



Leibniz-Institut für  
Astrophysik Potsdam

# Separating fundamental and harmonic sources in LOFAR solar type III radio burst images

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LOFAR Family Meeting, Olsztyn, 13 June 2023

# Solar observations with LOFAR

The Sun is a strong radio source:

- Thermal:  $10^6$  K corona
- Non-thermal: Flares, CMEs

Intensities:

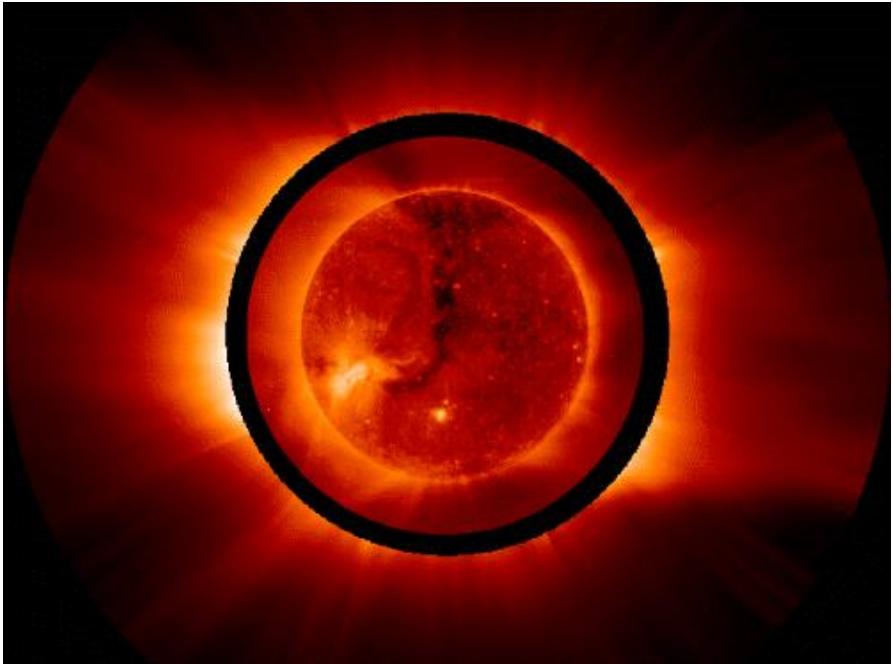
- Thermal: some  $10^4$  Jy
- Non-thermal: up to  $10^8$  Jy

Non-thermal radio wave emission:

- Plasma emission
- Energetic electrons in the Plasma
  - Electrostatic instability, Langmuir waves
  - Wave-wave interaction creates radio waves
  - Wave emission at local plasma frequency:

$$f = \sqrt{Ne^2/(m_e\epsilon_0)/(2\pi)}$$

and its harmonics



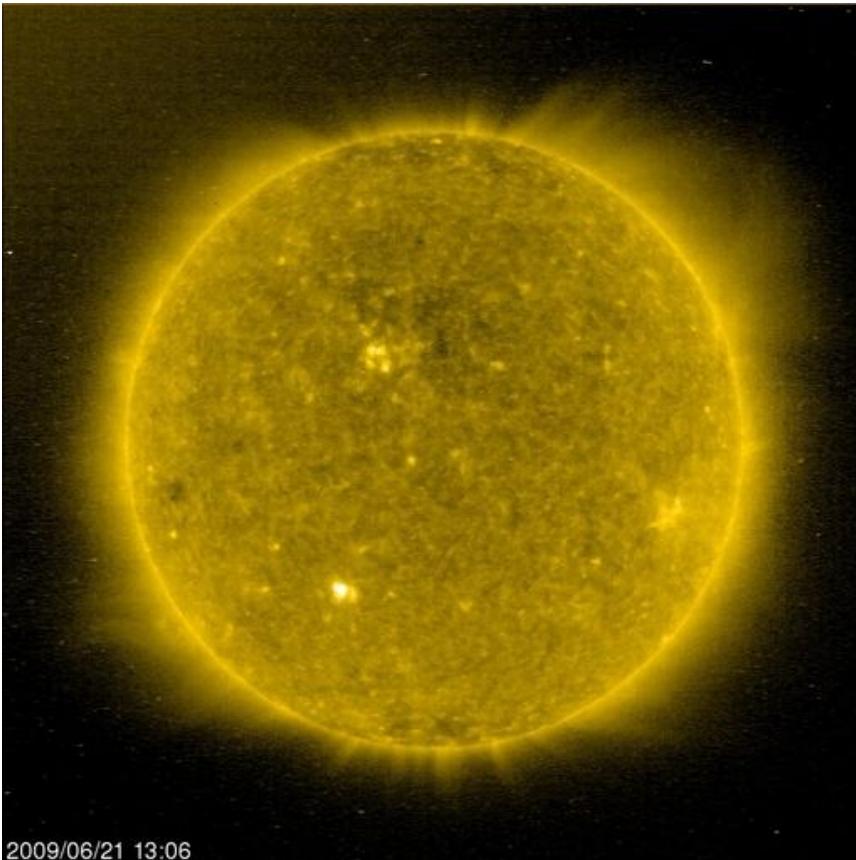
The frequency  $f$  depends only on the density  $N$

# LOFAR frequencies: Solar corona

f/MHz	r/R <sub>S</sub>
240	1.17
170	1.24
100	1.37
70	1.48
40	1.68
30	1.80
20	2.01
10	2.52

LOFAR frequencies:

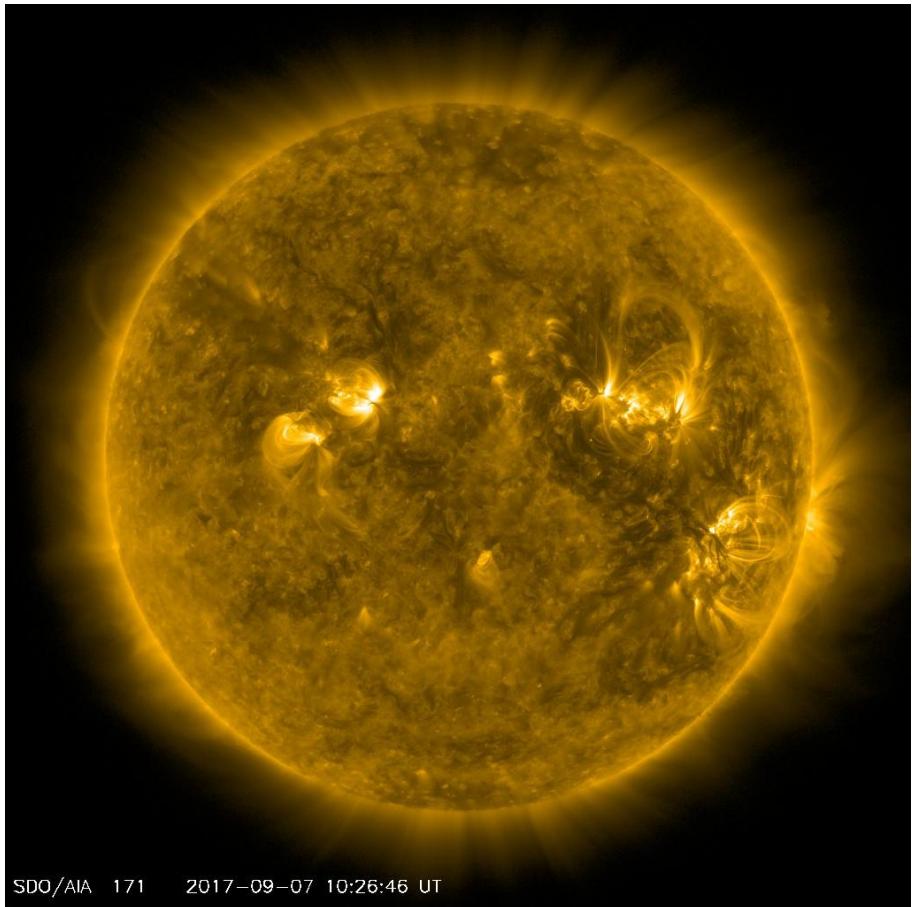
Middle and upper corona



# Solar observations on 7 Sep 2017

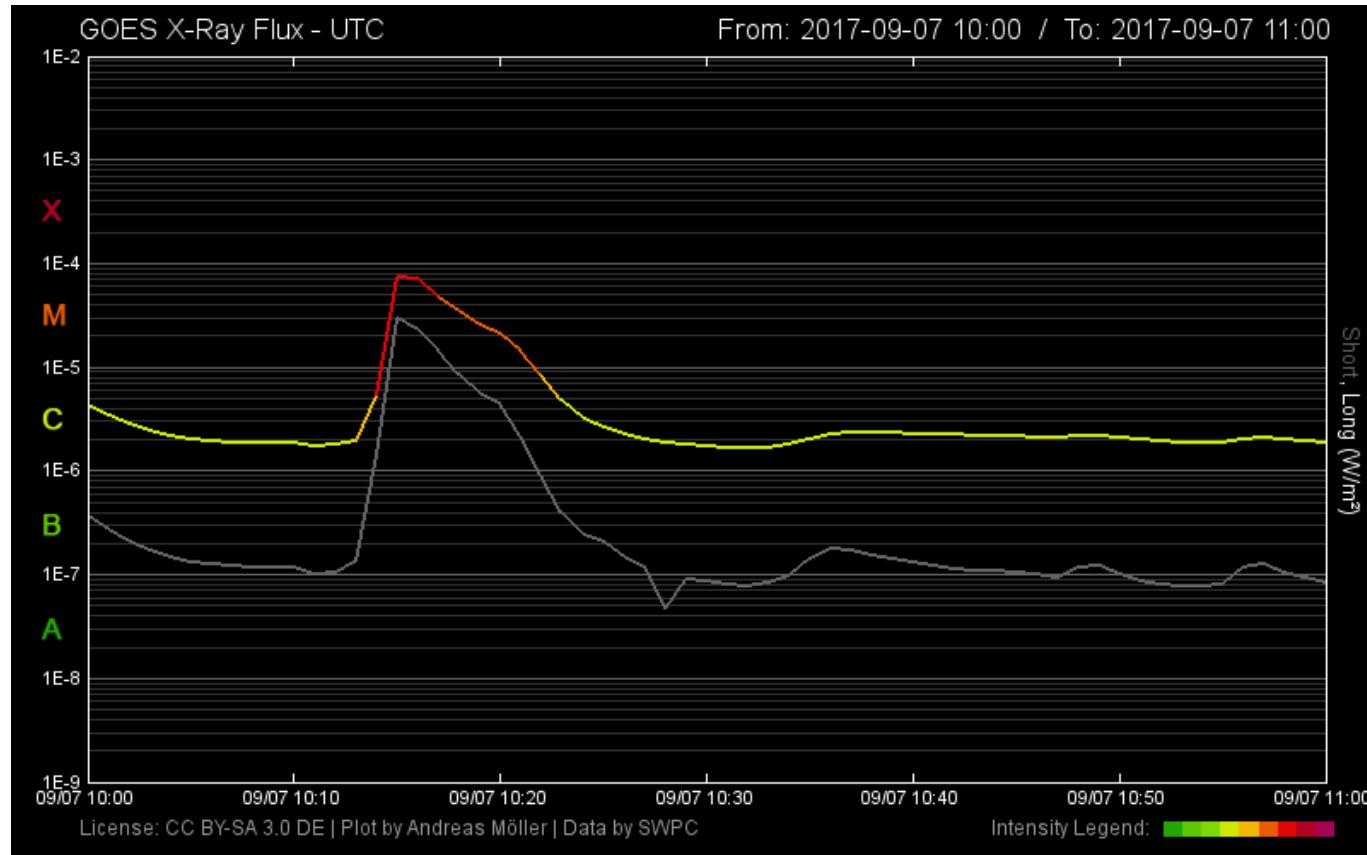
## Scheduled observations:

- Observations scheduled for enhanced solar activity
- 6 h observing time over noon
- 0.25 s imaging sequence
- Interferometric in LBA, dynamic spectra in LBA+HBA



SDO/AIA 171 2017-09-07 10:26:46 UT

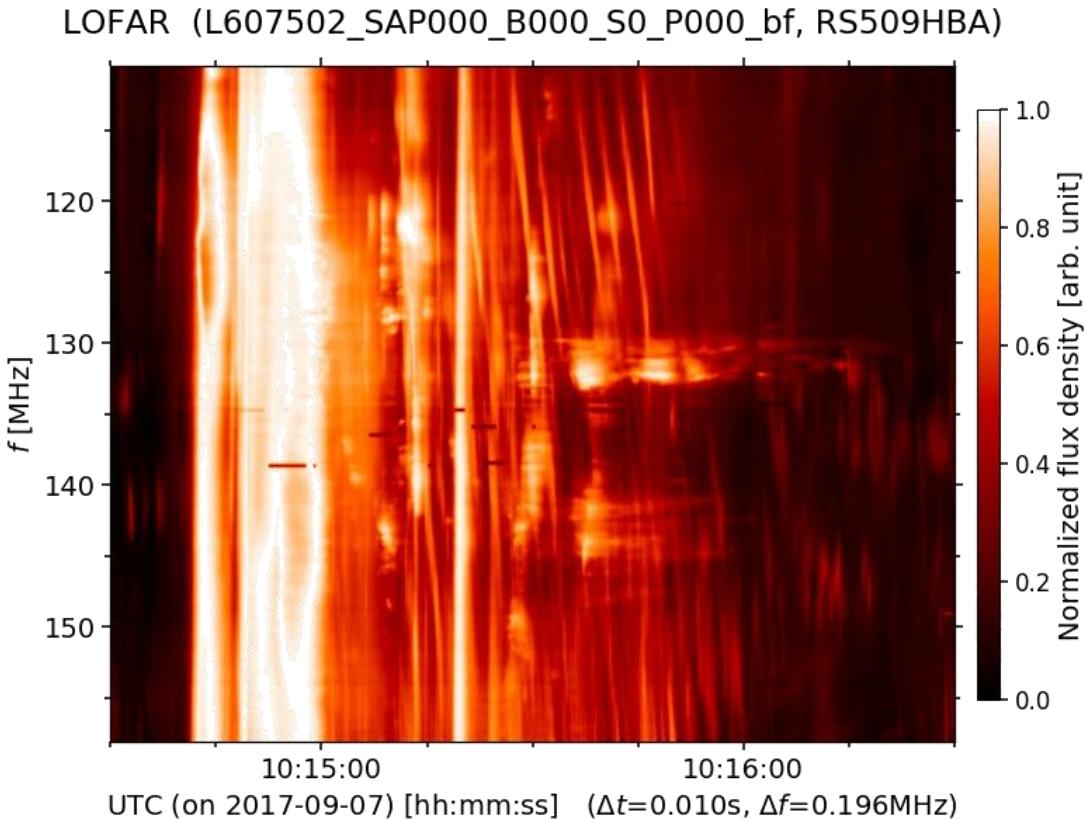
# M class flare at 10:14 UT



# LOFAR dynamic radio spectra: HBA

Solar flare:

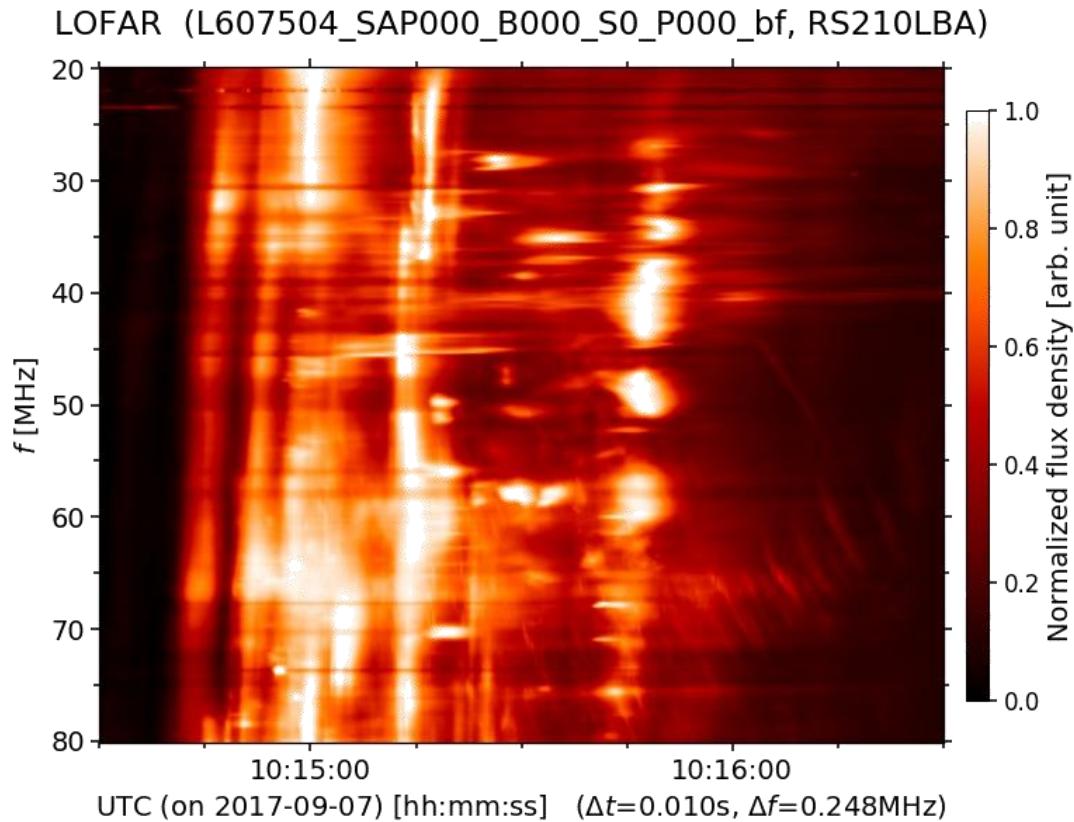
- M class
- Starting at 10:14:40 UT
- Several type III bursts



# LOFAR dynamic radio spectra: LBA

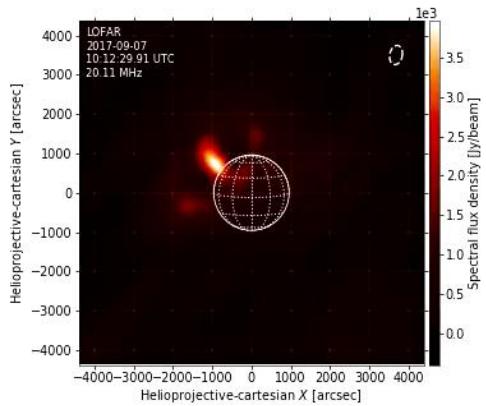
Solar flare:

- M class
- Starting at 10:14:40 UT
- Several type III bursts

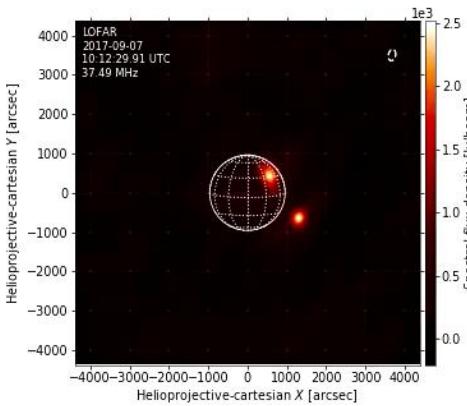


# LOFAR images for the M class flare

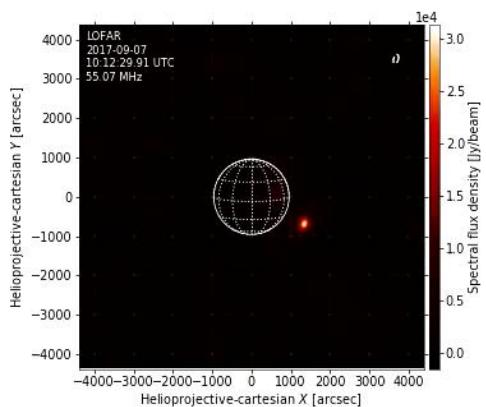
20 MHz:



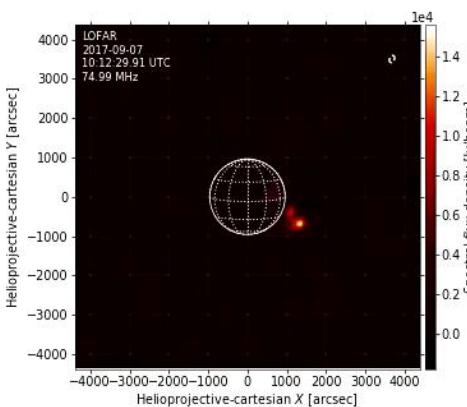
37.5 MHz:



55 MHz:



75 MHz:



# Fundamental and harmonic plasma emission: Sources and refraction in the corona

Given observation frequency:  $f_{\text{obs}}$

Plasma frequency:

$$f_p = (\mathcal{N} e^2 / (m_e \epsilon_0))^{1/2} / (2 \pi)$$

Refractive index:

$$n = (1 - f_p / f)^{1/2}$$

Fundamental emission:

$$f_p = f_{\text{obs}}, n \rightarrow 0$$

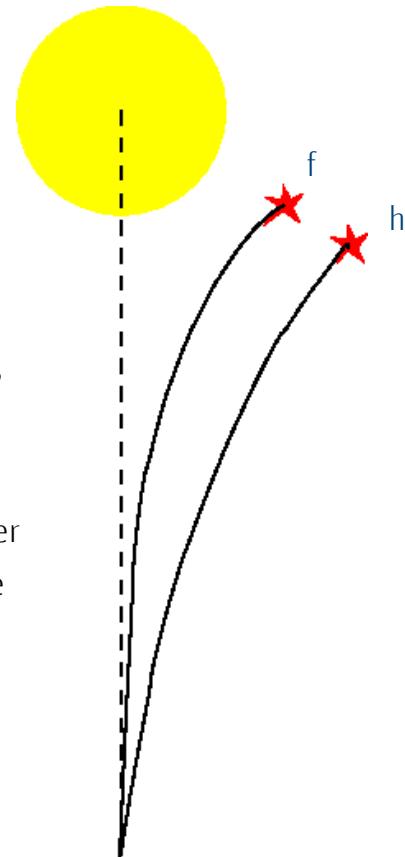
Harmonic emission:

$$f_p = f_{\text{obs}} / 2, n = 0.886$$

Fundamental and harmonic sources:

- h source: local plasma frequency is  $f_{\text{obs}} / 2$
- located higher in the corona
- less refraction towards the solar disk center in the large-scale coronal density decrease with height than for the f source

