Solar surges related to UV bursts:

Characterization through k-means, inversions, and density diagnostics.

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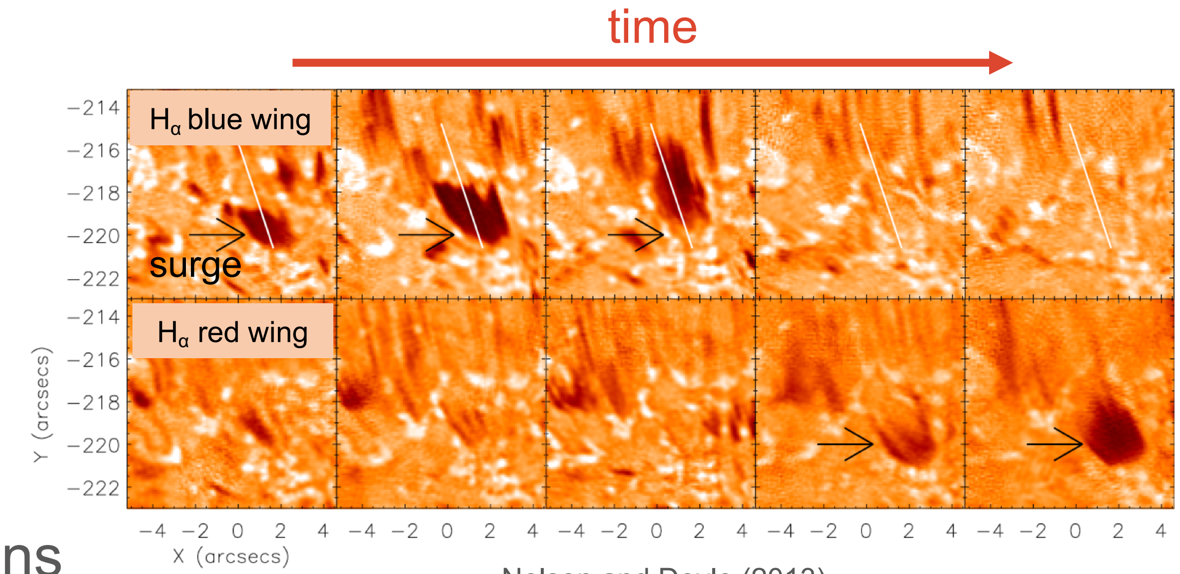
What is a surge?

Chromospheric ejection traditionally observed in H_α as blue-redshifted absorption (also observed in other lines like Ca II H&K, Ca II 8542Å, or He I 10830Å).

Observational properties

Velocities	20-50 km/s
Length	10-50 Mm
Lifetime	~10-60 min



Nelson and Doyle (2013)

They consist of thread-like structures and can be recurrent and have rotational motions

(e.g., Newton 1942, Roy 1973, Kurokawa and Kawai 1993, Schmieder et al. 1995, Canfield et al. 1996, Chae et al. 1999, Yoshimura et al. 2003, Liu and Kurokawa 2004, Jiang et al. 2007, Nishizuka et al. 2008, Liu et al. 2009, Yang et al. 2013 , Nelson and Doyle 2013, Vargas Domínguez et al. 2014, Kim et al. 2015, among others)

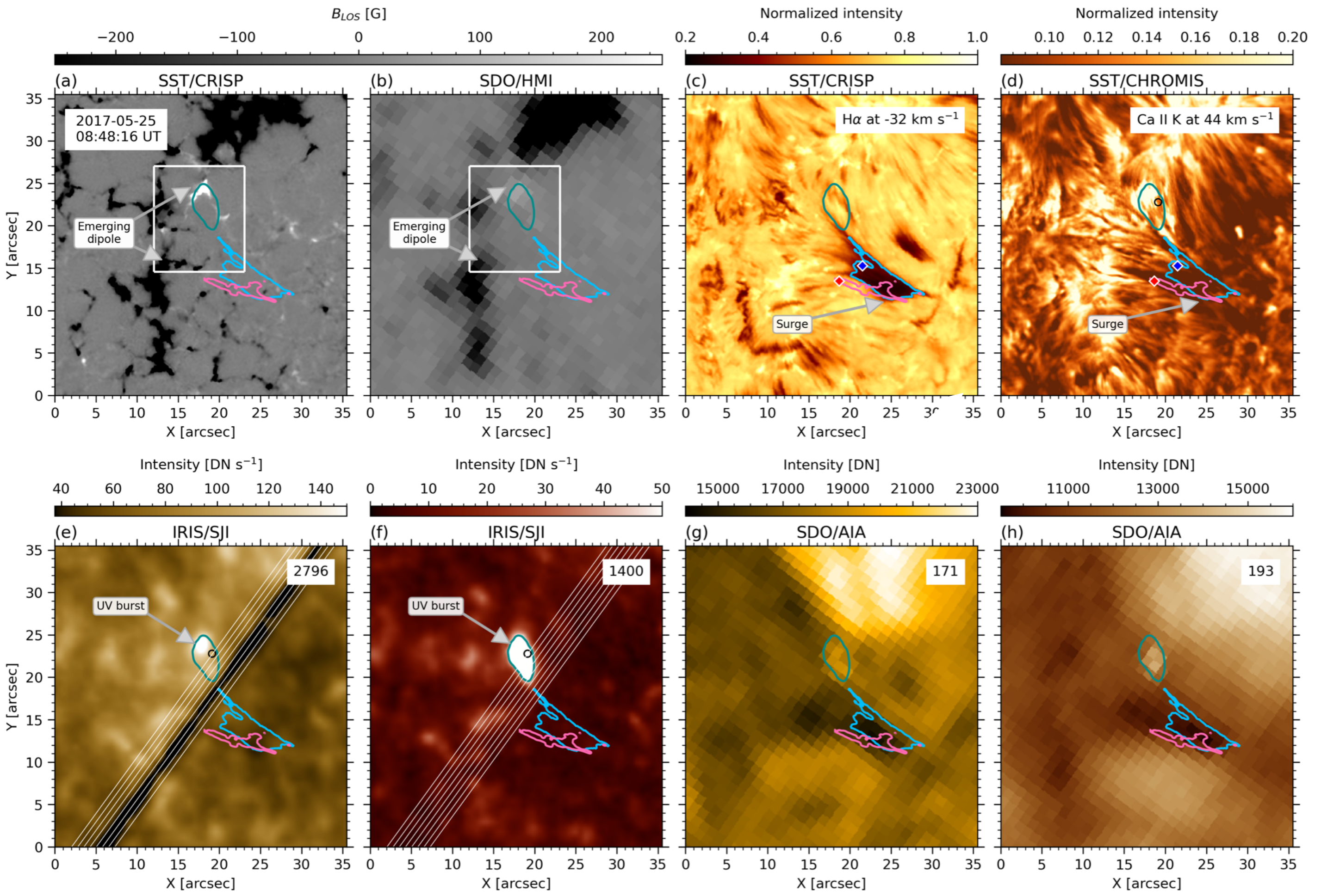
Introduction

- **Why are surges important?**

They are closely related to fundamental mechanisms like magnetic flux emergence and reconnection

