Cromosfera solară dezvăluită prin spectroscopie

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Seminarul Ştiinţific al Institutului Astronomic Român
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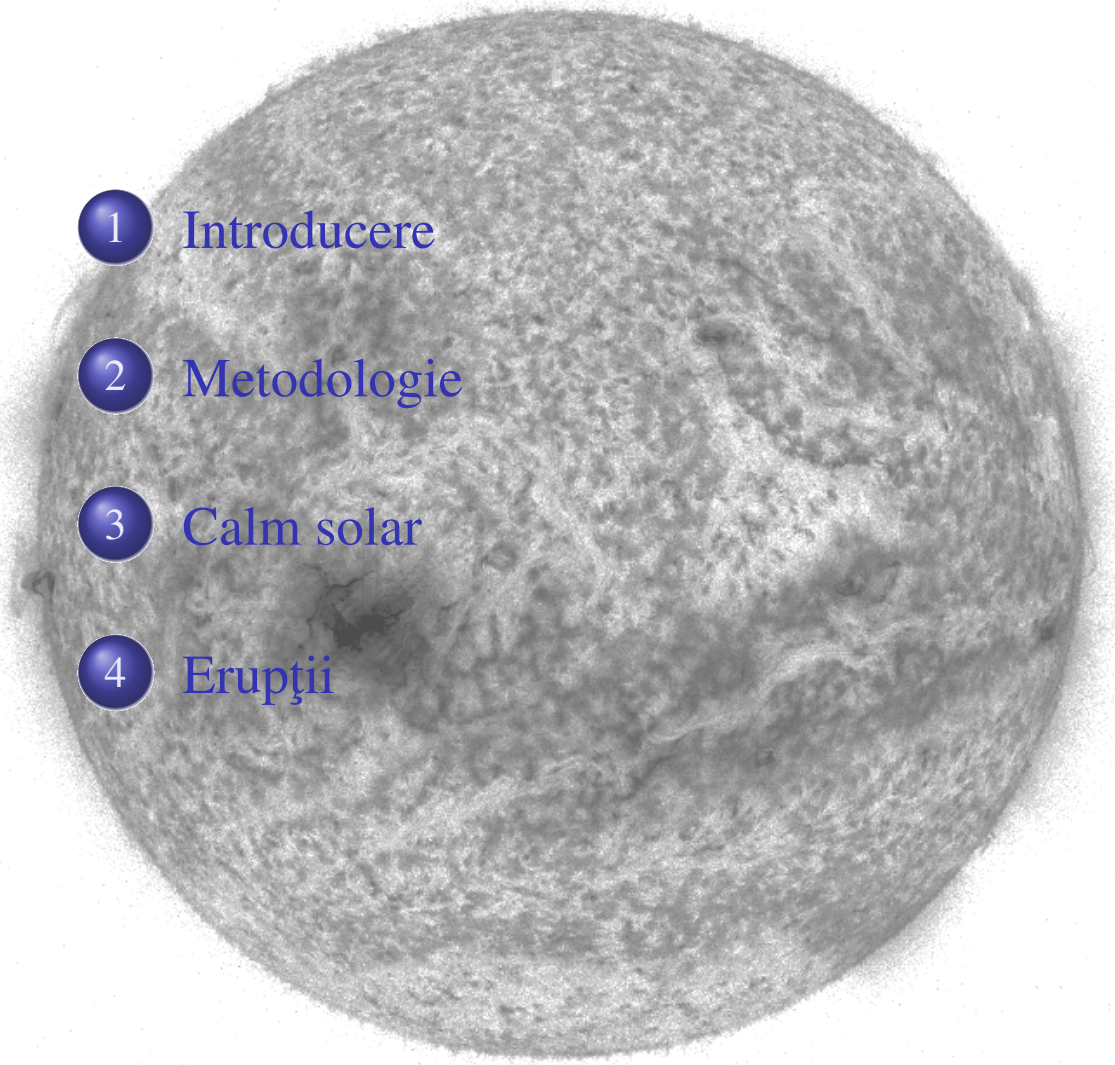
Outline

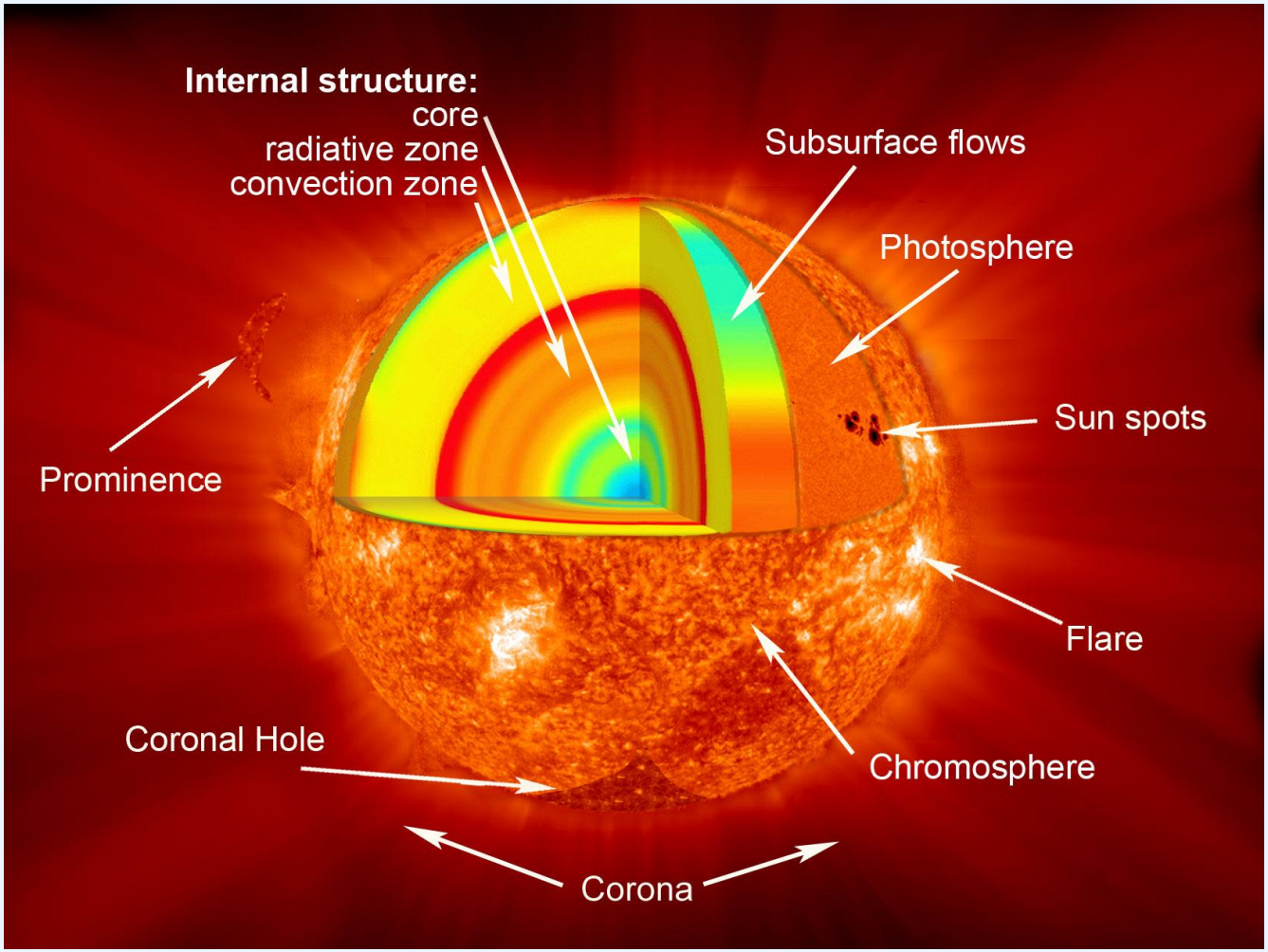


1. Introducere
2. Metodologie
3. Calm solar
4. Erupţii

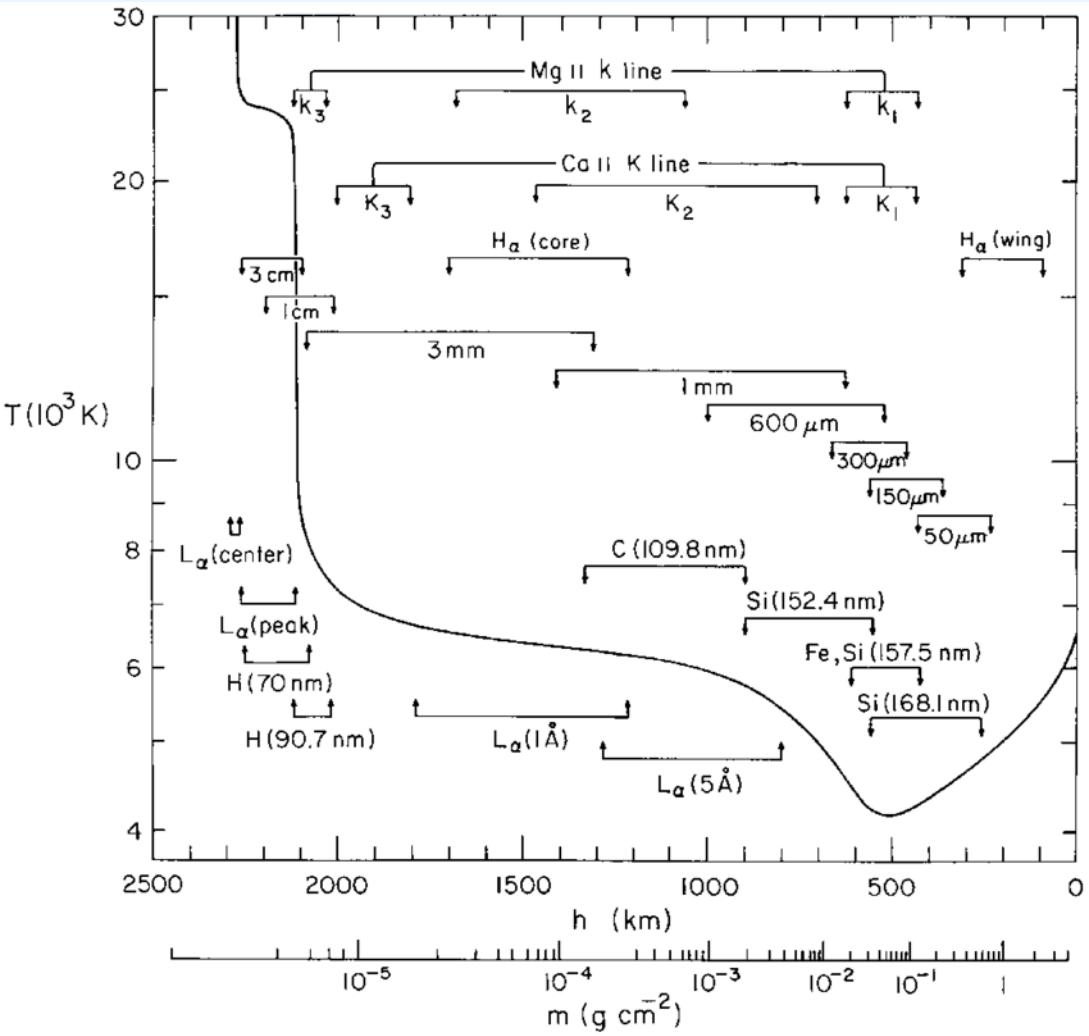
Outline

1. Introducere
   - Cromosfera solară
   - Spectrul solar
   - Emisia ionului Mg II
2. Metodologie
3. Calm solar
4. Erupţii

