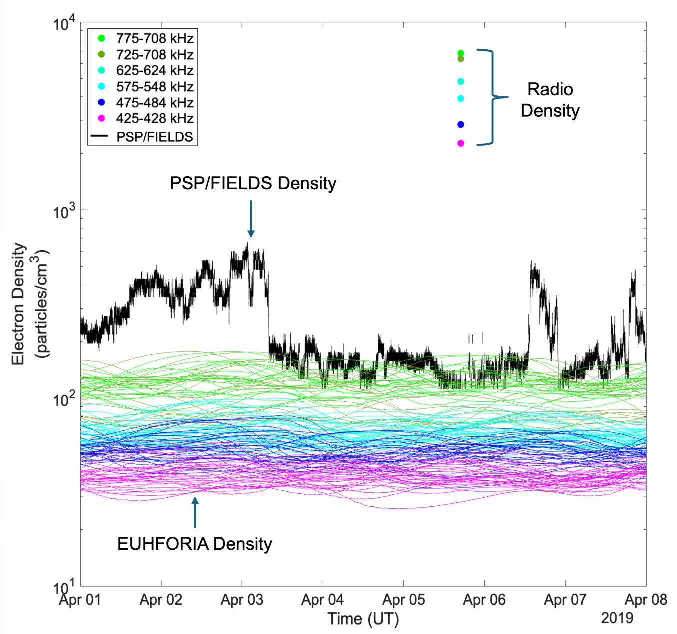
➢ existence of open and/or quasi open filed lines and increased possibility of the particle event if the associated active region is close to the West solar limb,

➢ mapping the impulsive phase of the flare.



- Using the type III radio bursts & direction finding method

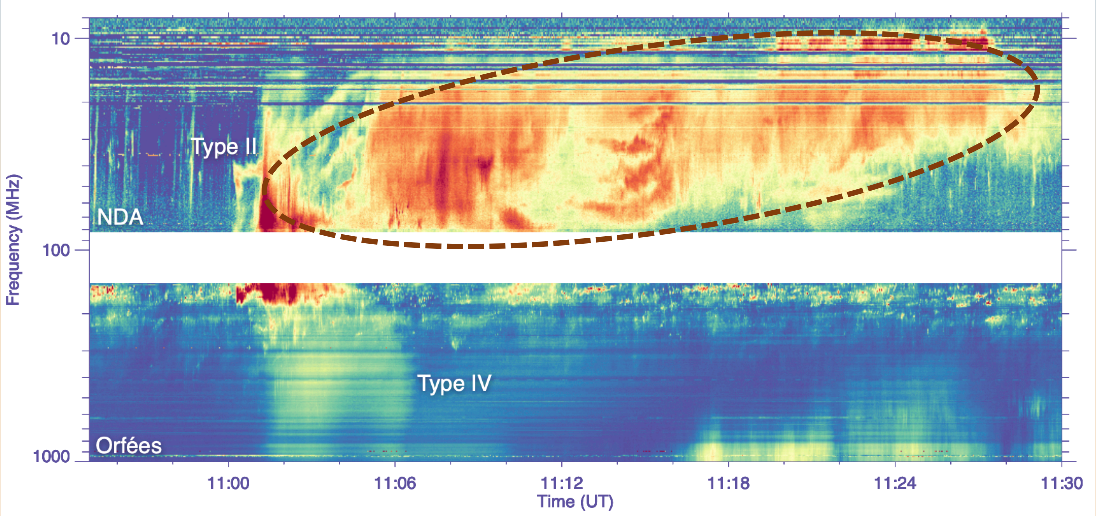
map the coronal electron density along the burst's propagation path & validate the accuracy of the coronal electron density obtained with the MHD models → EUHFORIA (Deshpande et al, in review).

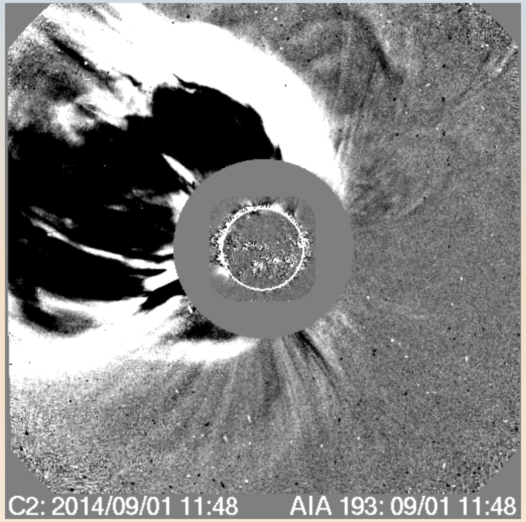


The 'radio densities' significantly larger than the 'EUHFORIA density'.

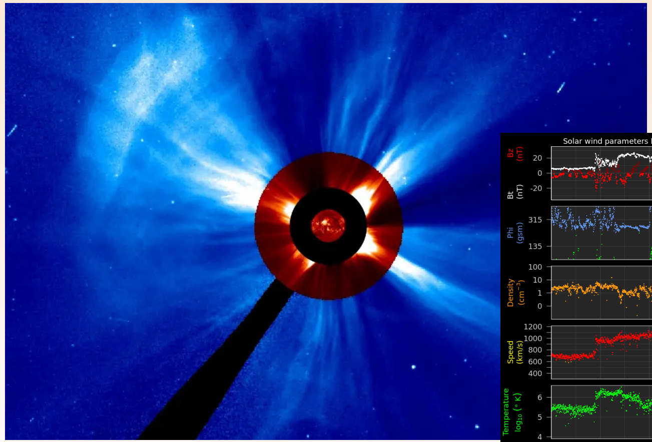
→ Is this due to the characteristics of the coronal regions through which the type III bursts propagate?

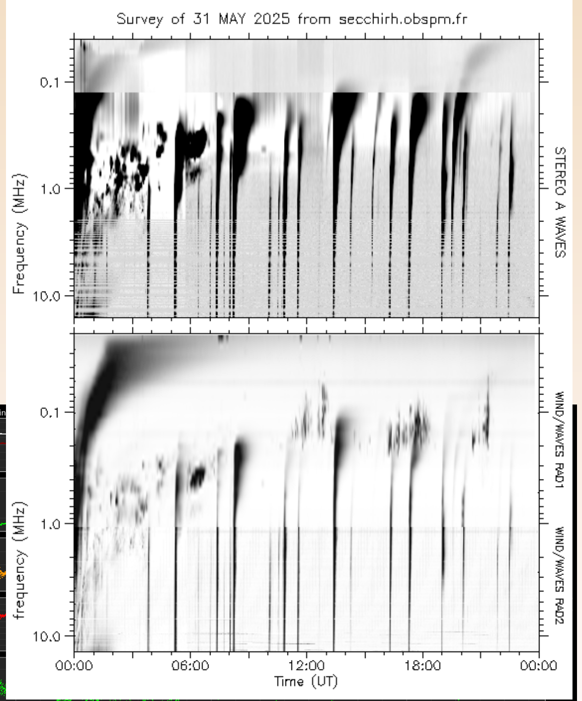
Radio observations for Space Weather: type IV radio continuum