(e.g., Kurokawa and Kawai 1993, Chae et al. 1999, Jiang et al. 2007, Kurokawa etal.2007, Brooks et al. 2007, Guglielmino et al. 2010, Wang et al. 2014, Vargas Domínguez et al. 2014, Kim et al. 2015, Yang et al. 2018, Guglielmino et al. 2018, Verma et al. 2020, among others)

Cabello et al. in preparation



Introduction

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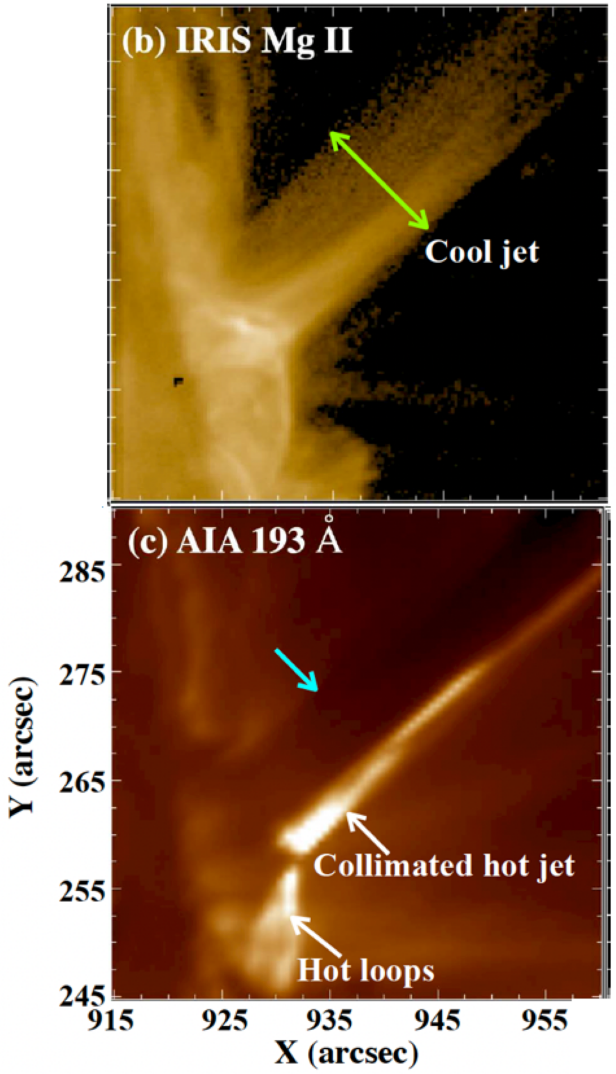
Joshi et al. 2020



Why are surges important?

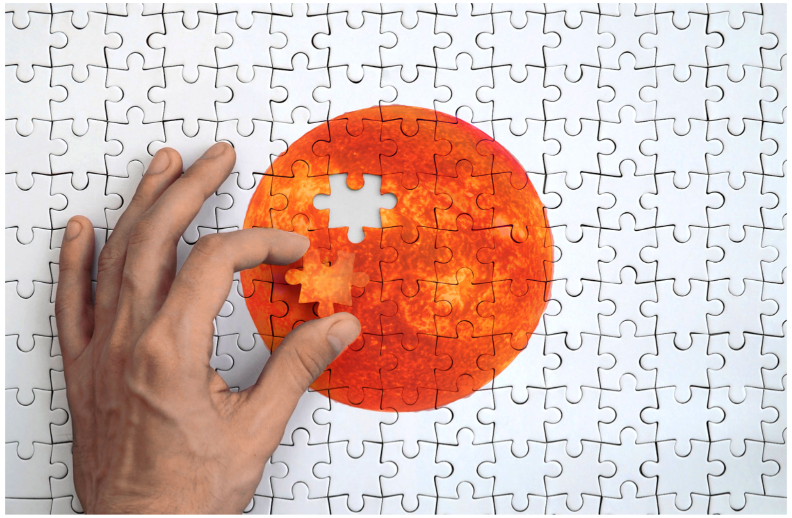
Surges are also associated with many other phenomena:

- Explosive events (EEs)
  (e.g., Madjarska et al. 2009, Nelson and Doyle 2013, Huang et al. 2017)
- Ellerman Bombs, UV Bursts
  (e.g., Watanabe et al. 2011, Vissers et al. 2013, Kim et al. 2015, Nóbrega-Siverio et al. 2017, Ortiz et al. 2020)
- UV, EUV, X-ray jets
  (e.g., Schmieder et al. 1995, Canfield et al. 1996, Chen et al. 2008, Zhang and Ji 2014, Joshi et al. 2020)
- Flares
  (e.g., Wang and Liu 2012, Huang et al. 2014, Schrijver and Higgings 2015)

Introduction

- **Surges are essential for the solar atmosphere puzzle**

  Understanding them will allow us to get a complete perspective of the solar atmospheric ejective and eruptive phenomena