Cromosfera solară

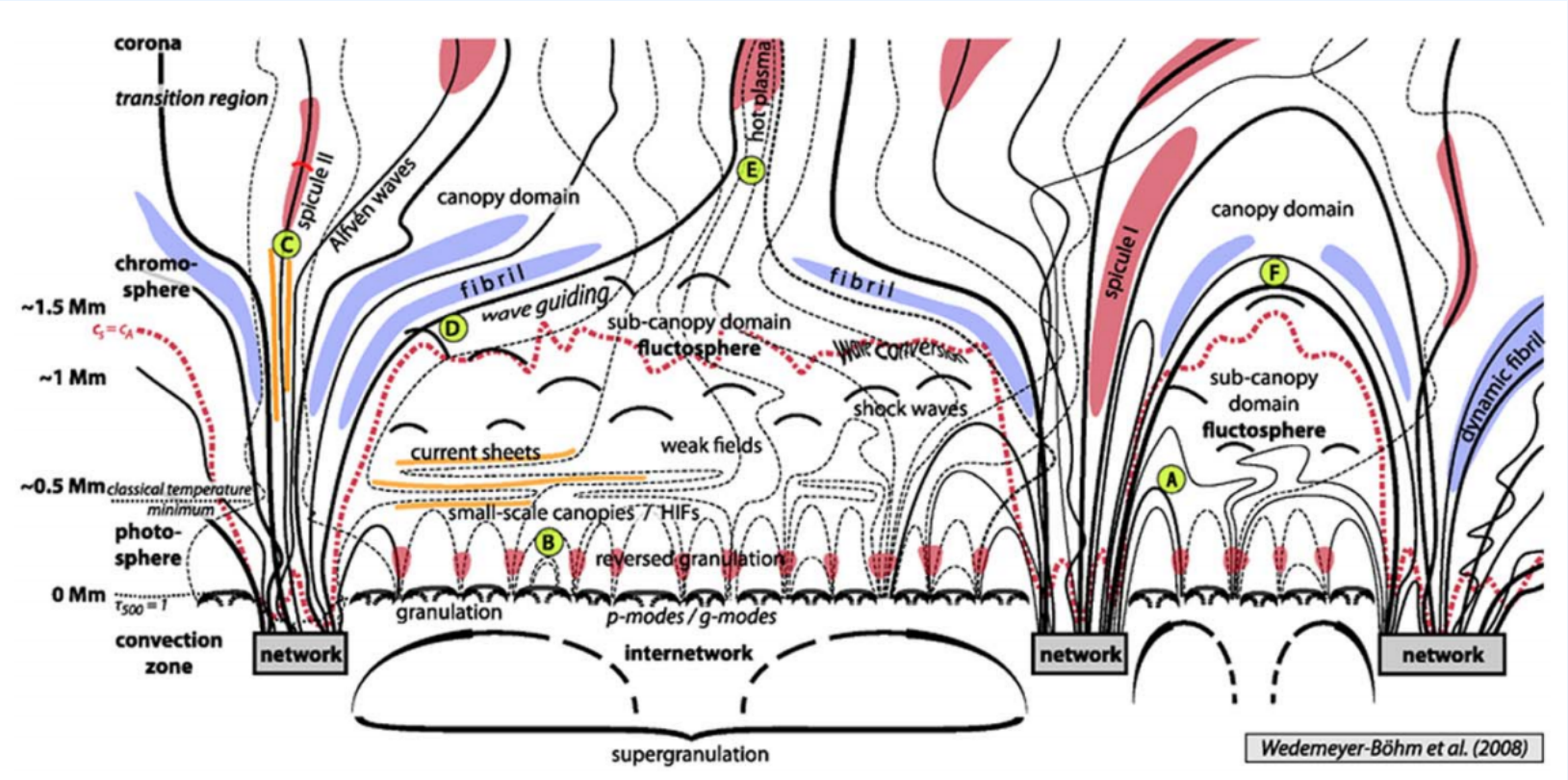


Cromosfera solară

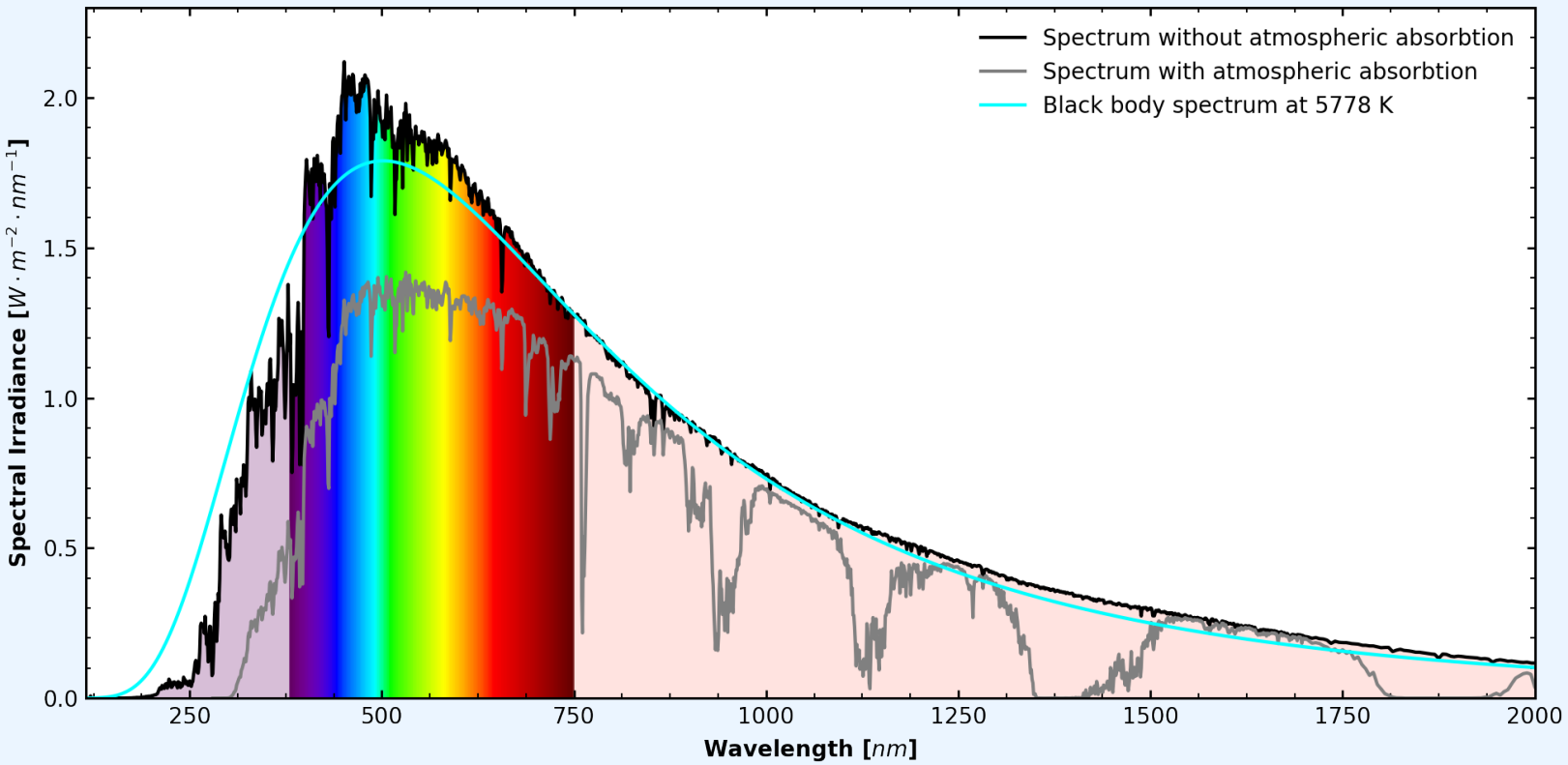


Vernazza et al. (1981)

