Imaging a Large Coronal Loop using Type-U Solar Radio Burst Interferometry

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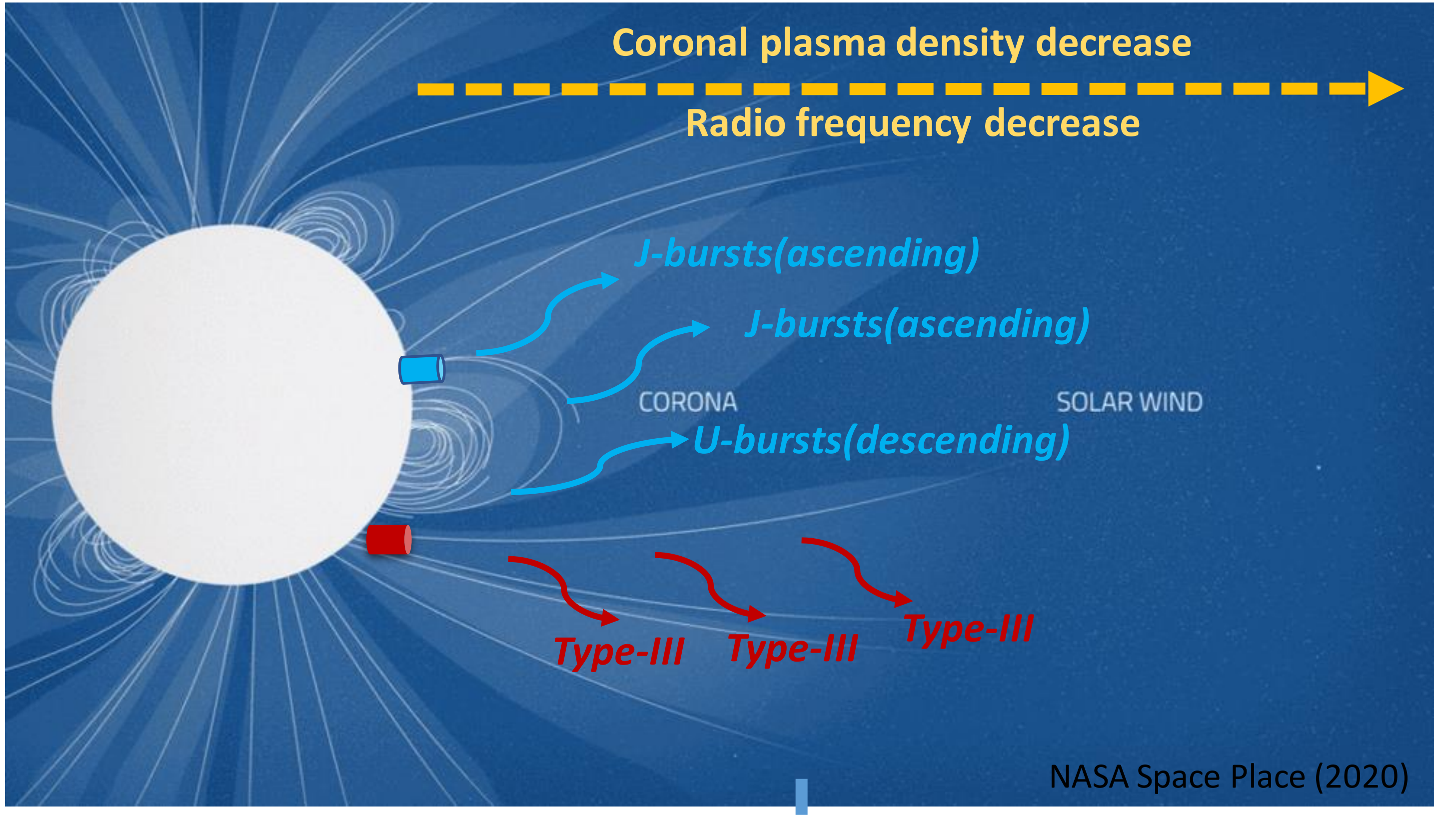
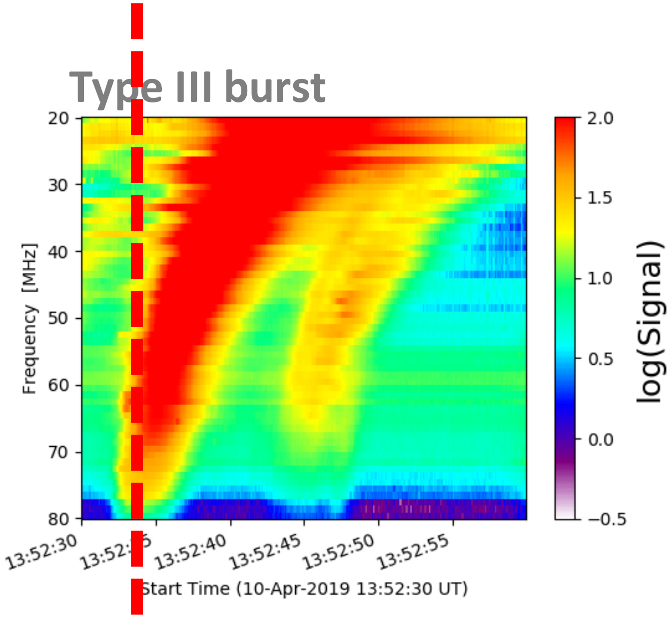
Type III bursts

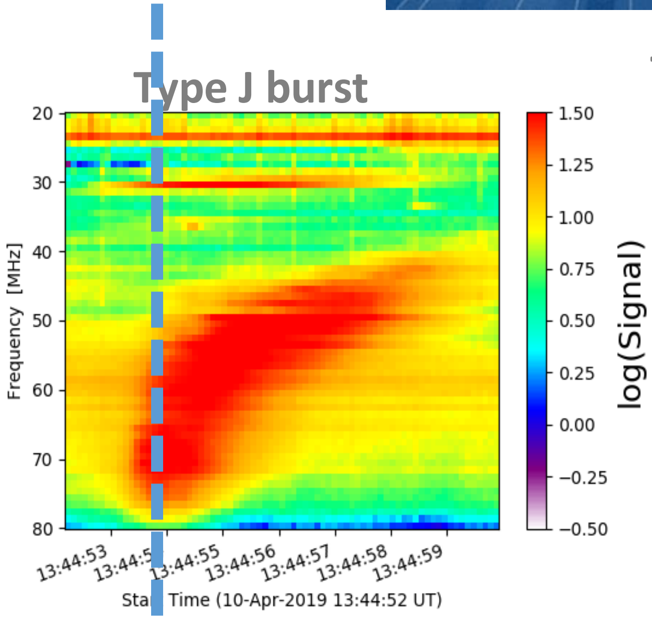
Type III bursts are signatures of accelerated electrons travelling along open magnetic tubes.