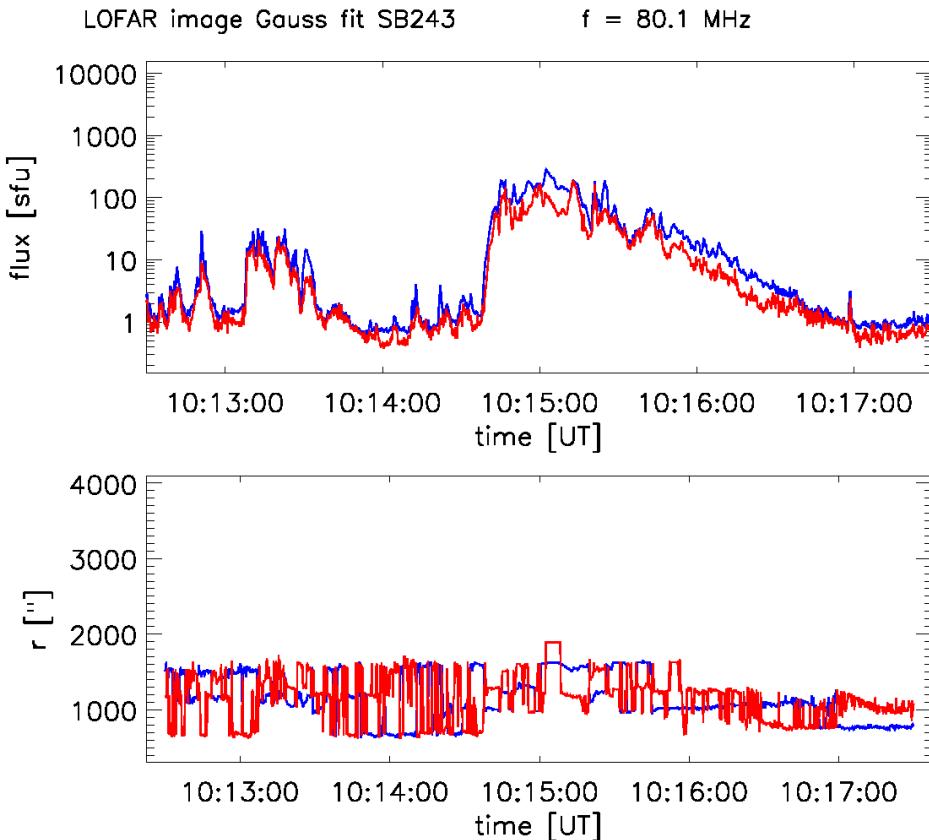
Separation of f and h sources



# Radial evolution of f and h sources

Gaussian fits:

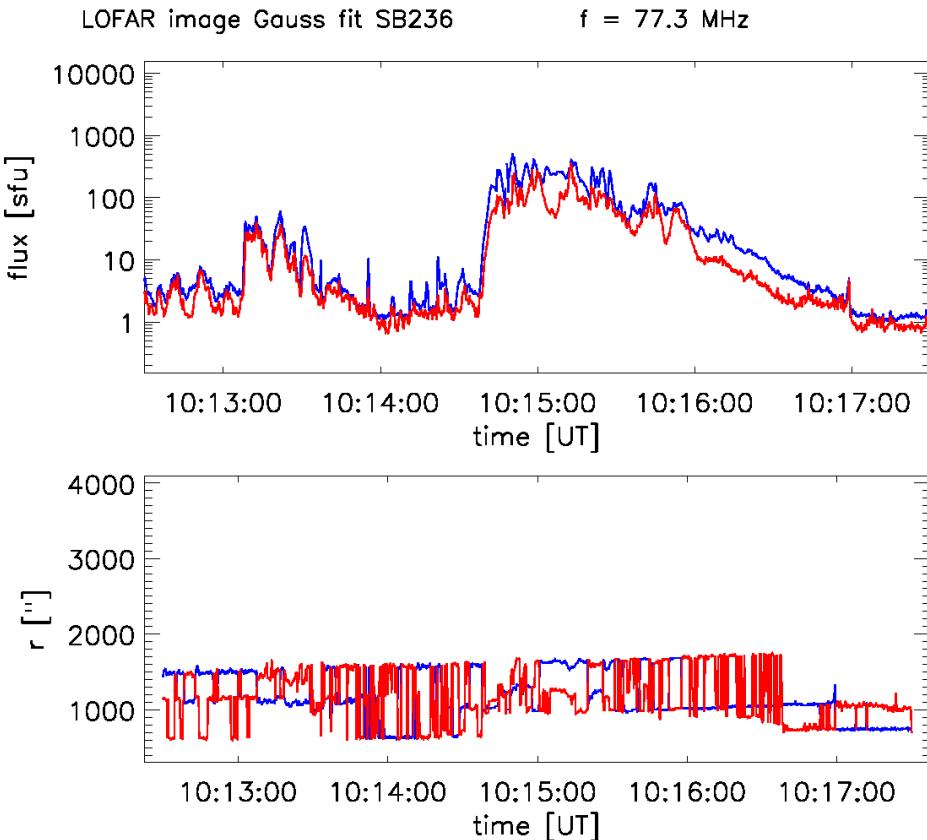
- Strongest source (blue)
- Subtract this source
- Second strongest source (red)