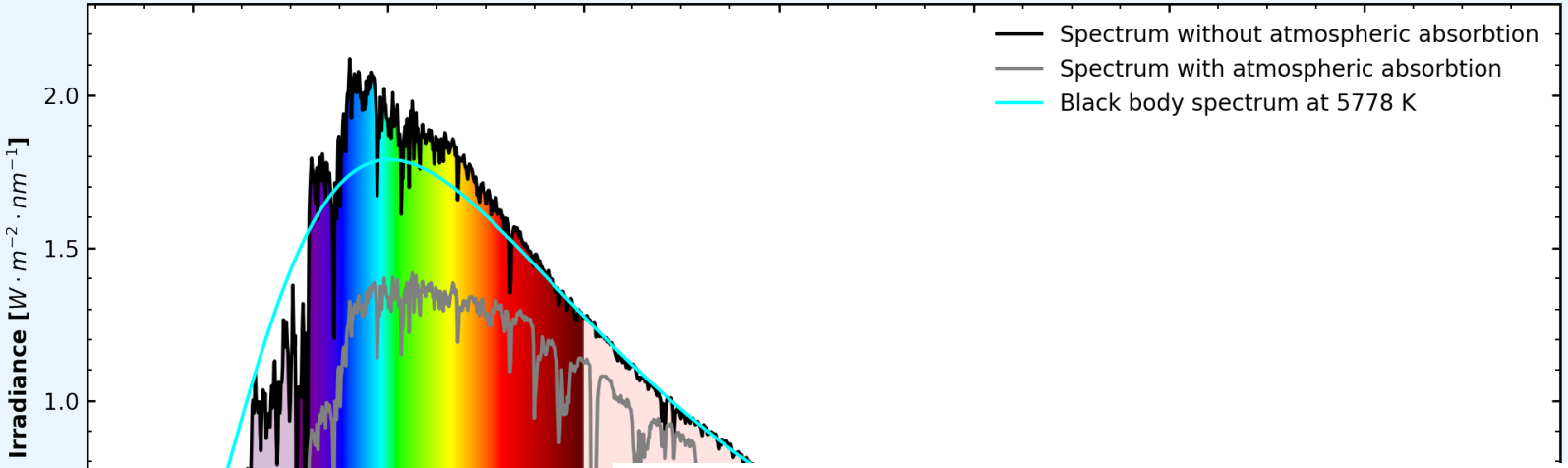
Cromosfera solară

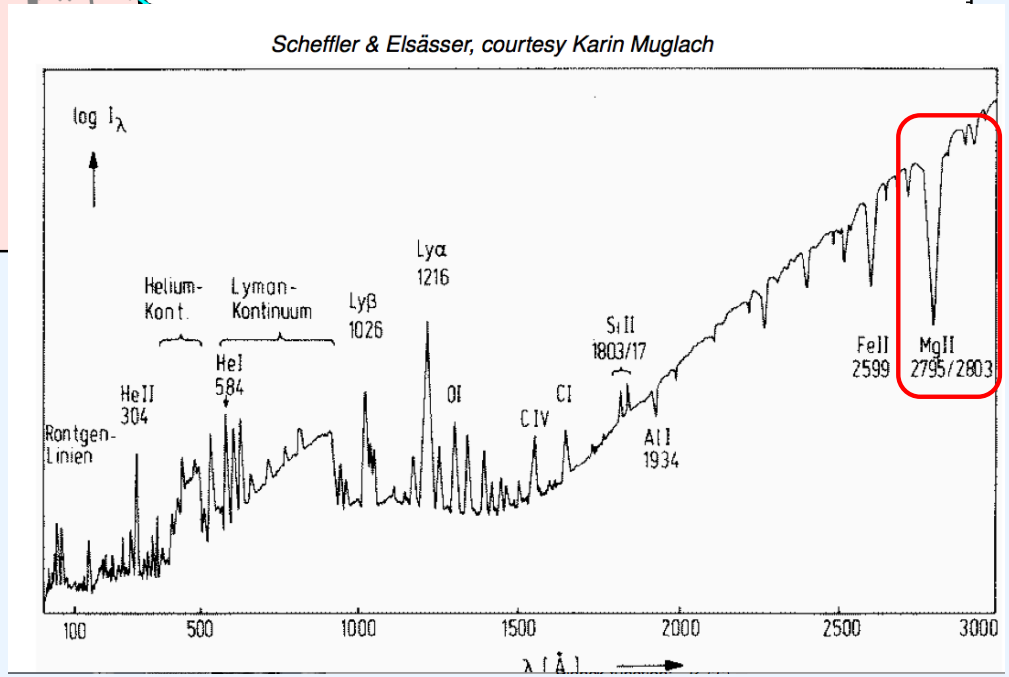


Spectrul Solar

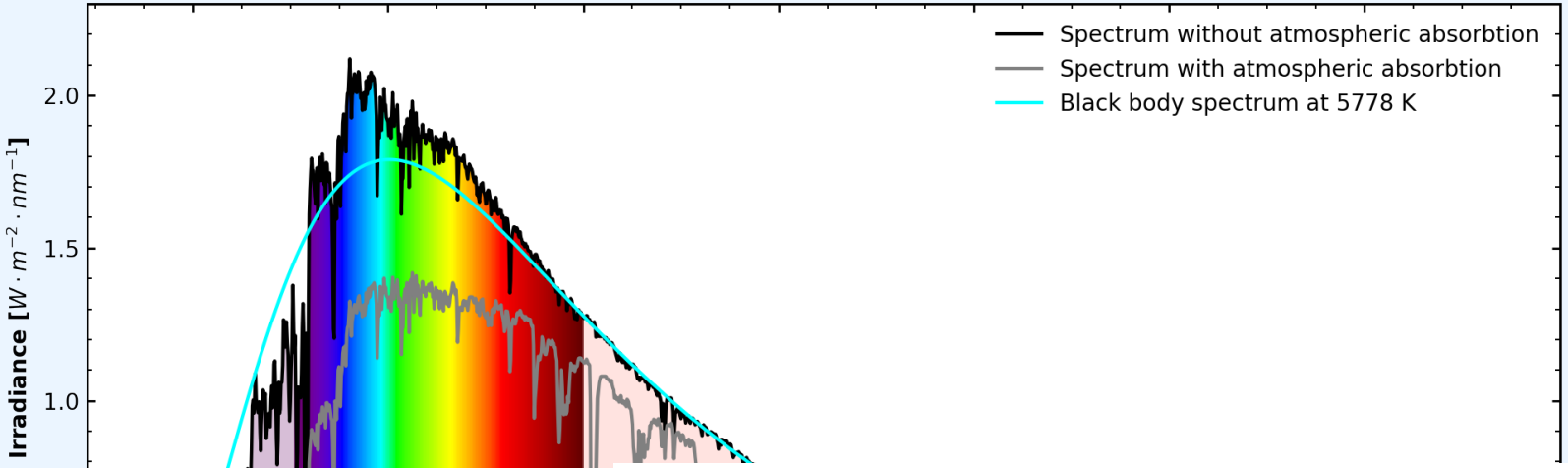


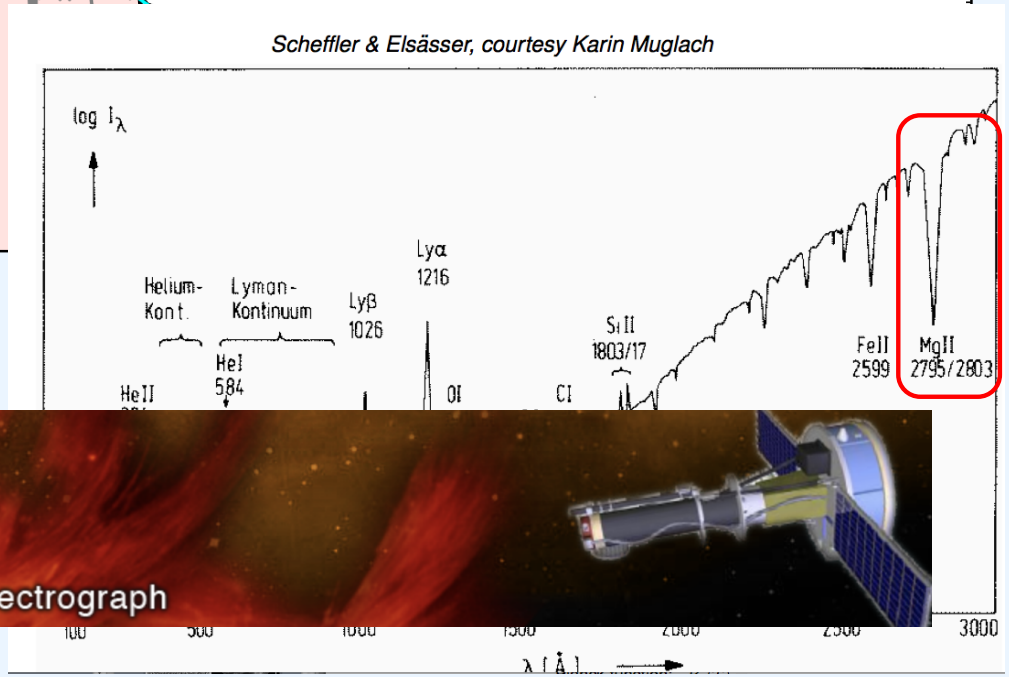
Spectrul Solar

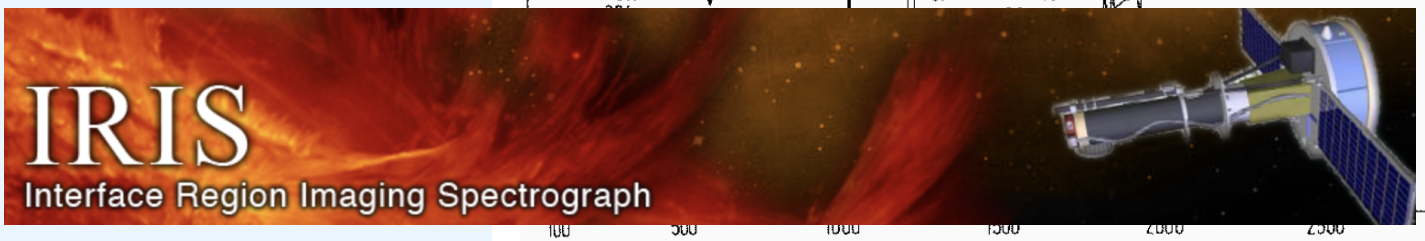


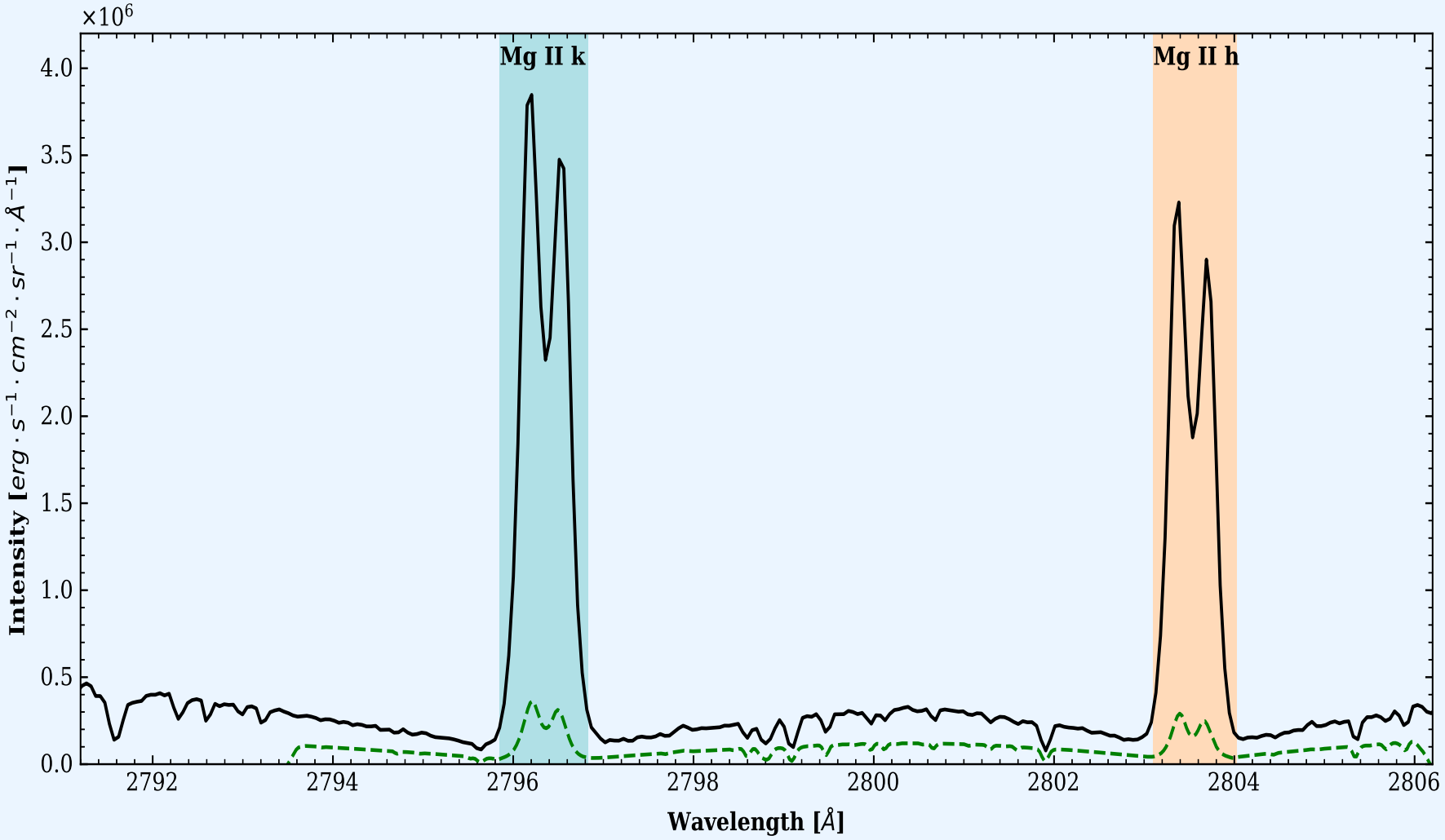


Spectrul Solar

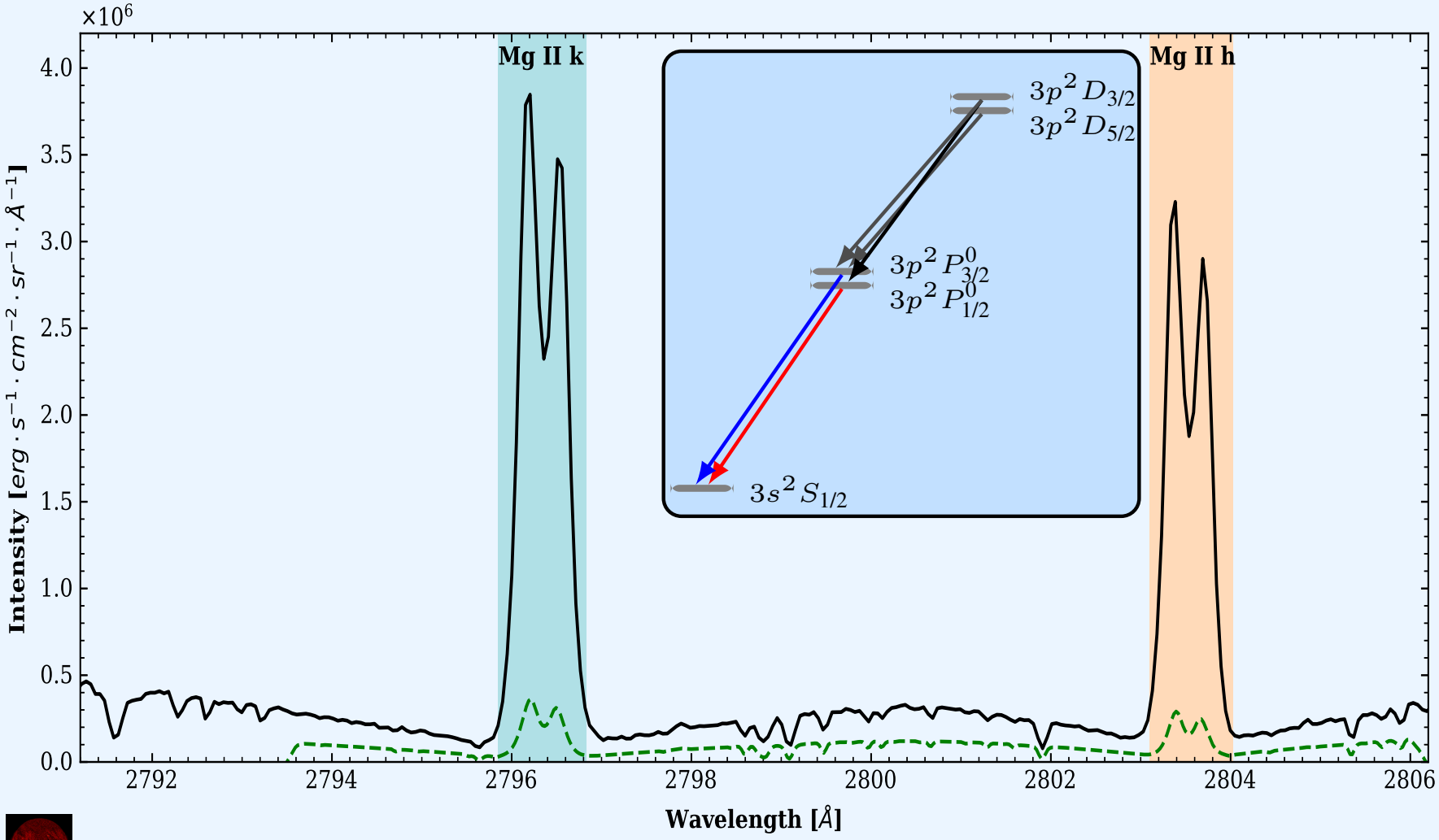




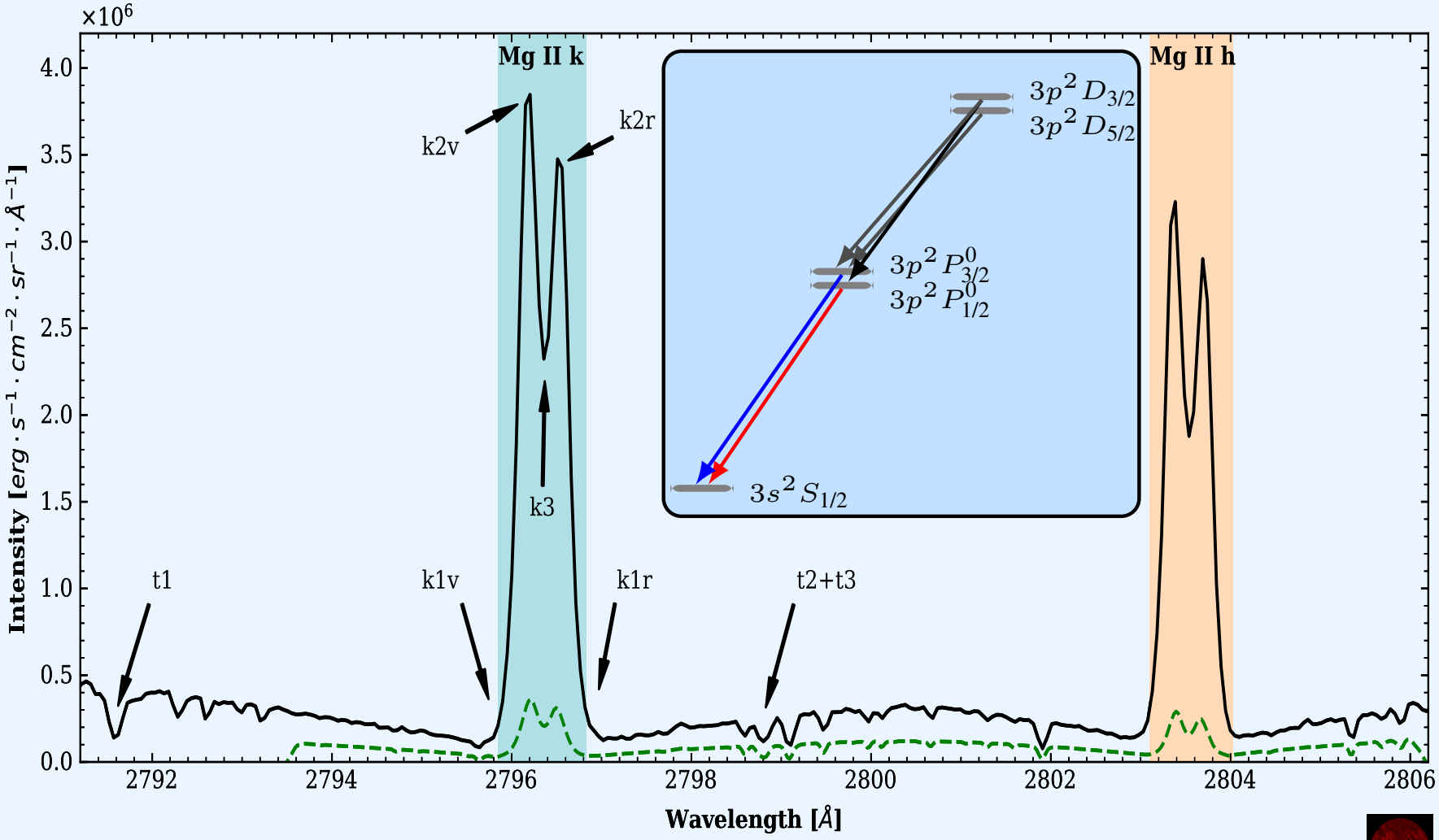




Average spectrum of the Mg II lines



Average spectrum of the Mg II lines



Average spectrum of the Mg II lines

Outline

1. Introducere
2. Metodologie
   - Intensitate absolută
   - Momentele profilului
   - Caracteristicile profilului
3. Calm solar
4. Erupţii

Intensitate absolută

Level 2 data product ⇒ calibrare lungime undă ⇒ $N(\lambda, t)$ în DN ⇒ $I(\lambda, t)$ în $erg \cdot s^{-1} \cdot cm^{-2} \cdot sr^{-1} \cdot$Å^{-1} folosind Liu et al. (2015)

$$I(\lambda, t) = \frac{N(\lambda, t) \cdot Q(\lambda) \cdot E(\lambda)}{t_{\text{exp}} \cdot \Delta\lambda \cdot A_{\text{eff}} \cdot \Omega}$$

unde,

- $N(\lambda, t)$ - intensitatea observată
- $Q(\lambda)$ - caracteristici instrumentale: 18 fotoni ·DN^{-1} pentru regiunea spectrală (De Pontieu et al., 2014)
- $E(\lambda) = h \cdot c/\lambda$ - energia fotonului
- t_{exp} - timp expunere
- $\Delta\lambda$ - rezoluţie spectrală,
- A_{eff} - aria efectivă (*iris_get_response.pro*)
- Ω - unghi solid

Momentele profilului

Intensitate integrată:

$$I_{\text{core}} = \int I(\lambda) d\lambda$$

Effectul Doppler:

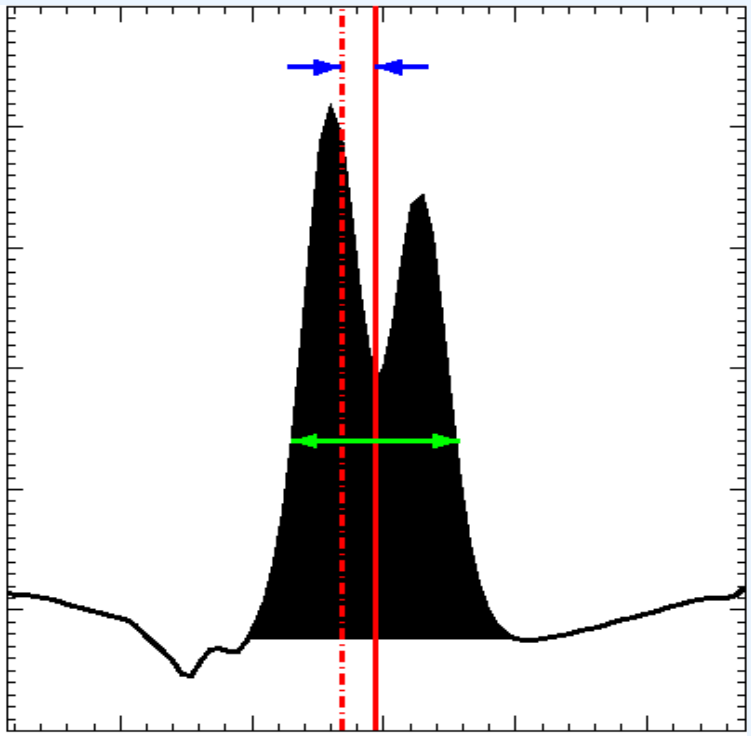
$$\Delta\lambda = \frac{\int \lambda I(\lambda) d\lambda}{\int I(\lambda) d\lambda} - \lambda_0$$

$\Rightarrow$ Viteză Doppler:

$$\Delta v = \frac{\Delta\lambda}{\lambda_0} \cdot c$$

Dispersia lungimilor de undă:

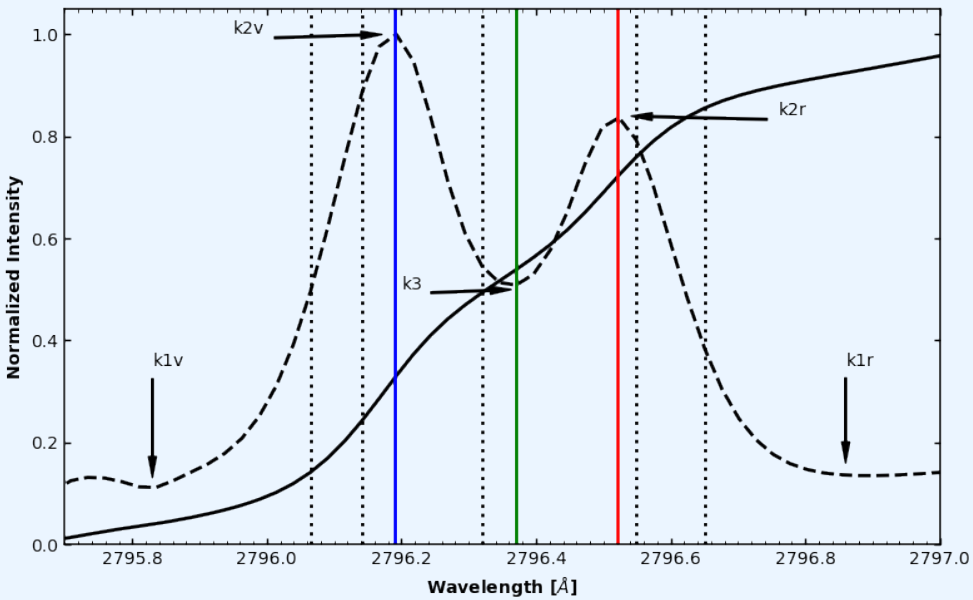
$$\sigma = \sqrt{\frac{\int (\lambda - \lambda_0)^2 I(\lambda, t) d\lambda}{\int I(\lambda, t) d\lambda}}$$