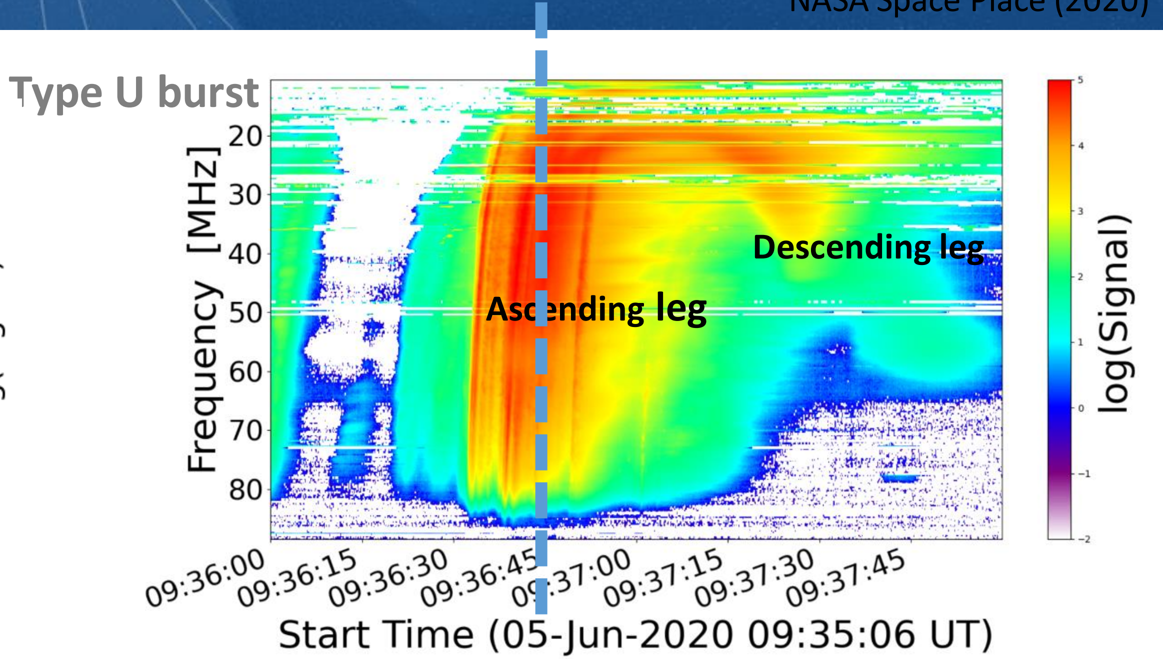
U-bursts and J-bursts

U-bursts and J-bursts (subgroup of Type III bursts) are signatures of accelerated electrons traveling along closed magnetic loops. (Were first reported by Maxwell and Swarup in 1958.)









Motivation 1:

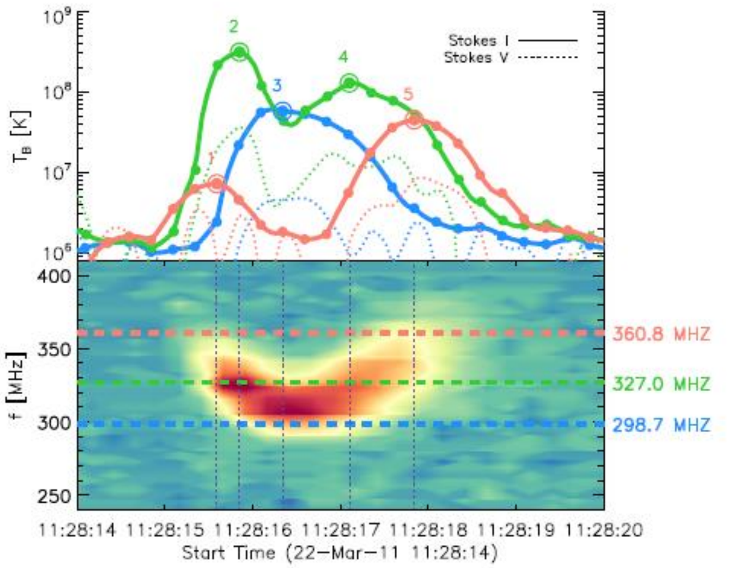
- **Large coronal loops reached middle corona has been poorly studied due to observational difficulties. (Middle corona: 1.5 to 6 $R_\odot$,** See Matthew J.West 2023**)**
  LOFAR LBA observed 20-80 MHz, ~1.5 to ~2.5 $R_\odot$

- **Not many U-bursts studies using radio images**. (e.g. Labrum & Stewart 1970, Sheridan et al 1973, Stewart & Vorphal 1977, Suzuki 1978, Aschwanden et al 1992, Aurass and Klein 1997, Reid & Kontar 2017, , Mancuso et al 2023).

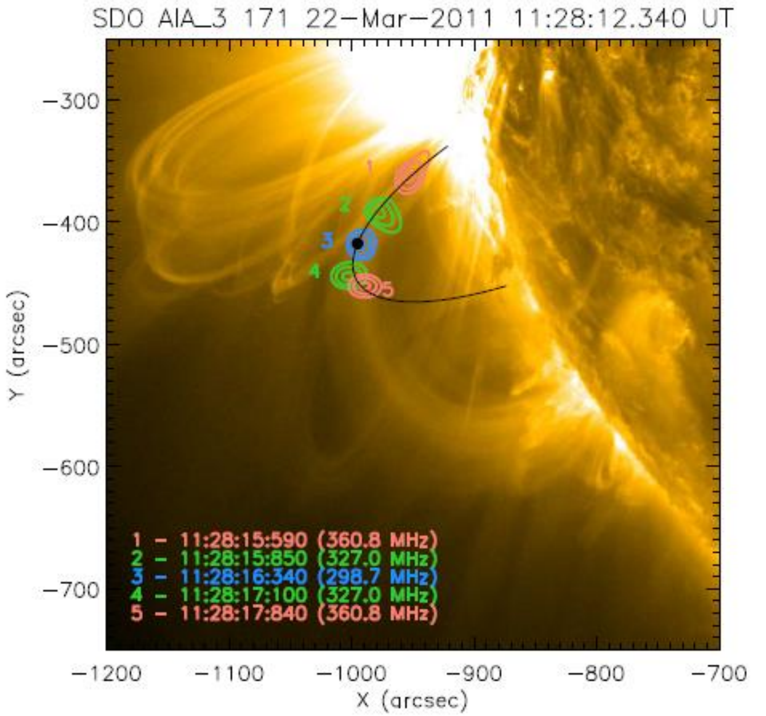
- **Previous U-bursts imaging have been limited by the number of frequency channels.** (e.g. Stewart & Vorphal 1977 used 80 and 130 MHz from Culgoora radioheliograph. Most recently, Mancuso et al 2023 used 3 frequencies at 298,327and 360 MHz, NRH)

- **In 'low-frequency' range, 10-90MHz, U-bursts imaging studies haven't involved the descending leg very well.** (e.g. In Reid & Kontar 2017 study, the U-burst has weak and defuse descending leg.)

By imaging a U-burst between 20 to 80 MHz that has clear and strong descending leg (20-40 MHz), This study is the first time to observe both upward and downward legs of a such large sized coronal magnetic loop reaches the middle corona with high resolution imaging spectroscopy.



Mancuso et al, 2023



Motivation 2:

- **Electron beam velocities** can be estimated from frequency drift rate by assuming a coronal density model and the loop geometry. Electron beam velocities of type U bursts from 0.2 to 0.25c (e.g. Labrum & Stewart (1970); Reid & Kontar (2017)…).