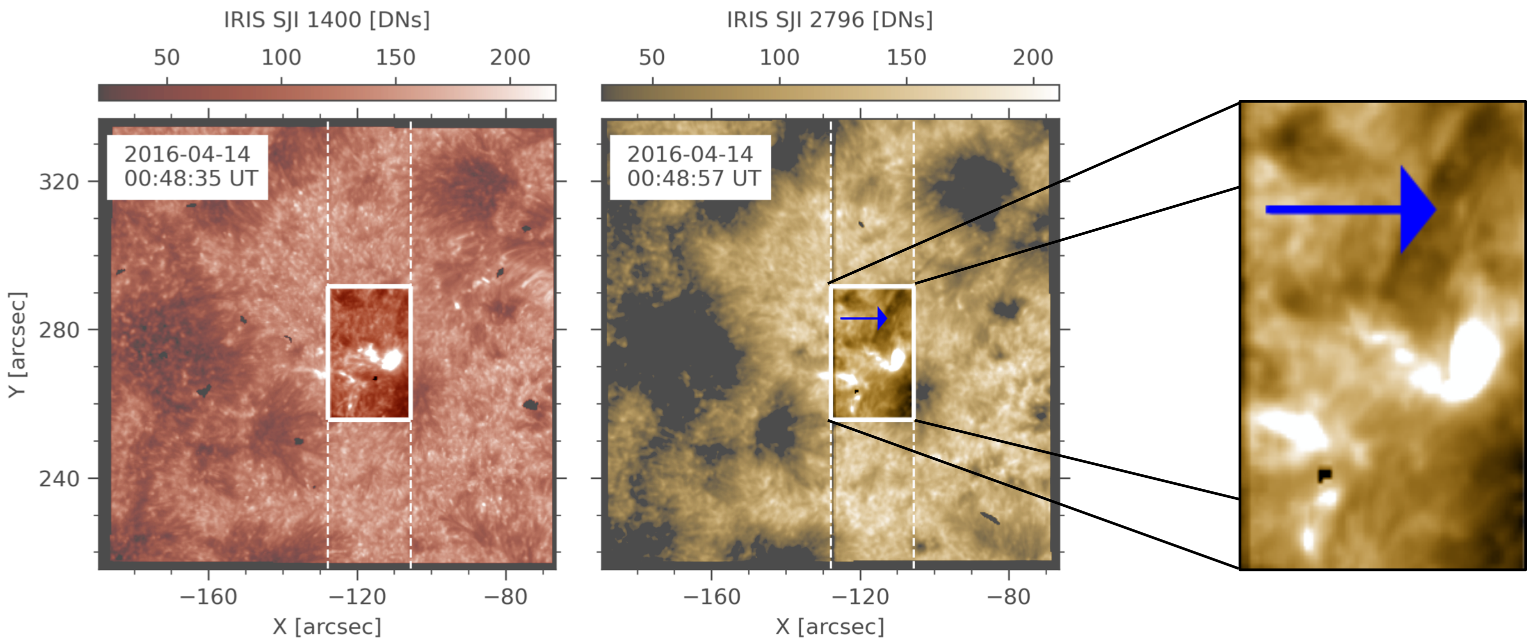


- **There are still fundamental open questions,**

  e.g., the characteristic densities and temperatures of surges

Observations and methods

Episode of recurrent surges and UV bursts observed with IRIS:



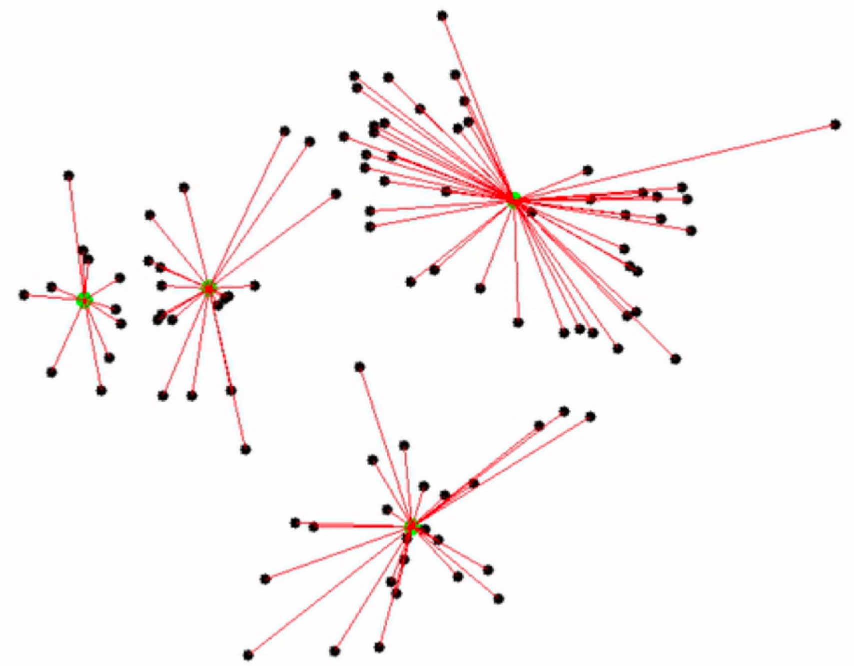
We study	Lines	Method
Low- and mid– chromosphere	Mg II h&k	k-means clustering algorithm. Inversions with the STIC code.
Transition region counterpart	O IV 1399.8 Å O IV 1401.2 Å	Density diagnostics

k-means:

- *k*-means is a clustering algorithm that classifies a set of *n* samples in *k*-disjoint groups (or clusters) of equal variance, minimizing the inertia:

$$\sum_{i=1}^{n} \sum_{j=1}^{k} \min\left(\left\|x_i - \mu_j\right\|^2\right)$$

Inertia is also know as the within-cluster sum-of-squares.



- *k*-means can be easily adapted to group line profiles.

