Characterization and formation of spicules in the Ca II K and Mg II k spectra

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Bose et al. 2019, A&A 631, L5

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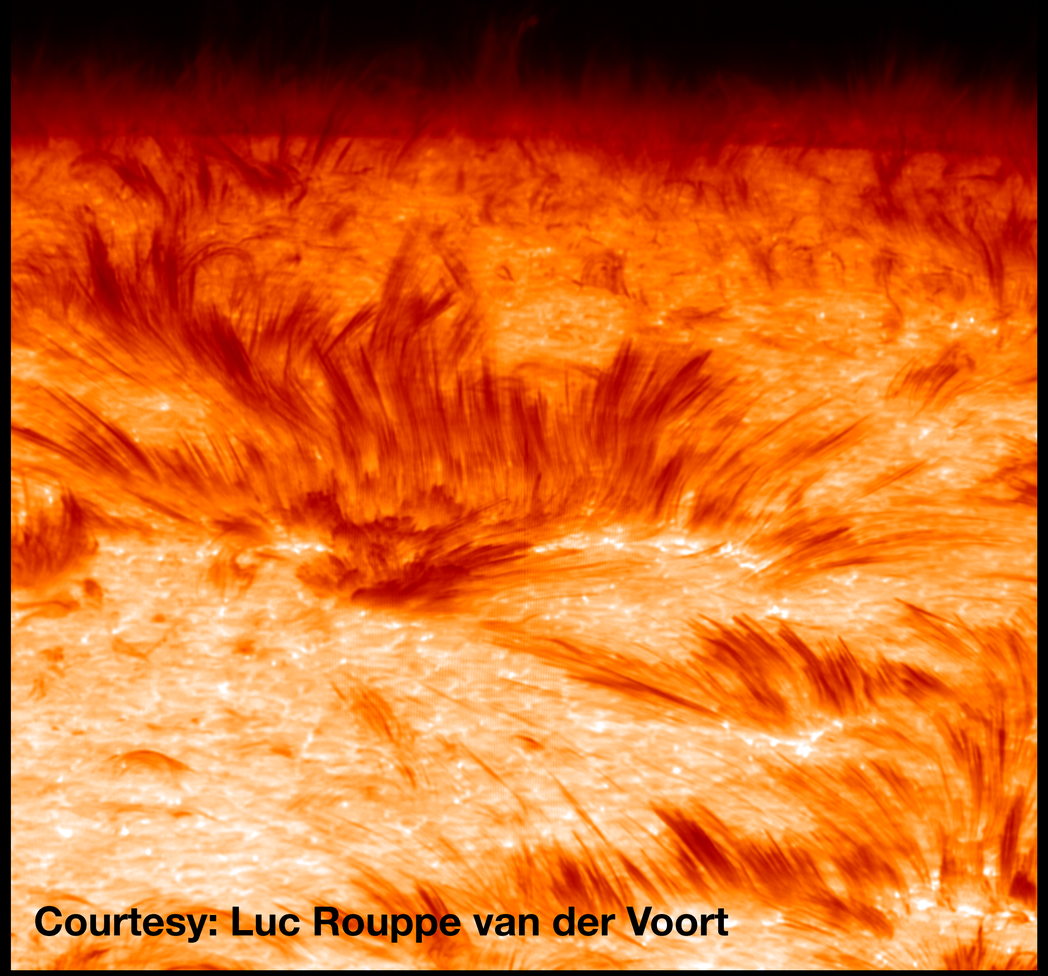
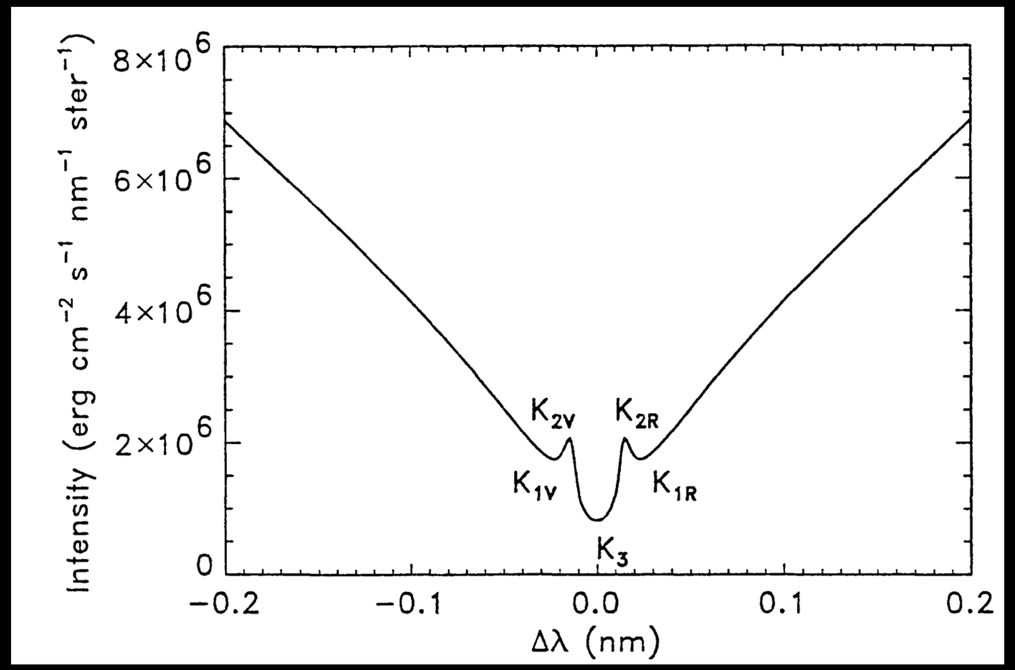
Chromospheric Spicules

- Ubiquitous and dynamic jets that permeate the solar chromosphere.
- Type II spicule are more dynamic with shorter lifetimes, vigorous sideways motion, and high apparent velocities (De Pontieu et al. 2007; Tsiropoula et al. 2012; Pereira et al. 2016).
- Heated beyond chromospheric temperatures: show signatures in the TR (De Pontieu et al. 2011; Rouppe van der Voort et al. 2015) and coronal diagnostics (Pereira et al. 2014; Henriques et al. 2016; Kuridze et al. 2016; De Pontieu et al. 2017a).
- Thought to play an important role in mass loading and heating of the solar corona (see, e.g. Martínez-Sykora et al. 2017; Tian 2017; Kontogiannis et al. 2018.)



CHROMIS Ca II K

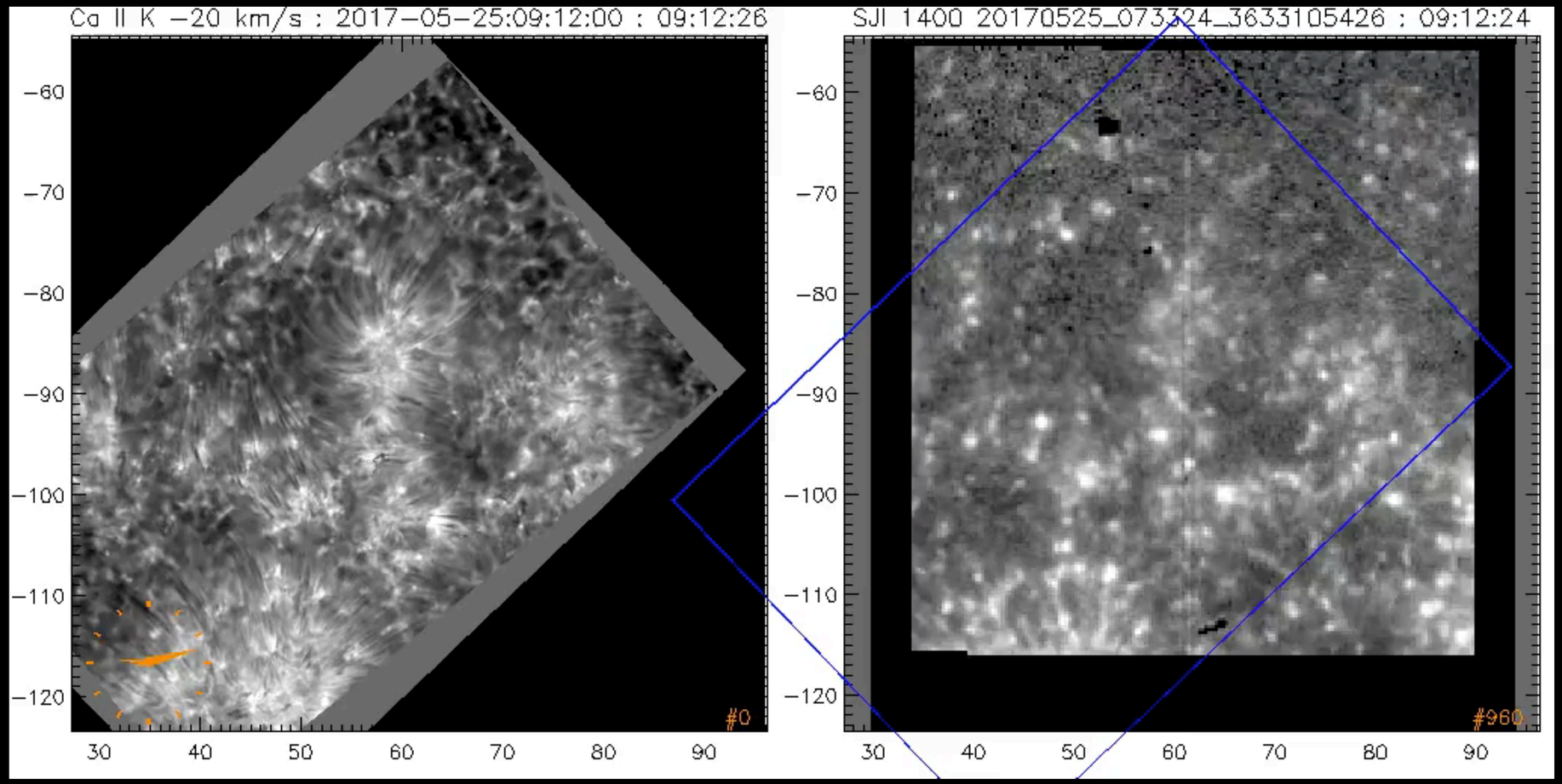
- **CHROMIS** records high resolution (< 0.1”) data in Ca II H&K.
- The H&K lines provides one of the richest diagnostics of the solar chromosphere.
- The intensity at K2/H2 peaks roughly correlates with the actual gas temperature (Bjørgen et al. 2018).
- Wavelength difference between the emission peaks provide a diagnostic of the velocity gradients in the upper chromosphere (Bjørgen et al. 2018).