Drift rate ← $$\frac{df}{dt} = \frac{df}{dn}\frac{dn}{dr}\frac{dr}{dt}$$ → *Electron beam velocity*

- **Coronal loop physical parameters** including background coronal plasma density scale height (**λ**), loop top plasma temperature (**T**), pressure (**P**) and minimum magnetic field strengths (**B**). (e.g. Aschwanden et al. (1992) ; **Zhang et al (2023)…**)
- **The standard coronal density models are not applicable to the descending leg of the U-burst due to the curved loop structure.** **Radio imaging is the solution.**

Infer plasma density model: $$n_e(h) = n_0 \exp\left(\frac{-h}{\lambda}\right)$$

Temperature $$T(r) = \frac{\beta}{1+\alpha}\frac{m_P \lambda g_{\mathrm{Sun}}(r)}{k_B}$$

Pressure $$P(h) = n_e(h) k_b T(h)$$

B field strength $$B(h) > [8\pi n_e(h) k_b T_e(h)]^{0.5}$$

By imaging the U-burst and use the centroid positions, we derived electron beam velocities and loop physical parameters to answer questions:

1. **Does the beam velocity remains constant?**
2. **Does loop's physical parameters varying along such large size coronal loop?**

The U-burst on Dynamic Spectrum

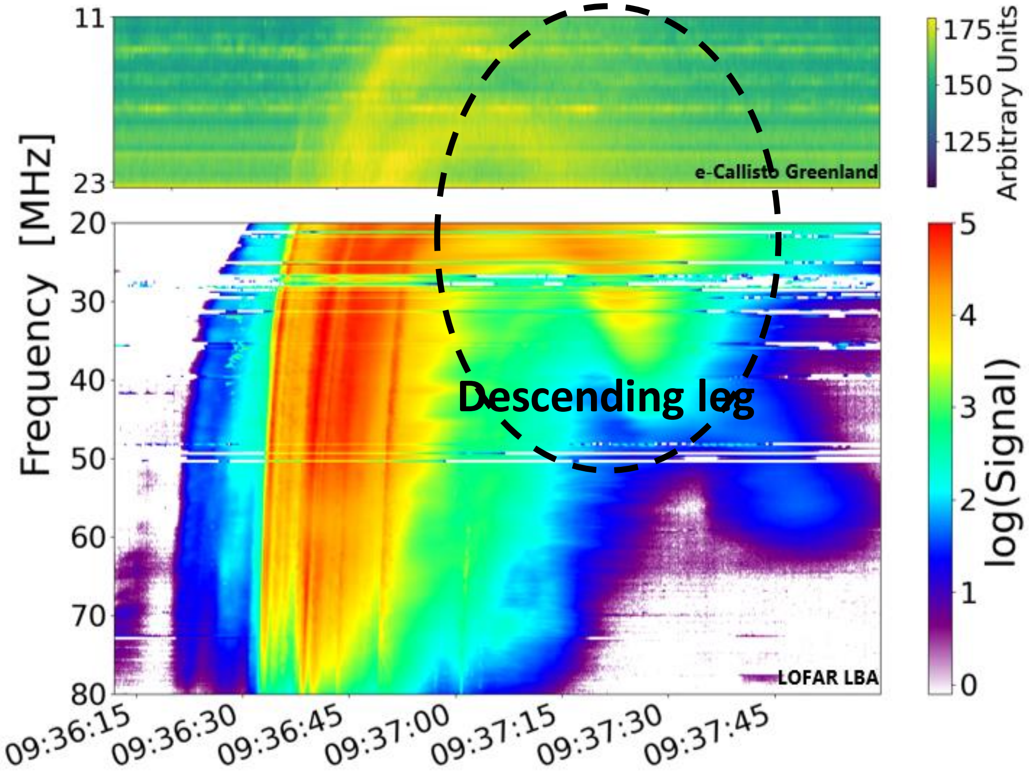
- The U-burst dynamic spectrum was detected by LOFAR from 20 - 80 MHz.

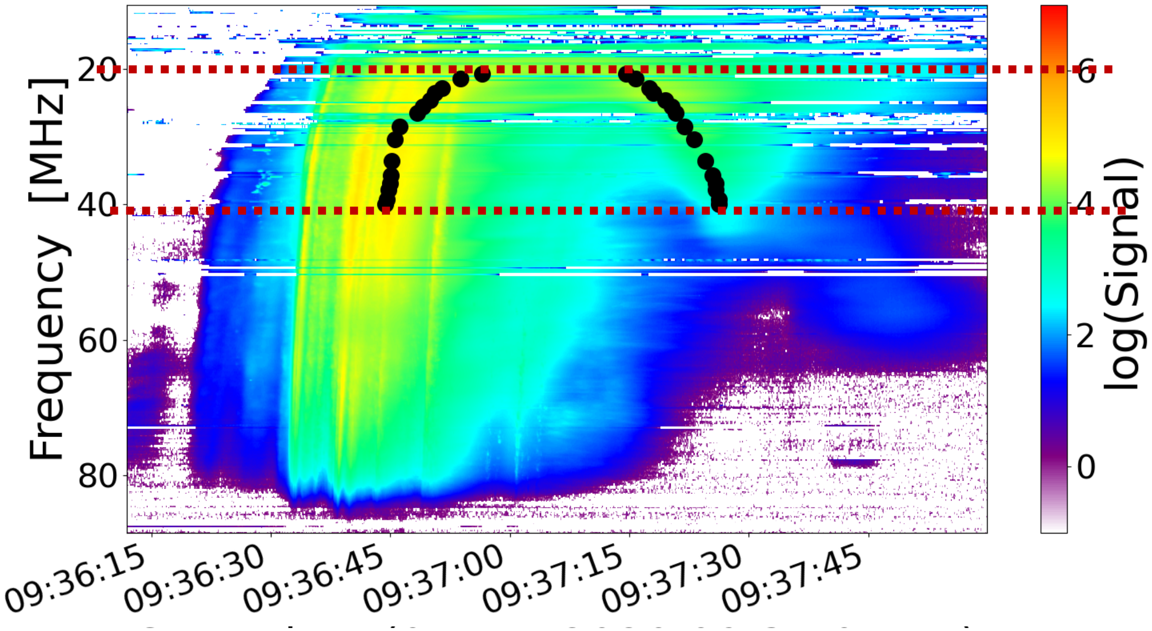
  05-June-2020, 09:36:30 UT.

- The spectrum shows a clear signal from the descending leg (20 - 40 MHz), which is not typically observed.

- Many type III bursts preceding the U-burst.

- The black dots on the bottom panel show the maximum flux points we selected from each frequency band for identifying the time profile of the ascending leg and descending leg between 20 - 40 MHz. We used them to identify the imaging time intervals.





U-burst Polarizations:

- The event was observed by the NDA with polarization measurement.

(NDA NewRoutine-Mefisto data)

- Compared to type III bursts in this event, The U-burst has a weaker (≲|0.2|) polarization degree.

- The ascending leg and descending leg have opposite polarization degrees.

- The polarization reversal is caused by the electrons changing their angle to the magnetic field.

- Low polarization degree implies **Second-Harmonic emission**!