(see, e.g., Pietarila et al. 2007; Viticchié & Sánchez Almeida 2011; Sánchez Almeida & Allende Prieto 2013; Panos et al. 2018; Sainz Dalda et al. 2019; Bose et al.2019; Joshi et al. 2020)

https://github.com/dnobrega/DNS/blob/master/dnspy/notebooks/k_means_test.ipynb

Analysis of Mg II h&k

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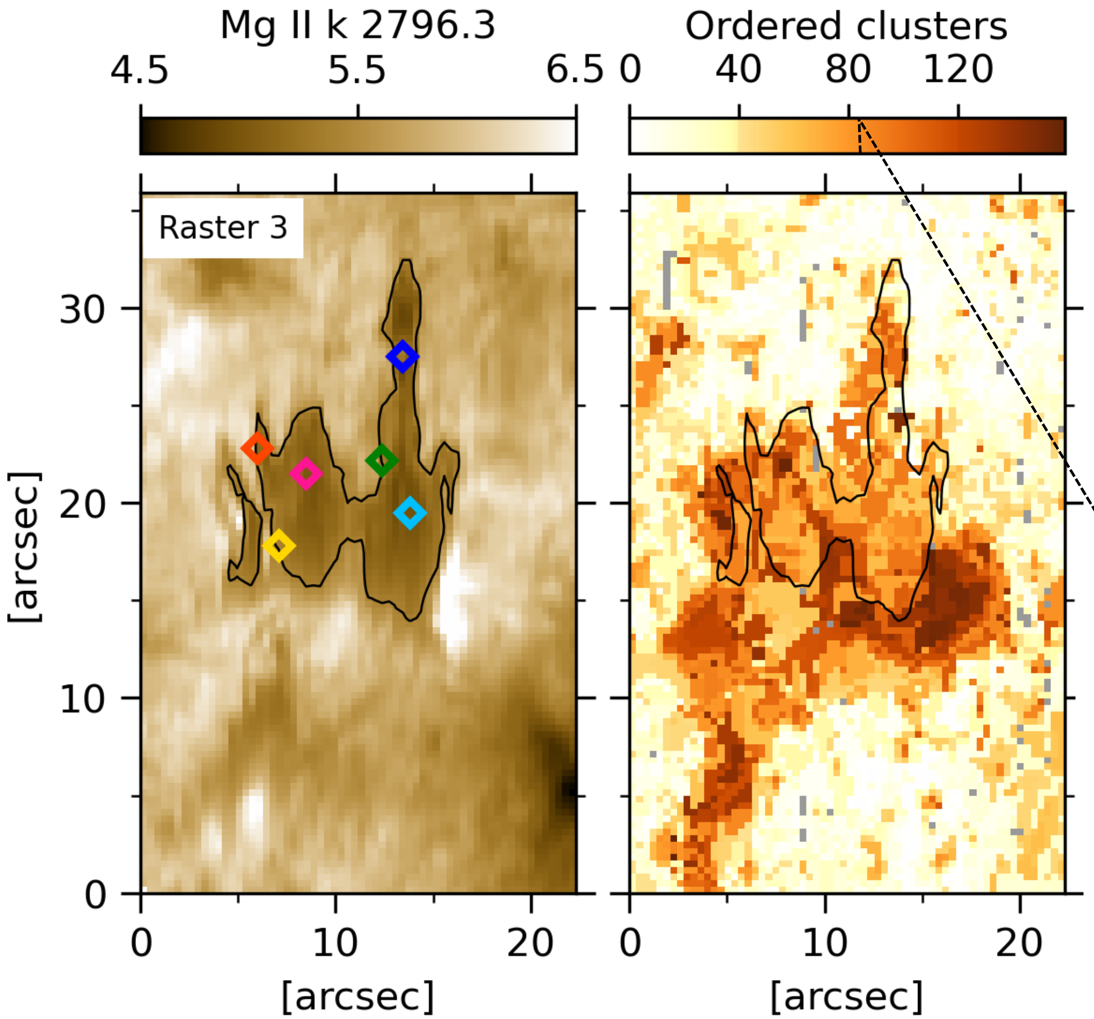
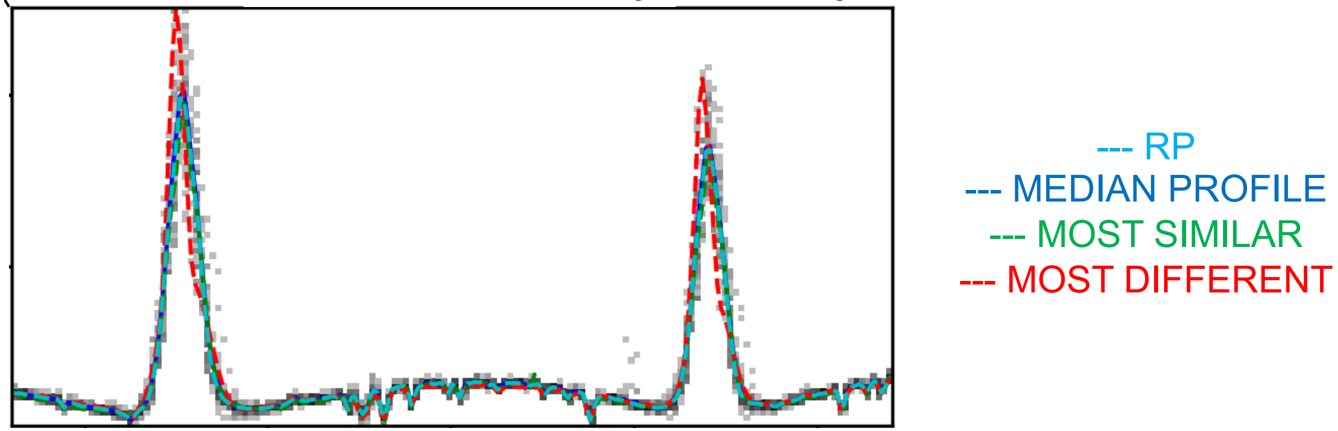