Theoretical Ca II K profile (Rutten and Uitenbroek 1991)

Enhanced Network co-observation with CHROMIS and IRIS

SST+IRIS: 25th May 2017

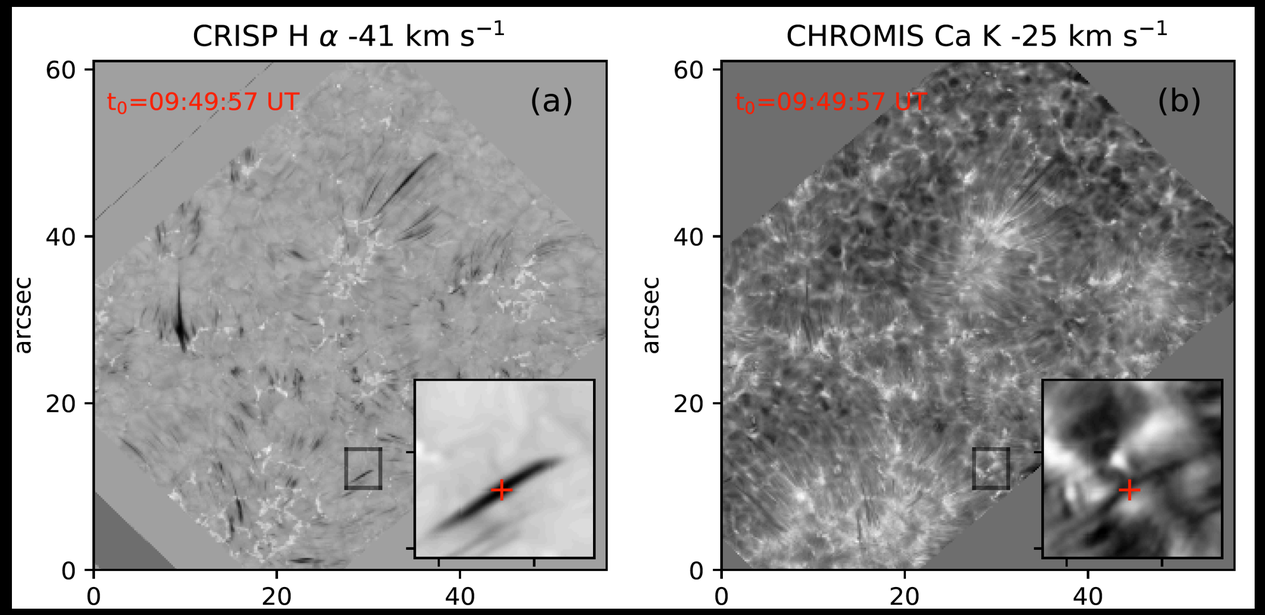


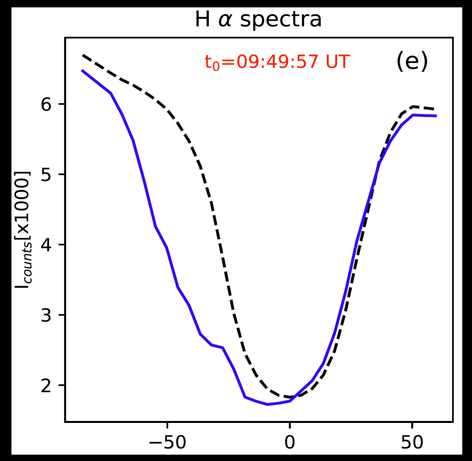
IRIS: Medium dense 8-step raster 2.32x60 8s Si IV Mg II h/k Deep x 2 Sp, exp 2s, raster cad 24s, SJI 1400 & 2976 cad 6s

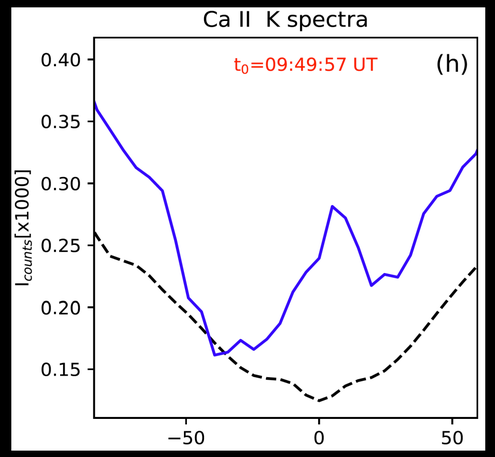
SST: CRISP H-alpha + Fe 630 cad 19s, CHROMIS Ca II K 42 pos, ±100 km/s cad 13.6s

On-disk spicules (RBEs) in Ca II K

- **Lower** contrast unlike H-alpha (for RBEs / RREs).
- **Not** a simple absorption spectra like H-alpha or Ca II 8542.



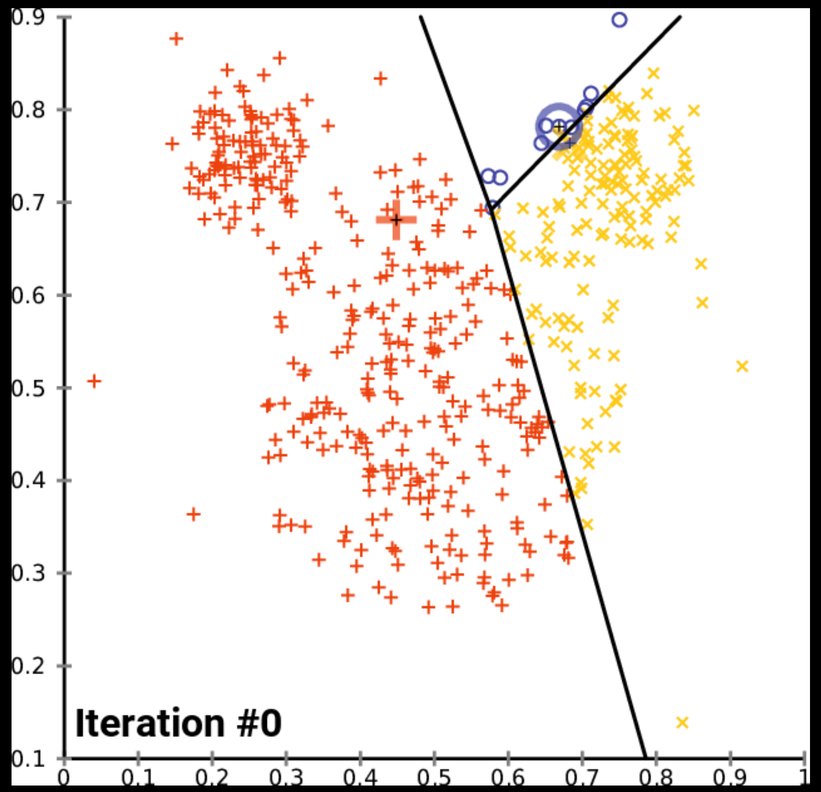




What can we do?

k-means clustering

- Technique introduced by MacQueen1967; Lloyd1982.
- Unsupervised machine learning technique- requires data but no labels.
- Resourceful in detecting patterns in a data.