$\Rightarrow$ Lărgimea profilului:

$$\text{FWHM} \approx 2.35\sigma \; d\lambda$$

Caracteristicile profilului



Distanţă dintre maxime:

$$W_{k2} = \lambda_{k_{2v}} - \lambda_{k_{2r}}$$

Asimetria liniei:

$$R_{k2} = \frac{(I_{k_{2r}} - I_{k_3}) - (I_{k_3} - I_{k_{2v}})}{I_{k_{2r}} - I_{k_{2v}}}$$

Adâncimea centrului de absorbţie:

$$D_{k3} = 1 - \frac{2I_{k_3}}{I_{k_{2r}} + I_{k_{2v}}}$$

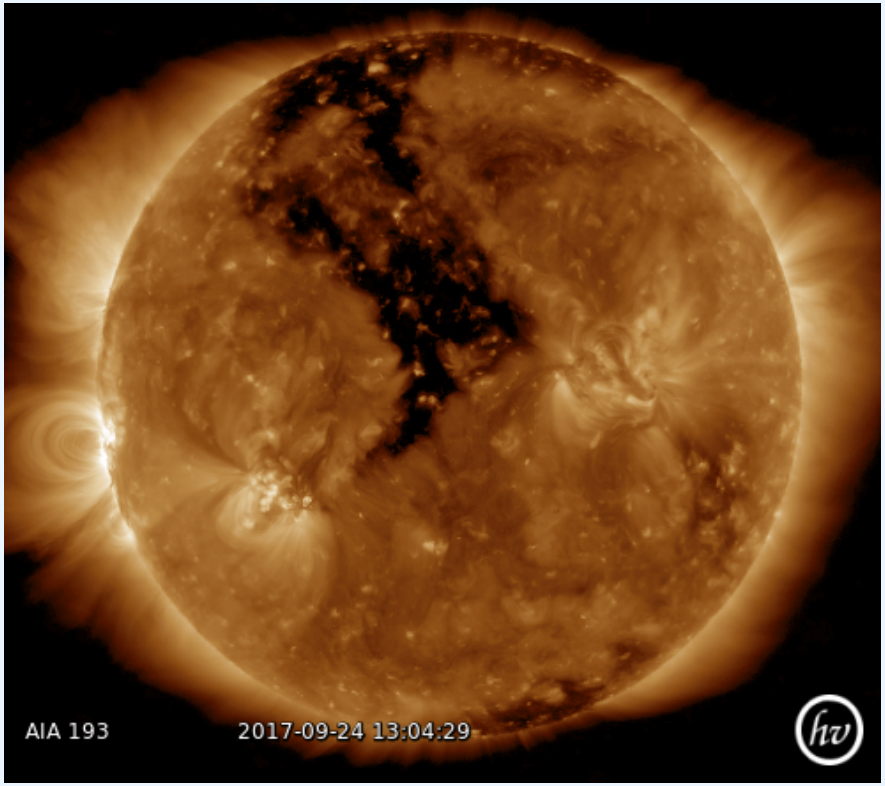
Raţia liniilor de emisie:

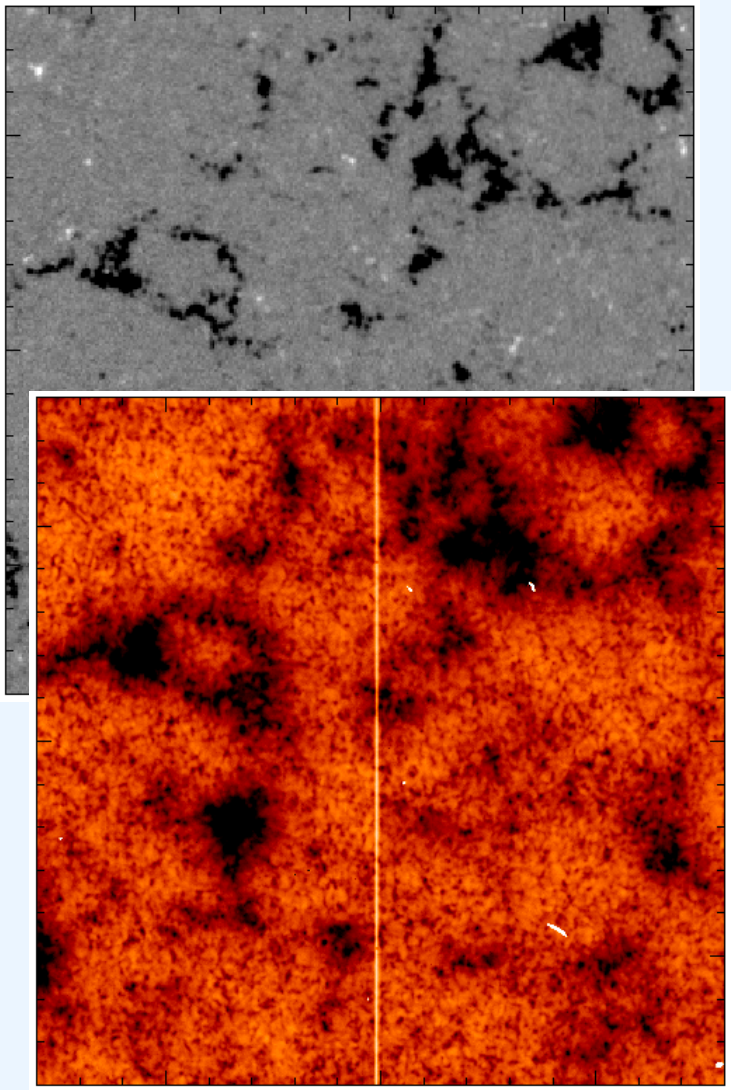
$$R_{kh} = \frac{I_k}{I_h}$$

Outline

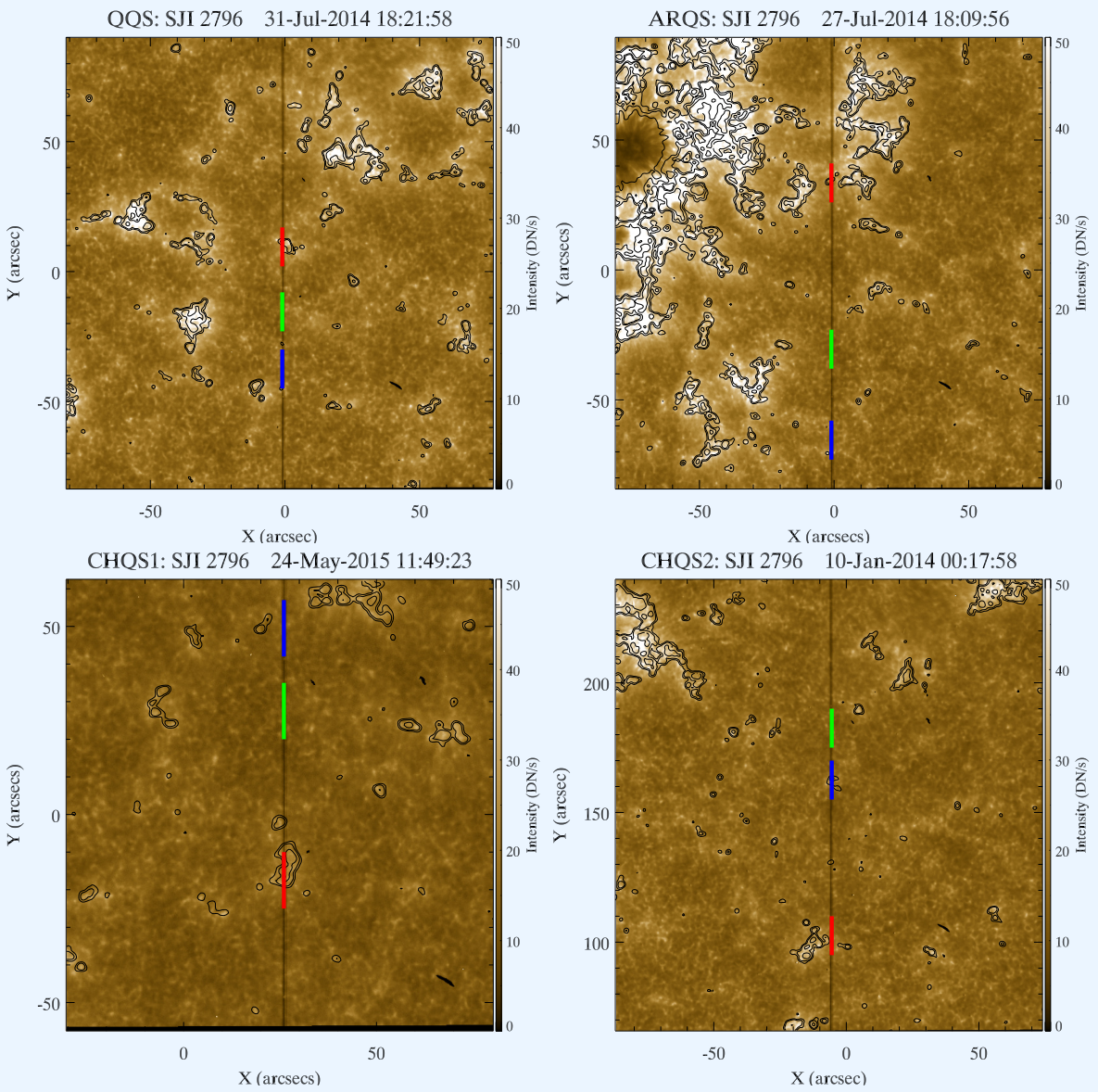
1. Introducere
2. Metodologie
3. Calm solar
   - Seturi
   - Analiză
   - Rezultate statistice
   - Proiect curent
4. Erupţii