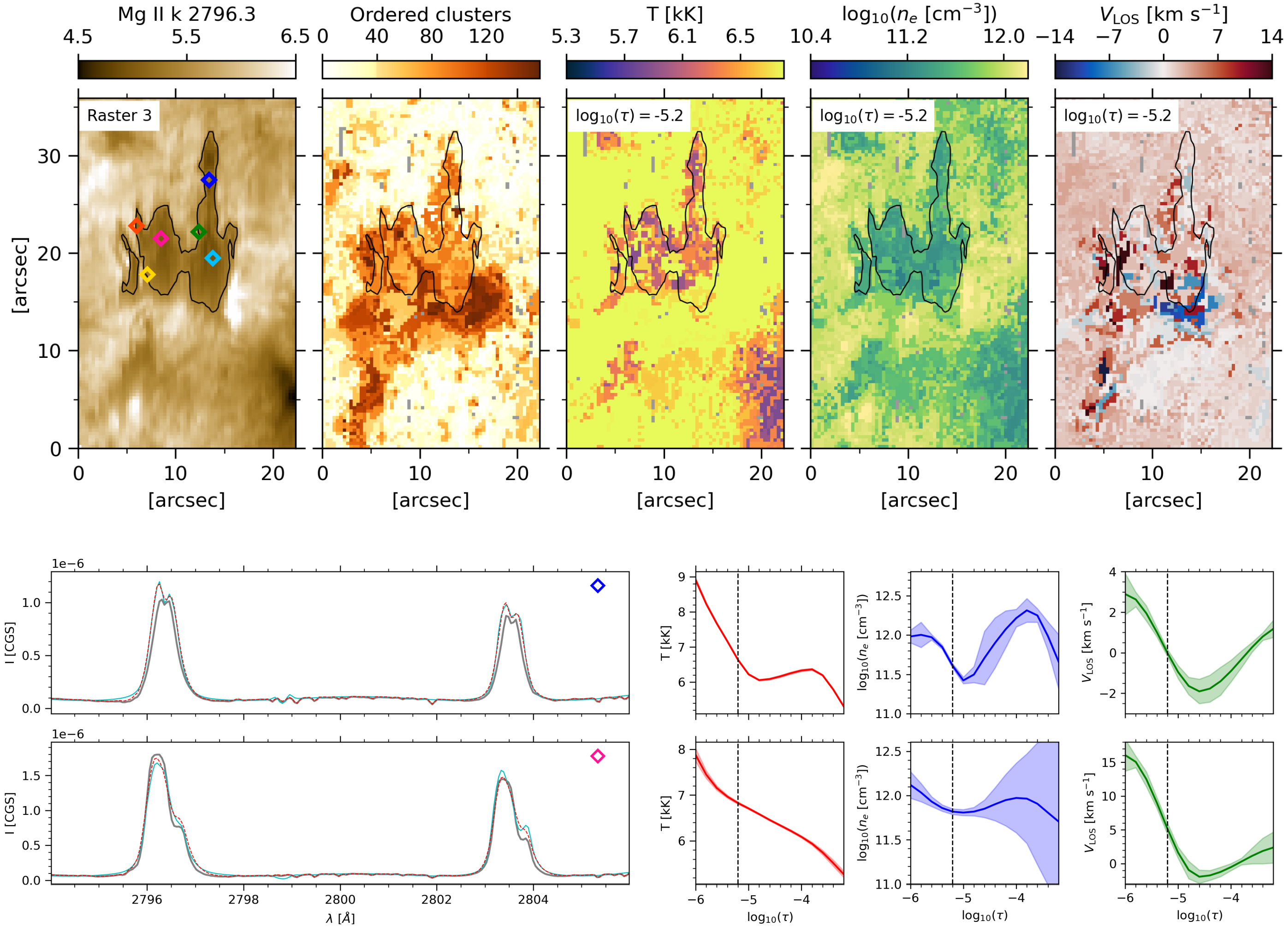
k-means:

- We can group similar Mg II h&k line profiles, identifying solar regions with similar properties.
- We find that k=160 is an optimum number of clusters.
- We reduce a factor 43.2 the original number of profiles that would be necessary to analyze.



Example: Cluster 83 contains 30 profiles

Analysis of Mg II h&k



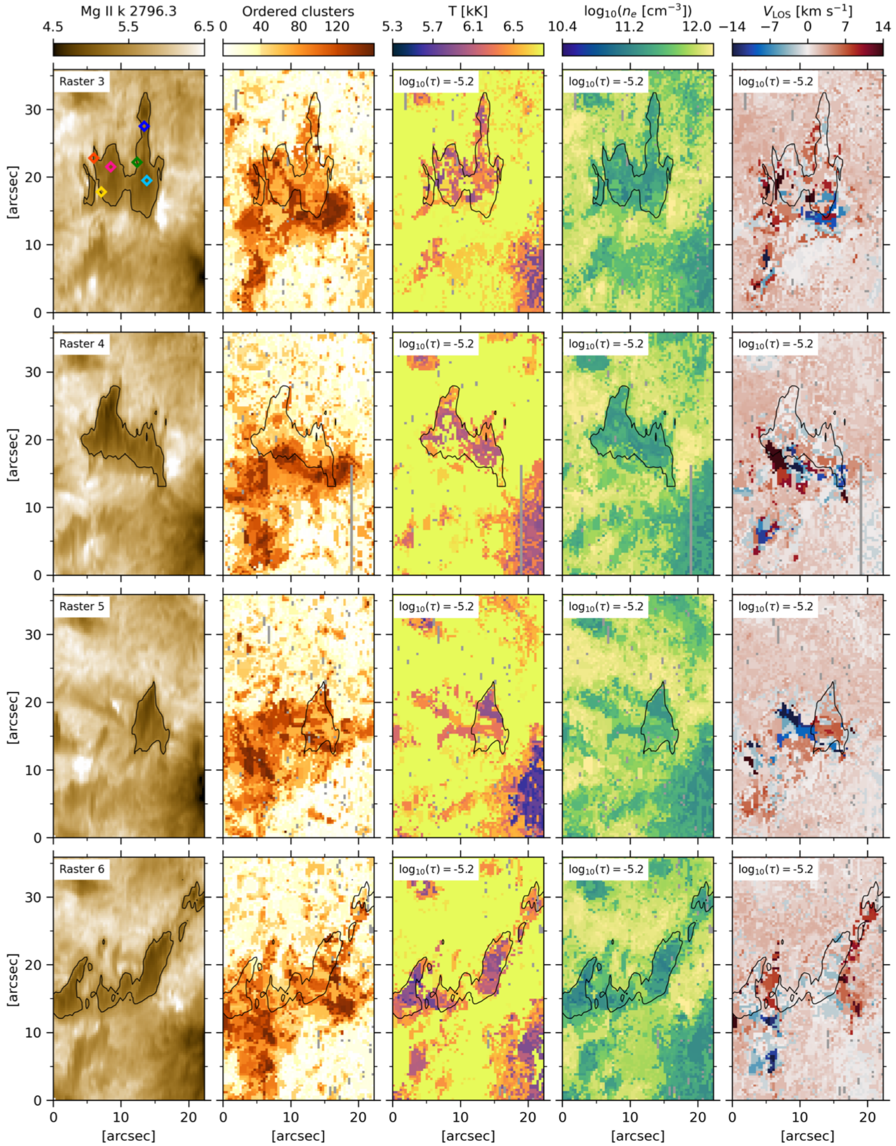
Mg II h&k inversions:

- The STIC[1] code assumes NLTE and includes partial frequency redistribution effects of scattered photons.
- Inversion scheme with 4 cycles:

	Nodes			
	1st cycle	2nd cycle	3rd cycle	4th cycle
Temperature	4	7	9	9
V_{LOS}	3	4	7	9
$V_{microturbulence}$	3	4	4	6

[1] STIC = STockholm Inversion Code (de la Cruz Rodríguez et al.2019, 2016): https://github.com/jaimedelacruz/stic

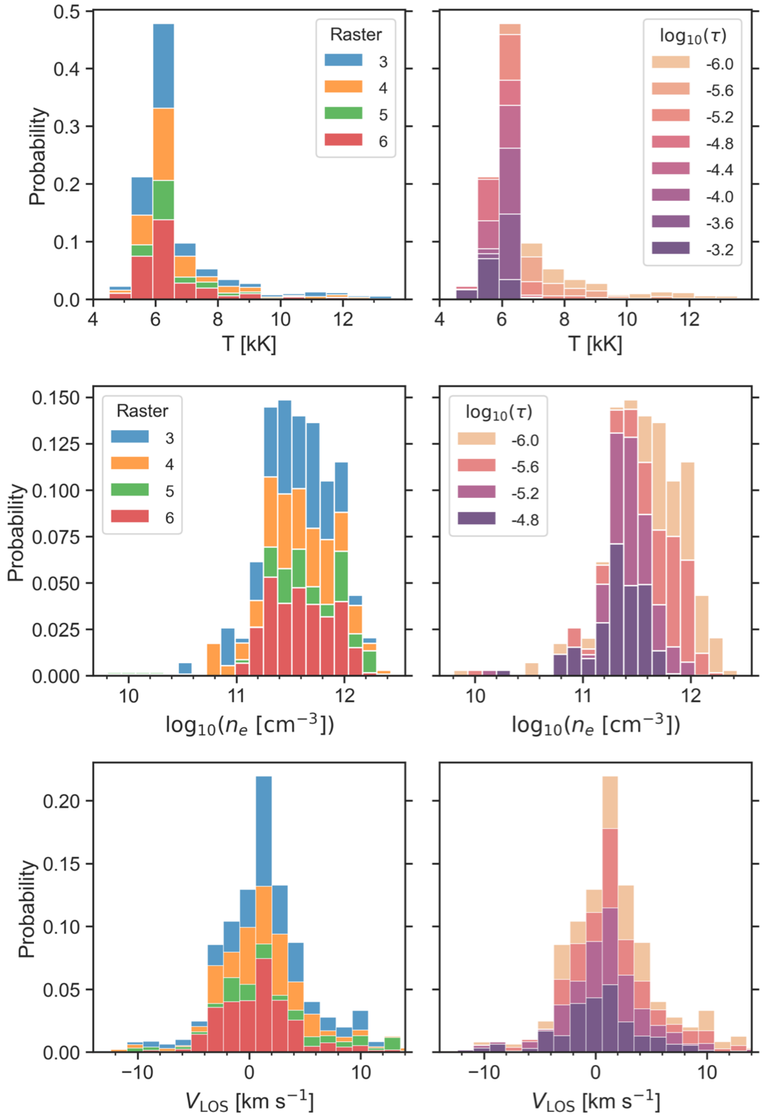
Analysis of Mg II h&k



Mg II h&k inversions:

- We combine *k*-means and inversions to study four different surges.
- We can derive physical properties of these key phenomena at different optical depths.
- We can also perform some statistics about these properties to characterize the surges.

Analysis of Mg II h&k



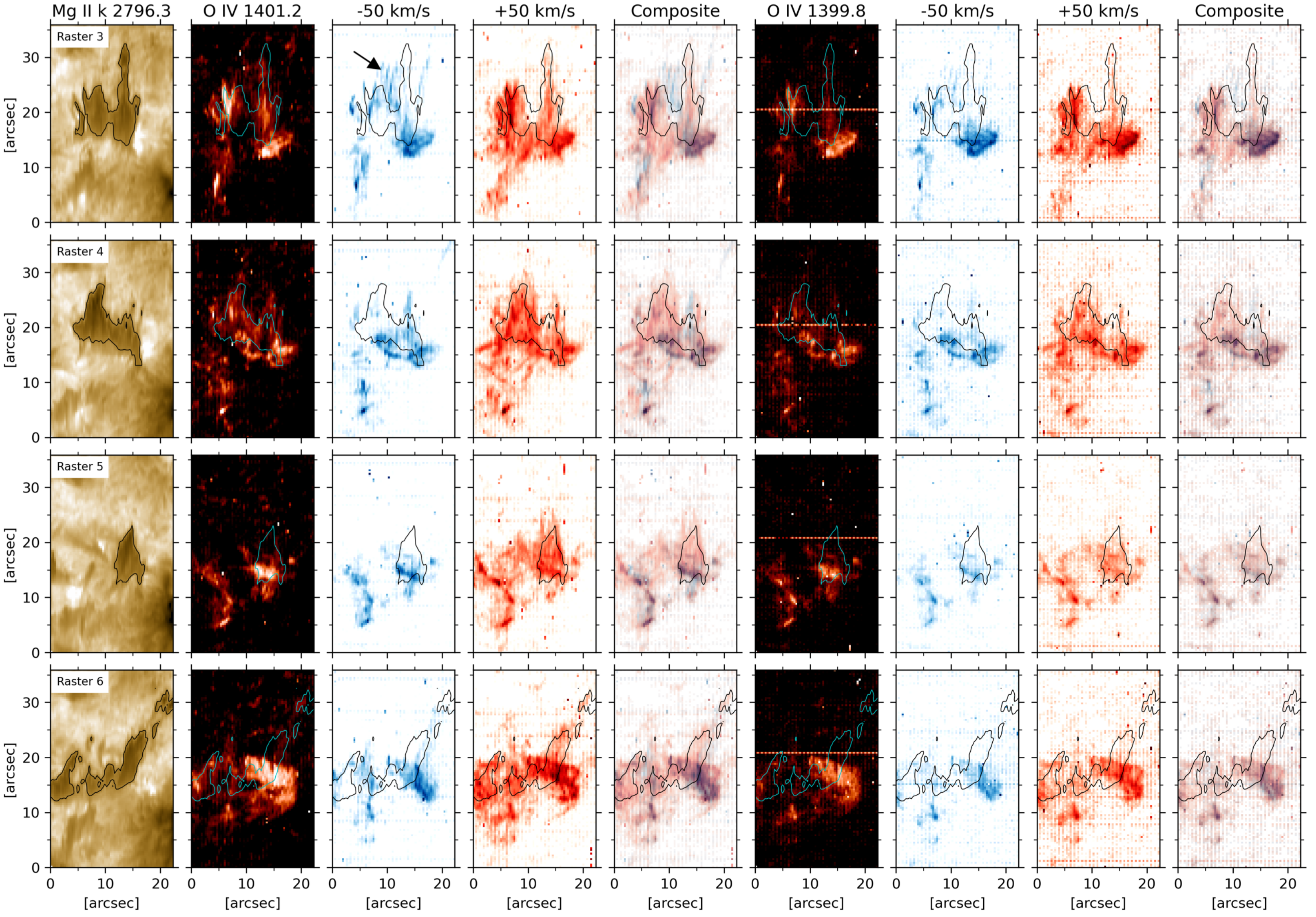
Statistics:

- Most probable temperature within the surges is around $T = 6$ kK, for optical depths between $-6.0 \leq log_{10}(\tau) \leq -3.2$.
- Most reliable results for electron number density, n_e, and line-of-sight velocity, V_{LOS}, are within $-6.0 \leq log_{10}(\tau) \leq -4.8$, with $n_e \sim [1.6\times10^{11}, 10^{12}]$ cm^{-3} and V_{LOS} of a few km s^{-1}.
- The four rasters analyzed show surges with similar properties.
- Cooler plasma with smaller electron number density is located in deeper layers of the surges.

Analysis of the O IV lines

O IV emission:

- We find evidence of enhanced O IV 1399.8 and 1401.2 Å emission within surges.
- This indicates that these phenomena have a considerable impact in the transition region even in the weakest far-UV lines.



Analysis of the O IV lines

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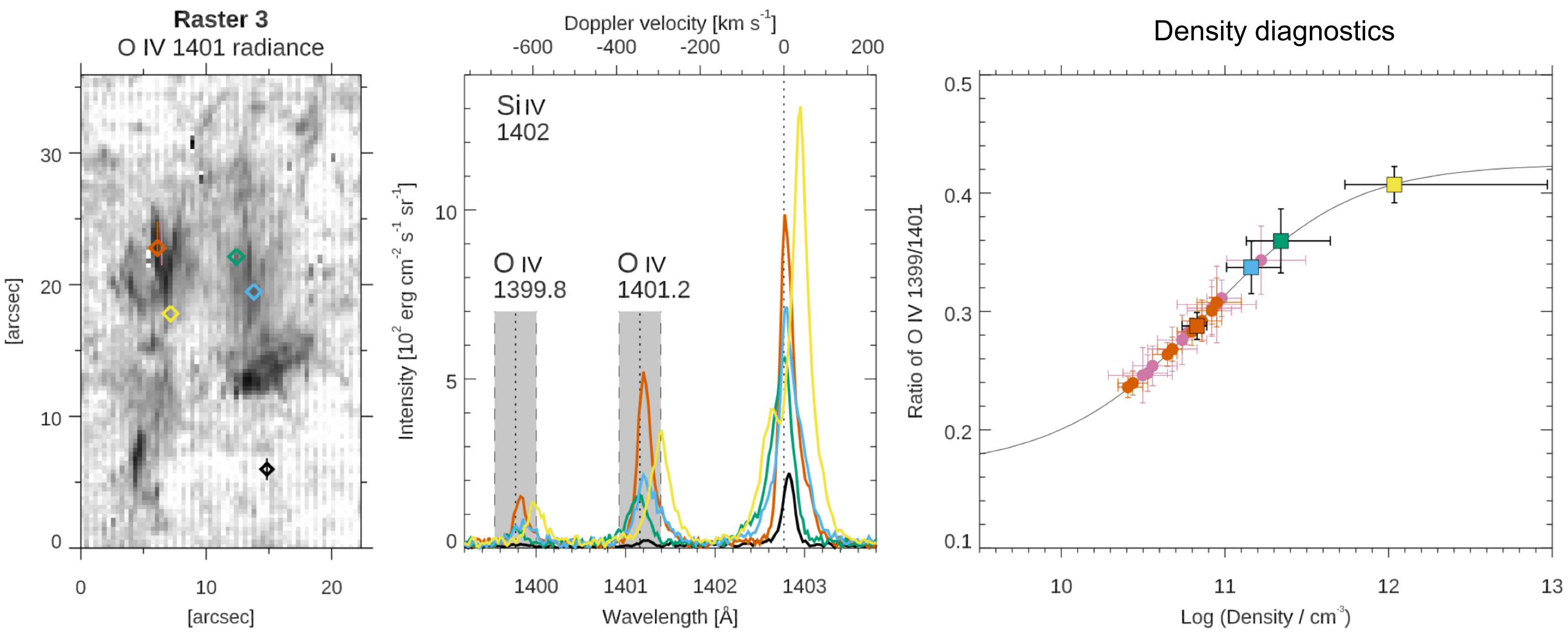
Density diagnostics

- O IV 1339.8/1401.2 ratio is largely independent of the electron temperature, and only weakly dependent on the electron distribution.
  (see, e.g., Feldman & Doschek 1979, Dudík et al. 2014, Polito et al. 2016a,b)



- We can estimate the electron density of the emitting surge layers.
- The electron density ranges from $2.5\times10^{10} - 10^{12}$ cm^{-3}