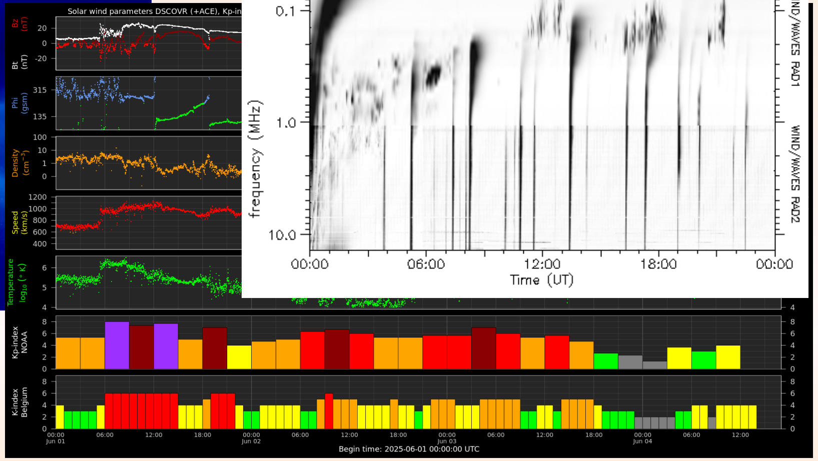


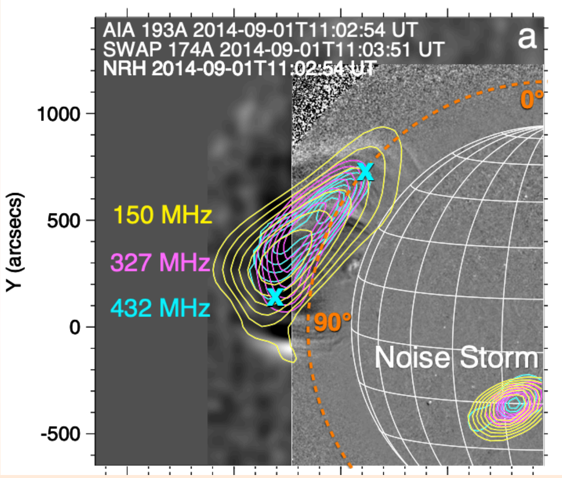


Intense & long-lasting type IV continuum
– always related to wide and fast CMEs.







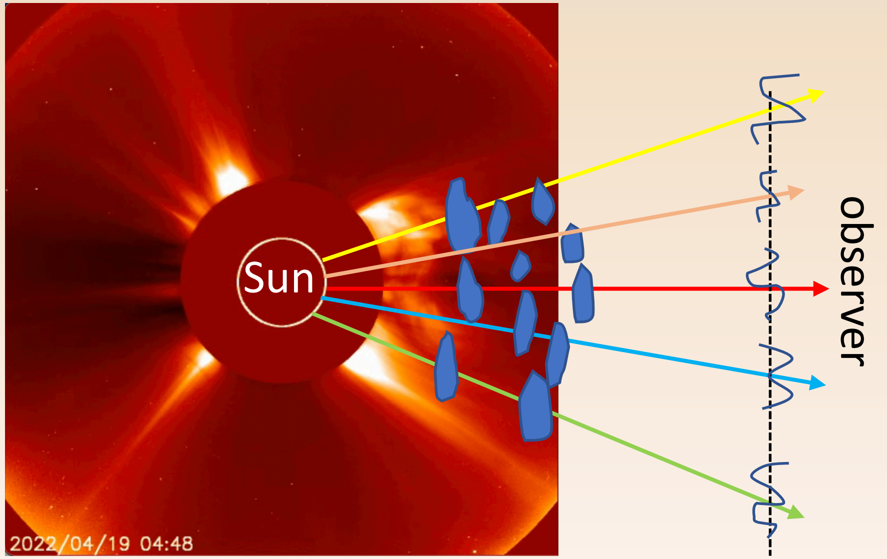


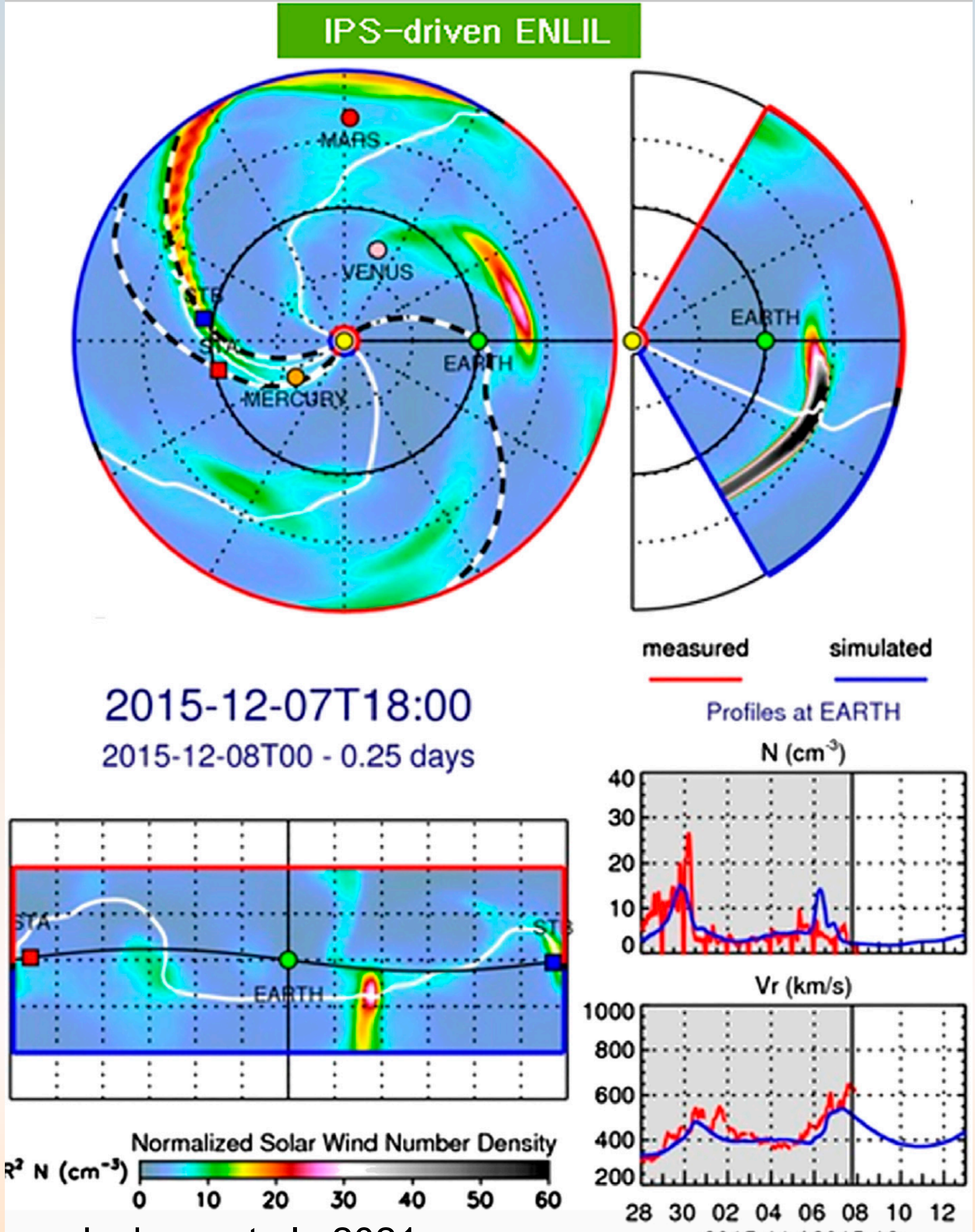
The energetic electrons may produce gyrosynchrotron emission from within the CME itself, allowing for a diagnostic of the CME magnetic field strength (e.g. Carley et al, 2017, 2020).

