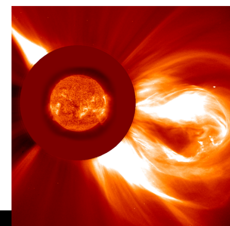


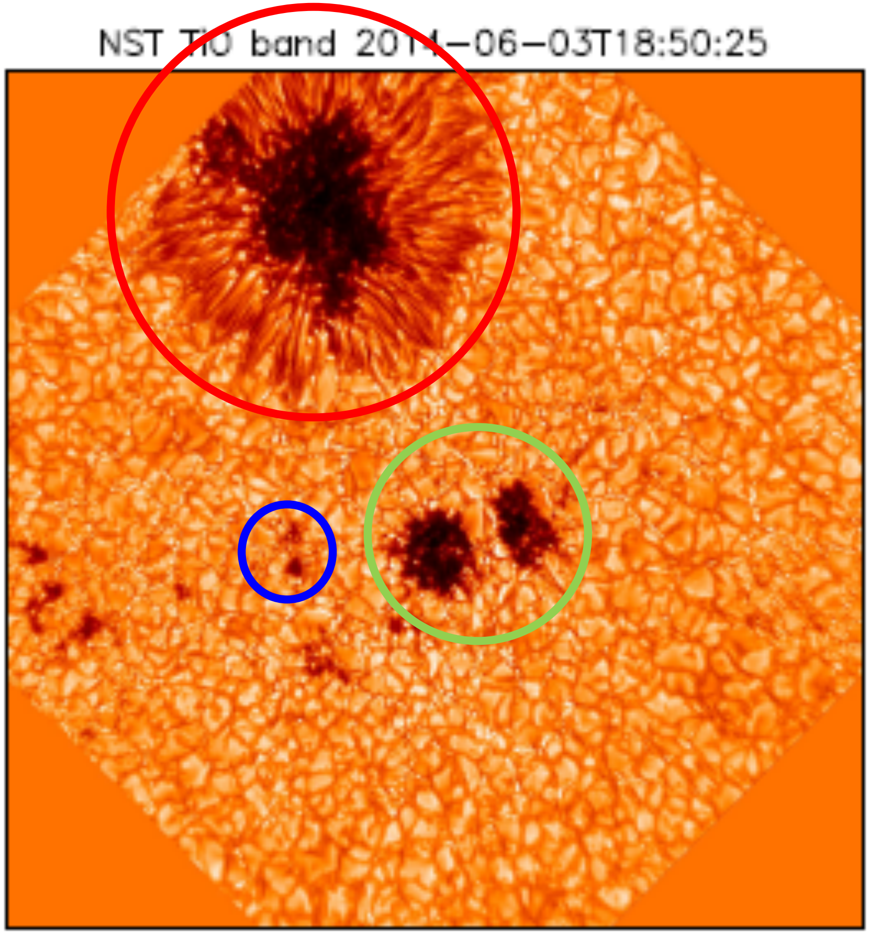
한국천문연구원
Korea Astronomy & Space Science Institute

Observations of Umbra waves with NST and SDO

Kyung-Suk Cho (趙京錫)

Collaboration with S.-C. Bong , I.-H. Cho (KASI),
J.C. Chae (SNU), V. Nakariakov (KHU)

Sunspots



Mature Sunspots
(Penumbral Sunspots)