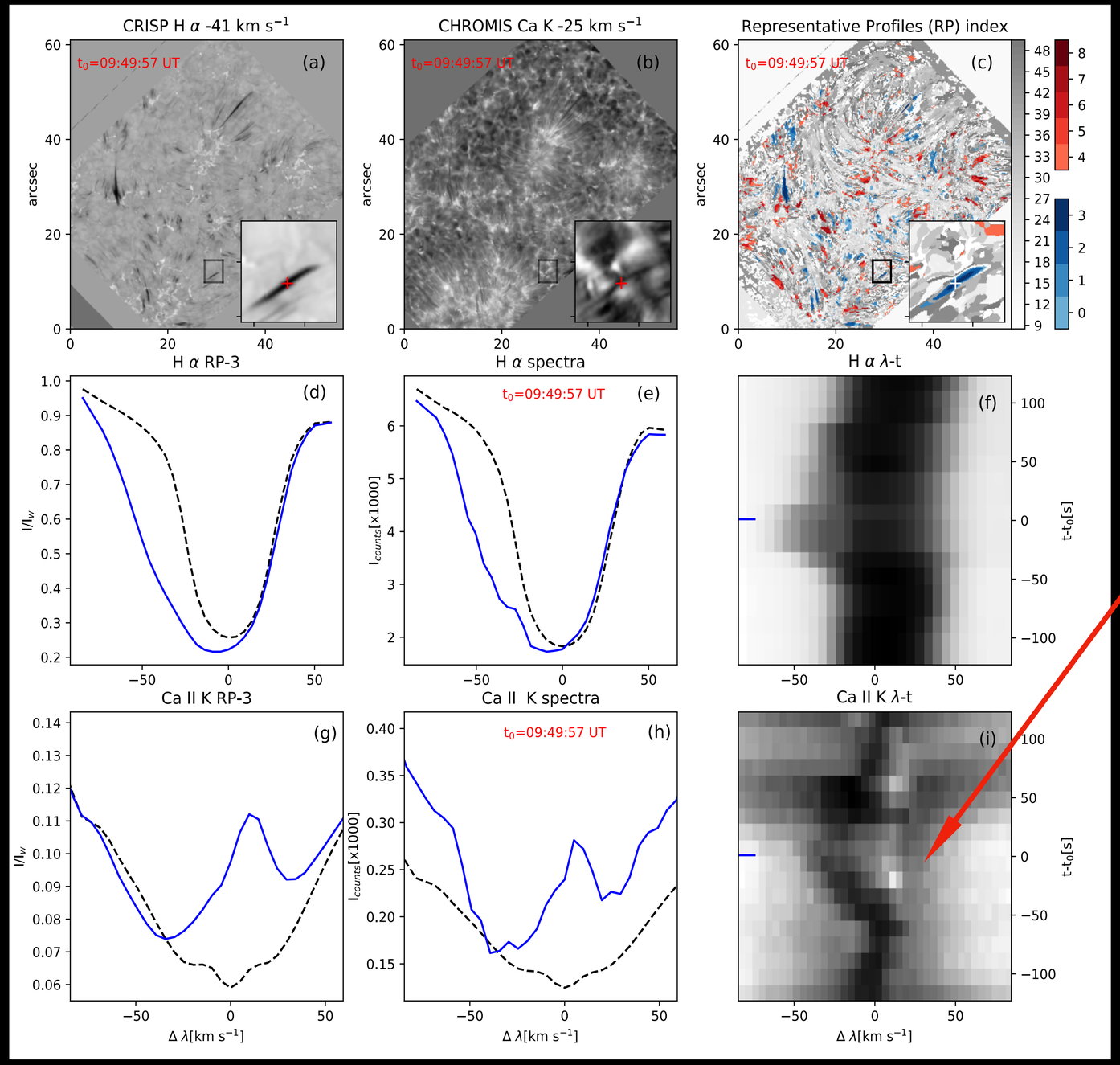


Courtesy: Wikipedia

Some applications in Solar Physics:
Viticchié and Sanchez Almeida 2011, A&A, 530
Sainz Dalda et al. 2019, ApJ, 875L

K-means on observed data

- *k*-means clustering on combined H-alpha and Ca II K spectra for each pixel on the FOV.
- Each spectrum per pixel was assigned to a so-called Representative Profile (RP) bin.
- **50** RPs were found to be optimum.



- **The Ca II K λt-slice shows:**
  - ✳ **Reveals continuity between the line-minimum at rest and the line-minimum at max shift.**

TIP: The line-cores for the most strongly-shifted spicules are likely the usual K3 features, merely Doppler shifted

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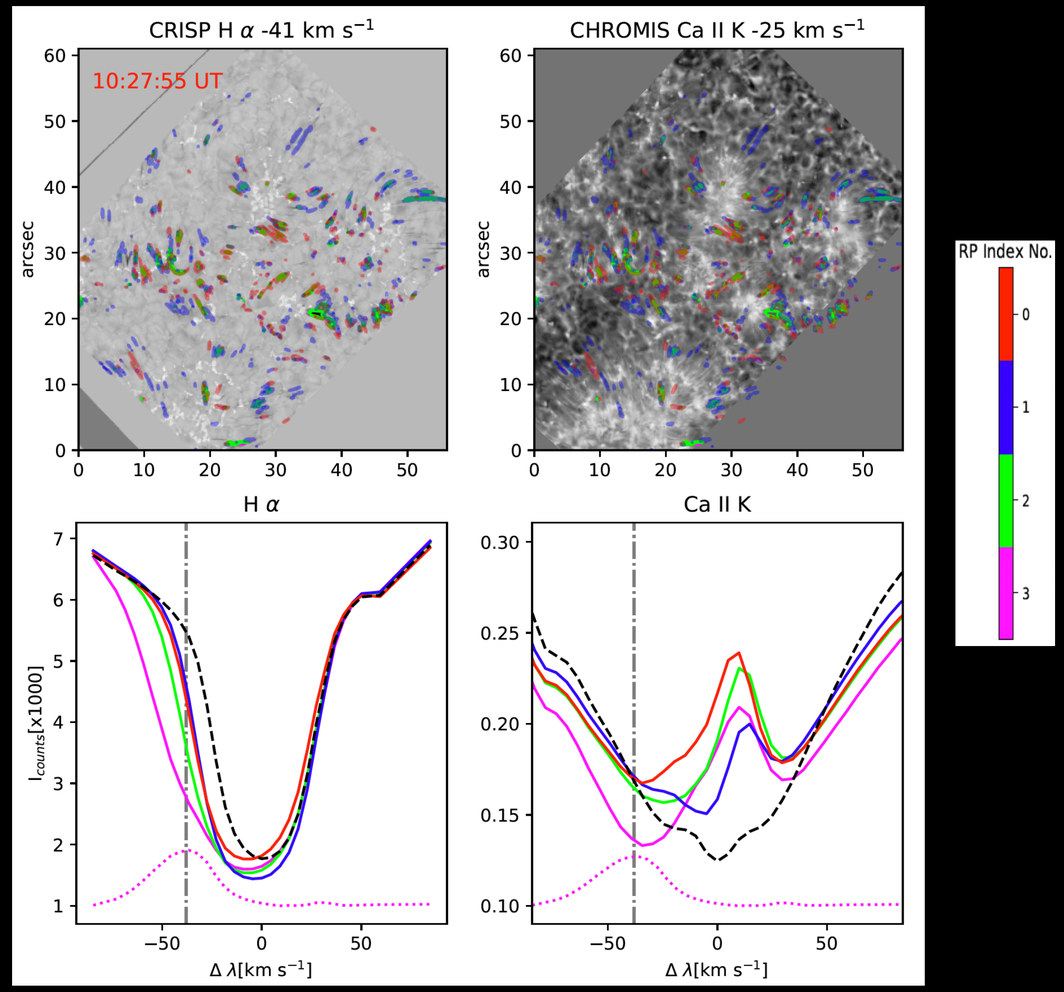
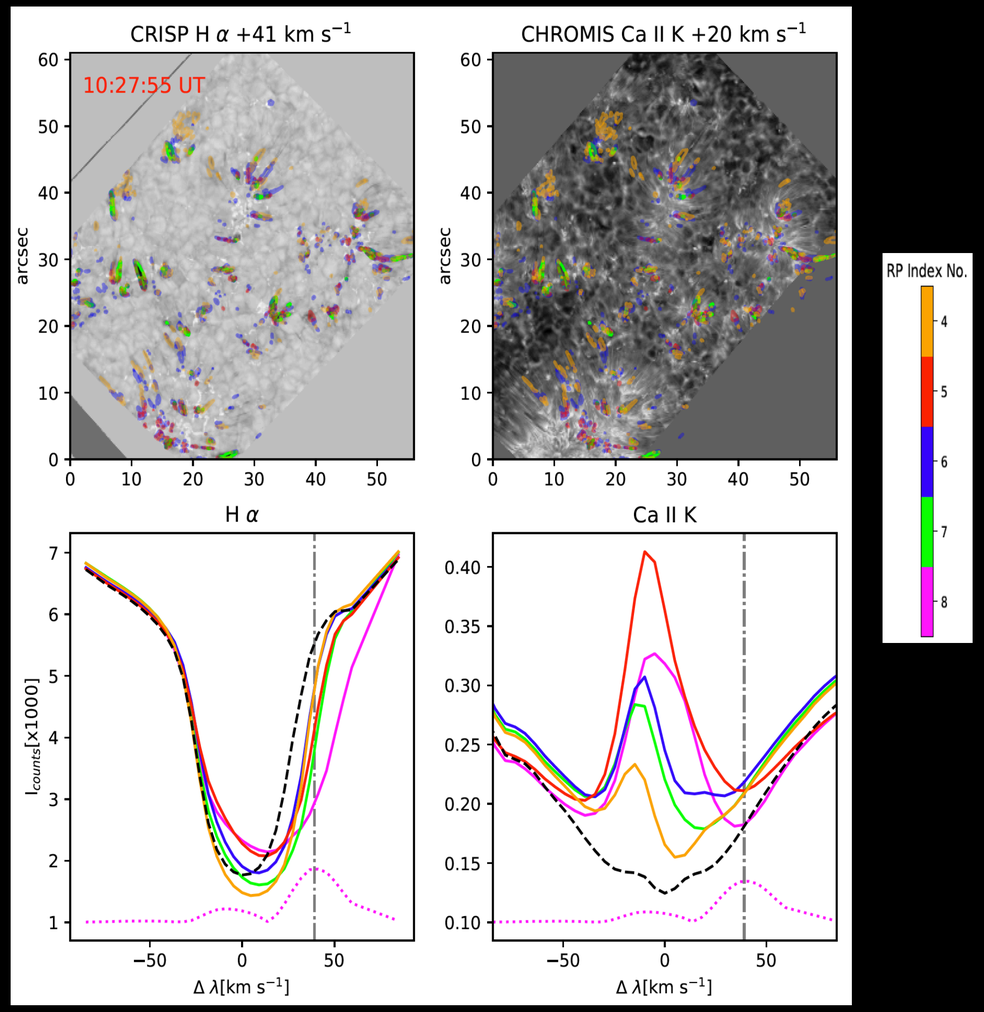
Representative bins for RBEs and RREs