Calm solar

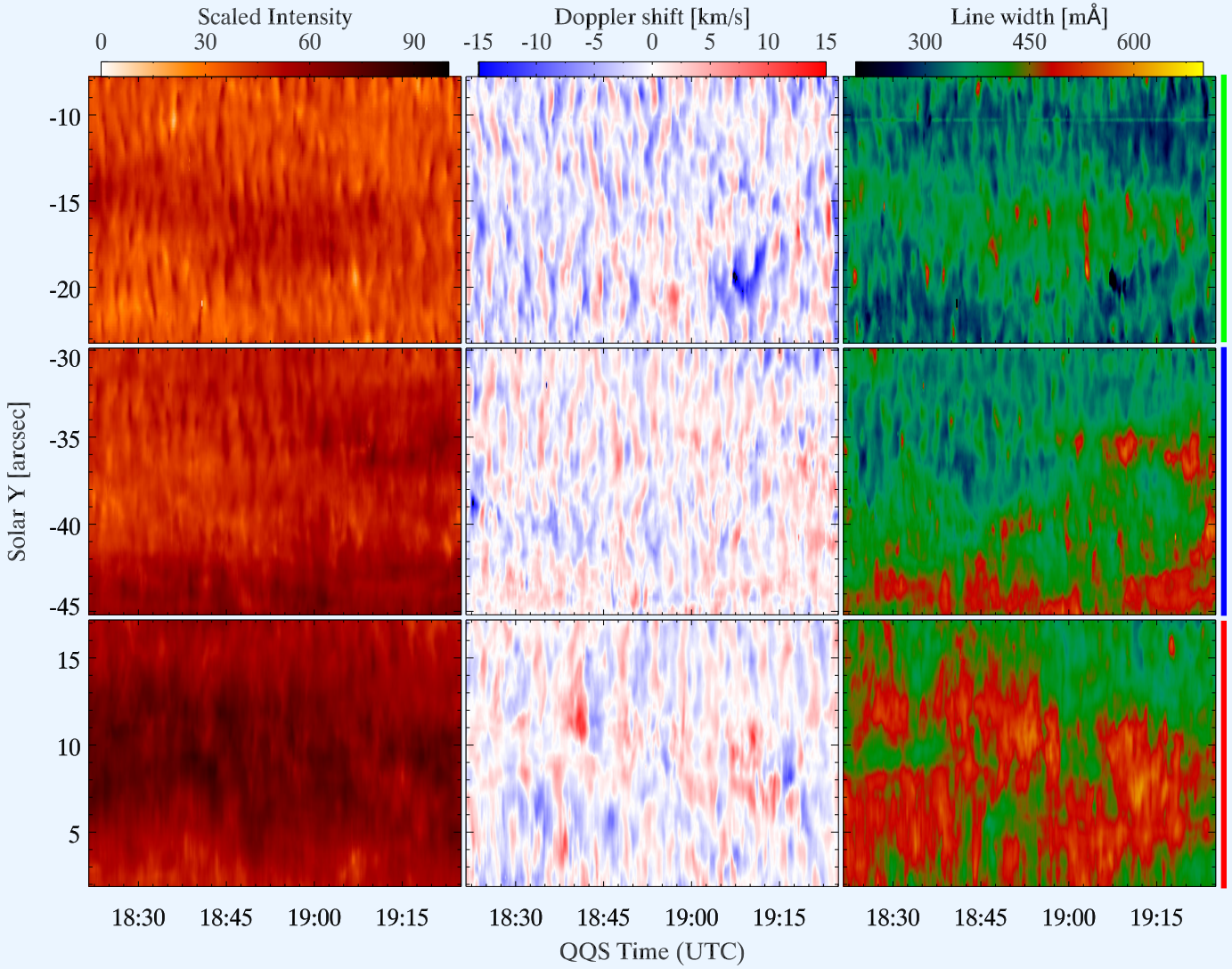




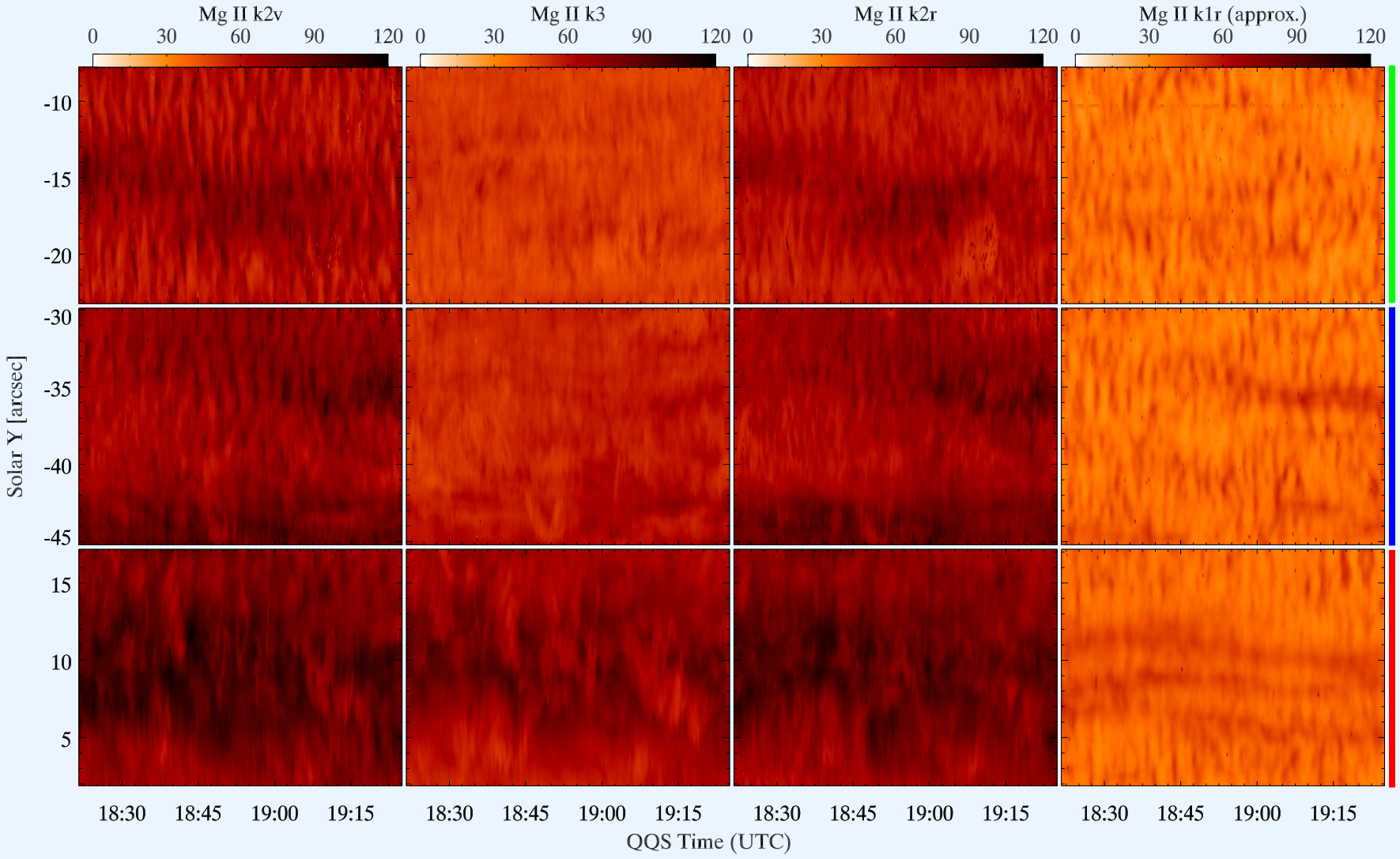
Seturi analizate



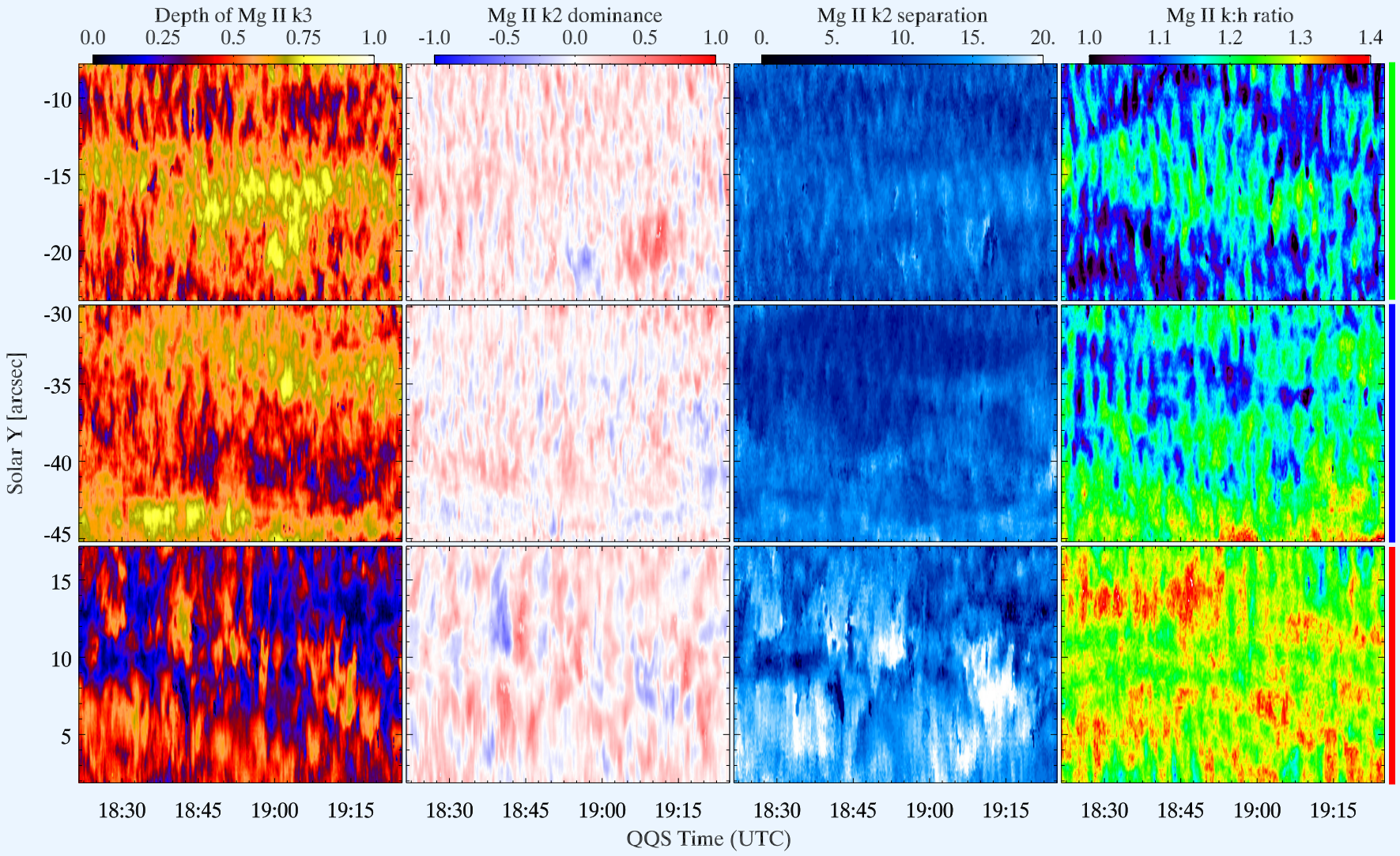
Momentele profilului



Caracteristicile profilului: Intensitate



Caracteristicile profilului: Relaţii



Fit parameters for the Mg II lines characteristics in the datasets, for different activity levels.

Set	Activity Level	Intensity (10^5) [erg cm^{-2} s^{-1} sr^{-1}]	Doppler Shift [km/s]	Line Width [mÅ]	Magnetic field [G]
QQS	Inter	0.62 ± 0.21	-0.97 ± 3.58	345 ± 42	1.07 ± 7.37
	Net	1.50 ± 0.64	0.05 ± 2.51	407 ± 65	2.21 ± 13.40
	E Net	2.68 ± 1.03	0.13 ± 2.65	454 ± 54	15.07 ± 27.02
ARQS	Inter	0.47 ± 0.17	-0.11 ± 2.32	312 ± 37	-0.02 ± 7.07
	Net	1.64 ± 0.61	-0.06 ± 2.34	426 ± 54	-2.54 ± 18.86
	E Net	3.09 ± 0.94	0.46 ± 2.31	495 ± 52	-17.75 ± 29.74
CHQS1	Inter	0.84 ± 0.27	0.64 ± 3.28	342 ± 70	-0.35 ± 5.94
	Net	1.73 ± 0.48	0.47 ± 2.53	446 ± 50	5.68 ± 9.62
	E Net	4.12 ± 1.13	0.17 ± 2.63	554 ± 48	195.04 ± 198.37
CHQS2	Inter	0.73 ± 0.28	-0.21 ± 3.74	398 ± 60	-1.06 ± 8.46
	Net	1.08 ± 0.50	-0.63 ± 4.07	441 ± 70	-10.45 ± 26.50
	E Net	2.61 ± 1.21	0.80 ± 3.50	507 ± 51	-31.64 ± 60.06

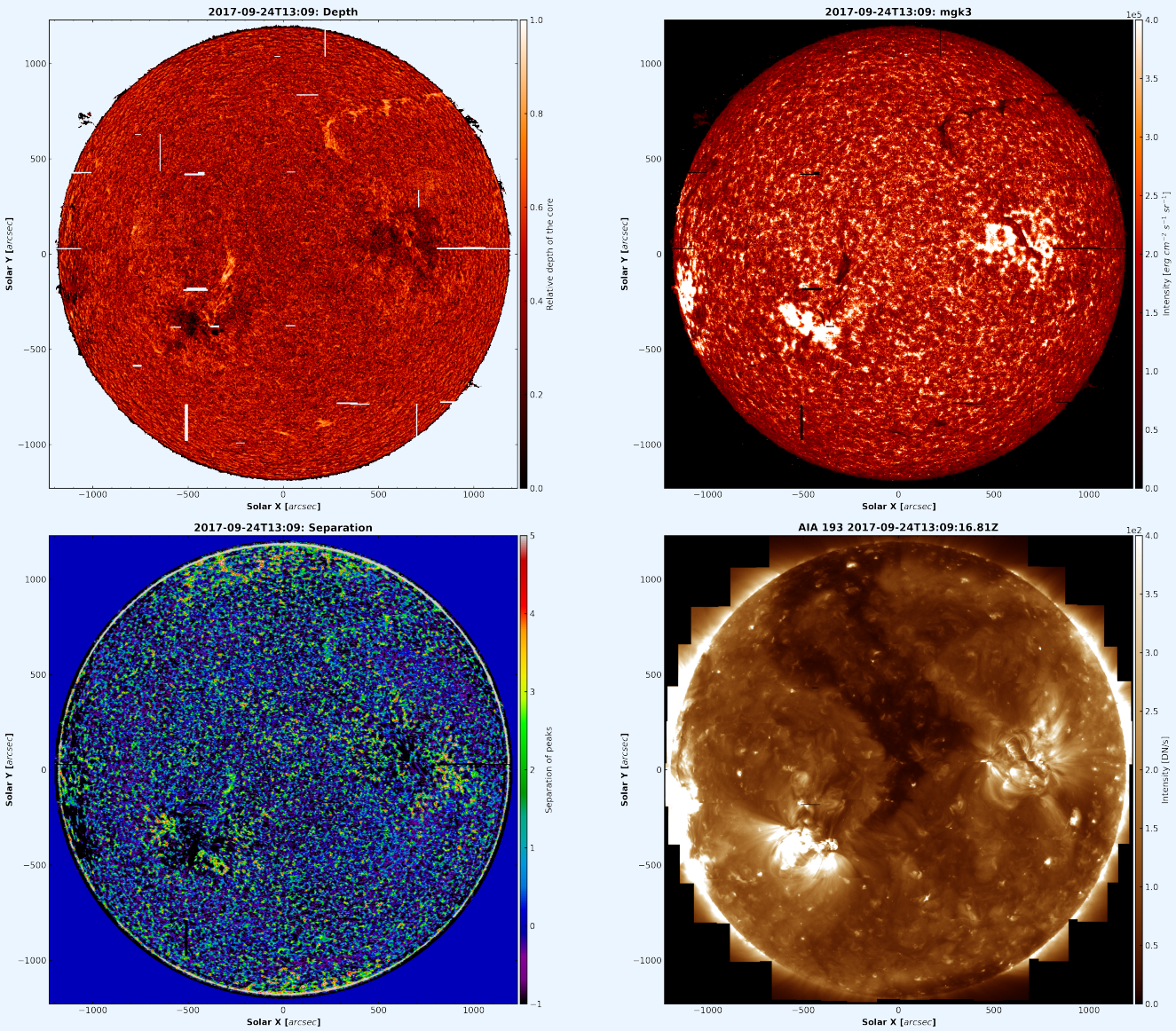
Set	Activity Level	Core Depths	Peak Dominance	Peak Separation mÅ	k:h Ratio
QQS	Inter	0.53 ± 0.12	0.07 ± 0.14	271 ± 38	1.12 ± 0.08
	Net	0.52 ± 0.12	0.04 ± 0.12	302 ± 56	1.19 ± 0.07
	E Net	0.33 ± 0.15	0.06 ± 0.16	323 ± 79	1.27 ± 0.05
ARQS	Inter	0.42 ± 0.12	0.04 ± 0.09	226 ± 31	1.08 ± 0.06
	Net	0.70 ± 0.09	0.05 ± 0.12	317 ± 38	1.20 ± 0.05
	E Net	0.36 ± 0.14	0.05 ± 0.13	355 ± 75	1.30 ± 0.05
CHQS1	Inter	0.52 ± 0.12	0.09 ± 0.16	309 ± 46	-
	Net	0.46 ± 0.11	0.05 ± 0.15	356 ± 53	-
	E Net	0.38 ± 0.16	0.04 ± 0.18	332 ± 81	-
CHQS2	Inter	0.43 ± 0.12	0.05 ± 0.17	309 ± 50	1.14 ± 0.08
	Net	0.47 ± 0.14	0.08 ± 0.19	358 ± 78	1.17 ± 0.05
	E Net	0.41 ± 0.16	0.02 ± 0.19	389 ± 86	1.27 ± 0.05

QQS: Enhanced_network

	B_{LOS}	D_{k3}	I_h (q)	I_k (m)	I_k (q)	I_{h1r}	I_{h2r}	I_{h2v}	I_{h3}	I_{k1r}	I_{k2r}	I_{k2v}	I_{k3}	R_{k2}	R_{kh}	W_{k2}	$\Delta\lambda_D$	Δv
B_{LOS}																		
D_{k3}	0.10																	
I_h (q)	0.33	-0.20																
I_k (m)	0.31	-0.24	0.96															
I_k (q)	0.33	-0.20	0.99	0.98														
I_{h1r}	0.22	0.05	0.52	0.39	0.48													
I_{h2r}	0.21	-0.17	0.75	0.72	0.73	0.32												
I_{h2v}	0.29	-0.12	0.88	0.87	0.88	0.38	0.51											
I_{h3}	0.18	-0.60	0.81	0.83	0.81	0.29	0.64	0.74										
I_{k1r}	0.18	0.02	0.45	0.38	0.43	0.46	0.29	0.35	0.28									
I_{k2r}	0.23	-0.16	0.80	0.80	0.80	0.33	0.87	0.55	0.68	0.31								
I_{k2v}	0.29	-0.12	0.87	0.88	0.88	0.36	0.51	0.98	0.73	0.34	0.55							
I_{k3}	0.17	-0.66	0.82	0.84	0.82	0.28	0.65	0.72	0.94	0.27	0.72	0.73						
R_{k2}	0.07	0.04	0.11	0.11	0.12	0.05	-0.33	0.48	0.08	0.05	-0.41	0.50	0.05					
R_{kh}	-0.01	0.04	-0.10	0.08	0.02	-0.30	-0.10	-0.04	-0.07	-0.20	0.02	0.02	-0.00	0.02				
W_{k2}	0.13	0.73	-0.18	-0.16	-0.16	0.08	-0.19	-0.23	-0.54	0.04	-0.18	-0.22	-0.56	-0.06	0.14			
$\Delta\lambda_D$	0.29	0.54	0.20	0.17	0.20	0.34	0.06	0.07	-0.18	0.32	0.08	0.06	-0.21	-0.05	0.03	0.69		
Δv	-0.05	-0.07	0.00	-0.01	-0.00	0.03	0.30	-0.32	0.00	0.06	0.36	-0.33	0.02	-0.78	-0.04	0.04	0.08	

Lacatus & Donea (in prep.)