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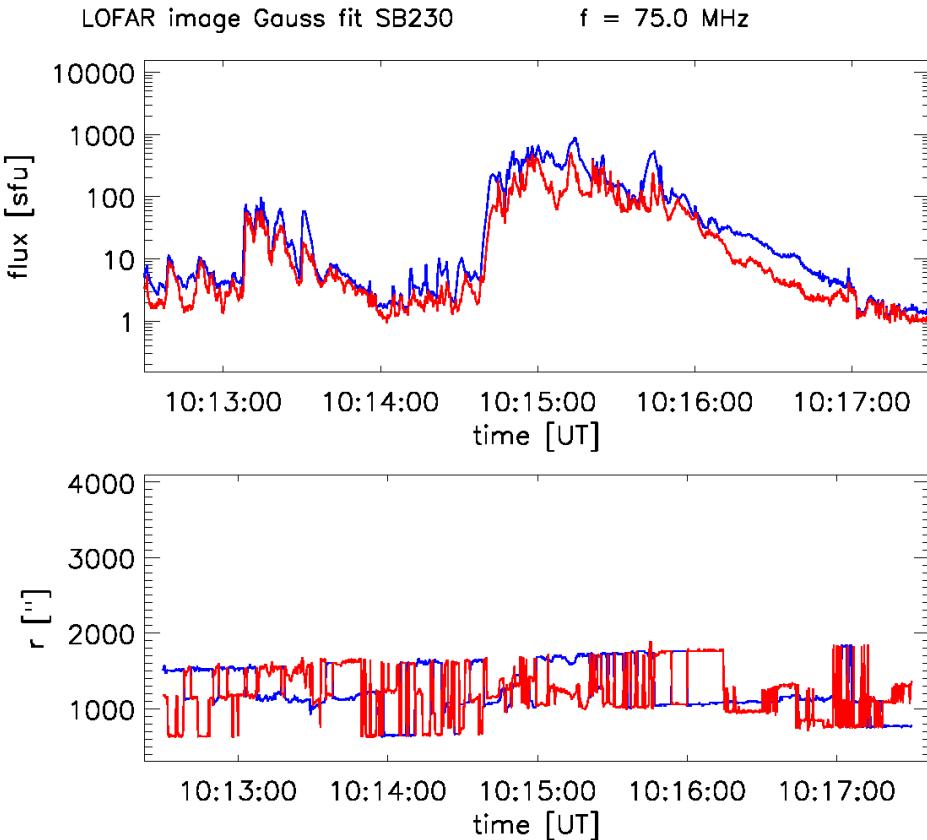
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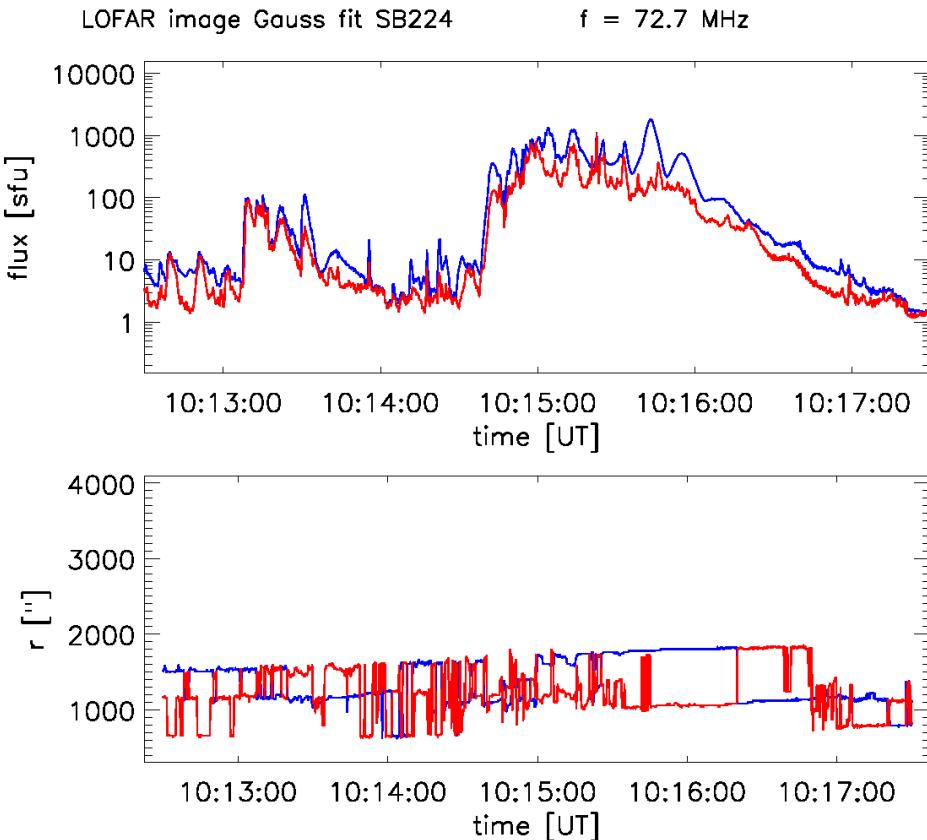
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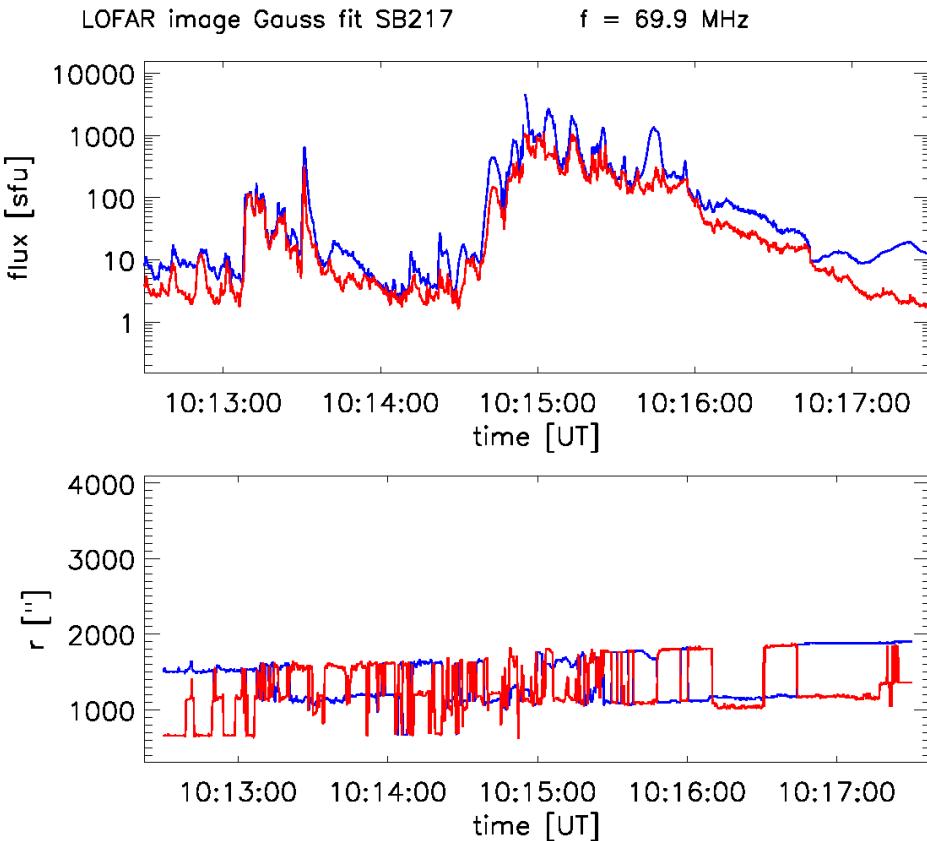
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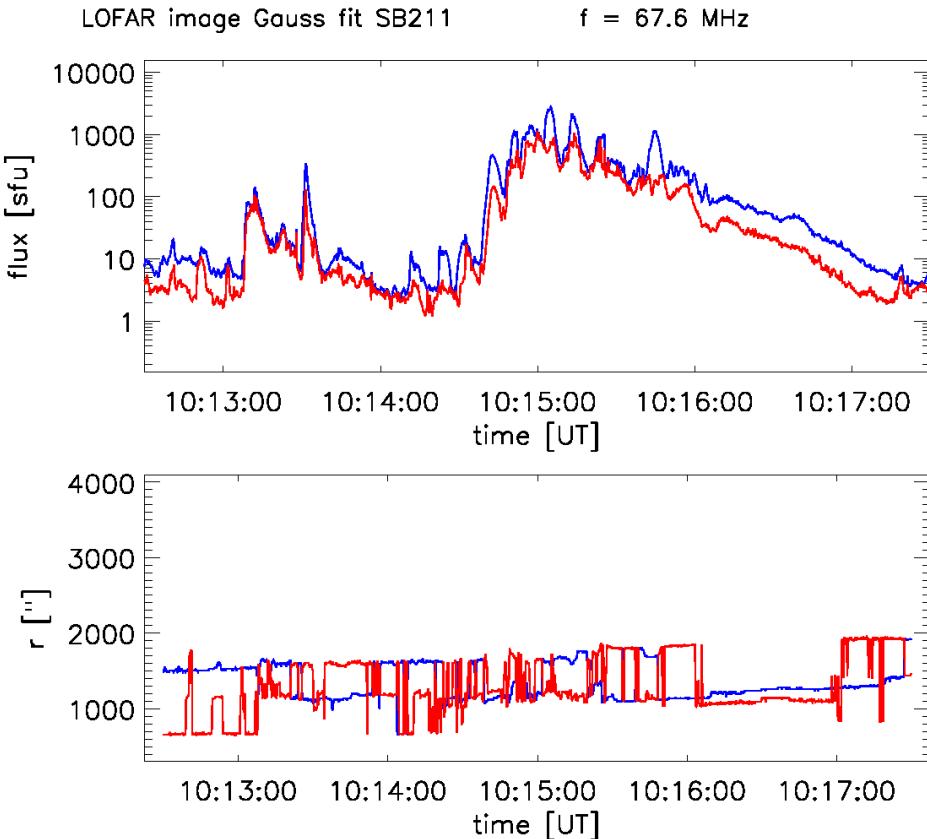
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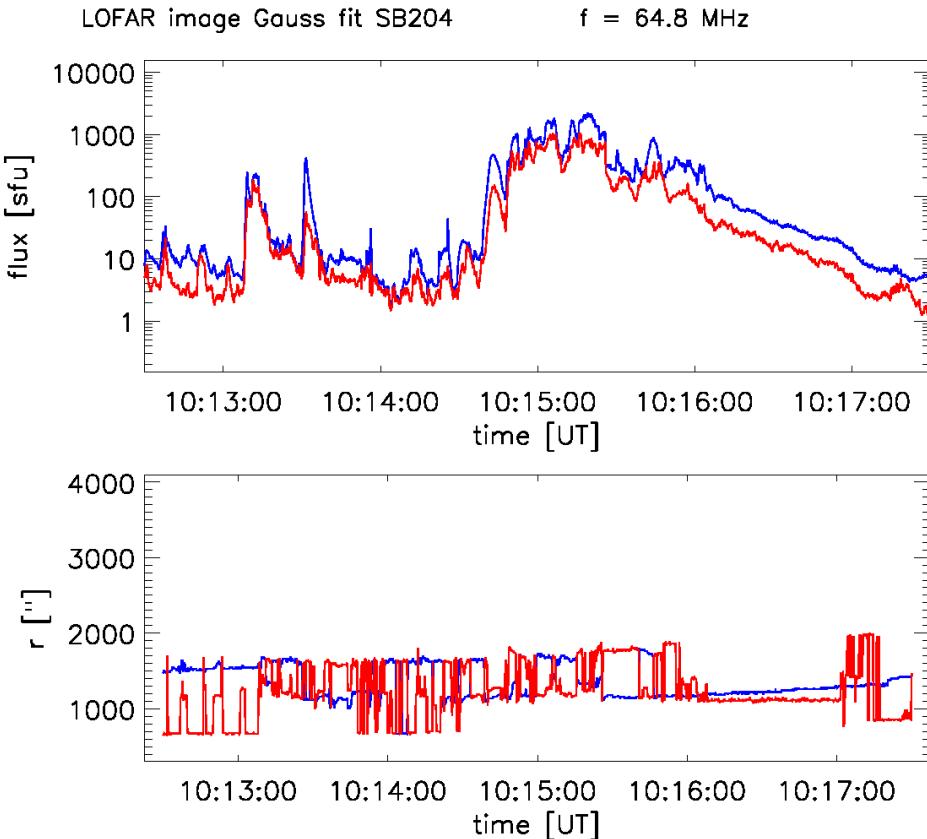
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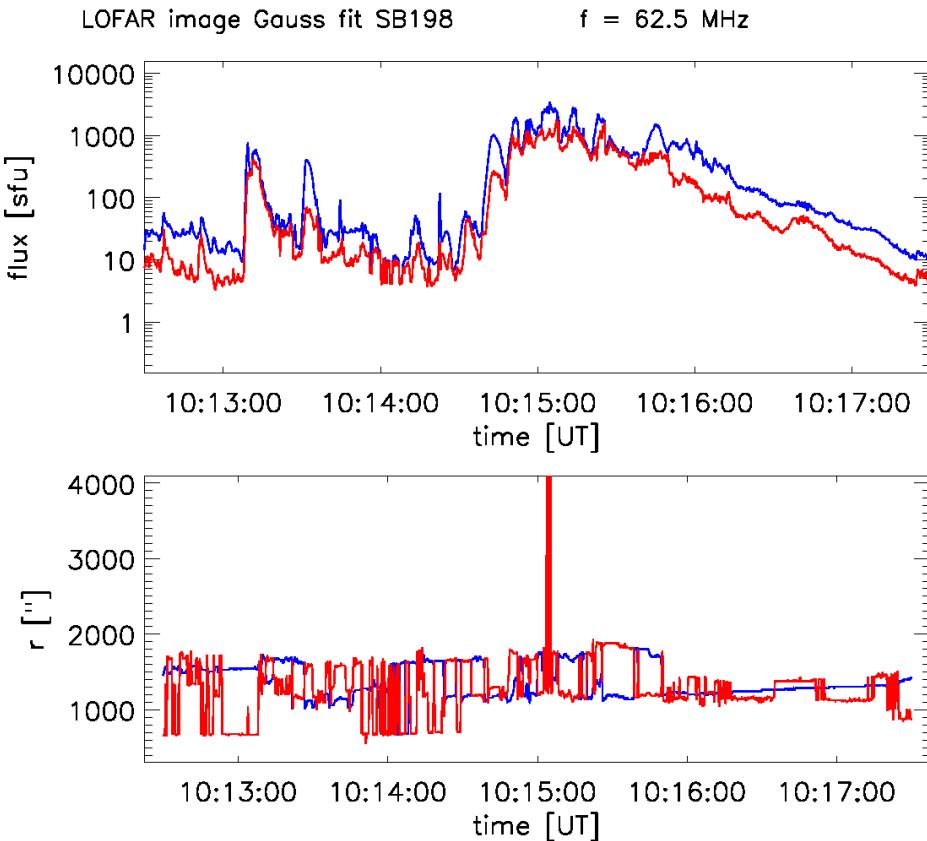
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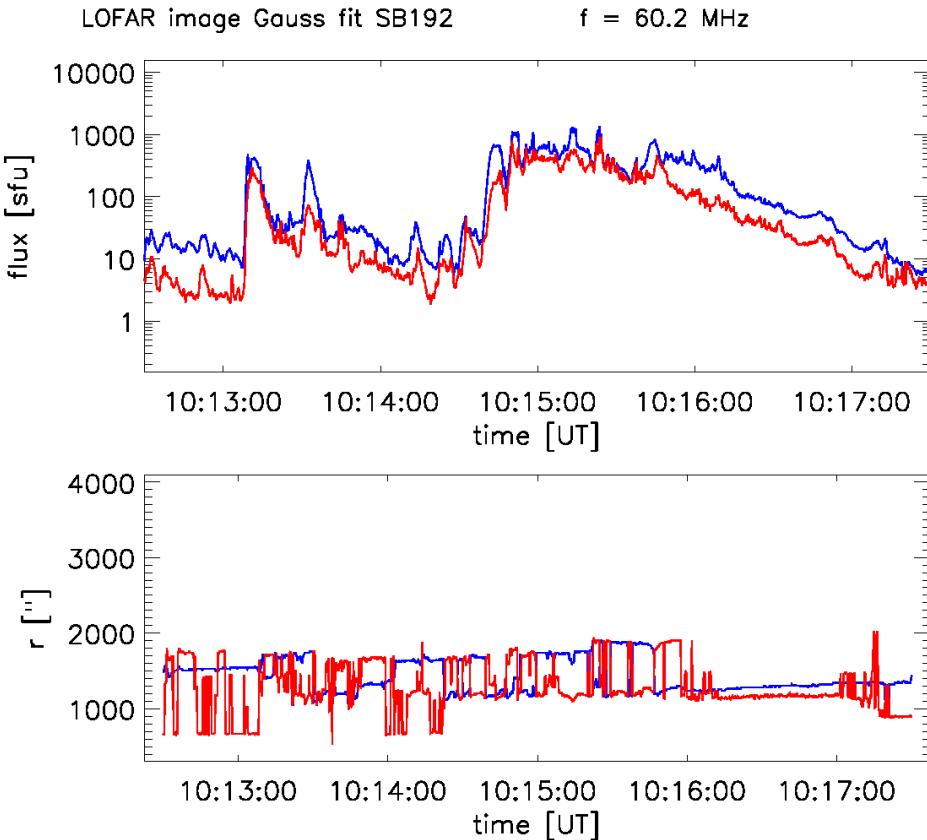
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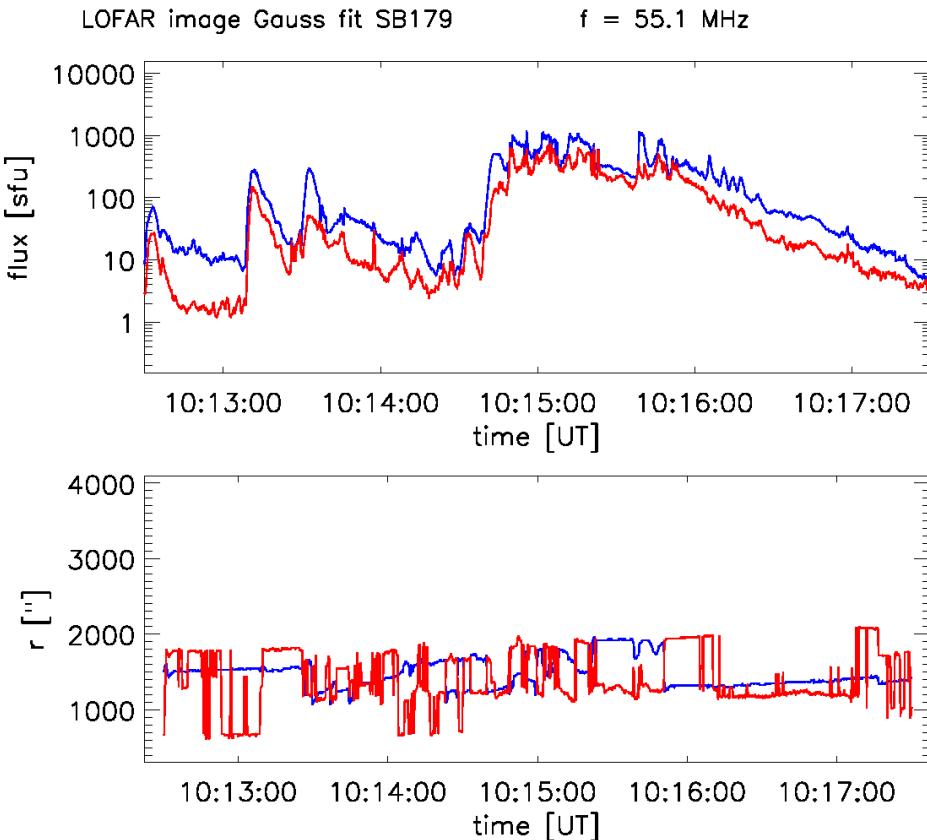
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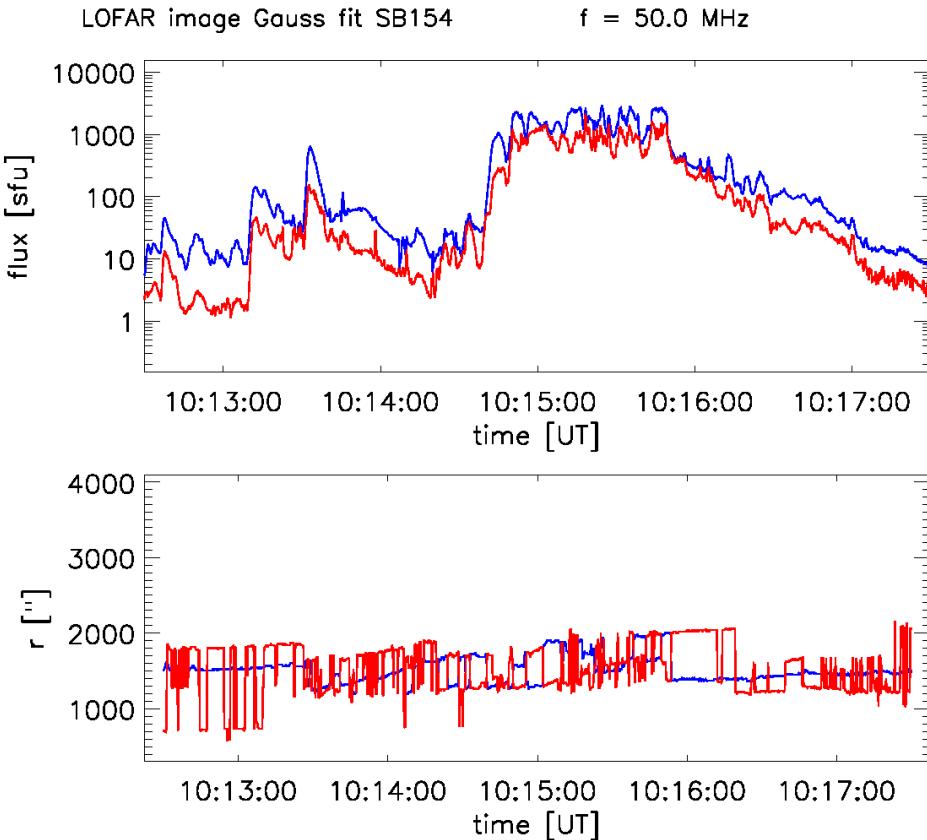
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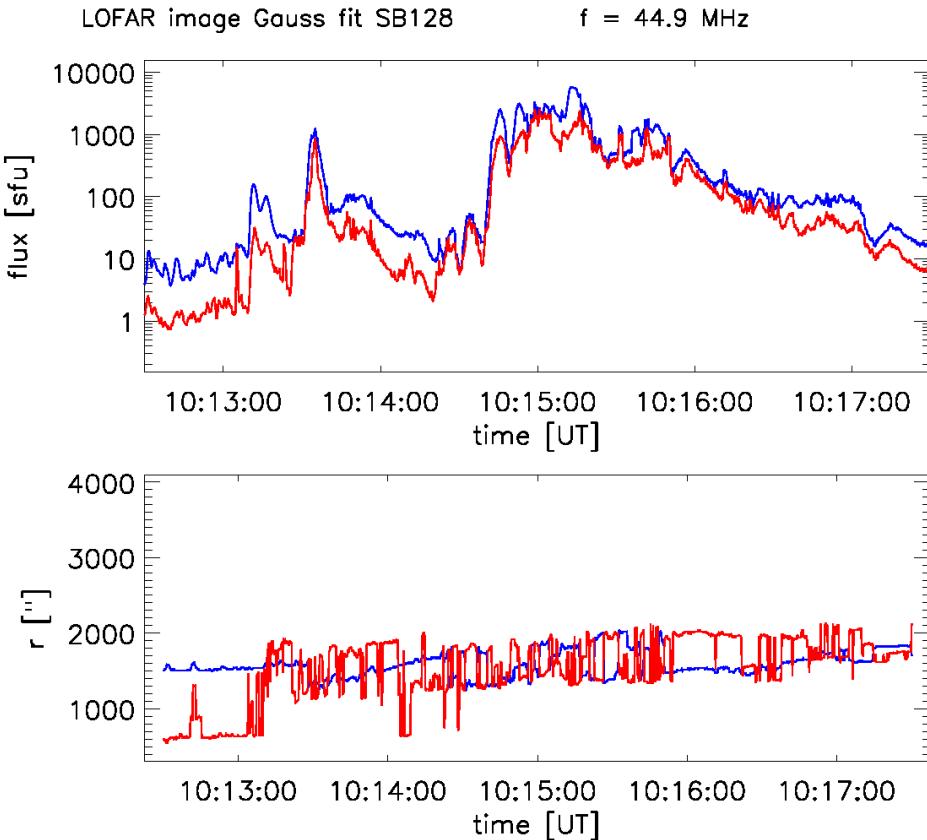