→ Importance of the radio-monitoring in the space weather!

Interplanetary scintillations (IPS) providing input to the models

- Interplanetary scintillations –IPS are the short time scale fluctuations of the radio waves from a distant radio source, traveling through the small scale density variations (~150 km) of the solar wind.



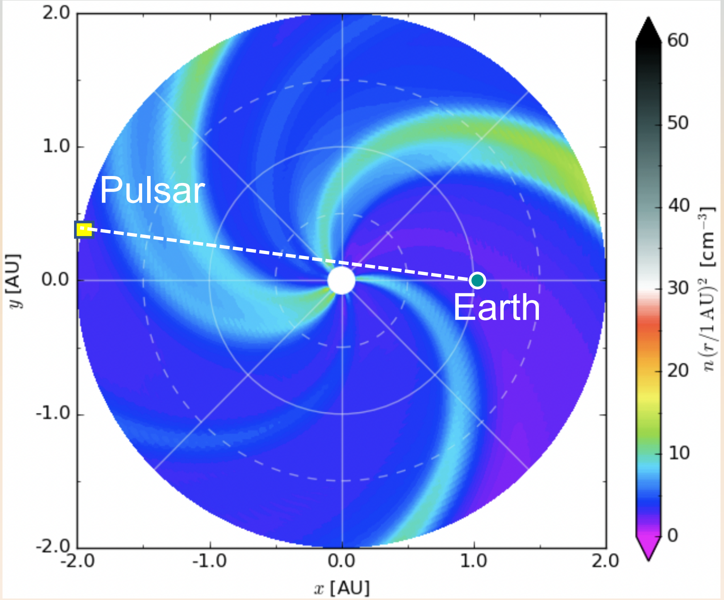


Jackson et al., 2021

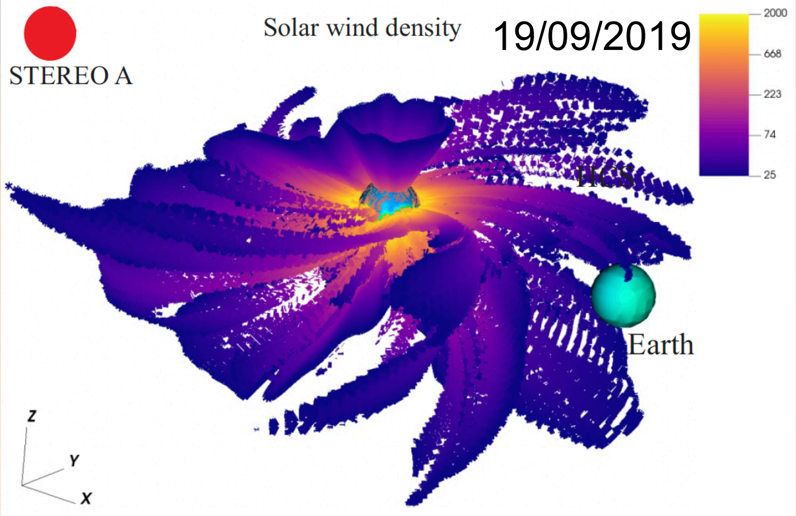
- The solar wind velocity/density maps obtained from IPS can be used for forecasting of the solar-wind and CMEs at Earth.
- Inputted to MHD models like ENLIL or EUHFORIA it can provide forecast of *n*, *v*, *T*, *B* at Earth.

e.g. Jackson et al., 2015, Jackson et al., 2020, Gonzi et al, 2020

LOFAR observations of Pulsars & solar wind modeled by EUHFORIA

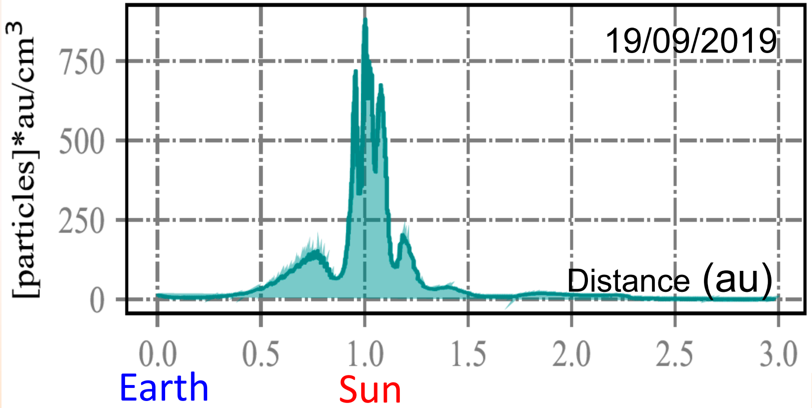


the heliographic equatorial plane

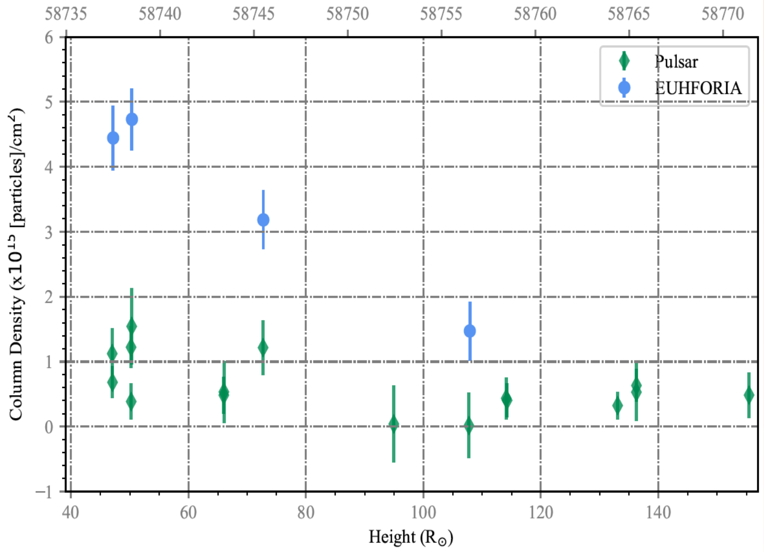


solar wind density modelled by EUHFORIA

Electron density along the LOS segment within the EUHFORIA's volume



EUHFORIA's column density & pulsar DM estimates of the SW contribution.