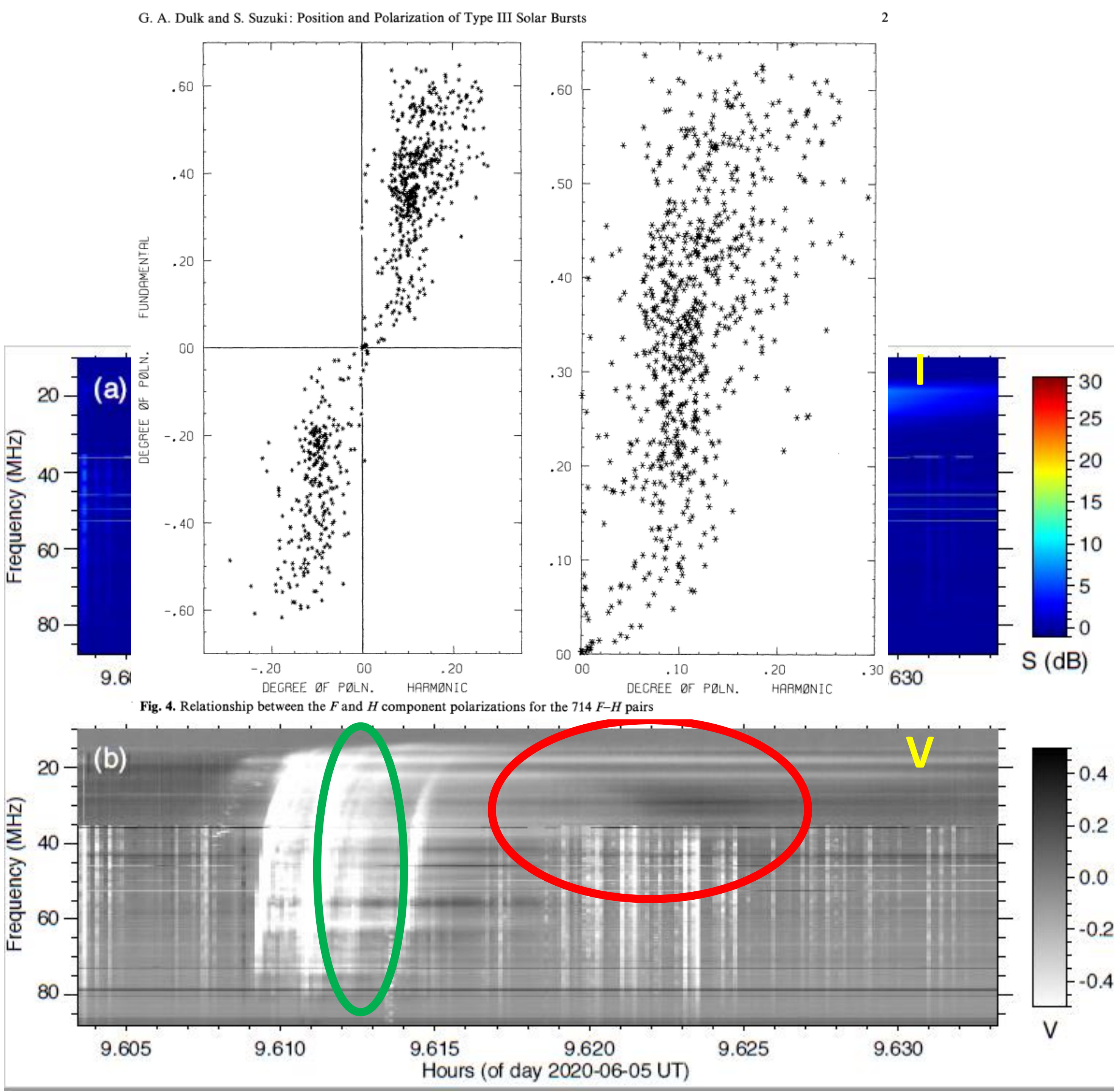
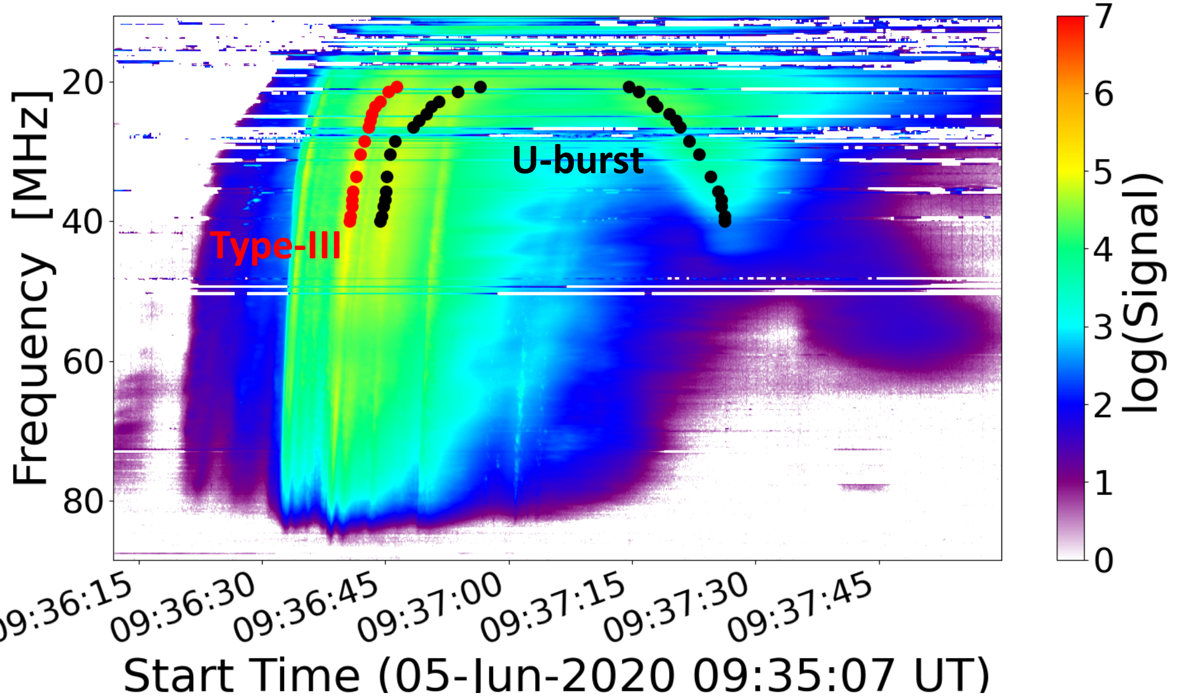
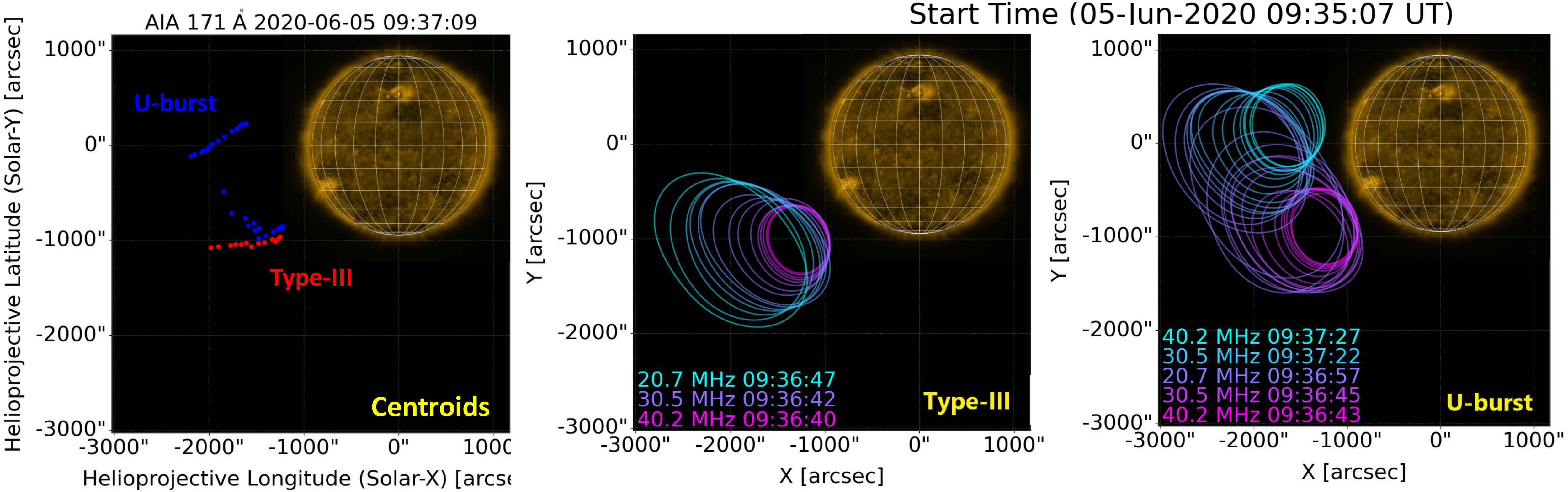