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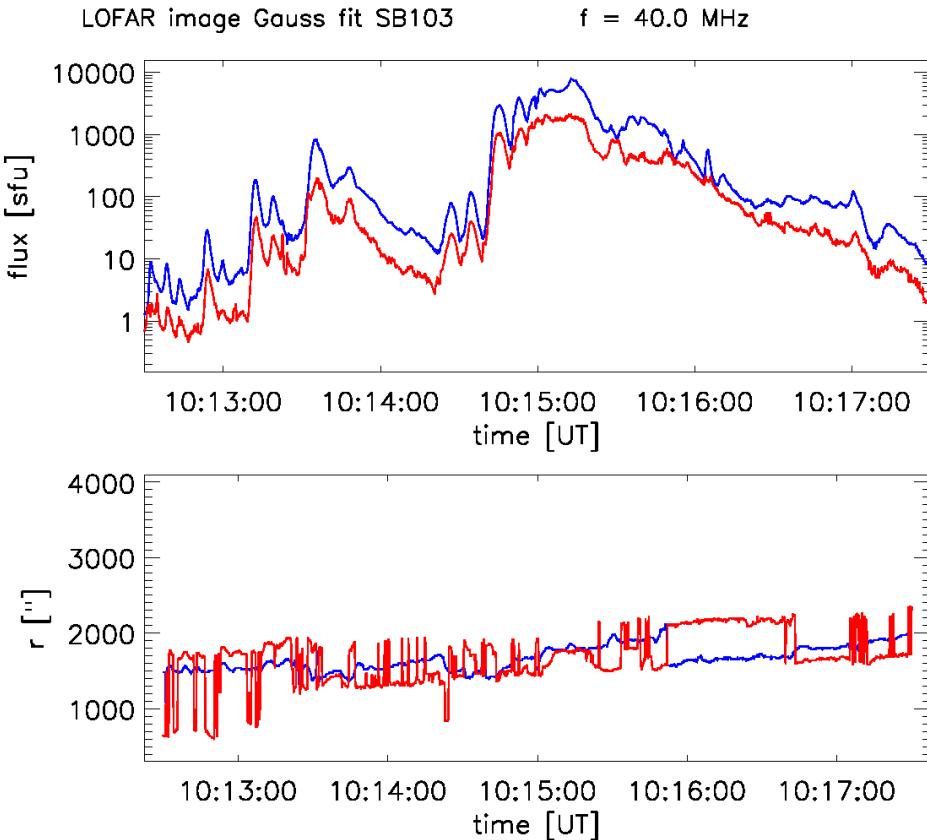
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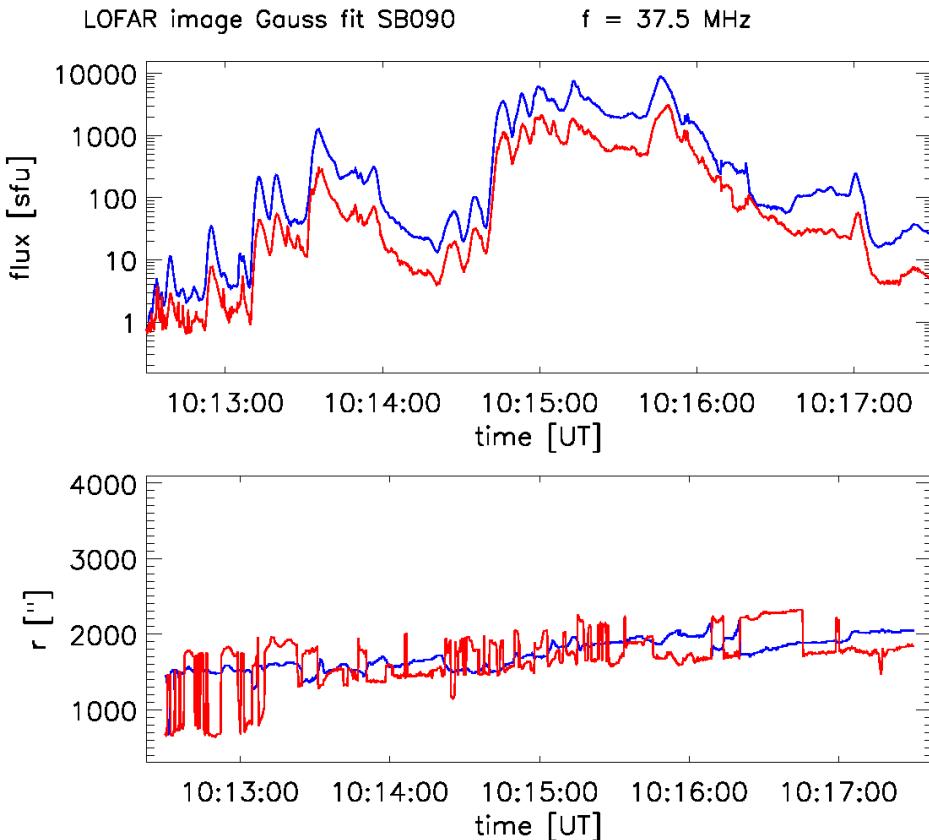
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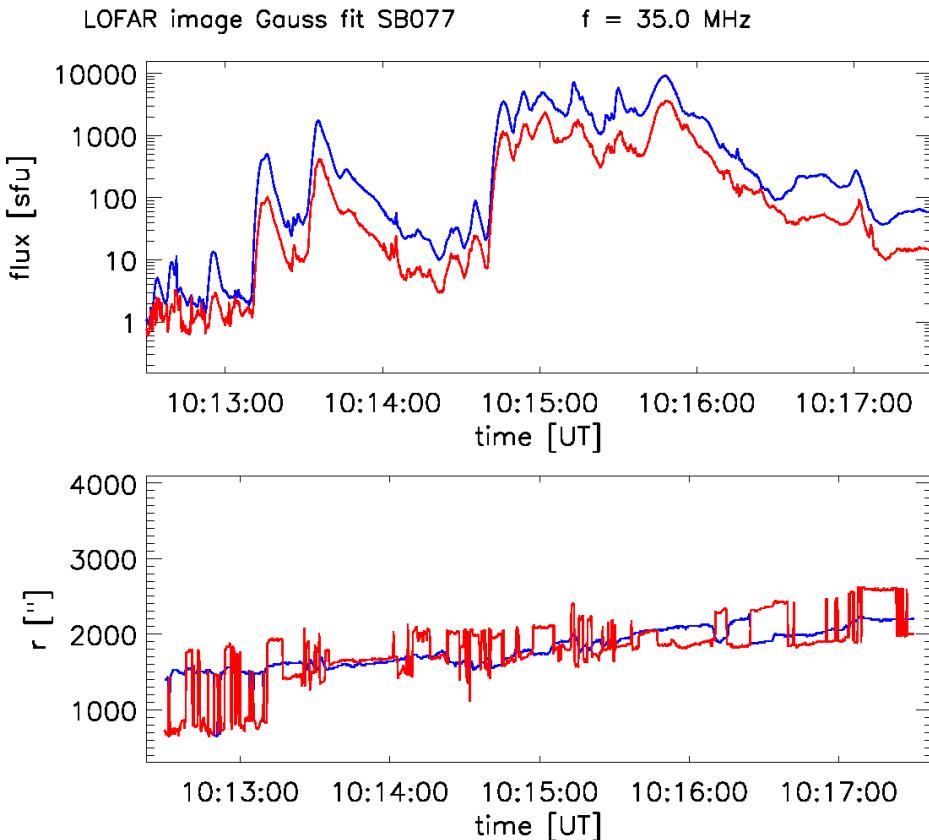
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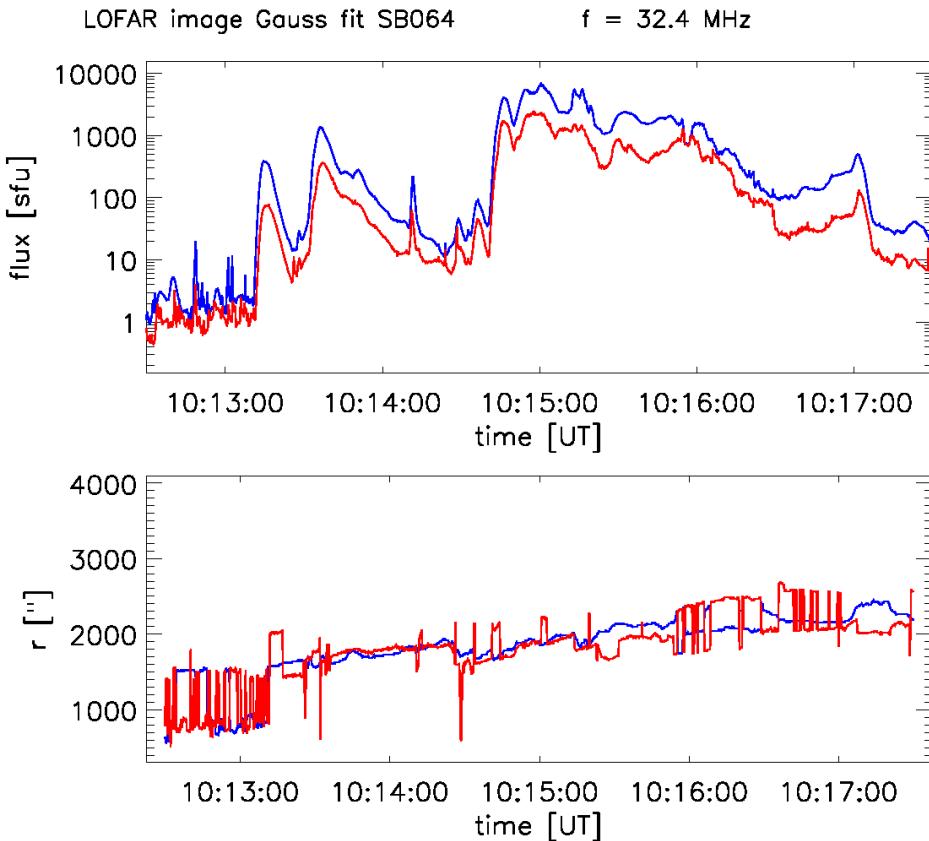
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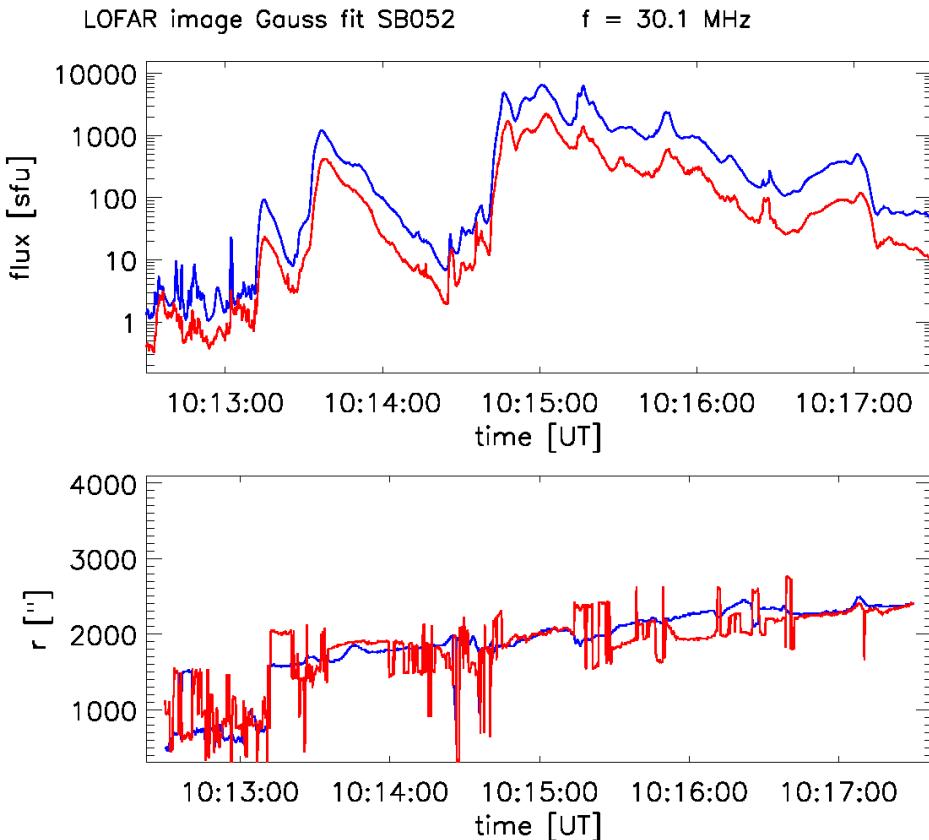
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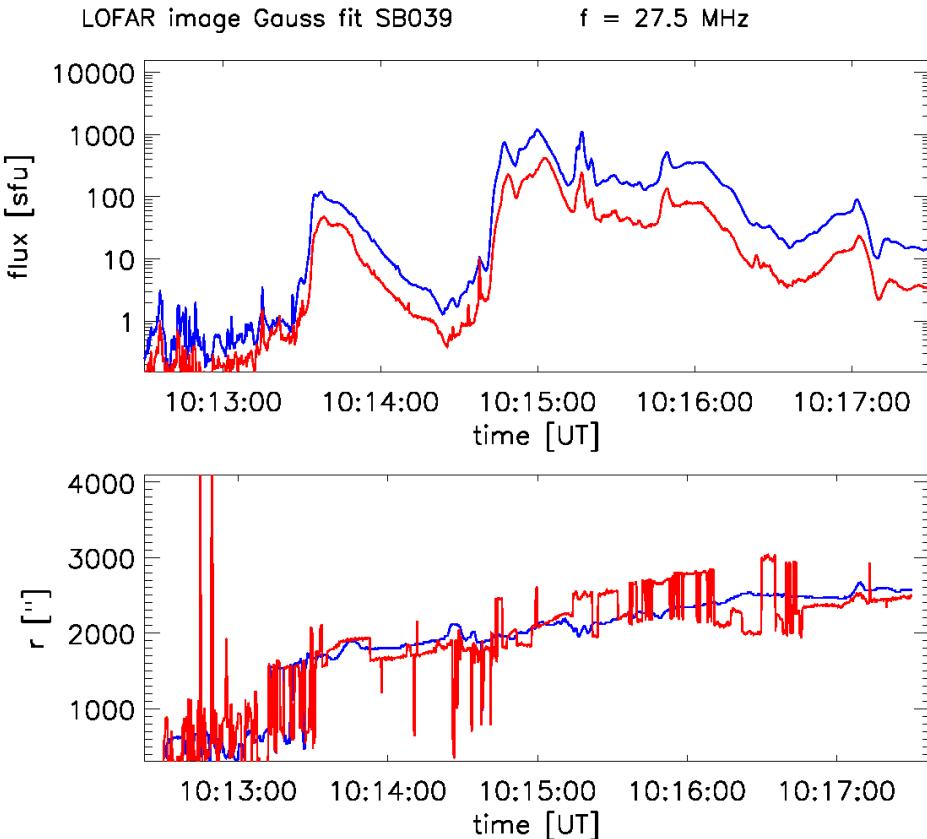
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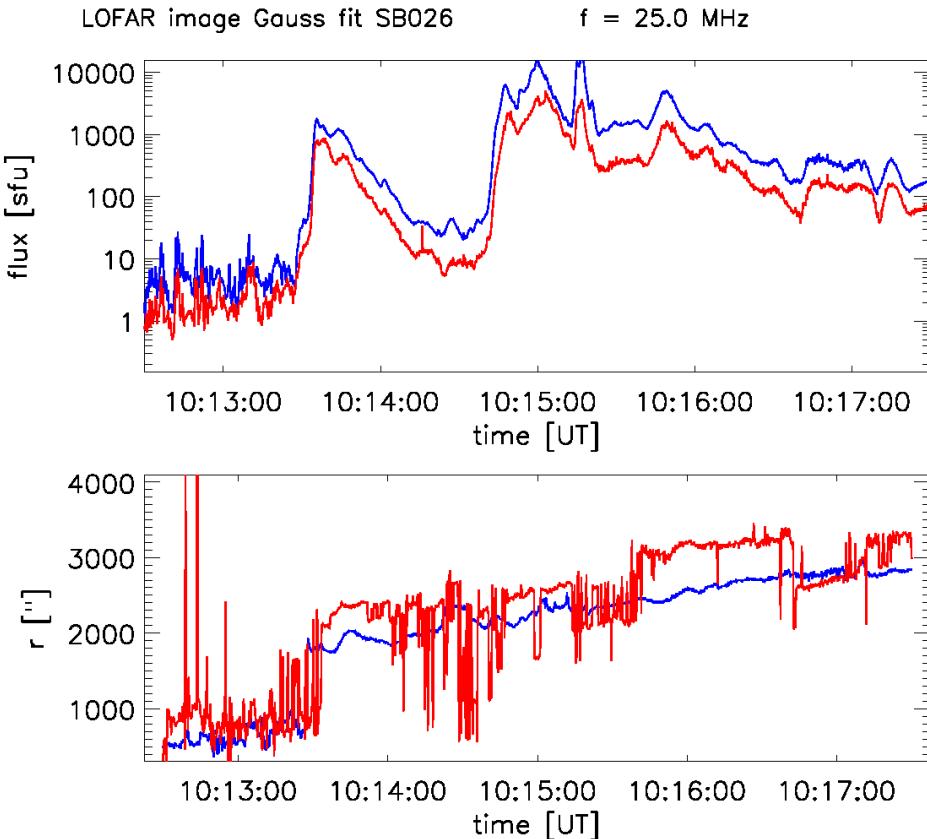
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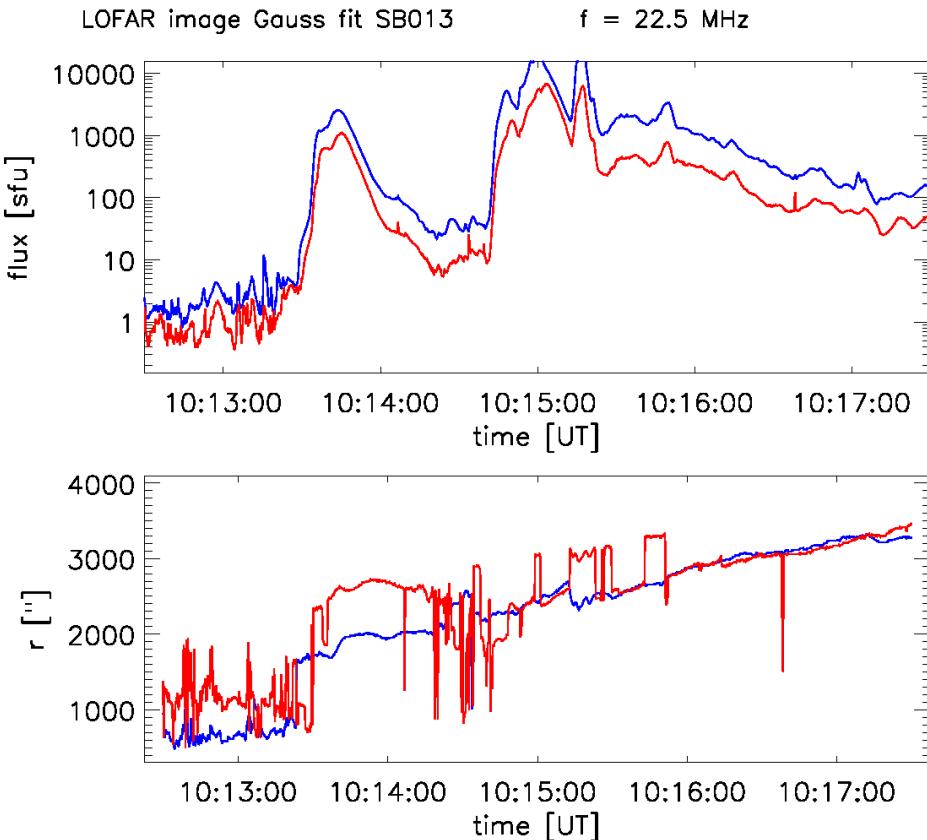
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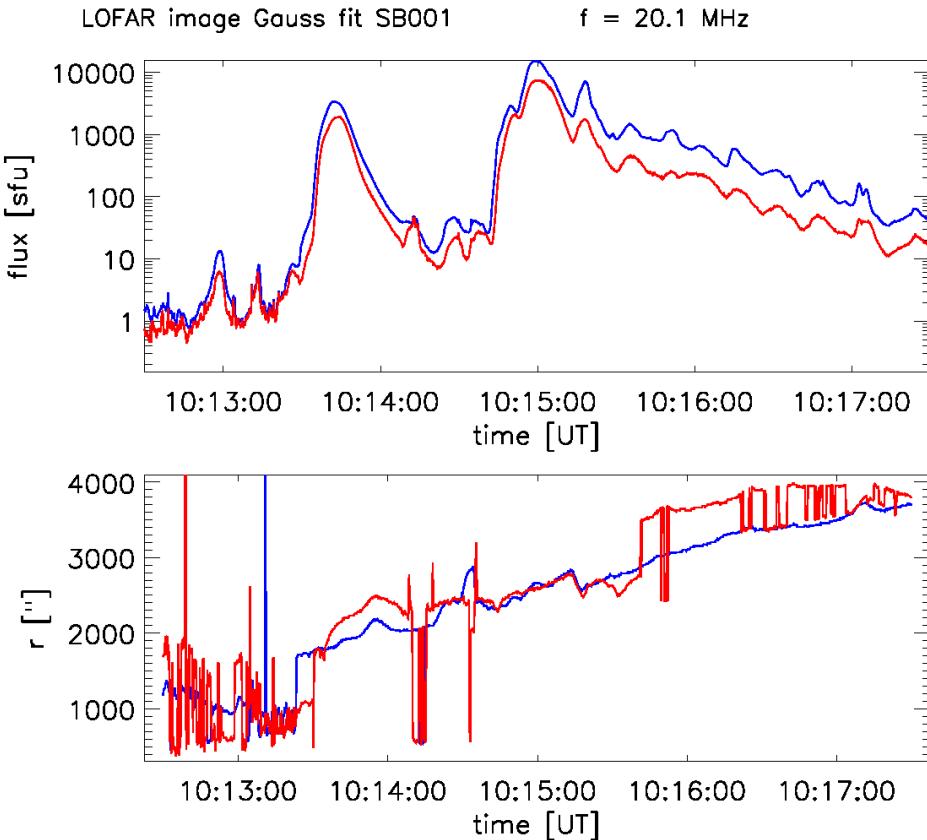
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# Positions of fundamental and harmonic sources