Shaifullah G.M., Magdalenic J. et al, 2024

1. Operational space weather & radio observations

Main requirements for the radio observations in space weather:

- Real-time or near real-time observations.
- Monitoring the Sun.
- Easily processed.

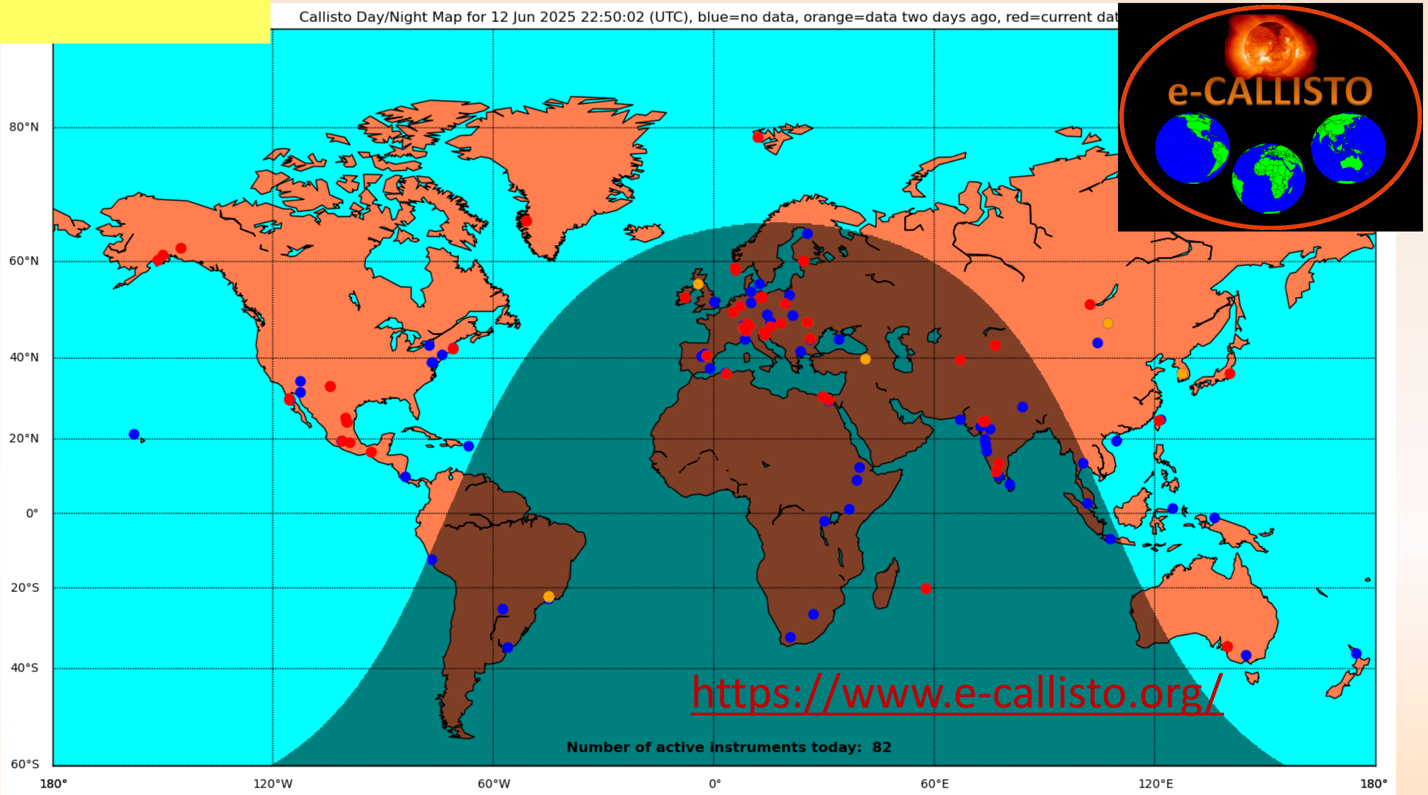
e-Callisto

International Network of Solar Radio Spectrometers, a Space Weather Instrument Array

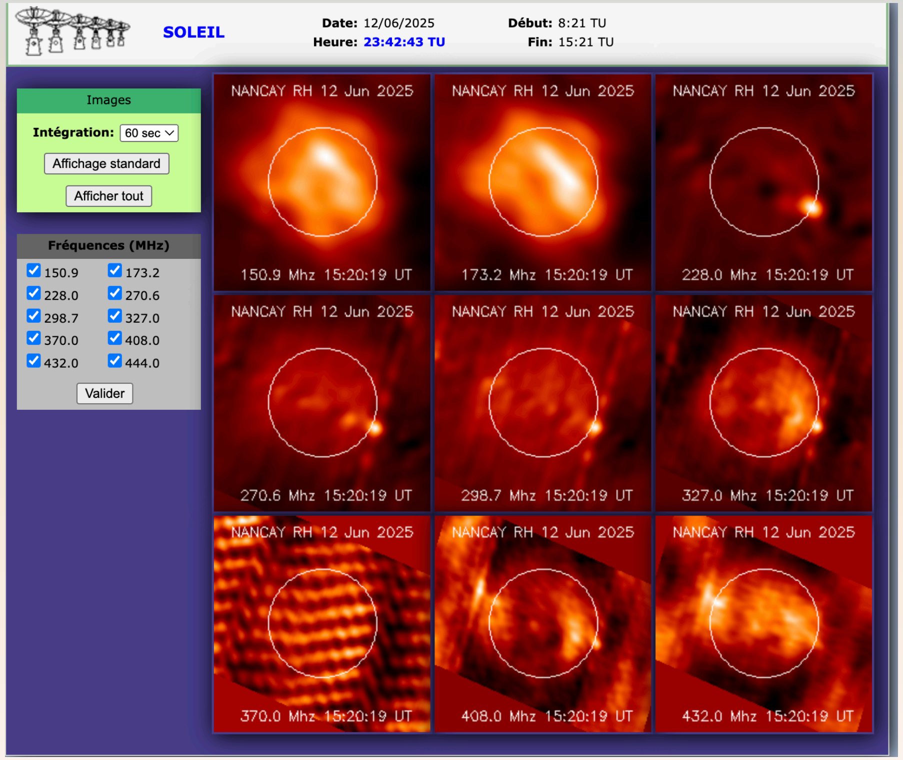
Goal: Understanding Transient Phenomenon in the Solar Corona