Fig. 4. Relationship between the *F* and *H* component polarizations for the 714 *F–H* pairs

U-burst Interferometric Imaging:

- We have imaged the U-burst primarily between 40 and 20 MHz to capture the curvature of the magnetic loop.
- 30 maximum flux points defined by the selected time intervals from 15 frequency subbands. (20.70 – 40.03 MHz)
- 50% contours. (FWHM source size)





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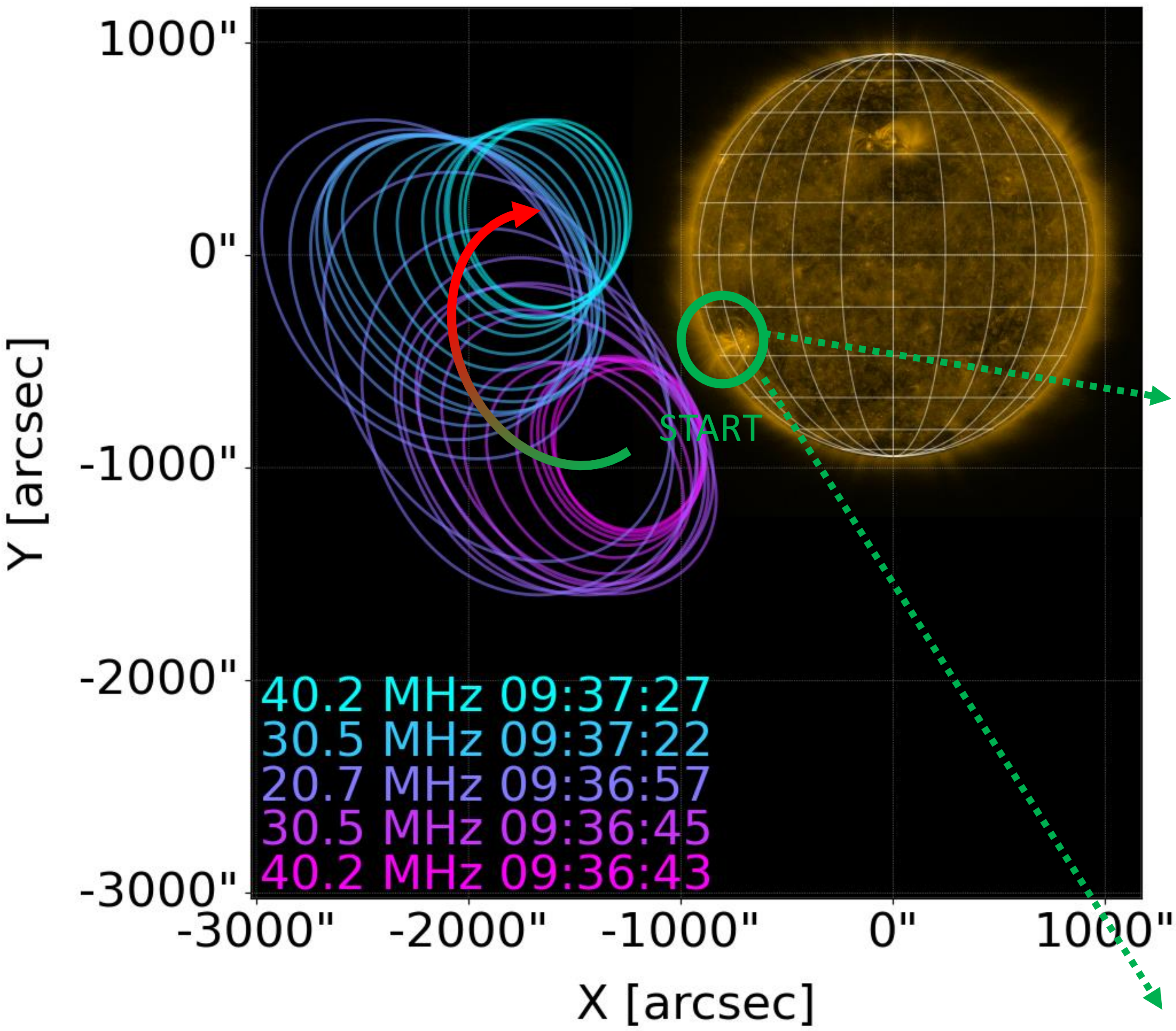
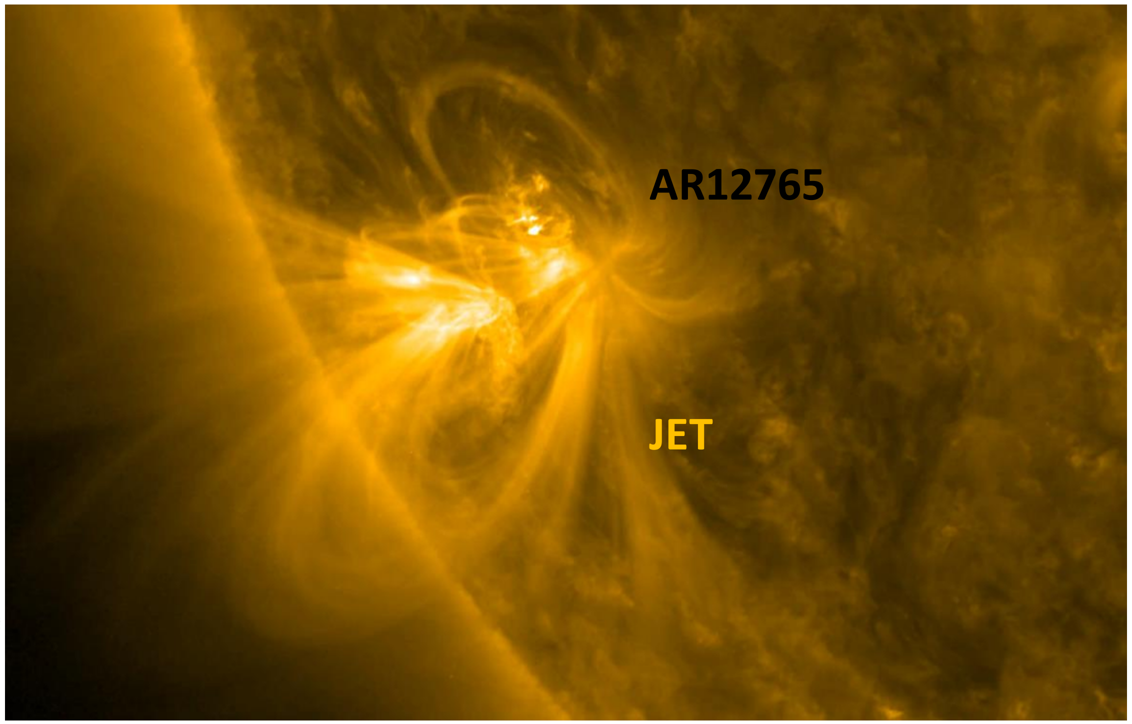


The U-burst electron beam accelerated by the active region AR12765, and the descending loop pointing to the Northern polar and active region.