Source positions:

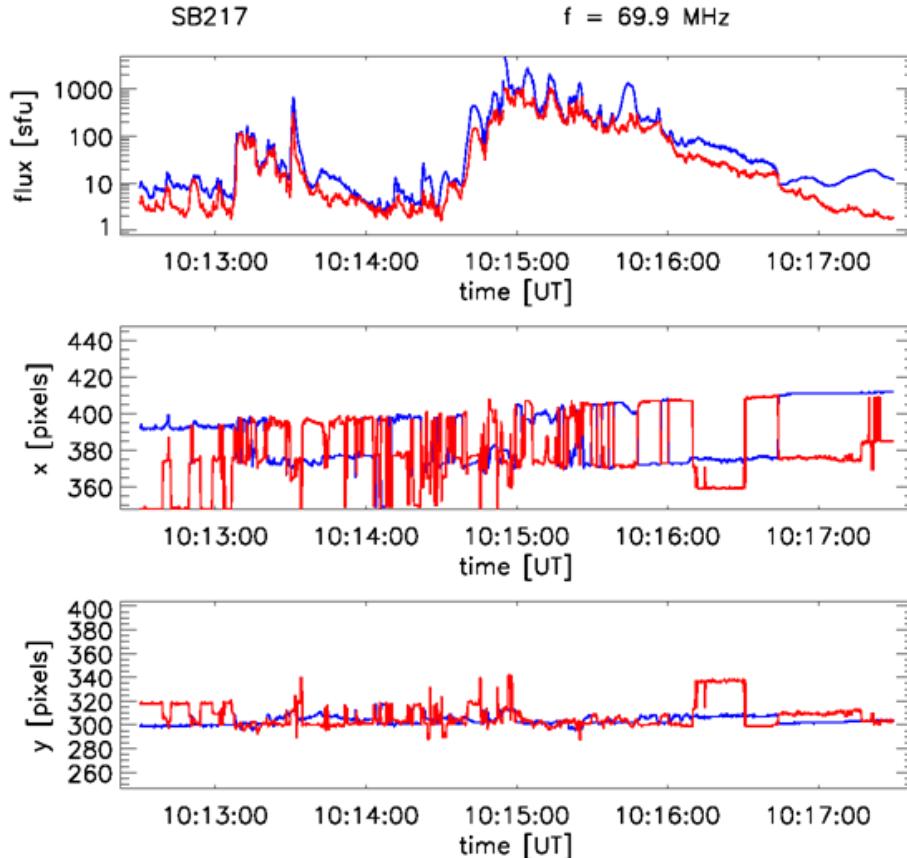
- (x, y) positions from Gaussian fits
- Compensate for drift over time