RBEs



RREs



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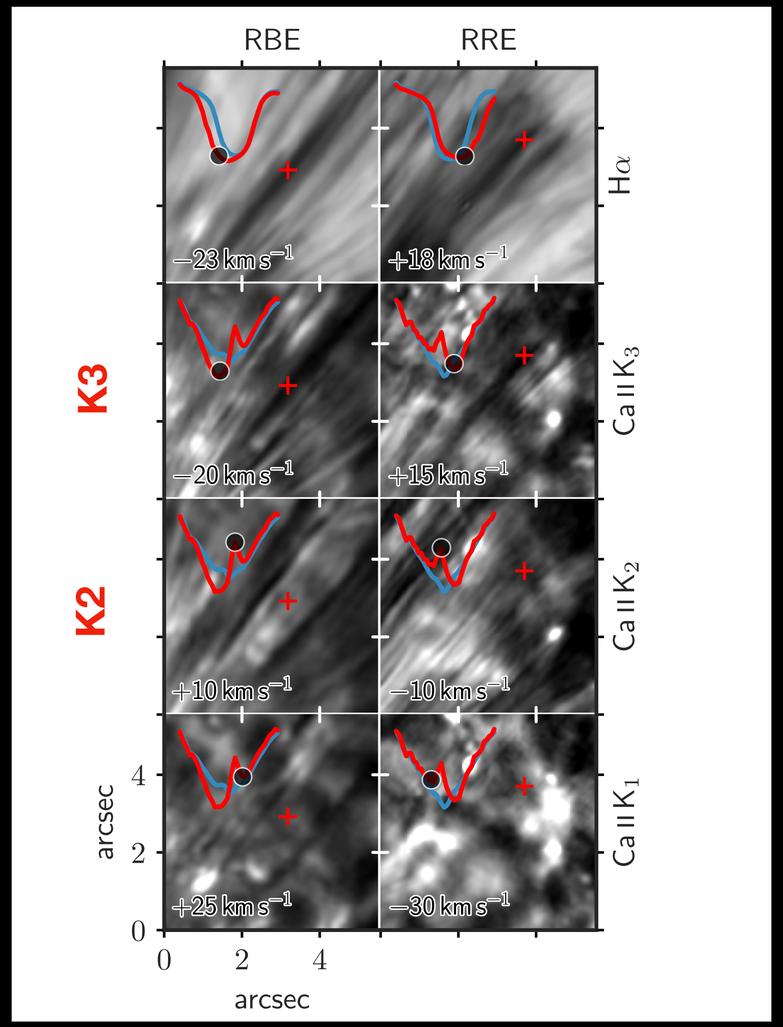
Line formation hypothesis

- Doppler shifted K3 cause a suppression of K2V / K2R.
- The ***opposite*** K2 features are enhanced due to a differential Doppler removal of upper-layer opacity (Athay 1970, Carlsson & Stein 1997, de la Cruz Rodriguez et al. 2015a, Bose et al. 2019a)
- **Opacity window effect.**



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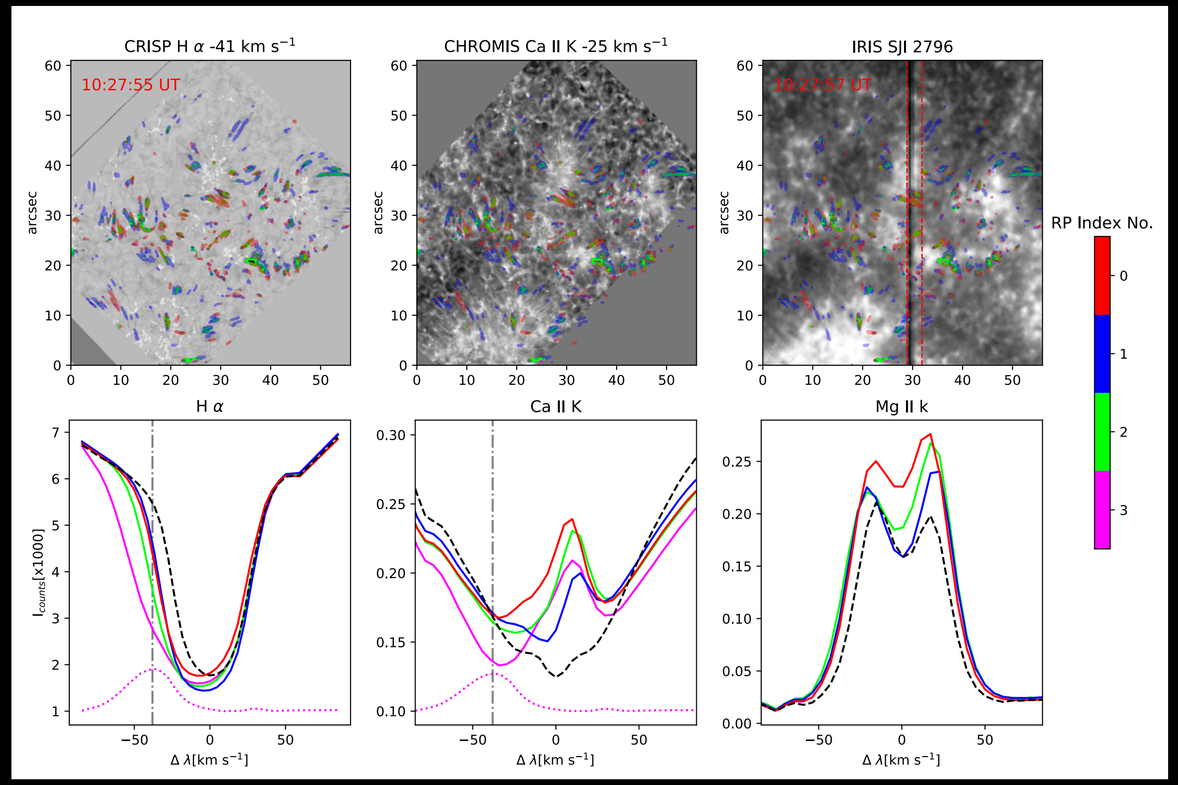
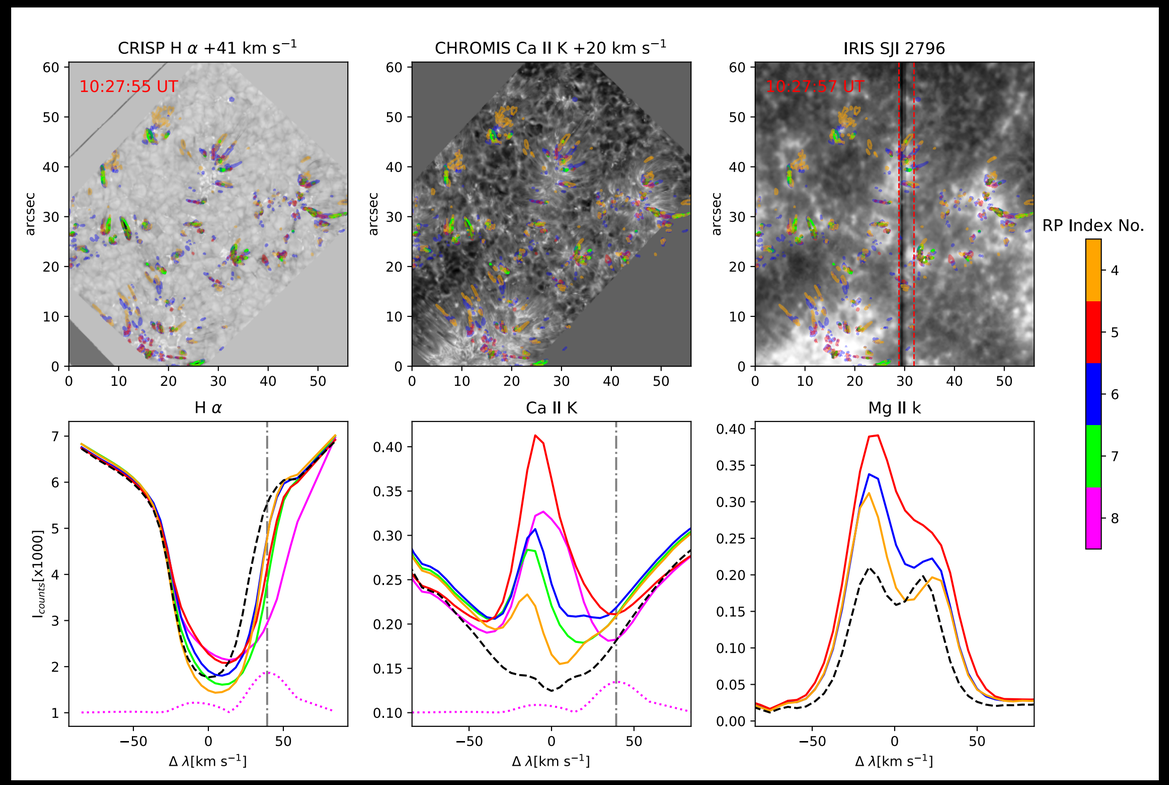
RBEs and RREs in IRIS Mg II k