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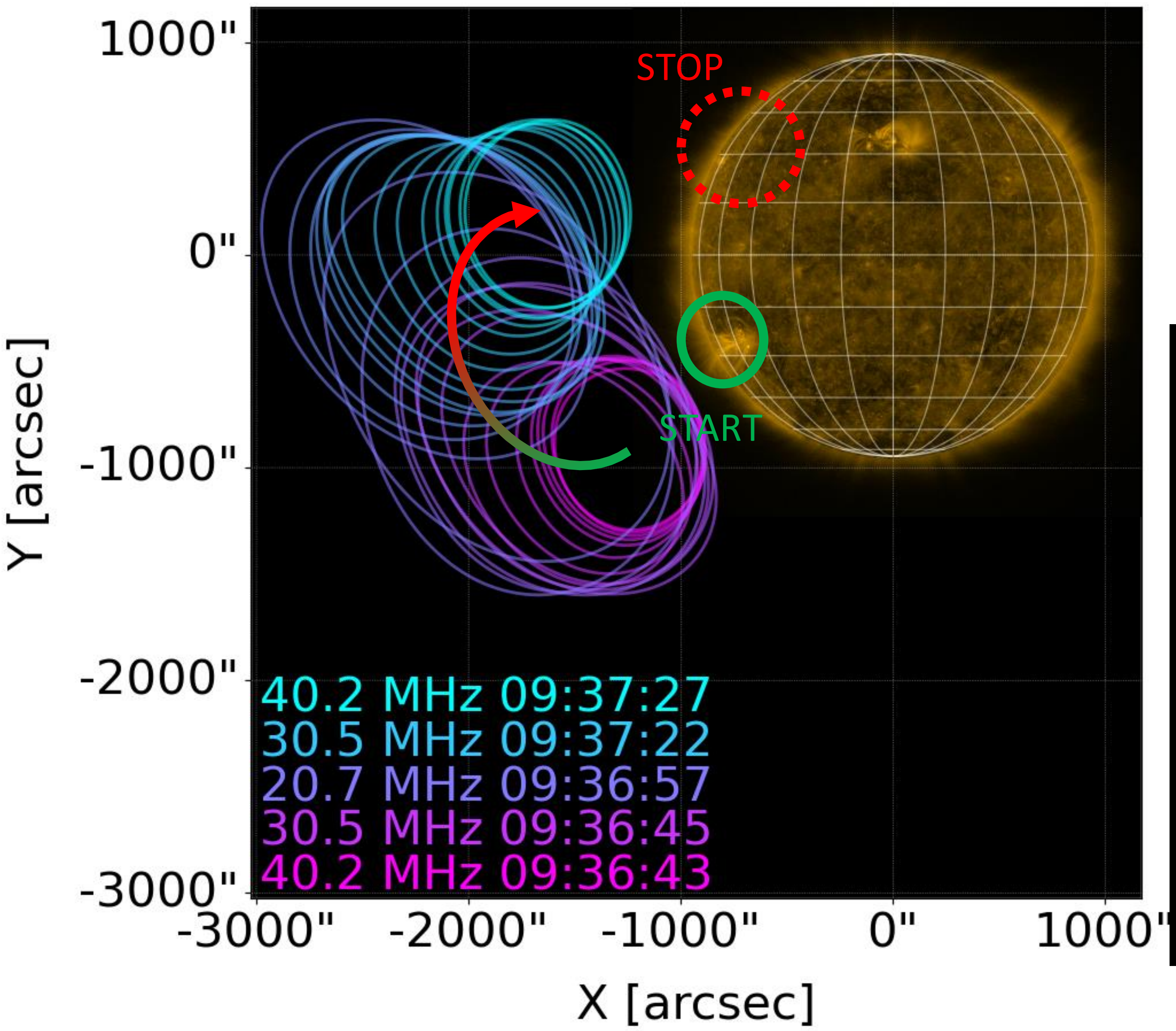

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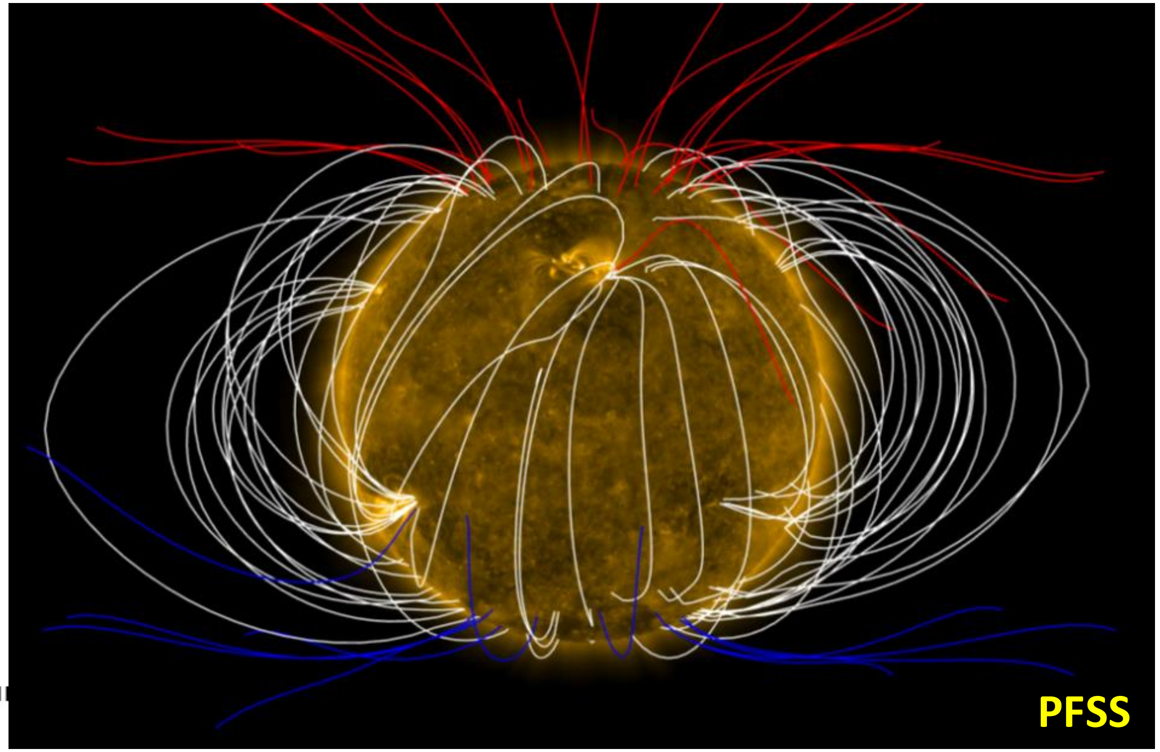
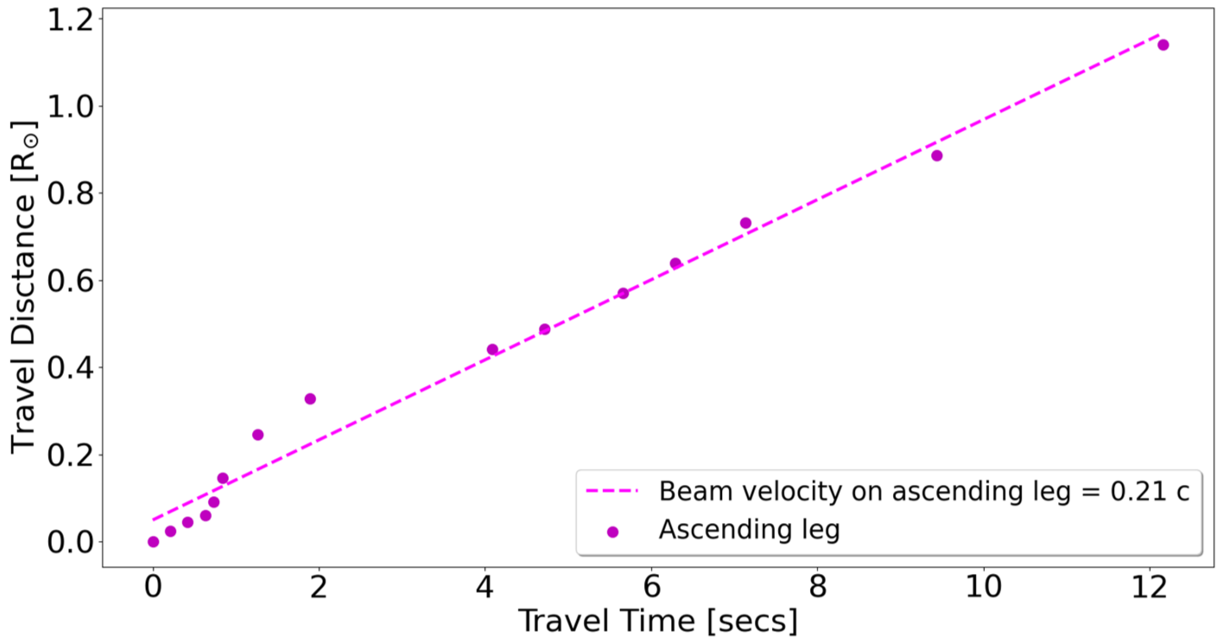