Fundamental and harmonic fluxes:

- Areas around (x, y)
- Integrate flux over these areas

Result:

Separate lightcurves for fundamental and harmonic sources



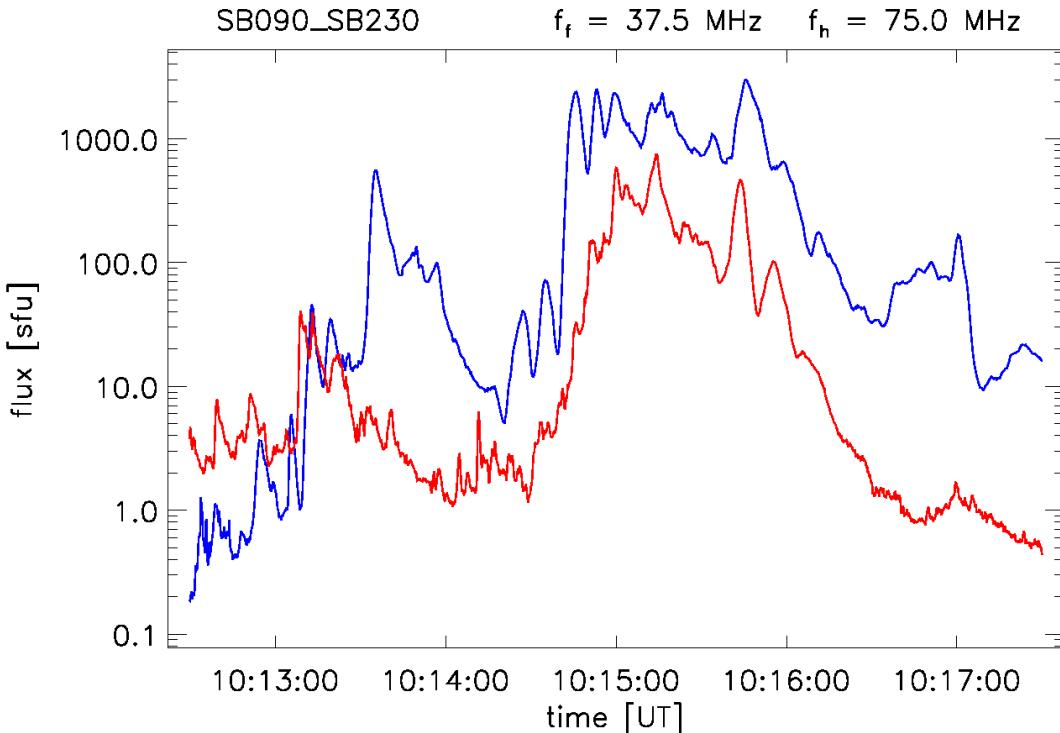
## Fundamental – harmonic pairs

Example: 37.5 / 75 MHz and lower:

- Fundamental emission at 37.5 MHz
- Harmonic emission at 75 MHz
- Originate from the same source region

Differences between lightcurves:

- Earlier onset for harmonic at 10:13:05 UT
- Not visible at 10:14:30 UT
- Source finding method can impact results
- Influence of coronal scattering, especially on fundamental emission