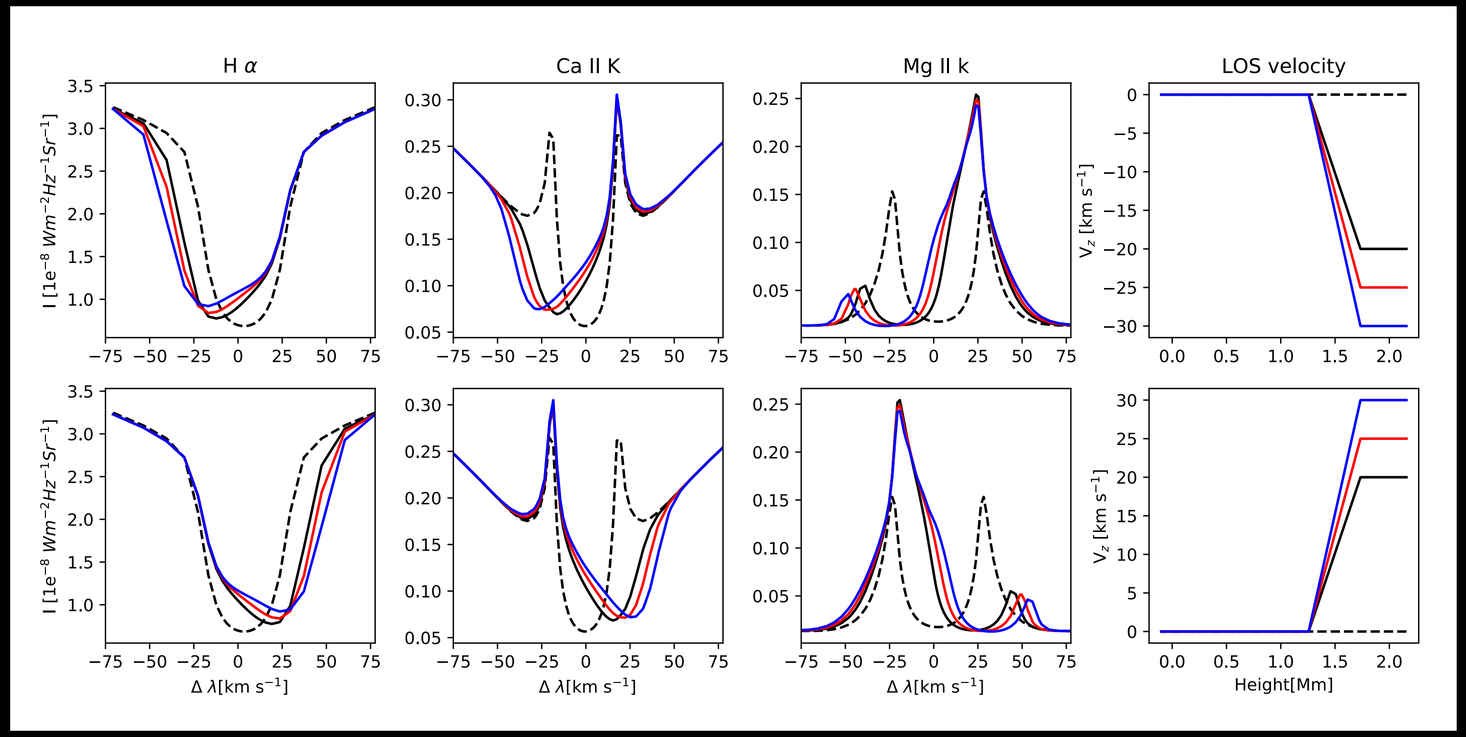
RBEs



RREs



Numerical experiment



Top row: Synthetic RBE-like profiles with negative LOS velocity stratifications
Bottom row: Synthetic RRE-like profiles with positive LOS velocity stratifications.

Bose et al. 2019, A&A 631, L5

- Synthesis using **RH1.5D** code.
- **FAL-C** (Fontenla et al. 1993) atmosphere with modified LOS velocity stratifications.
- Doppler-shift of the Ca II K3 and Mg II k3 are the same as the LOS velocity.
- Suppressed K2 (k2) peaks due to the strong flows.
- Opposite K2 (k2) peaks enhanced and widened.

Summary and Conclusions

1. Ca II K and Mg II k line formation influenced by the *opacity window effect.*

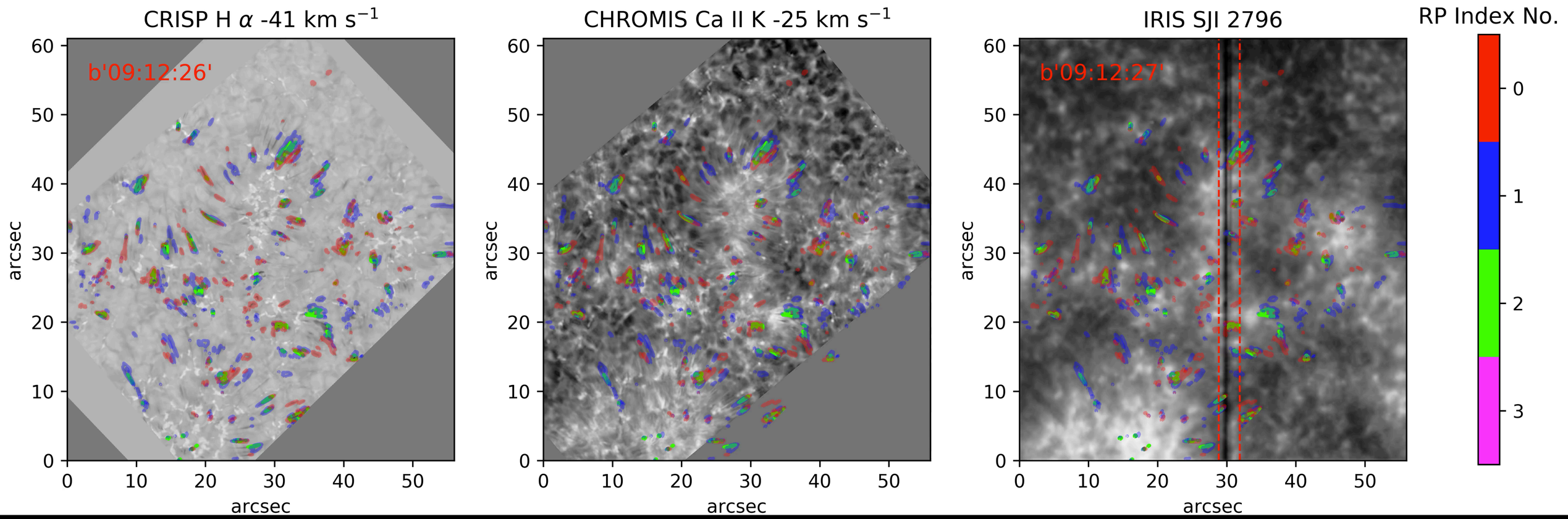
2. Possible indication of heating based mechanisms for **RREs.**

3. LOS velocity can now be measured directly by Doppler shifts of K3.

4. Doppler shifts in the range of 20-50 km/s with Ca II K confirm earlier measurements with the differential profile technique (Rouppe van der Voort et al. 2009; Kuridze et al. 2016).