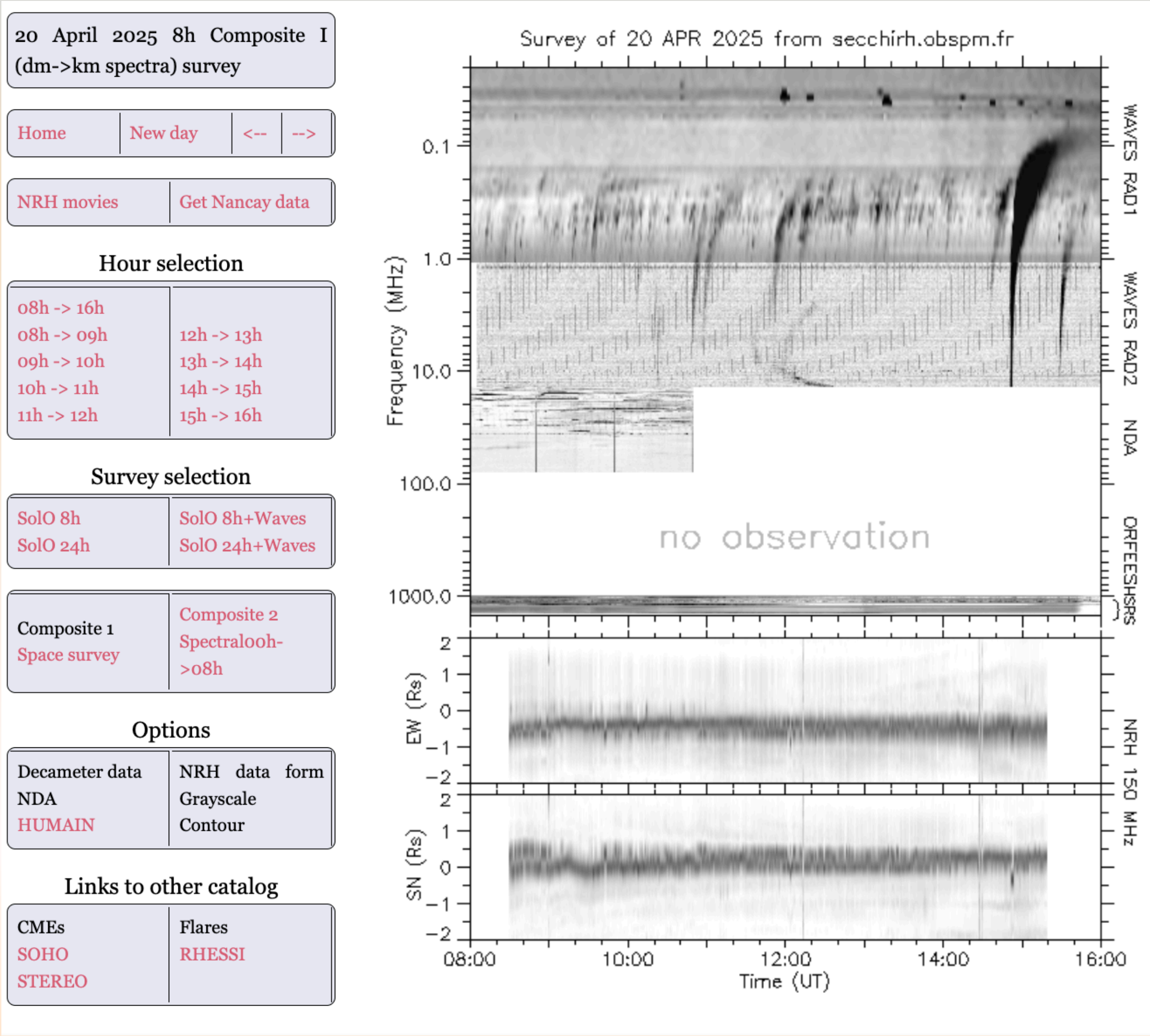
Callisto & e-Callisto network:

- Designed 2006 by Christian Monstein.
- Number of stations world-wide → approximately 24h coverage!
- Between 45 and 870 MHz.
- Easy collectable and easy assessable radio observations.



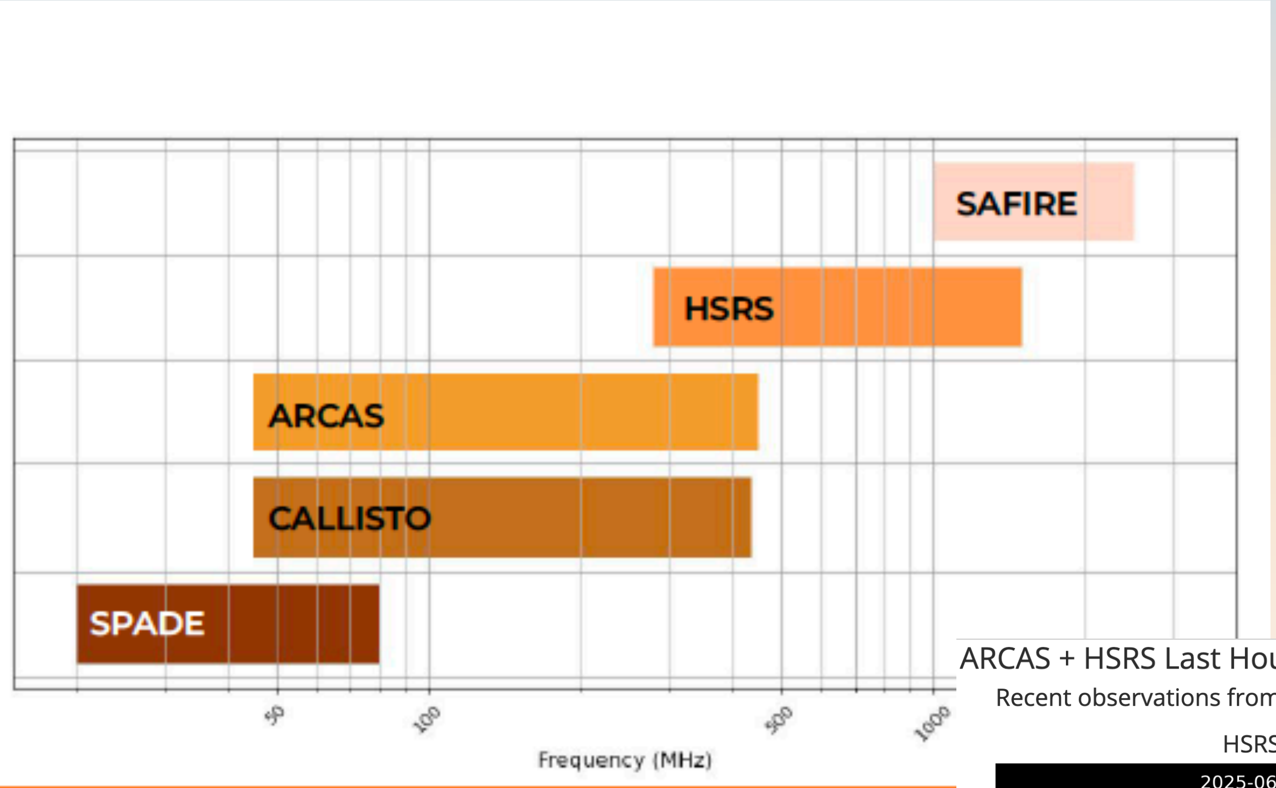
“Nançay monitoring radio observations” + space-based observations