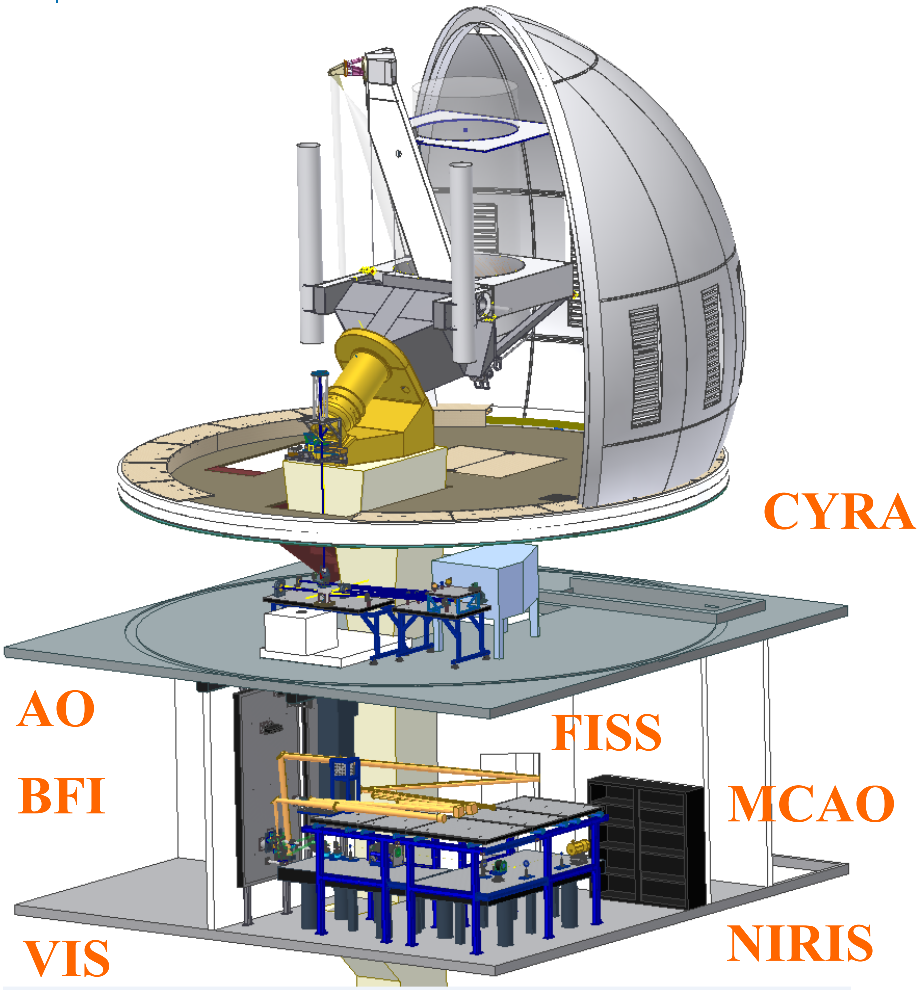
Transitional Sunspots

Pores
(Penumbra-less sunspots)

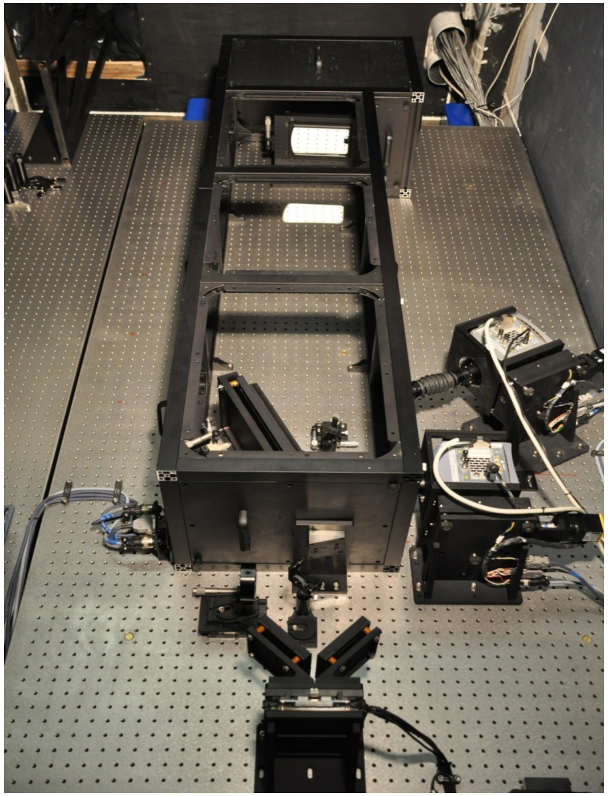
Tlatov & Pevstov (2014)