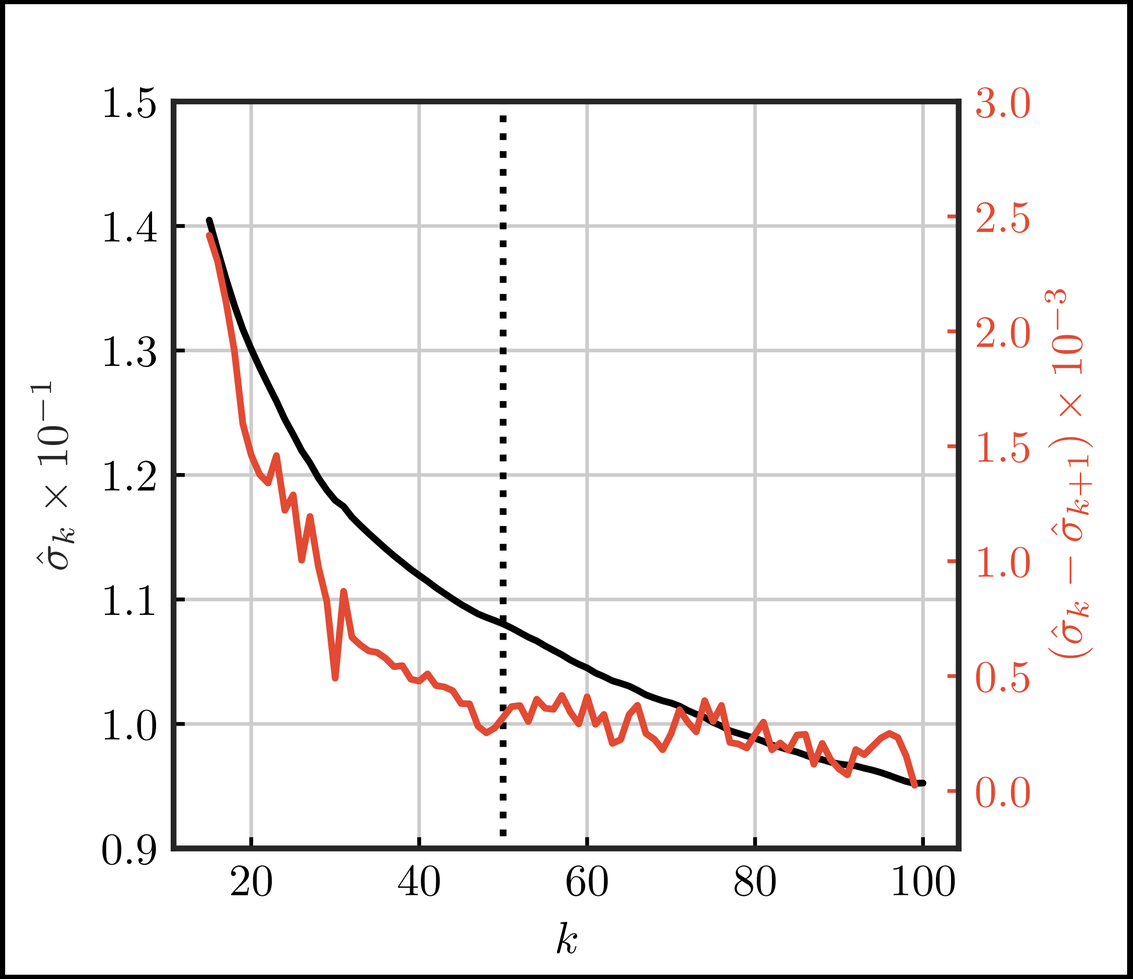
5. These Doppler velocities constitute the actual LOS mass flows in spicules, with apparent motion >100 km/s attributed due to alternate mechanisms such as rapidly propagating heating fronts (De Pontieu et al. 2017b).