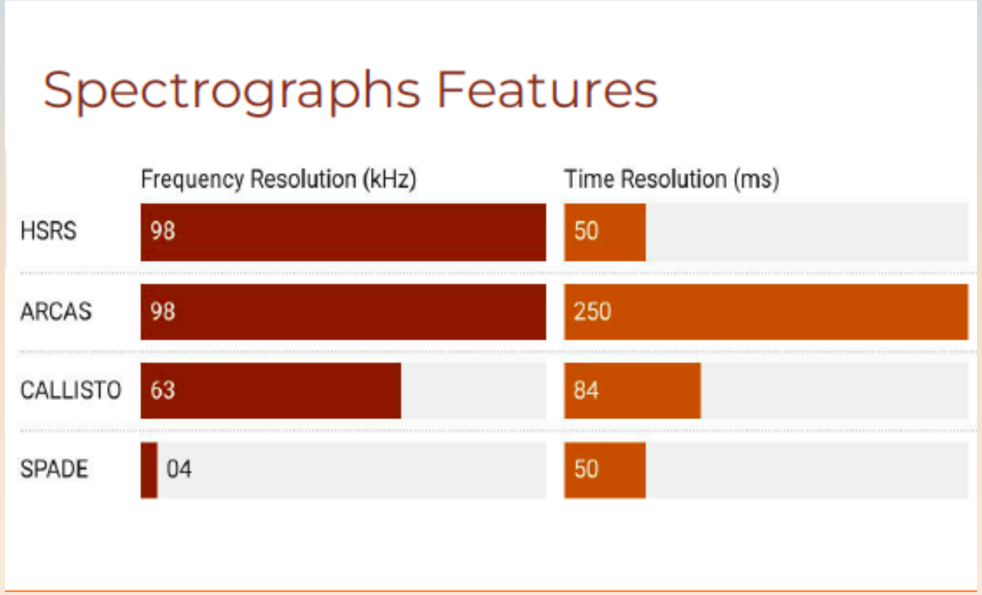




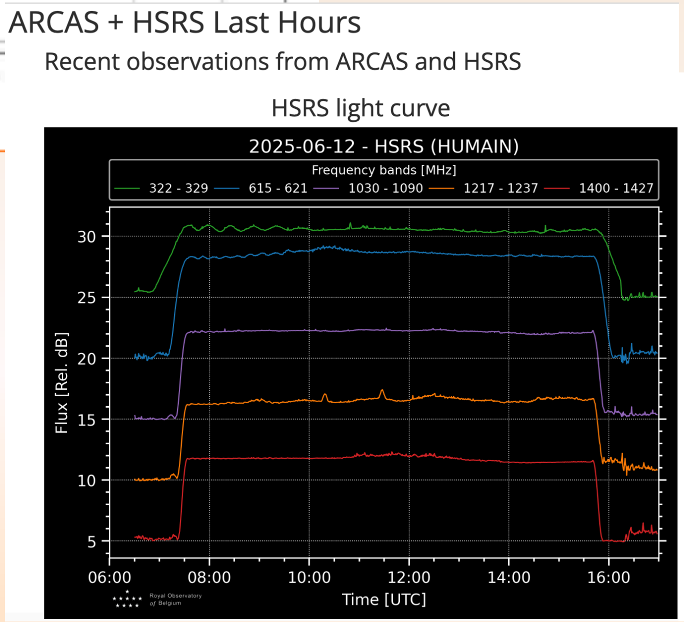
https://secchirh.obspm.fr/spip.php?page=survey&hour=day&survey_type=1&dayofyear=20250420

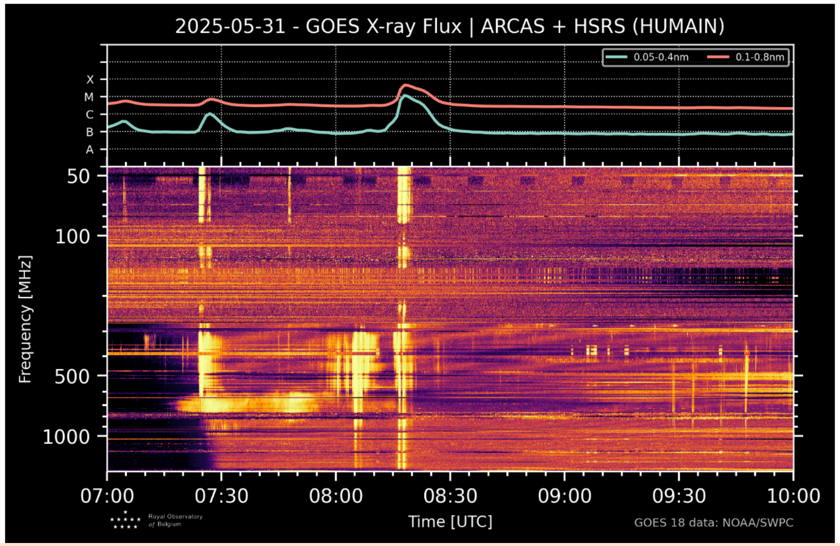
Space weather dedicated radio observations at HUMAIN - Belgium





https://sidc.be/humain/home





Automatic detection of radio bursts – Royal Observatory of Belgium

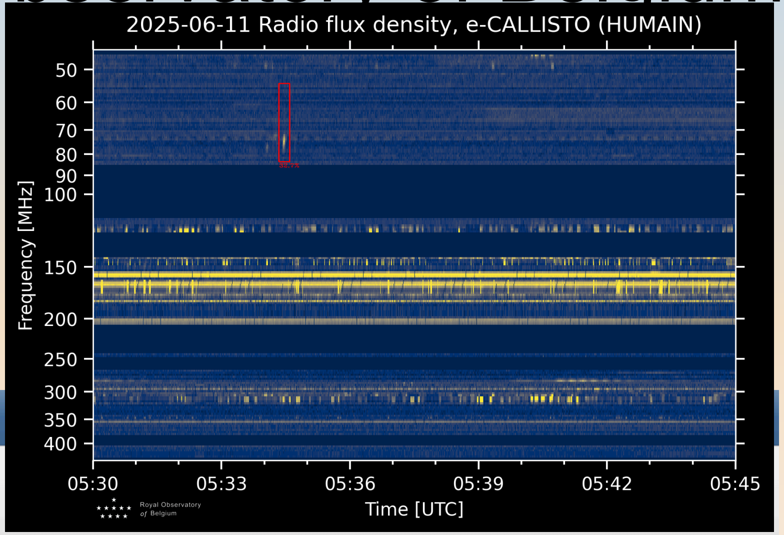
CALLISTO Latest Burst

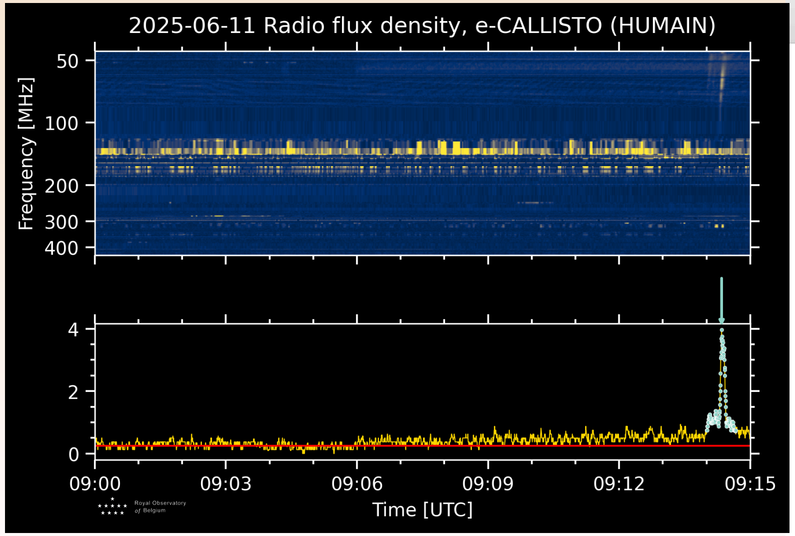
List of bursts - 2025-06-11

This is an experimental product based on CALLISTO observations. It detects bursts, but is not yet able to classify them. Bursts are given a quality index, which gives an idea of their nature and/or intensity: 0 means weak burst or non solar emission, 1 to 3 means solar burst of increasing intensities (1:small, 2:medium, 3: strong).