Such plots can provide information  
on coronal radio wave propagation

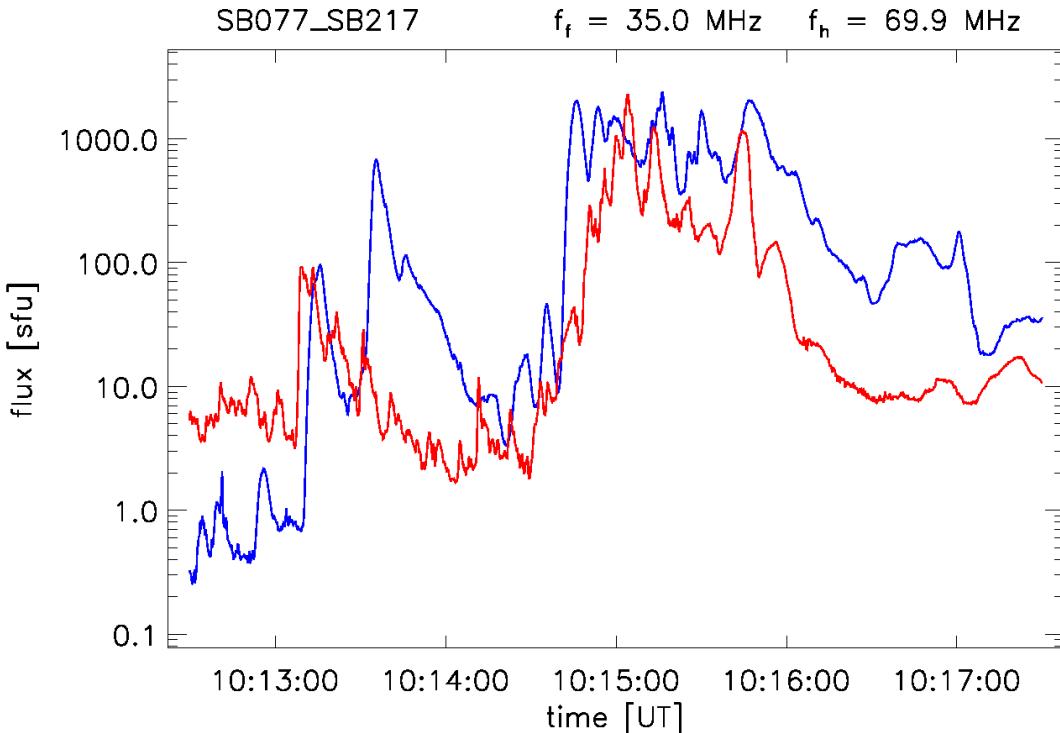
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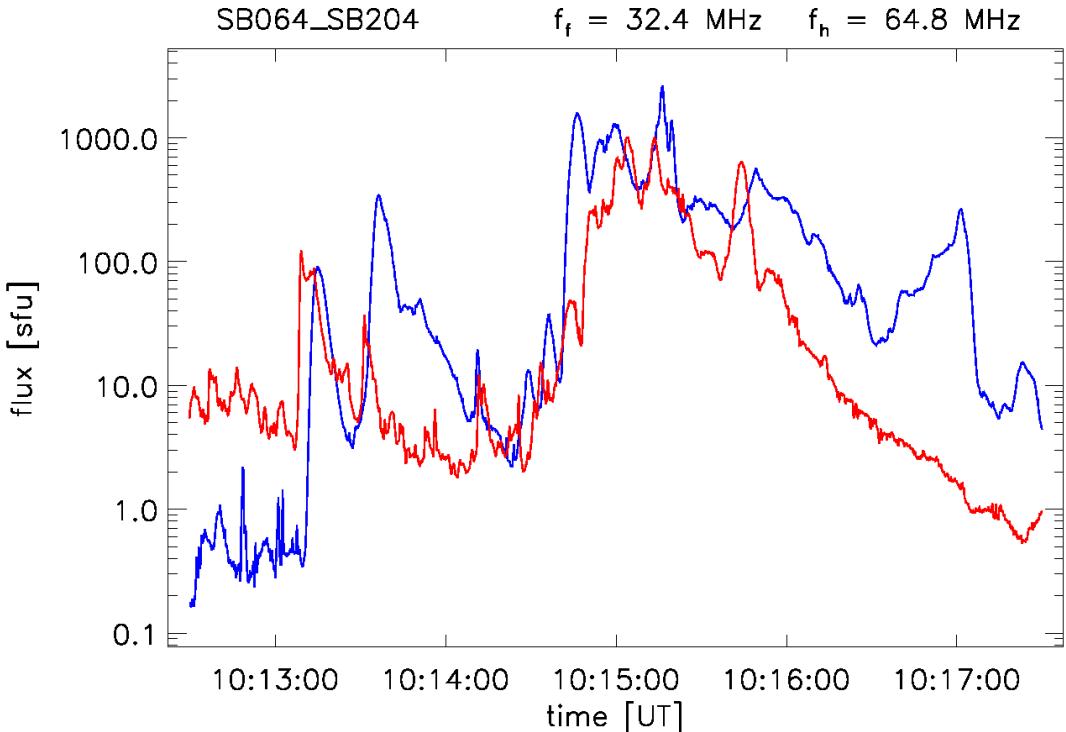
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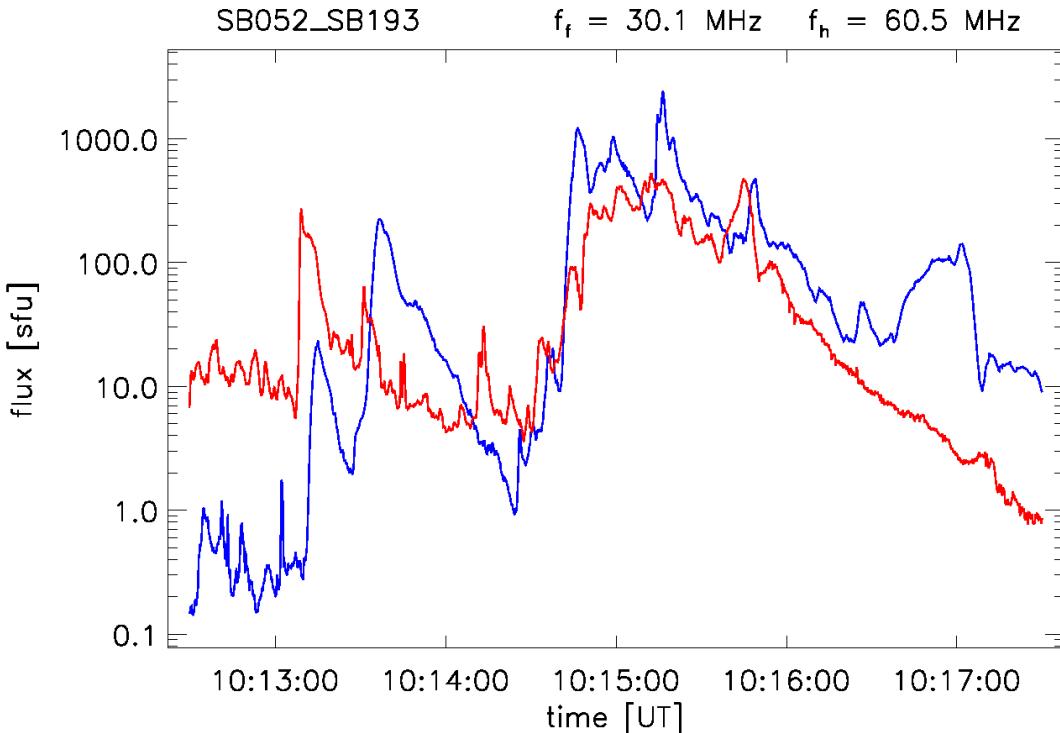
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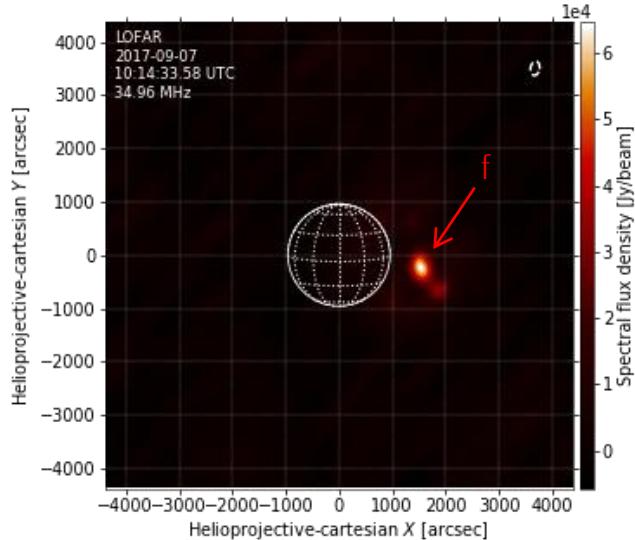
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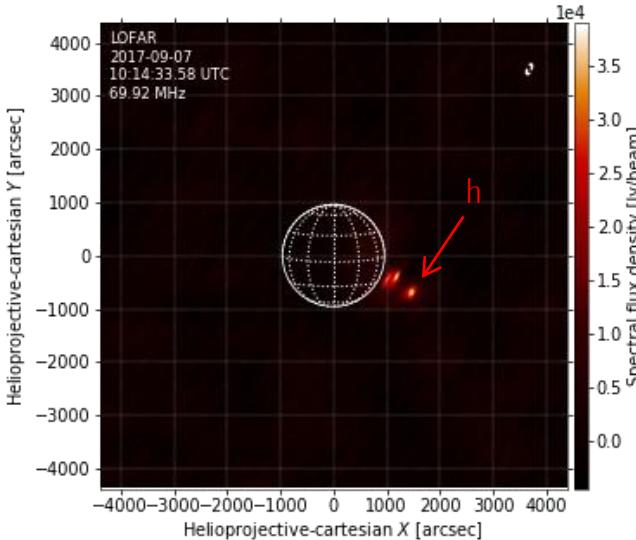
# Relative positions of fundamental and harmonic sources



Position of fundamental source:

$$x = 1528'', y = -226'', r = 1545''$$

$$\Delta x = -98'', \Delta y = -441'', \Delta r = 33''$$



Position of harmonic source:

$$x = 1430'', y = -667'', r = 1578''$$

Same source region: Scattering and refraction is stronger for fundamental emission

→ Insights into radio wave propagation in the corona

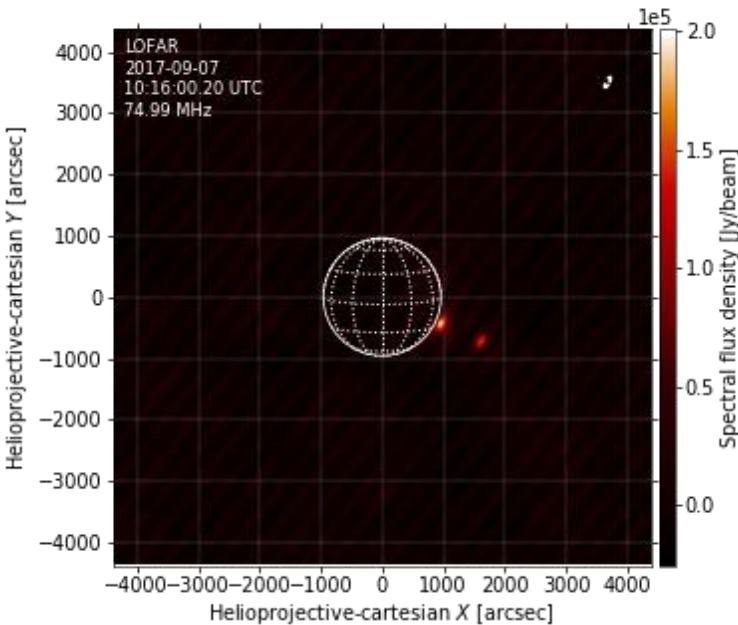
# Summary and conclusion

## LOFAR M class flare observations:

- Dynamic radio spectra and images
- Dominated by strong type III emission
- Images show intermittent dual source structure

## Interpretation: fundamental and harmonic emission

- At given frequency: Outer source is harmonic, inner is fundamental
- Separate lightcurves for both sources
- Fundamental-harmonic pairs: Same source region
- Study coronal radio wave propagation and emission characteristics



# Outlook

## Radio burst observations at low frequencies:

- Harmonic emission at 20 MHz corresponds to a plasma frequency of 10 MHz
- Fundamental emission is inaccessible to ground-based telescopes
- High corona, transition to interplanetary space

Useful aspect for joint observations with spacecraft like Parker Solar Probe and Solar Orbiter