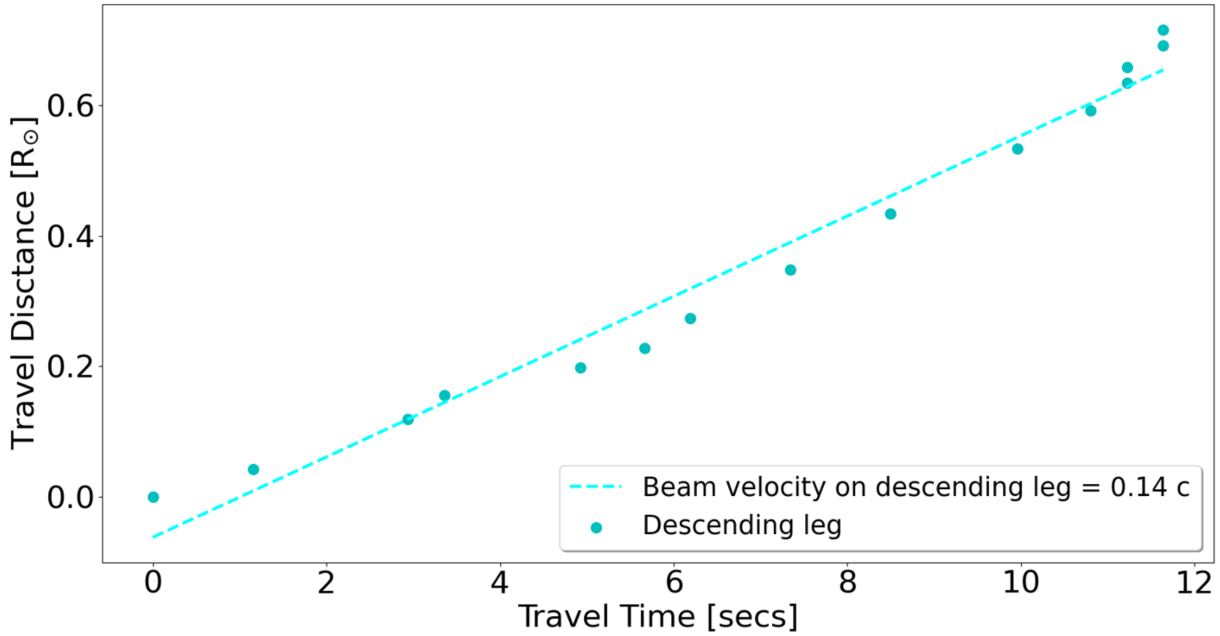
Electron Beam Velocities:

We determined electron beam velocities from the distance between radio source centroids in the image verses travel time.

We assumed radio sources on the same leg distribute on the same longitudinal plane. (AR12765 or on the limb)

We found that the beam velocity on the ascending leg was 0.21c (the speed of light), while it was 0.14c on the descending leg. We reported that the electron beam **decelerated** while traveling along the coronal magnetic loop.





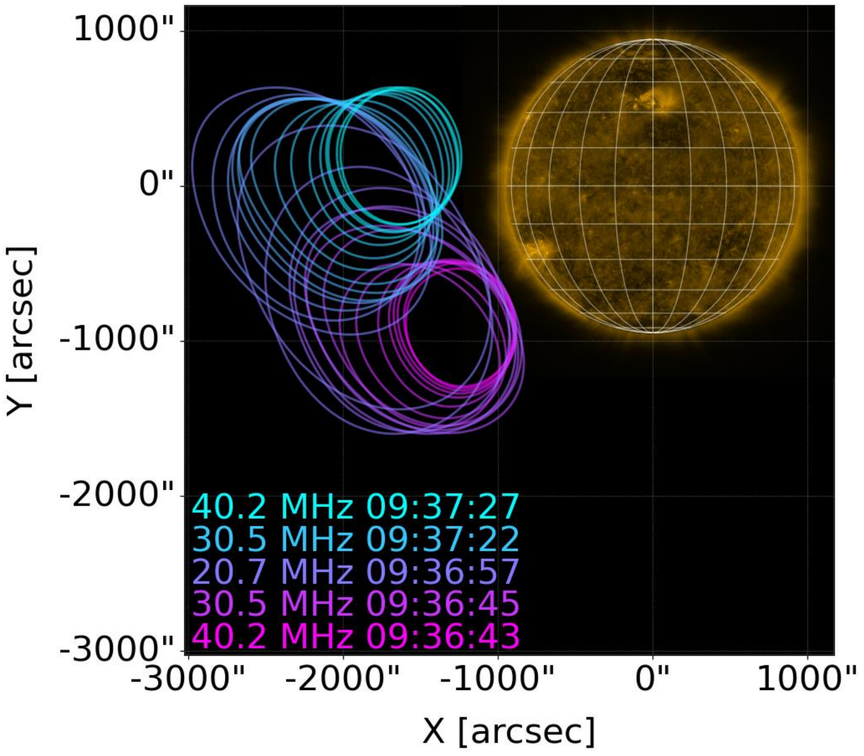
Radio Source Size:

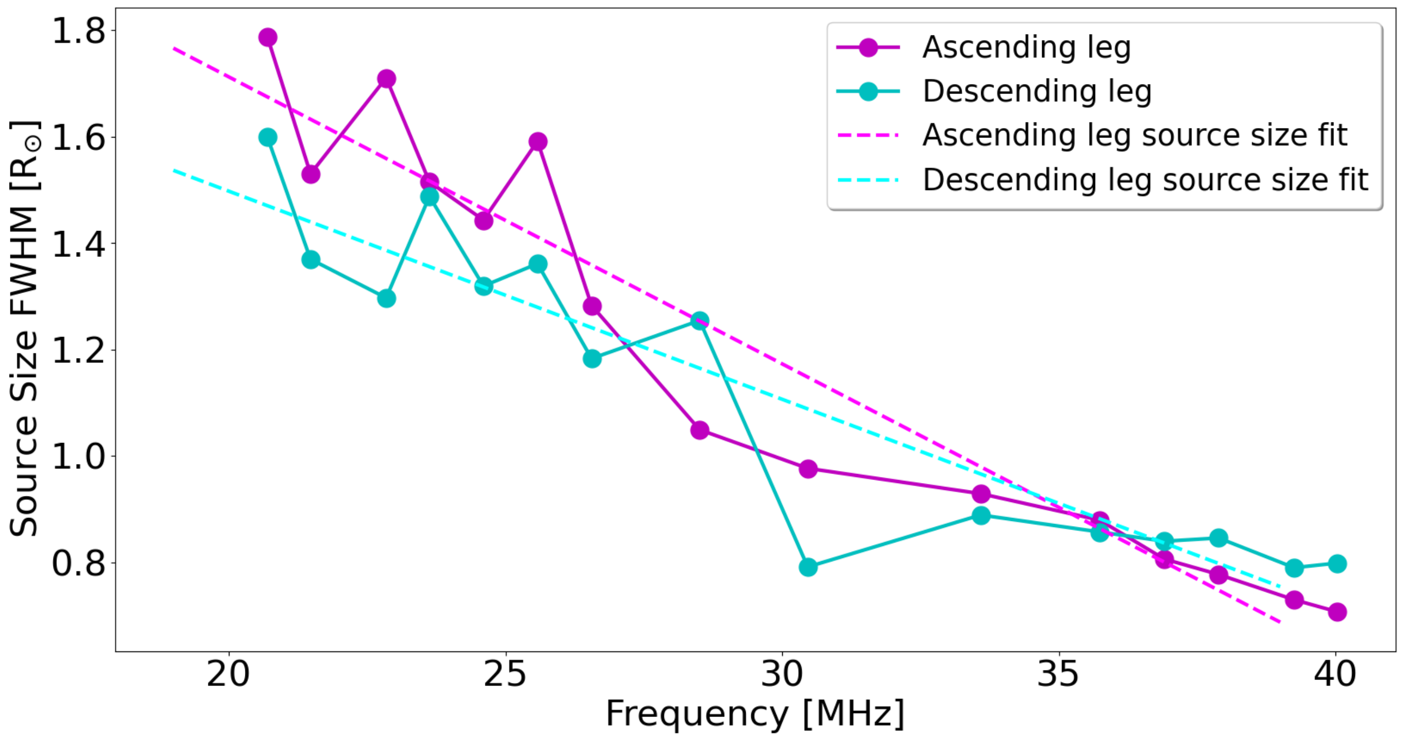
The change in the radio source size can reflect the change of the loop cross-section, that is an important loop geometry characteristics.

The size of the radio source increased while the electron beam was traveling along the ascending leg , and decreased while it was traveling along the descending leg.

At a **similar rate.**

We also found that the radio source size are similar on both leg.





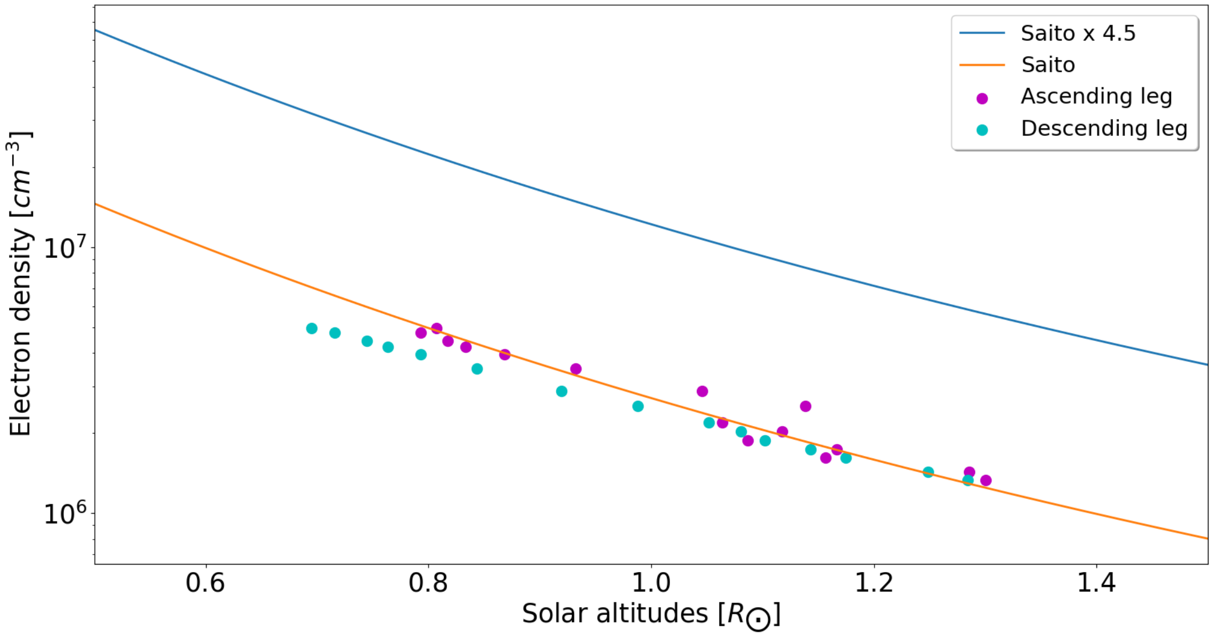
Coronal Loop Physical Parameters:

This study	Ascending	Descending
Second-Harmonic	Image (V from fit)	Image (V from fit)
Loop apex altitude (from photosphere)	1.3 $R_\odot$	1.3 $R_\odot$
Beam velocity	0.21 c	0.14 c
Density Scale height	0.38 $R_\odot$	0.43 $R_\odot$
Temperature	1.43 MK	1.71 MK
Pressure [mdyn cm^{-2}]	0.6	0.7
Magnetic field strength [G]	0.12	0.13

symmetrical loop

We inferred coronal loop plasma density model directly from the LOFAR image.

Ascending and descending leg have similar plasma parameters.



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Zhang et al. (2023) 1.37$R_\odot$ — *Aschwanden et al. (1992)* 0.18$R_\odot$

Plasma Parameters	Large Coronal Loops	Small Coronal Loop
Density scale height	0.36 ± 0.07 $R_\odot$	0.51 ± 0.09 $R_\odot$
Density	$(4.5 \pm 1.4) \times 10^6$ cm^{-3}	6.3×10^9 cm^{-3}
Temperature	1.0 ± 0.2 MK	7.0 ± 0.4 MK
Pressure	0.0007 ± 0.0003 dyn cm^{-2}	6.1 ± 0.4 dyn cm^{-2}
Minimum magnetic field strength	$\geq 0.13 \pm 0.03$ G	≥ 12 G

Conclusions:

- We imaged the U-burst using LOFAR interferometric images, finding a large structure around 1.3 solar radii in altitude.

- The U-burst is Second-Harmonic emission, classified by the NDA polarization measurements. The ascending leg and descending leg have opposite polarization degree, as expected.

- Electron beam velocity appears to decrease over the course of the coronal loop. From 0.21c (ascending leg) to 0.14c (descending leg).

- Radio source expanded and contracted on both legs at a similar rate.

- Ascending and descending leg have similar plasma parameters, suggesting a symmetrical loop. (Average T=1.57$\pm$0.15MK, P= 0.65 mdyn cm^{-2}, B > 0.12G)

Extra Discussions:

- **Scattering effect:**
  - The observed radio sources positions dragged away from the solar disk. However, it doesn't affect the velocity estimations.
  - The 30-35MHz FWHM scattering radio source size (major axis of elliptical source)at around 1 $R_\odot$. (see Kontar et al. 2019)
  - The U-burst is second-harmonic emission, scattering effect might not significant.

- **Projection effect:**