Move over the png link for quickview

Date	Start time	End time	Quality		
2025-06-11	05:09:38	05:09:55	1	PNG file	FITS file
2025-06-11	05:28:58	05:29:05	1	PNG file	FITS file
2025-06-11	09:14:00	09:14:40	1	PNG file	FITS file





Data Analysis Center

- Home
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- CALLISTO
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  - CALLISTO Archives
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  - CALLISTO Burst Archives
  - CALLISTO Latest AI Burst
  - CALLISTO AI Burst Archives

CALLISTO Latest AI-Detected Burst

Latest AI-detected radio bursts on: 2025-06-11

This is an experimental AI deep learning prototype using object detection to detect solar radio bursts in Humain CALLISTO observations. In the future, burst type classification is also planned.

The latest detected bursts are listed in descending order. Hover over the spectrogram hyperlink for quickview.

Start Time [UTC]	End Time [UTC]	Frequency Range [MHz]	Confidence [%]	Spectrogram	Raw File
09:14:16.404039	09:14:27.288112	48 - 85	80.8	View	Download
07:33:07.734246	07:33:25.874367	46 - 61	40.6	View	Download
05:34:20.099730	05:34:35.216497	54 - 84	32.7	View	Download
05:10:18.690454	05:10:29.574527	47 - 83	27.9	View	Download
05:09:42.410212	05:09:55.712968	46 - 83	36.3	View	Download

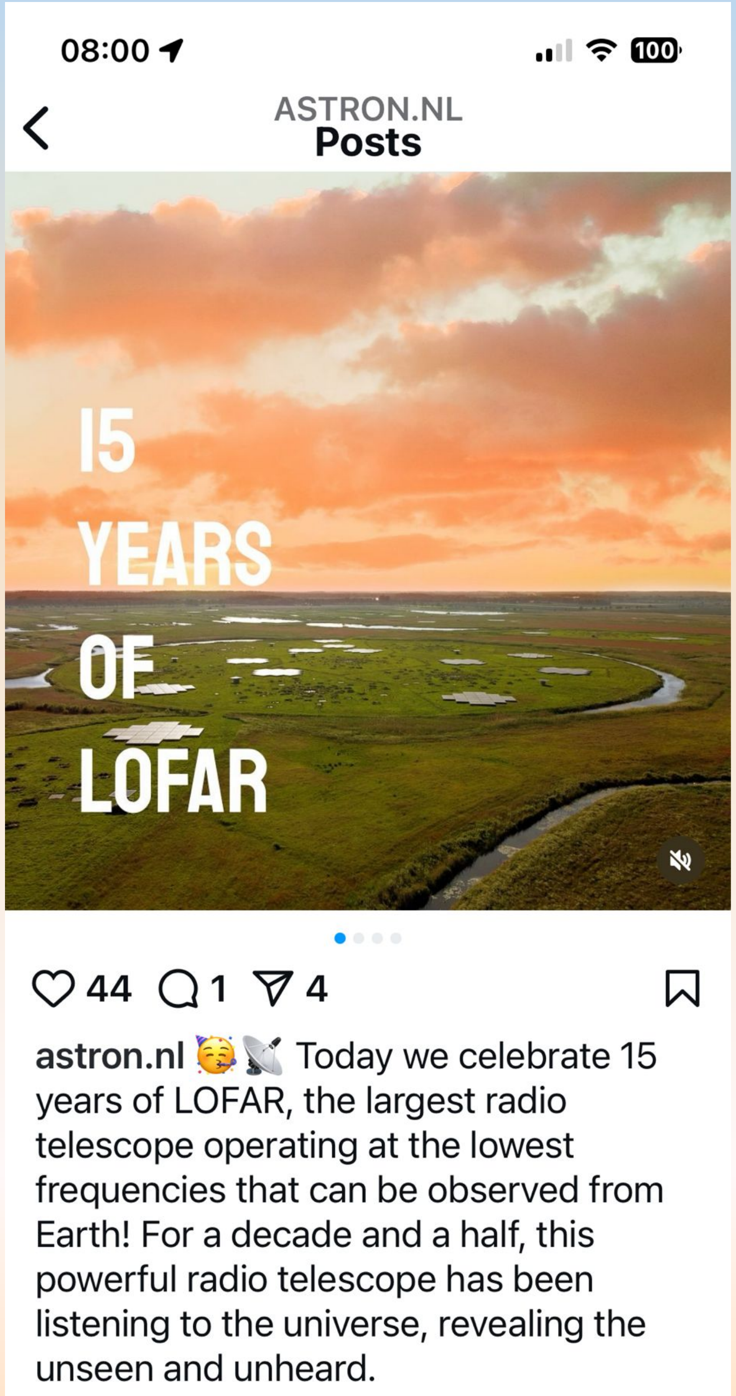
2. Space weather science & radio observations

- In order to improve our understanding of the space weather phenomena
  → Put radio observations in the context - combine radio observations with observation at other wavelengths & modelling.

- Non-solar dedicated instruments can significantly improve our understanding of the space weather phenomena (e.g. LOFAR & MWA)!

  → Write observing project proposals. Coordinate!

  → Combine space-based radio observation (STEREO, Wind, PSP, Solar Orbiter..) with the ground based one!



Conclusion:

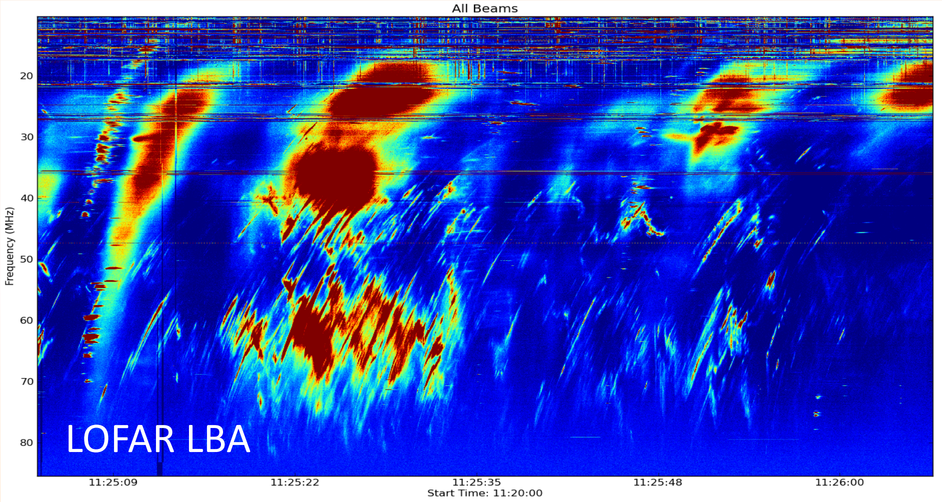
- Solar radio observations map the plasma processes all the way from the Sun to Earth and beyond! Therefore, they are very important:

  ➡ in the studies of variety of plasma processes on the Sun,
  for the CME and space weather science and
  for the operational space weather forecasting.