Proiect în desfăşurare



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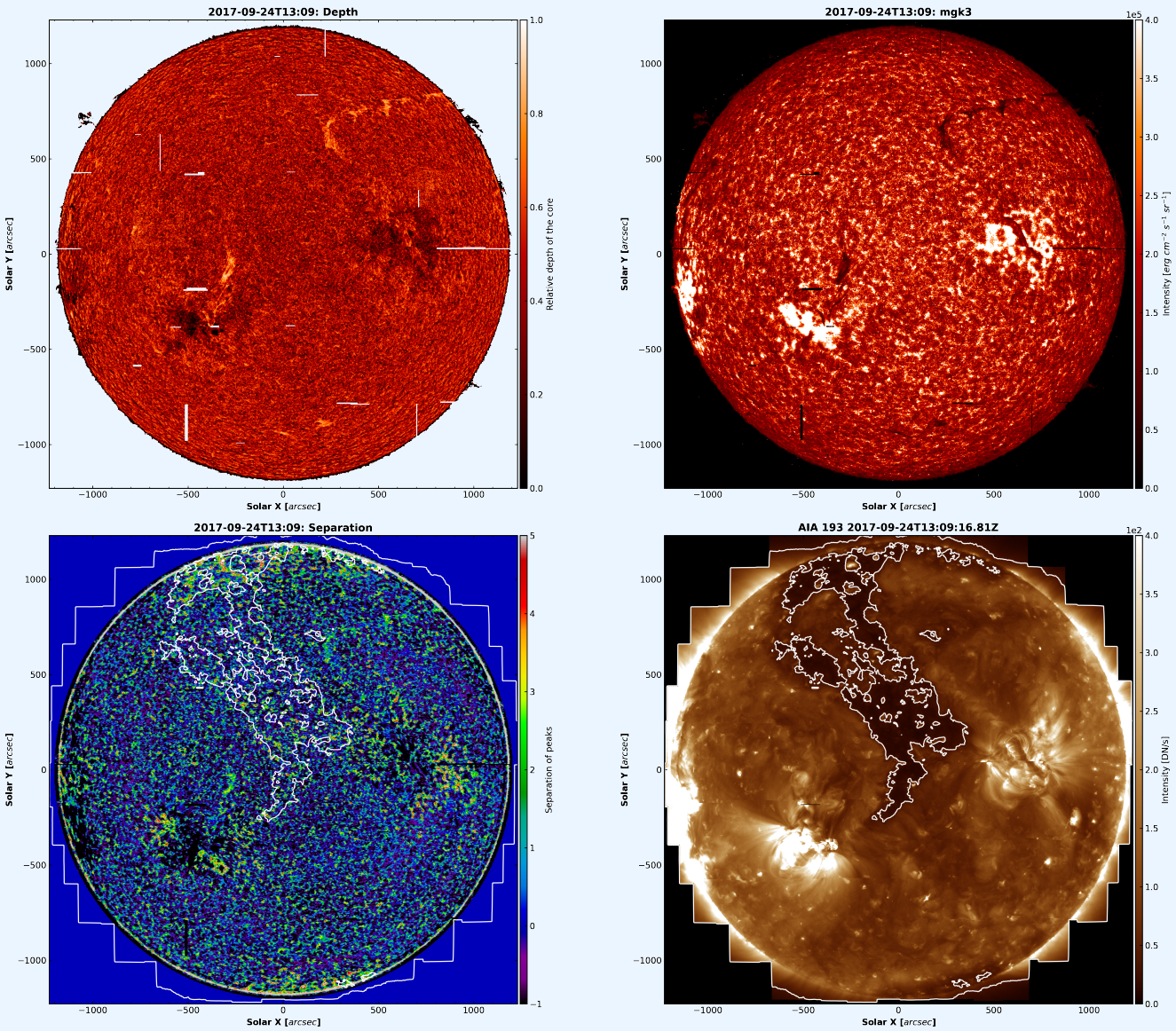
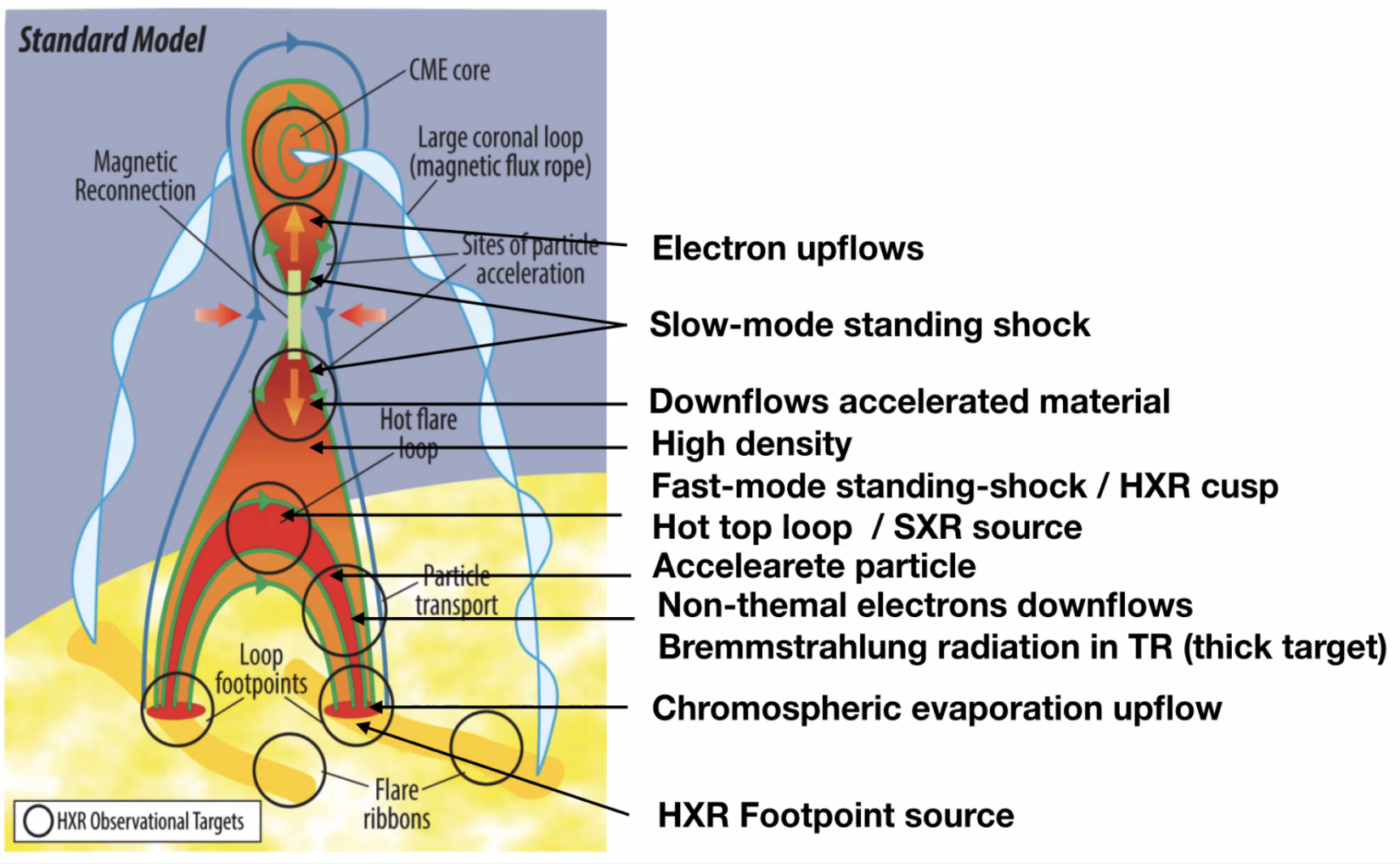


Outline

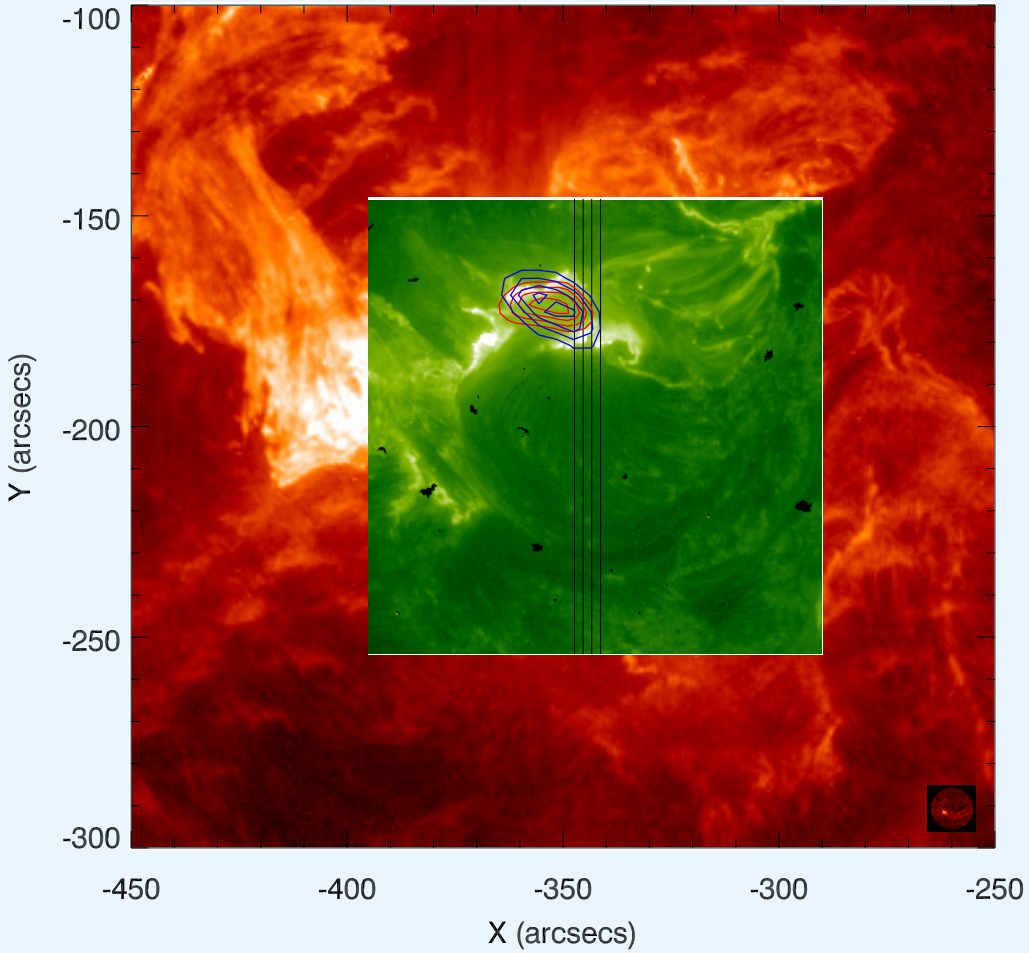
1. Introducere
2. Metodologie
3. Calm solar
4. Erupţii
   - Model teoretic
   - Exemplu
   - Efecte spectrale
   - Ploaie coronală
   - Analiză

Model Erupţie



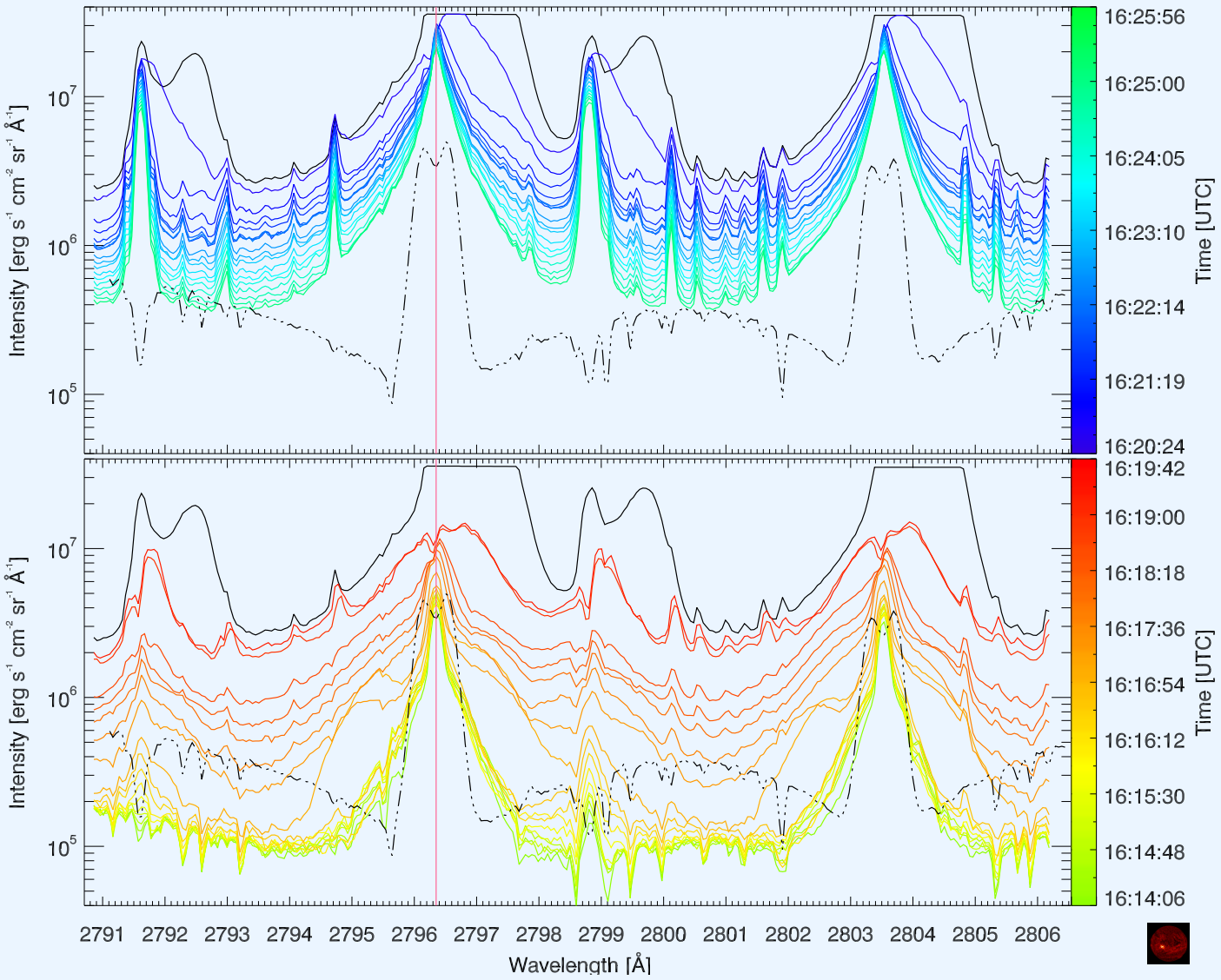
Cartoon model based on Yokoyama & Shibata (1998)