Temporal evolution

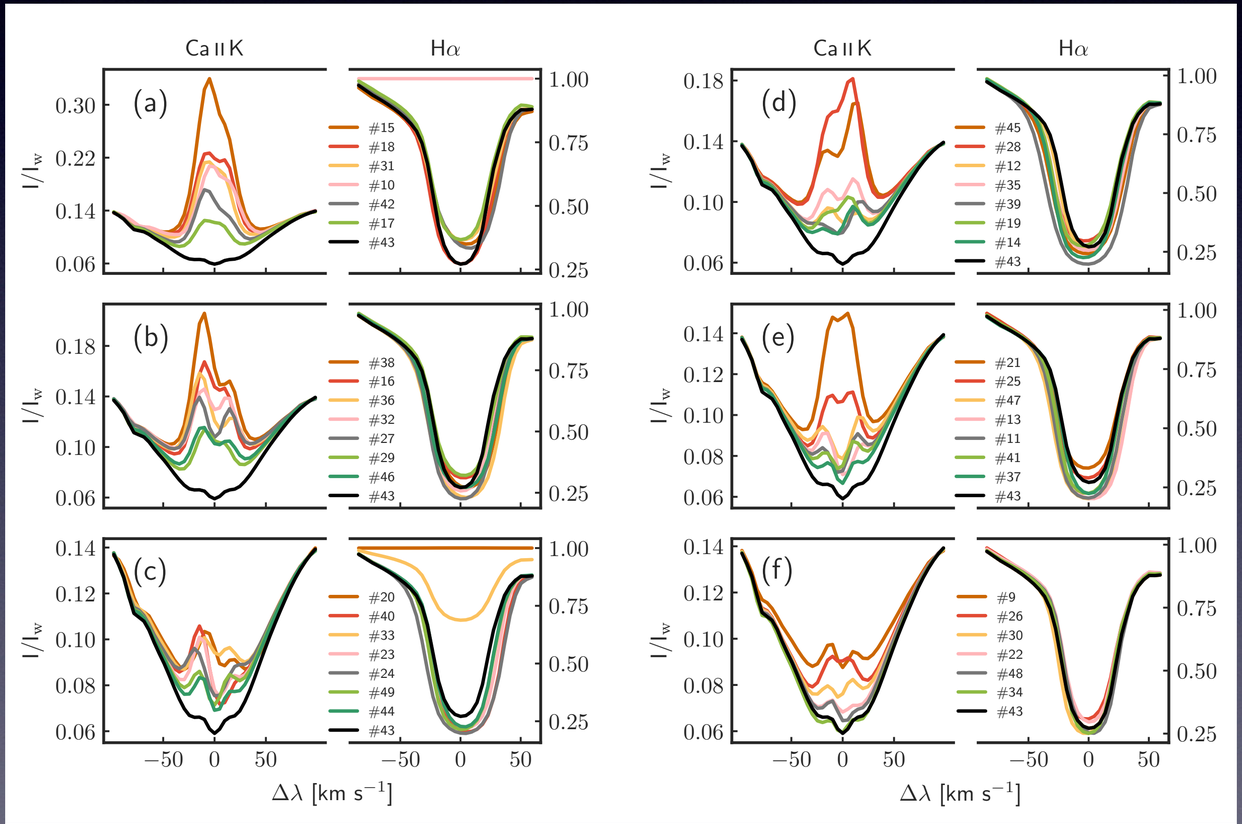


Appendices

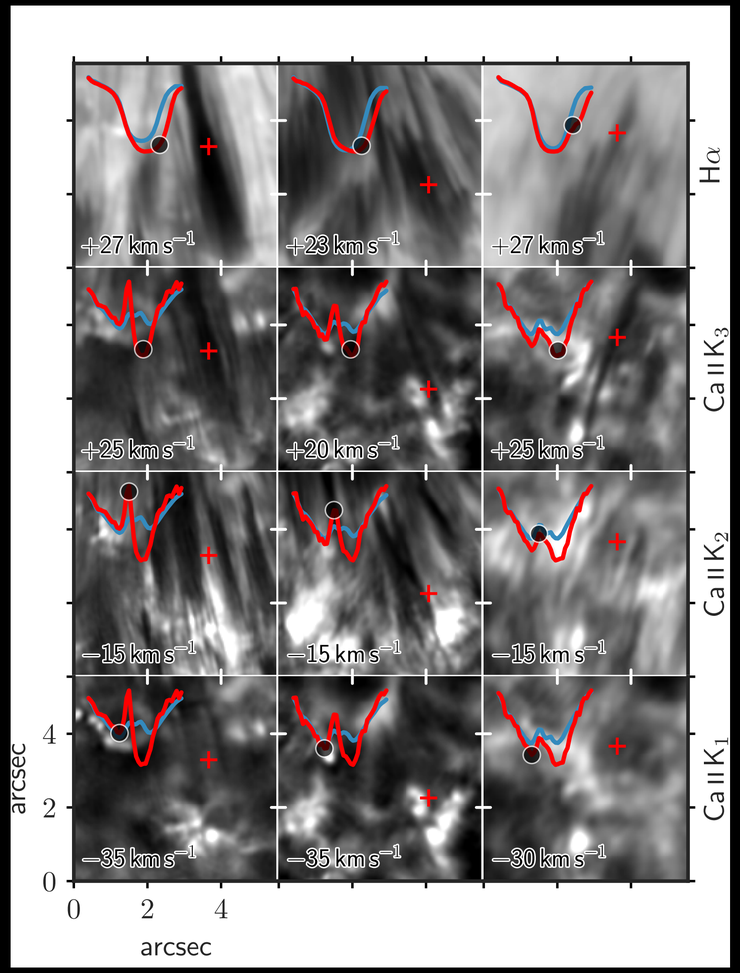
Optimum number of clusters

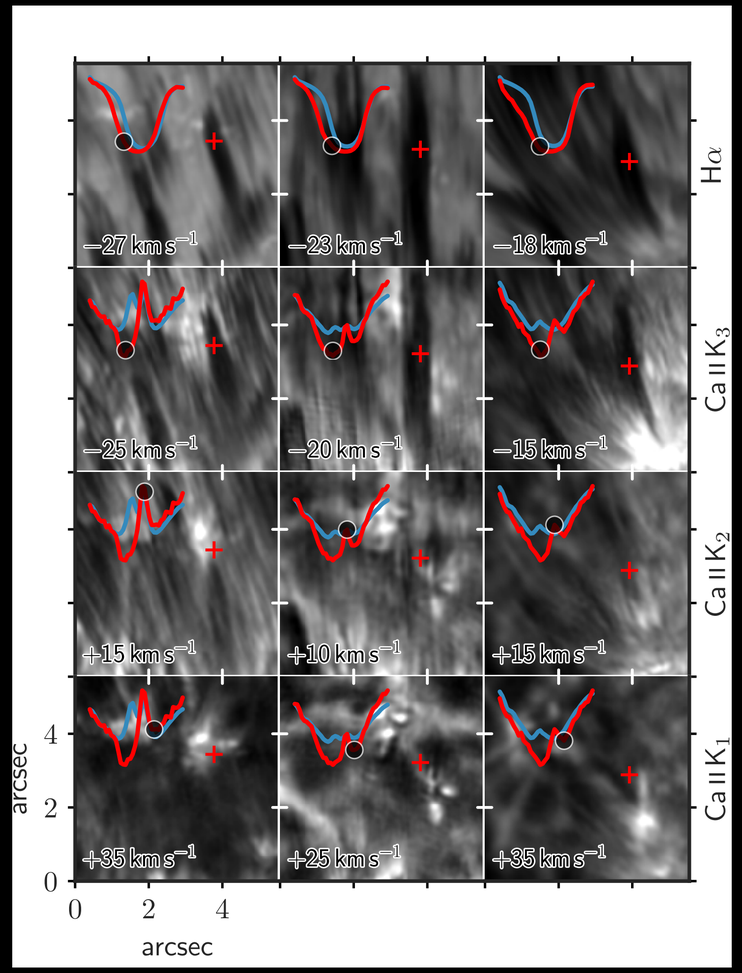


Cluster centres

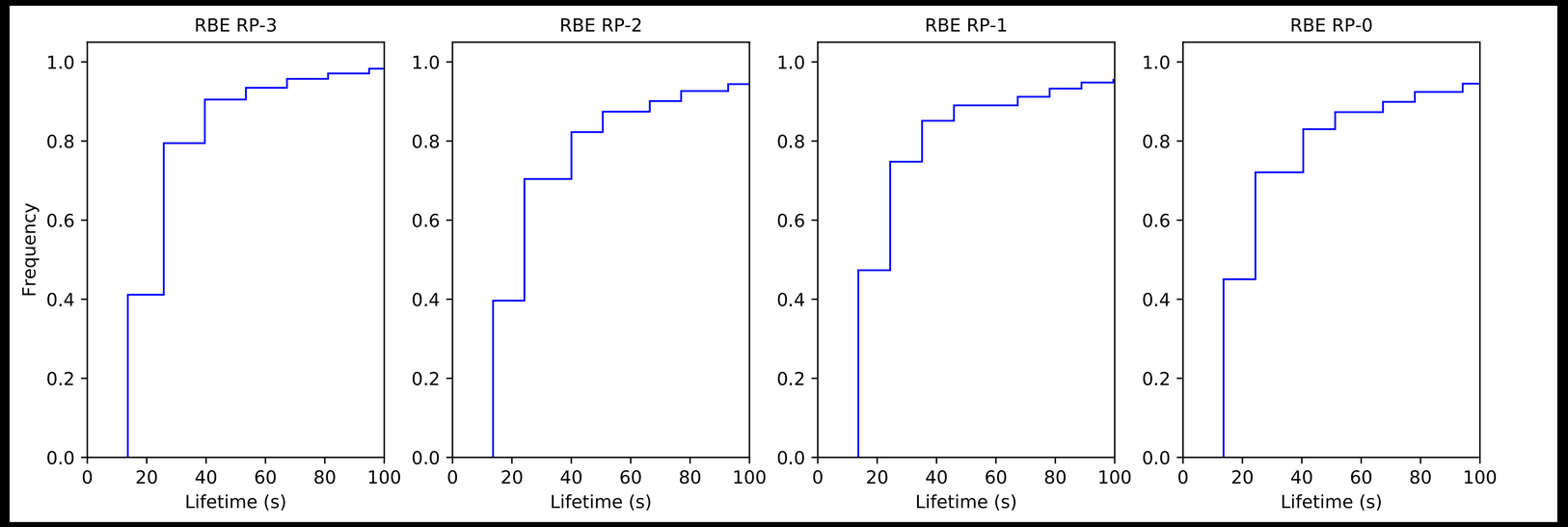


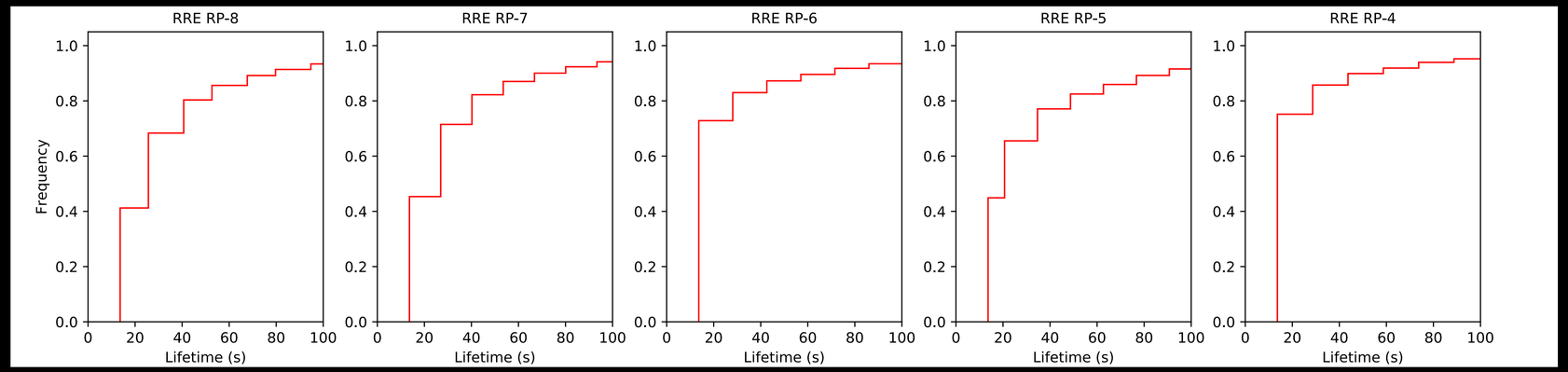
Opacity window effect



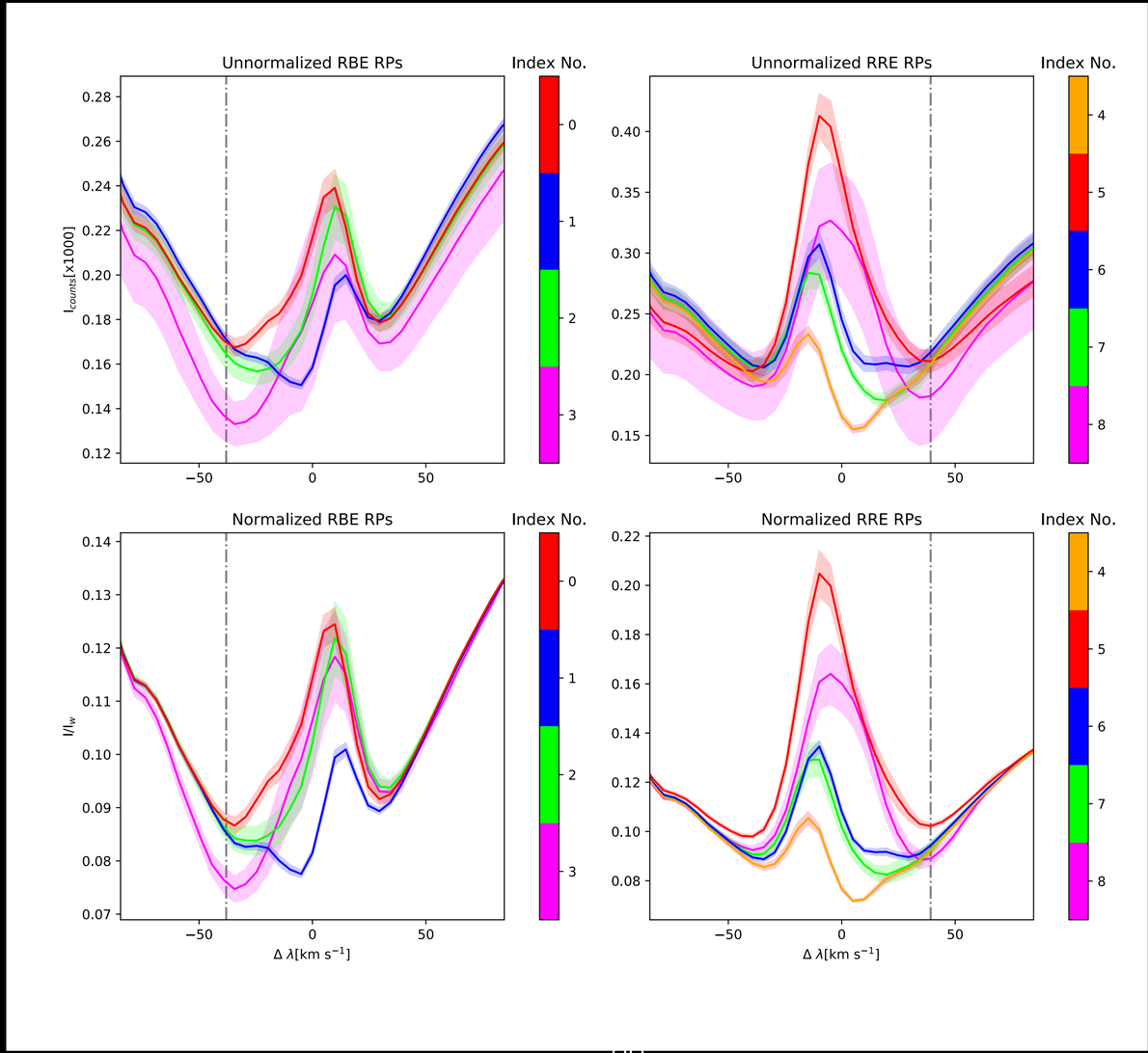


Lifetime statistics

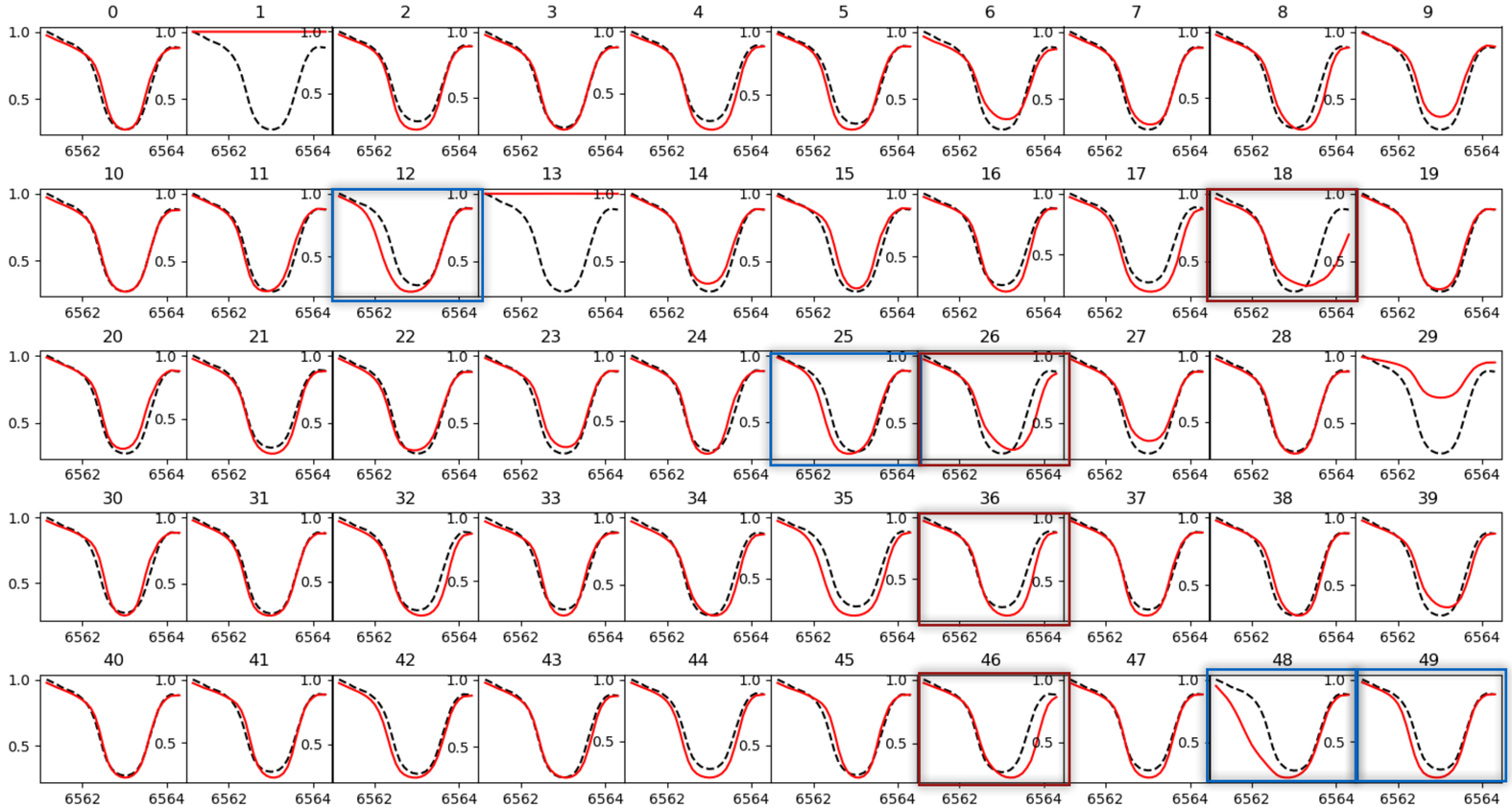