Advice:

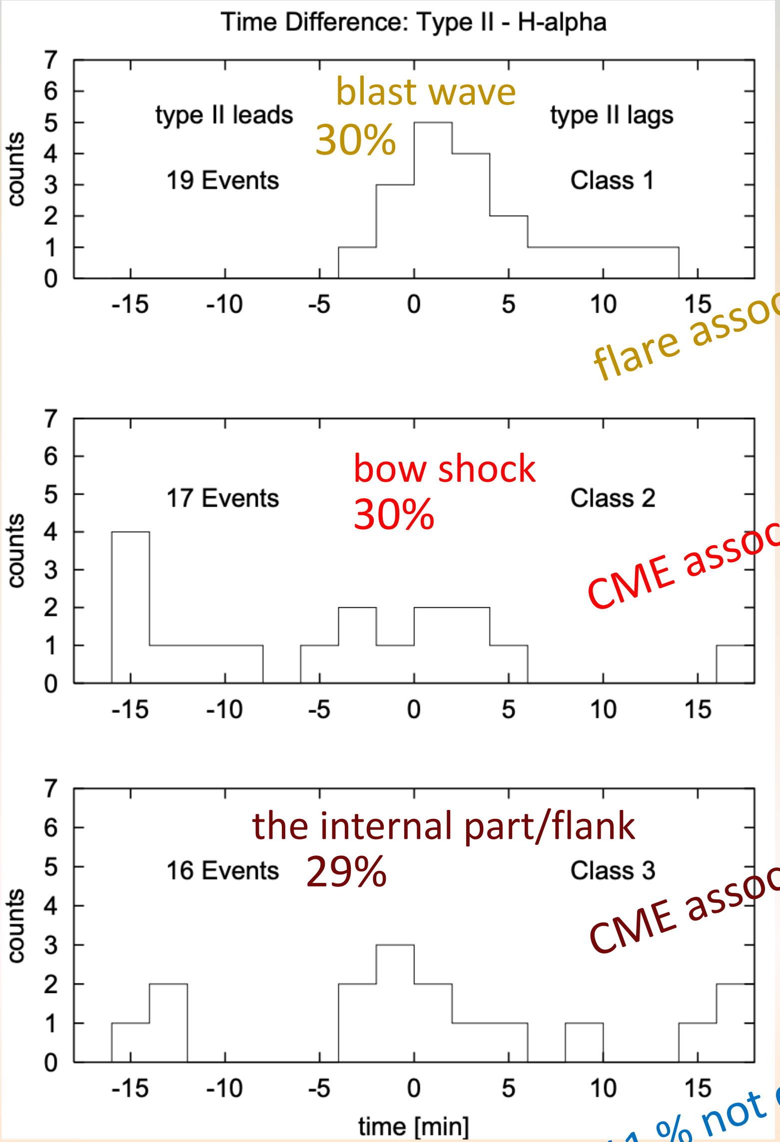
1. Always use radio observations in combination with observations at different wavelengths.
2. Consider different scenarios & not unified models!
3. Employ observations & modeling.

Thank you for your attention!



Origin of coronal shock waves & metric type II bursts

- 20 events in 1997 & 43 events in 1999/2000.

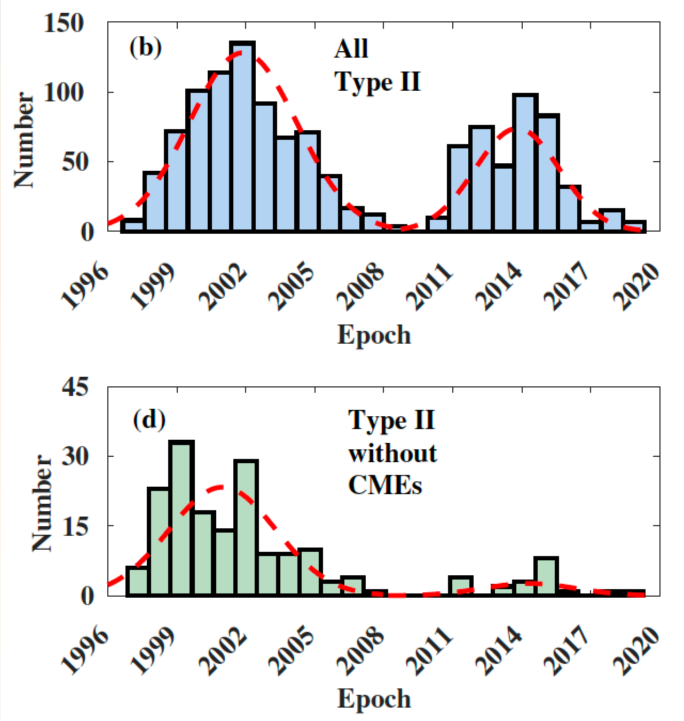


Majority on-disc flares!

some could be faint & weak CMEs!

Claßen & Aurass, 2002

- solar cycle 23 and 24



Kumari et al, 2023

- 3 - 4% of CMEs accompanied by type II bursts.
- Majority of the type II bursts (48%) related to fast and wide CMEs.

Type IIs without CMEs

- solar cycle 23 – 20.7 %
- solar cycle 24 – 4.6 %

14.8 %

Abstract:

A talk on recent advances on solar radio monitoring and space weathering.

The Earth is under the continuous impact of the solar wind plasma flow and its transients, such as coronal mass ejections (CMEs) which can produce disturbed geomagnetic conditions. Such a solar eruptions are associated with a rich variety of physical processes, e.g. plasma heating, mass motions, waves and shocks, and acceleration of energetic particles. The majority of these processes are accompanied by radio emission. The most frequently observed radio emission are type II, type III and type IV radio bursts which provide precious information on different solar phenomena across a broad range of temporal, spatial and energy scales. Combining ground- and spaced-based radio observations permits us to track the radio emissions mapping the plasma processes all the way from the low corona up to the interplanetary space. This characteristic makes solar radio emission important component of the operational space wearther services.

In this presentation I will discuss how the solar radio observations can be employed in the space weather diagnostics, and what is the recent progress brought by the novel ground-based (e.g. LOFAR and MWA) and space-based instruments (e.g. Parker Solar Probe and Solar Orbiter). The focus will be on the radio burst which can provide information about the space weather important solar eruptive phenomena such as flares, CMEs (coronal mass ejections), but also on the associated shock waves.