March 11, 2015 X2.1

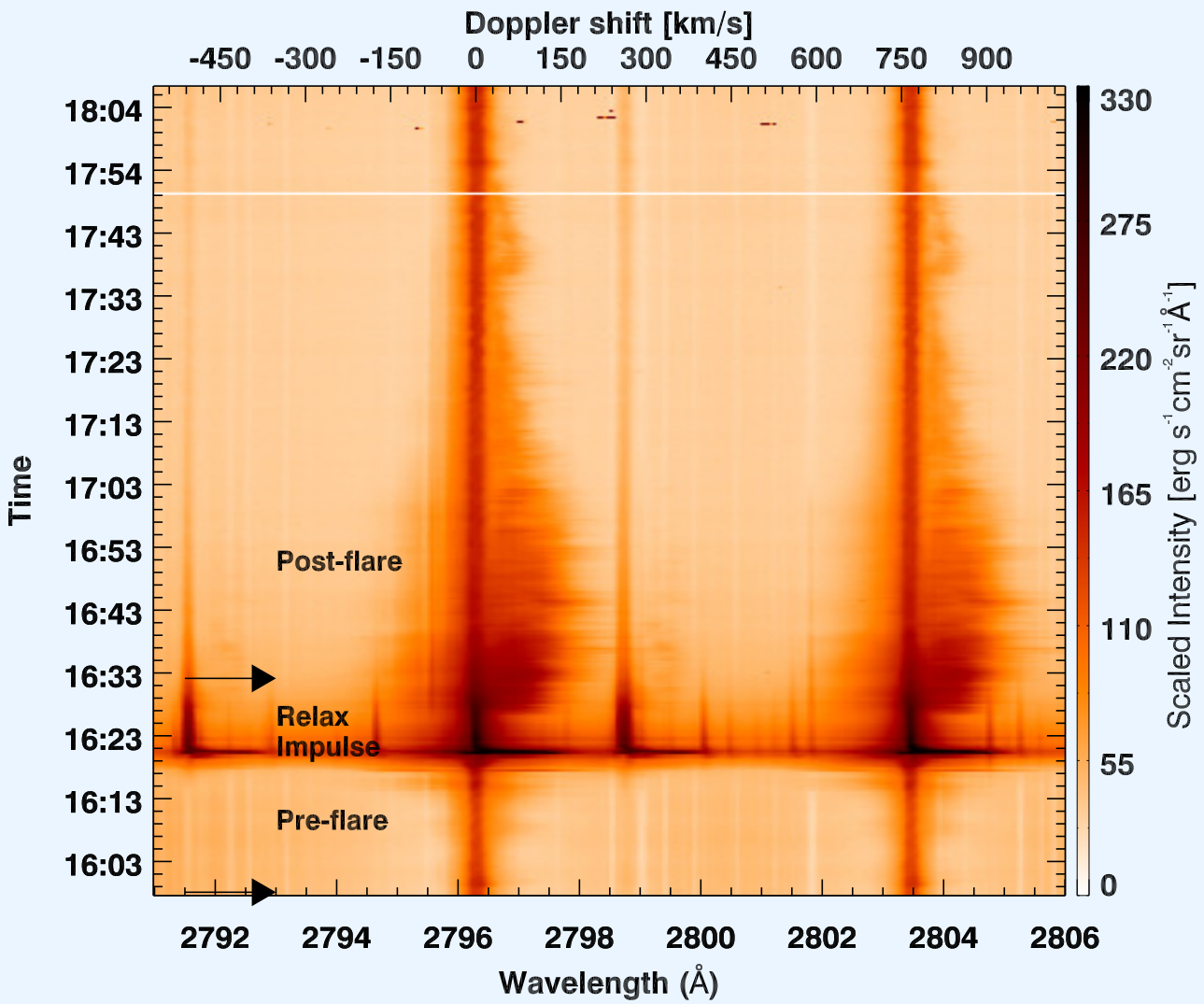


Position of the soft (red) and hard (blue) X-ray kernels with respect to the IRIS SG slit positions (black vertical lines). The background (red) is SDO/AIA 304 emission and the foreground (green) is IRIS/SJI 1330 Å.

Emisia Mg II k&h



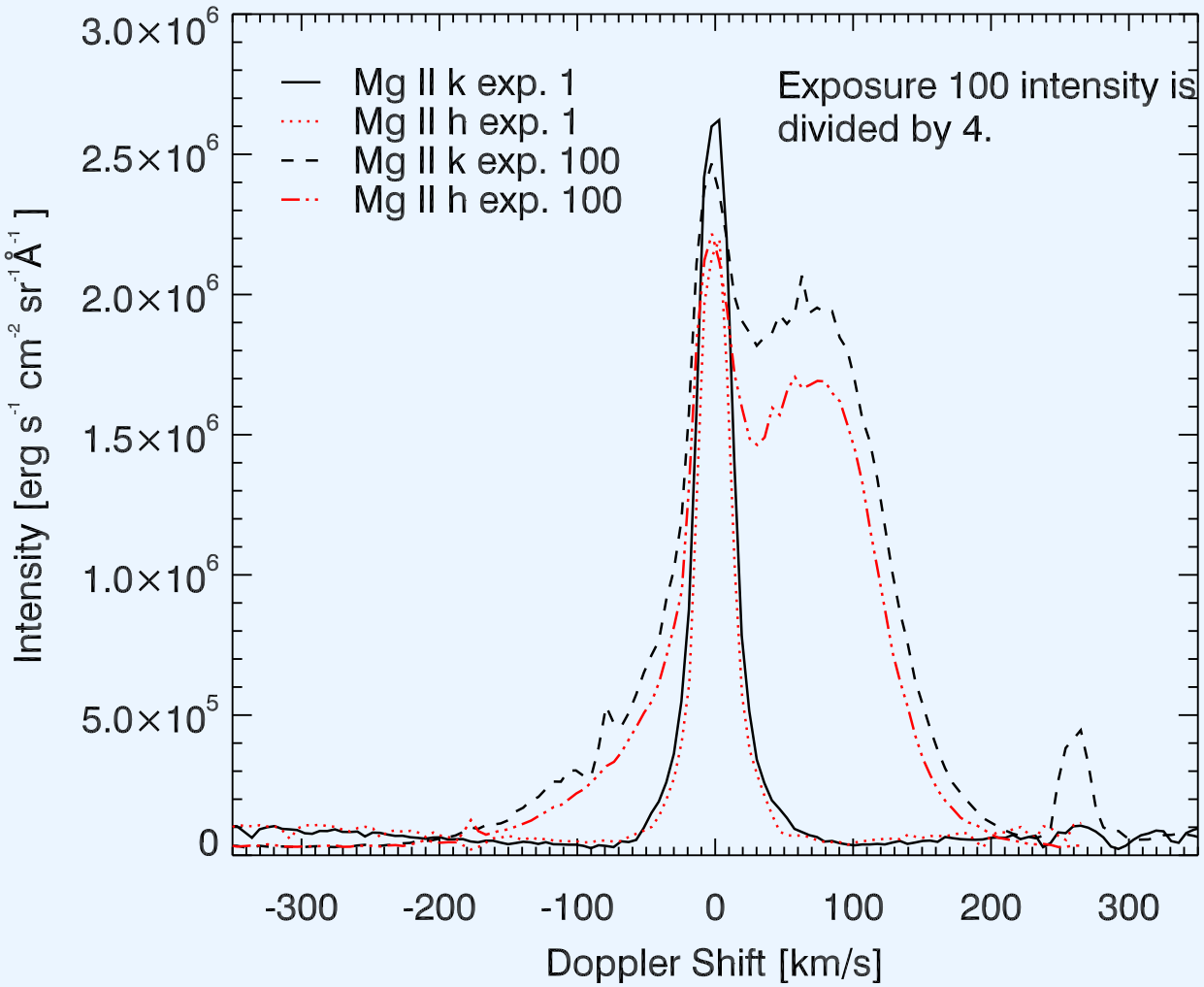
Date observaţionale



The Mg II spectral profile evolution at -175" (slit 0).

Lacatus et al. (2017)

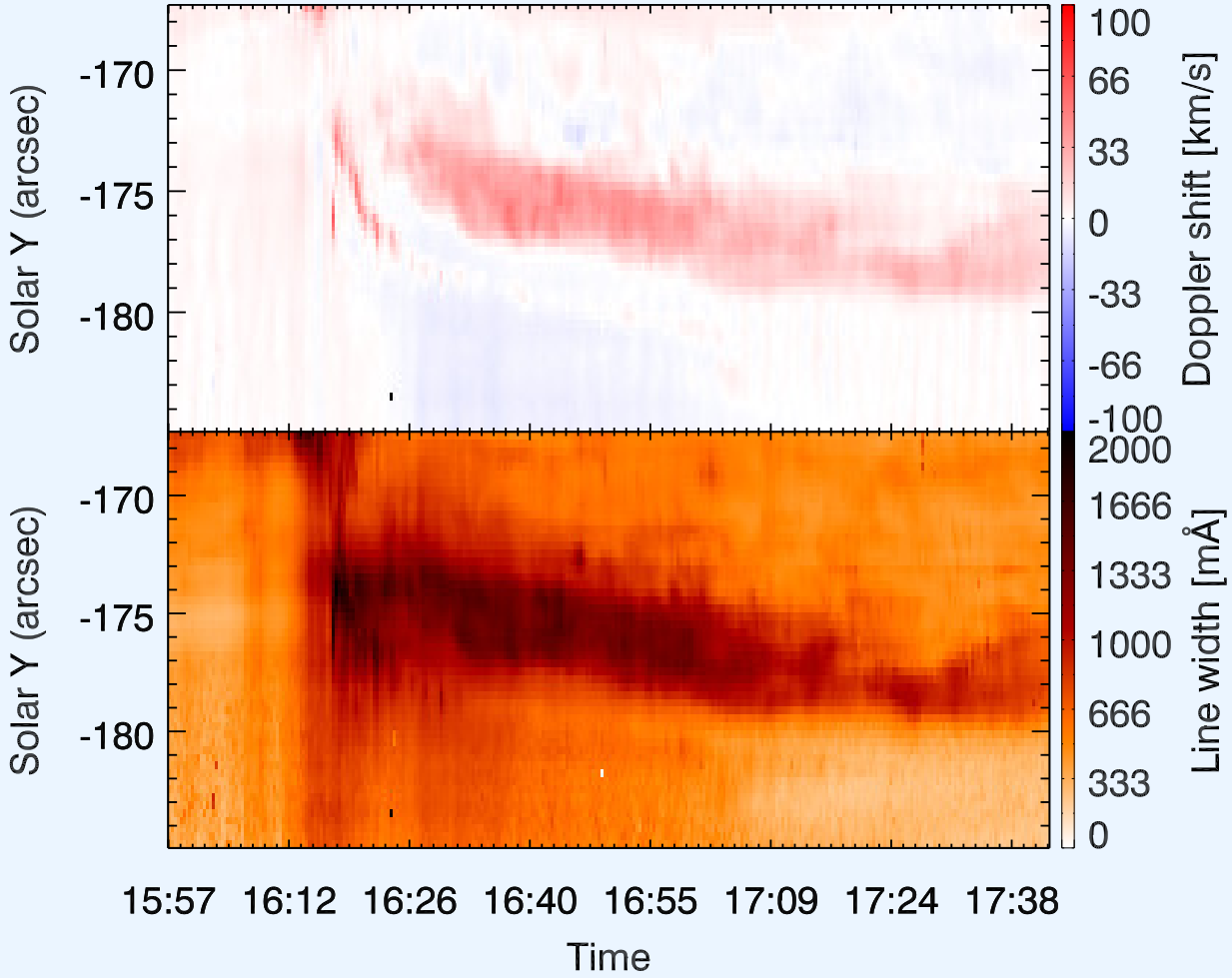
Date observaţionale



Mg II k&h line profile changes in the Post-flare times compared to Pre-flare. The Post-flare emission has been scaled.

Lacatus et al. (2017)

Date observaţionale



Evolution of Doppler Shift and Line widths for the Mg II k line in the peculiar profile region.

Lacatus et al. (2017)

Elemente distinctive

Observed frequency-integrated intensity (erg cm^{-2} s^{-1} sr^{-1})

Multiplet	Mg II	Mg II	C II	Si IV
	$3p - 3s$	$3d - 3p$	1334 + 1335	1403
Phase				
QS	5.36×10^5	...	6070	572
Pre-flare	1.83×10^6	...	5.16×10^4	2840
Impulse	4.36×10^7	$\approx 1.36 \times 10^7$	1.73×10^7	$> 3.86 \times 10^6$
Relax	2.77×10^7	4.81×10^6	4.39×10^6	3.51×10^5
Post-flare	$\mathbf{1.82 \times 10^7}$	$\approx \mathbf{4.51 \times 10^5}$	$\mathbf{1.45 \times 10^6}$	$\mathbf{2.04 \times 10^5}$

- Sudden onset 6 min after flare.
- Region 20 pixels across (6") or 4-5 Mm.
- No obvious self-reversed of broad components.
- Smooth profile across Doppler shifts $\Longrightarrow$ unresolved motion.
- Total PF intensity higher than core $\Longrightarrow$ not scattering, plasma pocket.
- Mg II k/h ratio $\approx$1.15 (thin 2:1) and C II 1334/1335 Å ratio $\approx$ 1. (thin 1:2)$\Longrightarrow$ optically thick plasma?
- PF profile width of 150 km/s and $\sim$70 km/s redshift $\Longrightarrow$ 4X more energy in unresolved motions than in resolved ones $\Longrightarrow$ Magnetic fields play important role?

Analiză teoretică

Line opacity $\varepsilon \approx \dfrac{C_{31}}{A_{31}+C_{31}} \quad \ll \quad P_{esc} \approx \dfrac{1-\exp(-\tau_0)}{\tau_0}$

Radiation Anisotropy

τ_0 for h is $\approx 1/2$, and for k is ≈ 1, only outermost strands will be seen.

Emission effectively thin across strand

$$I_{thin} = \frac{h\nu_{ji}}{4\pi} n_1 C_{ji} \frac{W}{\cos\theta} \approx 1.1 \times 10^7 \text{erg cm}^{-2}\ \text{s}^{-1}\text{sr}^{-1}$$

Mg II transitions Observed intensity ratio of triplet to h& k is 1/40:

$$\frac{I_{3d-3p}}{I_{3p-3s}} \approx \frac{C_{3s-3p}}{C_{3s-3d}} \approx \frac{1}{6} exp\left(\frac{4.86}{T_{e4}}\right) \Rightarrow\ T_{e4} \approx 2-2.5$$

Doppler shift $\sim$ 70 km/s shift $\Rightarrow$ plasma dropped from $\sim$ 5 Mm

Sudden onset $\times 2$ increase in intensity in < 40 s. Small scale motions ($\xi_{10} \approx 100$ km s^{-1}) within a coherent downflow of 70 km s^{-1}.

Broad lines origin: Scattering inside the strand can not lead to emission so far from core. Therefore we assume:

$\xi \approx v_A = \frac{B}{\sqrt{4\pi\rho}} \ \Rightarrow\ B \approx\ 17G$ in chromopshere

The kinetic energy density $\sim 2 \times 10^{10}$ erg cm^{-2}.

X-class flare: 10^{11} erg cm^{-2} s^{-1} for $\sim 10^{2-3}$ sec, total energy density $\Rightarrow$ 10^{13-14} erg cm^{-2}, so only 1/1000 needed for waves.