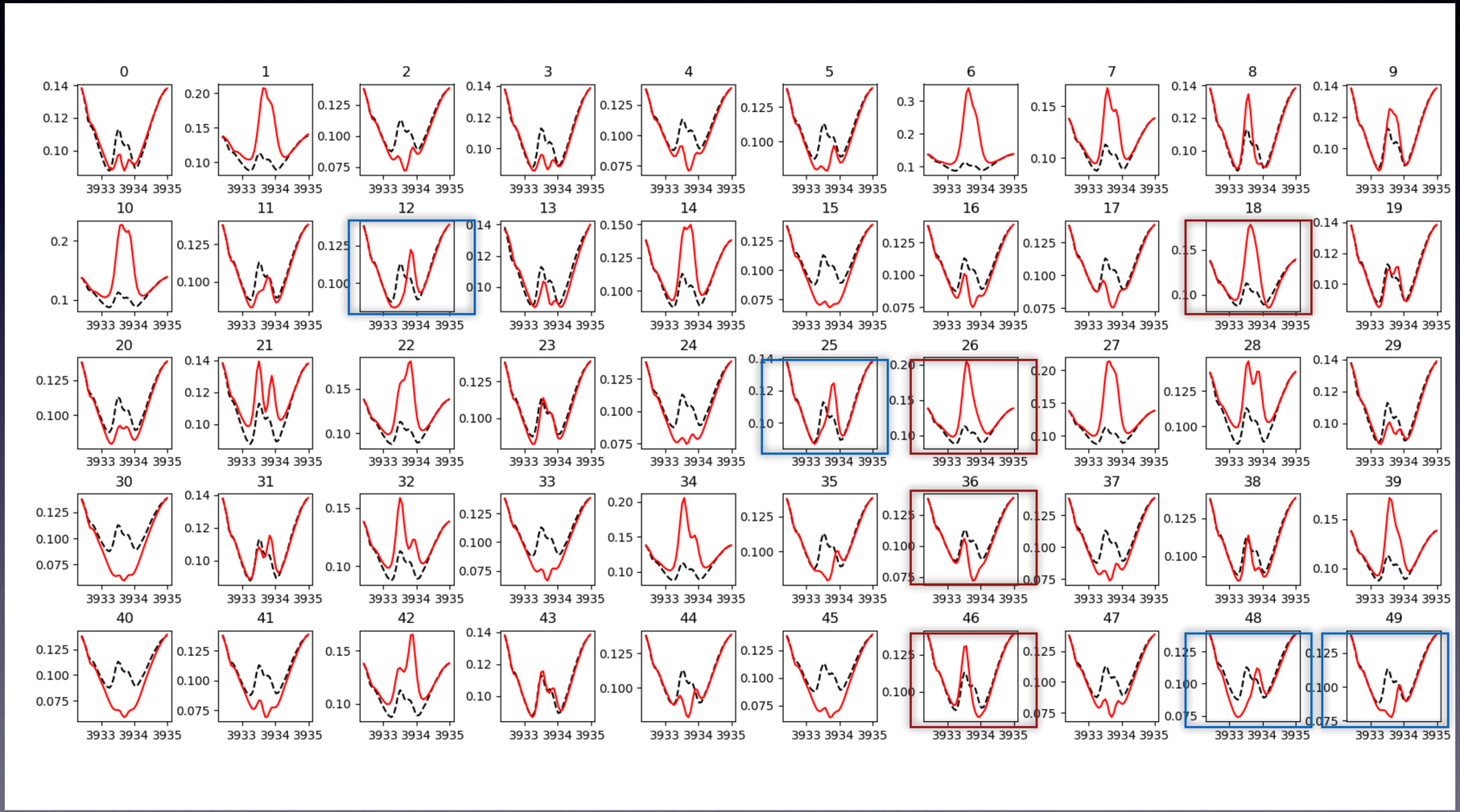
K-mean significance plots



H-alpha RPs


0 1 2 3 4 5 6 7 8 9
10 11 12 13 14 15 16 17 18 19
20 21 22 23 24 25 26 27 28 29
30 31 32 33 34 35 36 37 38 39
40 41 42 43 44 45 46 47 48 49
1.0
0.5
6562
6564

Ca-K RPs


0 1 2 3 4 5 6 7 8 9
10 11 12 13 14 15 16 17 18 19
20 21 22 23 24 25 26 27 28 29
30 31 32 33 34 35 36 37 38 39
40 41 42 43 44 45 46 47 48 49
3933 3934 3935