Simulations

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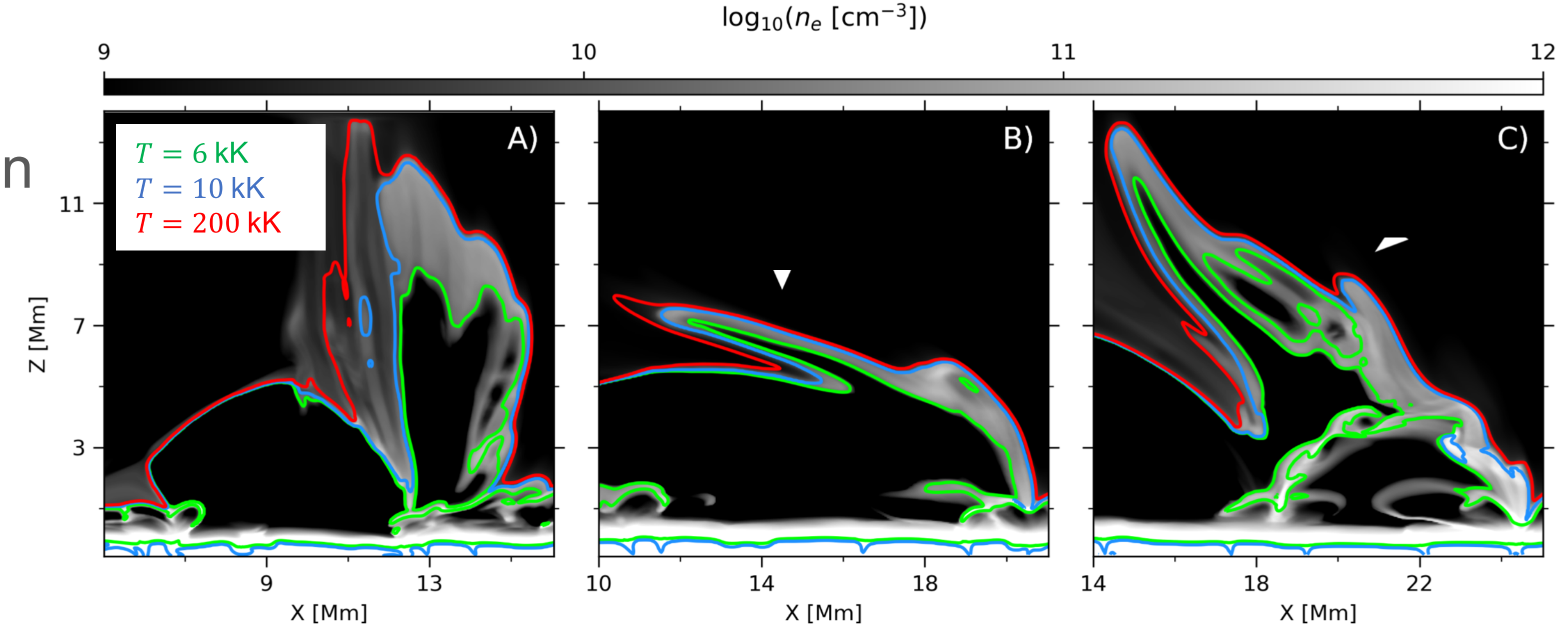
Results:

- The numerical simulations by Nóbrega-Siverio et al. 2016, 2017, 2018 performed with the Bifrost[1] code provide theoretical support in terms of the topology: cool core around $T = 6$ kK and lower n_e deeper in the surge.

- They also provide explanation to the location of the O IV emission within the surges.



Bifrost code (Gudiksen et al. 2011): https://ui.adsabs.harvard.edu/abs/2011A%26A...531A.154G/abstract

Conclusions

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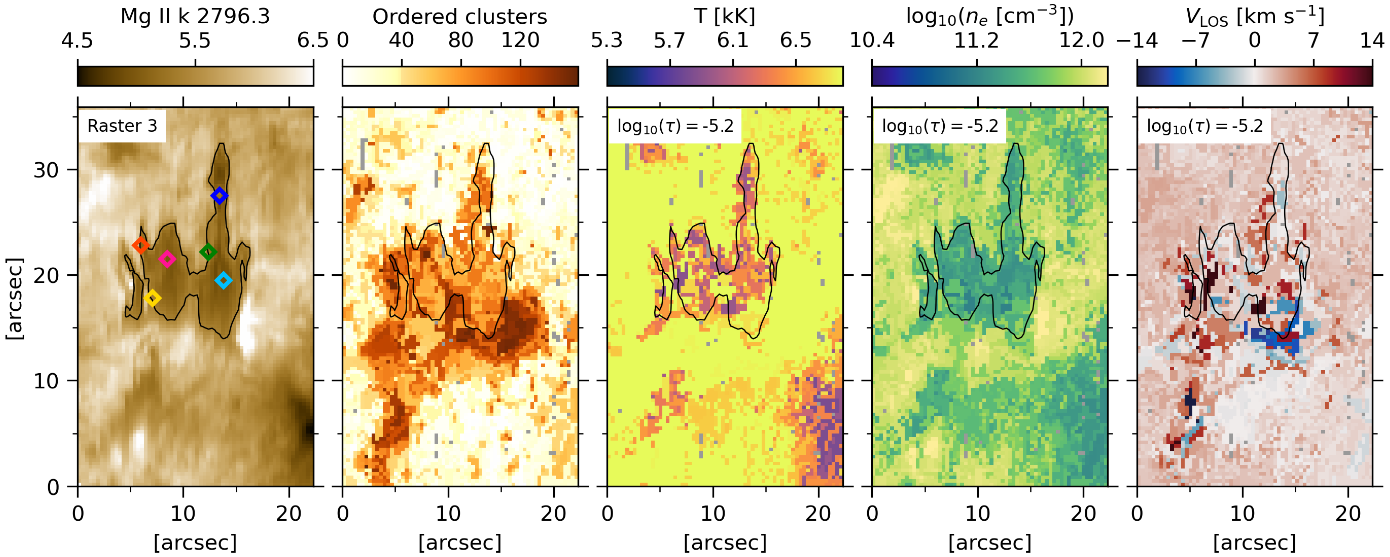
From the chromospheric analysis:

- We have carried out a *k*-means clustering finding that surge have particular Mg II h&k profiles.
- For the first time, we have provided physical properties of the surges through inversions, finding that surges show temperatures around $T = 6$ kK, $n_e \sim [1.6\times10^{11}, 10^{12}]$ cm^{-3} and V_{LOS} of a few km s^{-1}.



Conclusions

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From transition region analysis:

- We have also found observational evidence of O IV emission related to surges even in the weakest lines.
- A first comparison with simulations, show striking similarities with the observational findings in terms of the topology and the location of the O IV brightenings.