Analiză teoretică

• Total radiated flux in Mg II h&k $\approx \pi I t_r \approx 3 \times 10^{10}$erg cm^{-2}
$\Rightarrow$ Total radiative fluxes from chromosphere 4-10$\times$ higher (Anderson & Athay, 1989): 10^{11} erg cm^{-2}
• The line width and intensity decrease in time, suggesting slow decay of waves, with energy converted to heating by phase mixing, resonant absorption, ion-neutral interactions, etc.
• For reference, an Alfvénic wave with a period of 10 seconds ($\omega \approx 0.6$ rad sec^{-1}), oscillating in the plasma with $n_{12} \approx 1$ and $n_{n12} \approx 0.1$, consisting entirely of neutral helium. The ion-neutral helium collision time, $\tau_{ni} \approx 10^{-3} n_{n12}^{-1} \approx 10^{-2}$ sec^{-1}, which gives $\omega\tau_{ni} \approx 6 \times 10^{-3}$. Under this regime the wave energy dissipation time (Holzer et al., 1983) is

$$\tau_D \approx \frac{n_{12}}{n_{n12}} \frac{1}{\tau_{ni}\omega^2} \approx 2500 \text{ sec.}$$

Observed decay time of $\approx 10^3$ seconds may or may not be naturally explained without needing to invoke dynamical MHD processes, depending on the (unknown) frequency ω of the oscillations.

Concluzii

Liniile de emisie rezonantă ale atomului de Magneziu în primul stagiu de ionizare (Mg II) prezintă importante variaţii în funcţie de nivelul de activitate solară, dar oferă informaţii corespunzatoare mai multor "înalţimi" din cromosferă dacă luam în calcul detaliile structurale ale profilului.

Conditii de activitate redusa: efecte la marginea supergranulelor

- Intensificări ale intensităţii şi lărgimii profilelor
- Separarea maximelor însotiţă de scăderea adâncimii centrului de absorbţie
- Contrastul dintre zonele inactive pure şi găurile coronale este partial vizibil în separarea maximelor de emisie

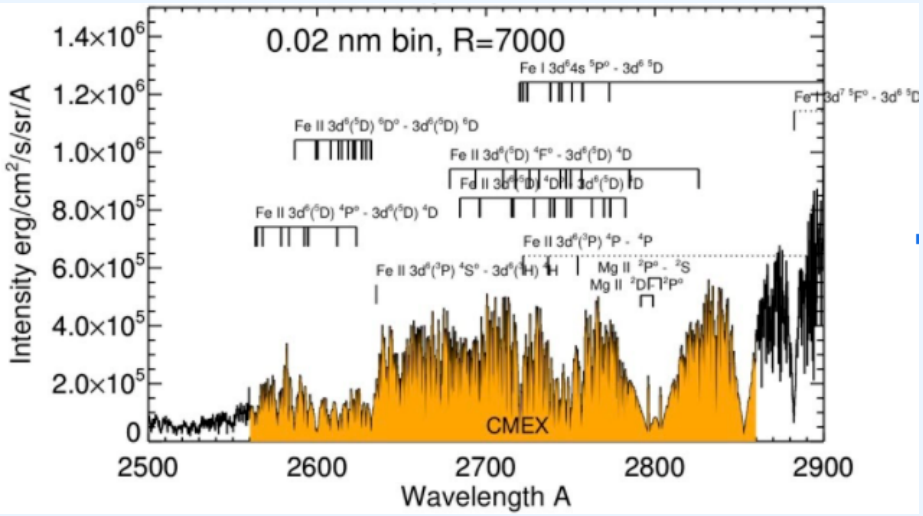
Condiţi eruptive

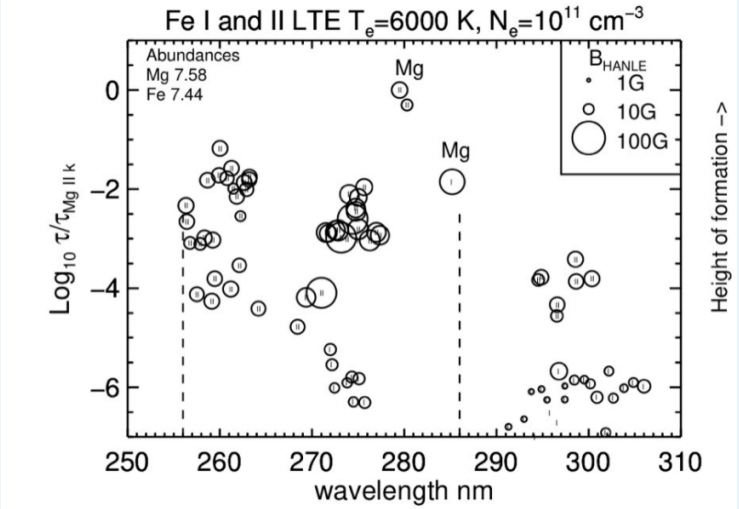
- Profilul nu prezintă centru de absorbţie $\Rightarrow$ comprimarea zonei de emisie
- Liniile subordonate sunt în emisie $\Rightarrow$ gradient de temperatură
- Intensificarea emisiei şi lărgimii liniei $\Rightarrow$ miscări turbulente
- Destabilizare filamentului precede erupţia cu cel putin 10 minute
- Deplasare Doppler spre roşu persistentă în ploaia coronală
- Lărgirea liniilor cauzată de mişcări la scală mică în interiorul unei plasme anisotropice
- Cauză plauzibilă: Amortizare unor unde Alfvénice excitate în faza impulsivă a erupţie în interiorul plasmei din ploaie coronală

Încotro?

Rezultatele spectroscopice sunt limitate de lipsa informaţiilor care ar clarifica ambiguităţile observaţionale. Posibile rezolvări:

- Multiple linii sensibile la condiţii atmosferice din întregul volum
- Măsurători de câmp magnetic în cromosferă
- Multiple linii sensibile la efecte ale câmpului magnetic: efectul Hanle şi efecte magneto-optice (iluminare anizotropică, variaţii de câmp magnetic)
- Modelare ale emisie acestor ioni, considerând structuri atomice suficient de detaliate, efecte radiative, în afara condiţiilor de echilibru termic local
- Utilizarea de metode de inteligenţă artificială în prelucrarea şi modelare datelor observaţionale.





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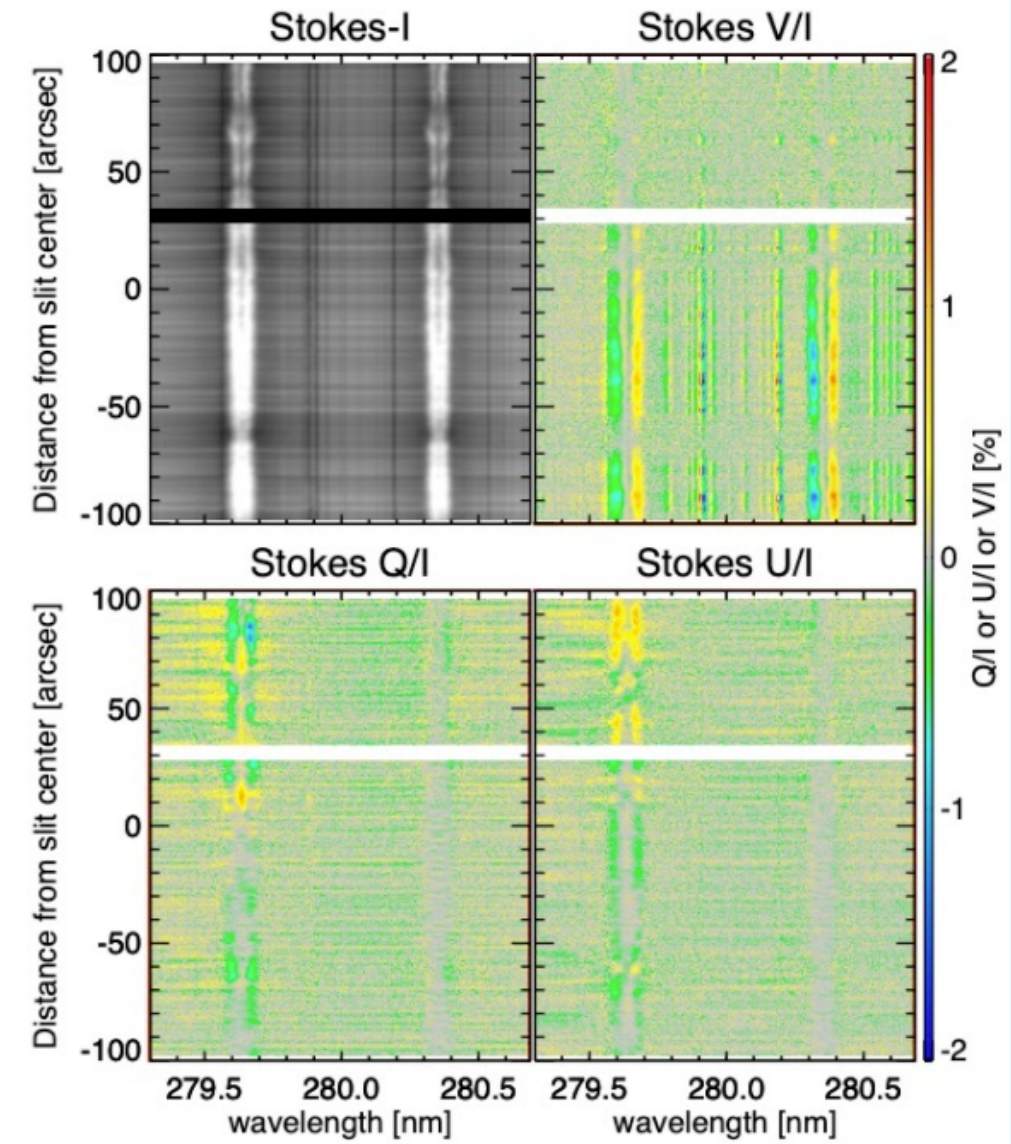
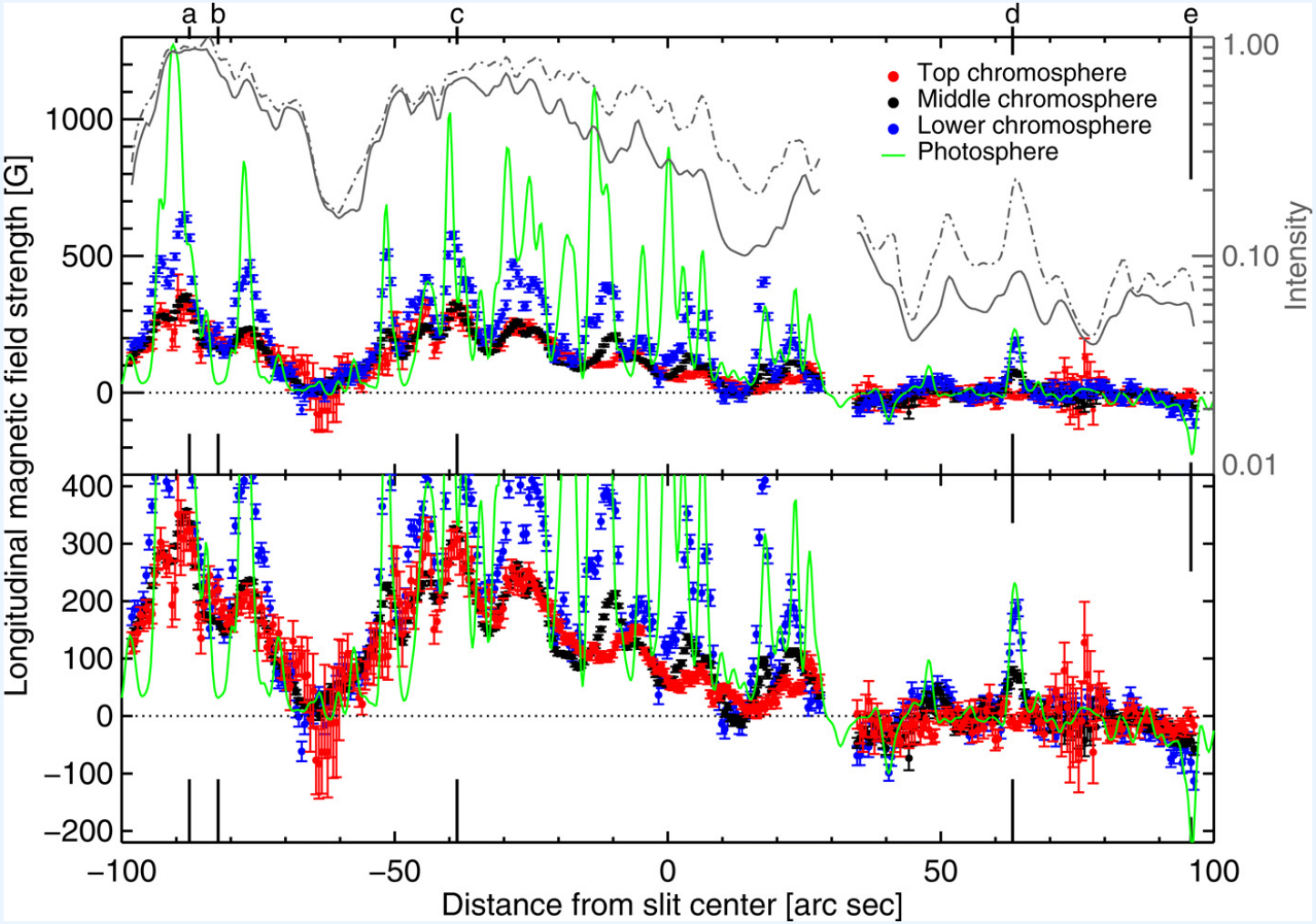


Ishikawa et al. (2021)

Încotro?



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Vă mulţumesc pentru atenţie!

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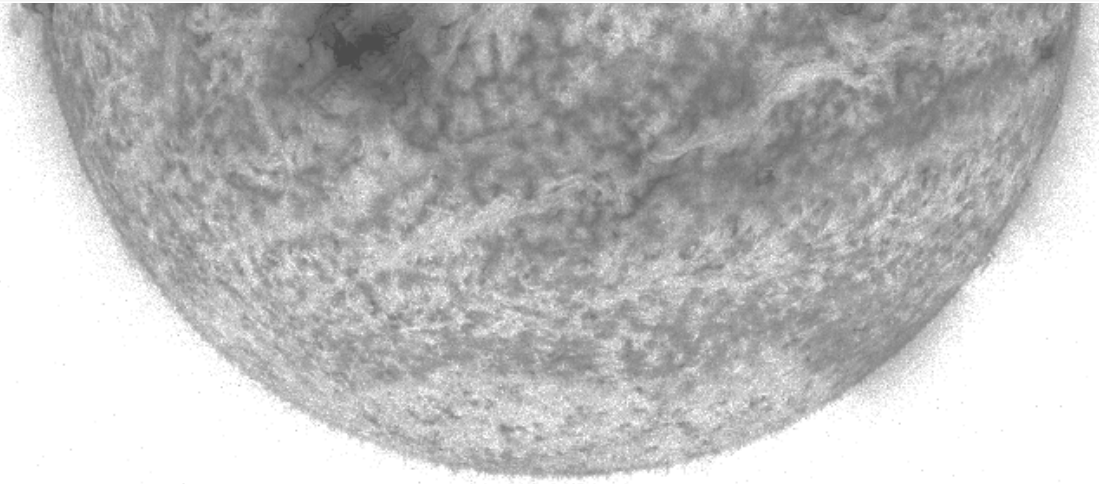
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