(1) Intensity and Doppler Oscillations in Pore Atmosphere using NST

NST/FISS @ BBSO

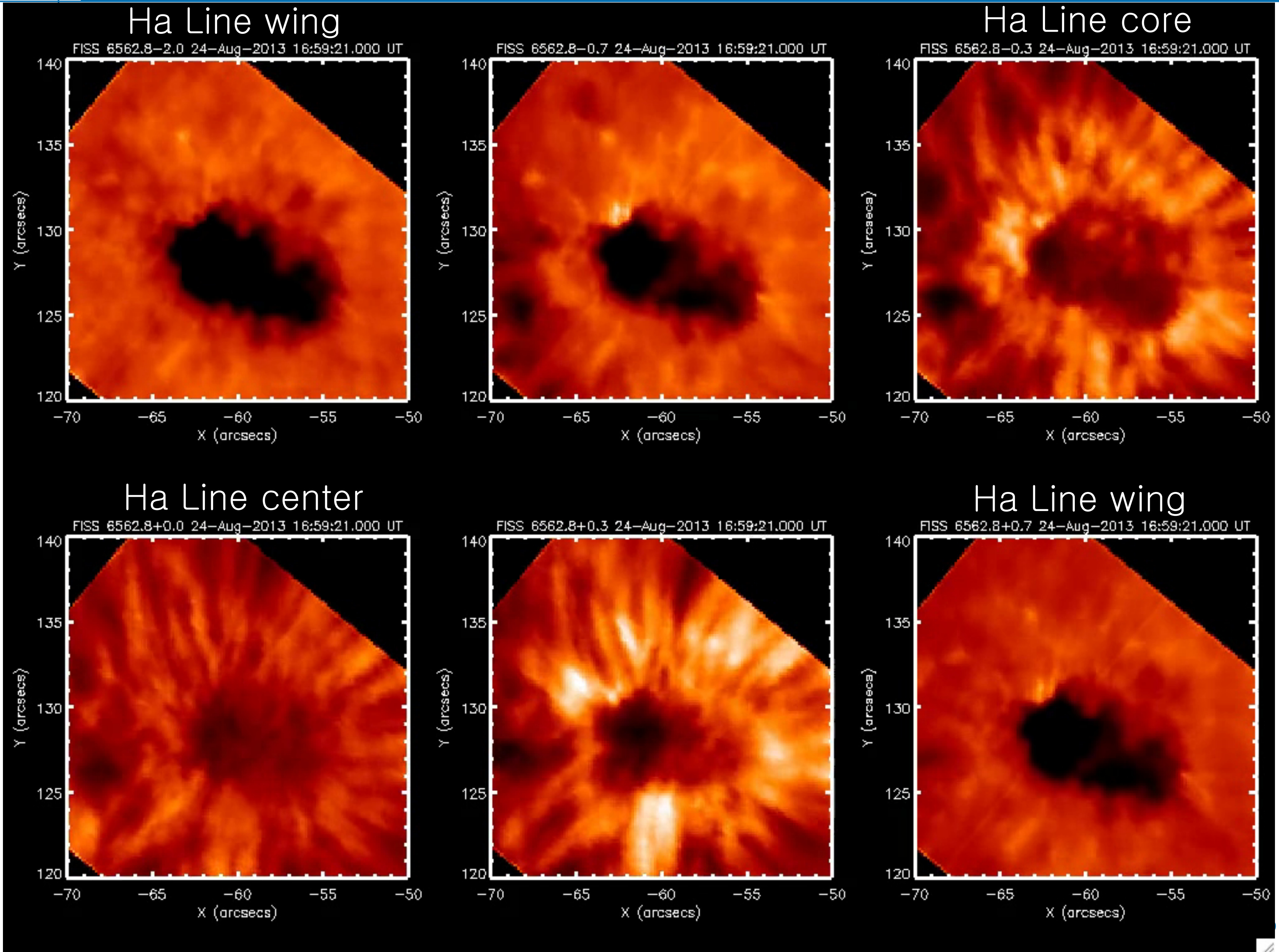


Fast Imaging Solar Spectrograph (FISS)

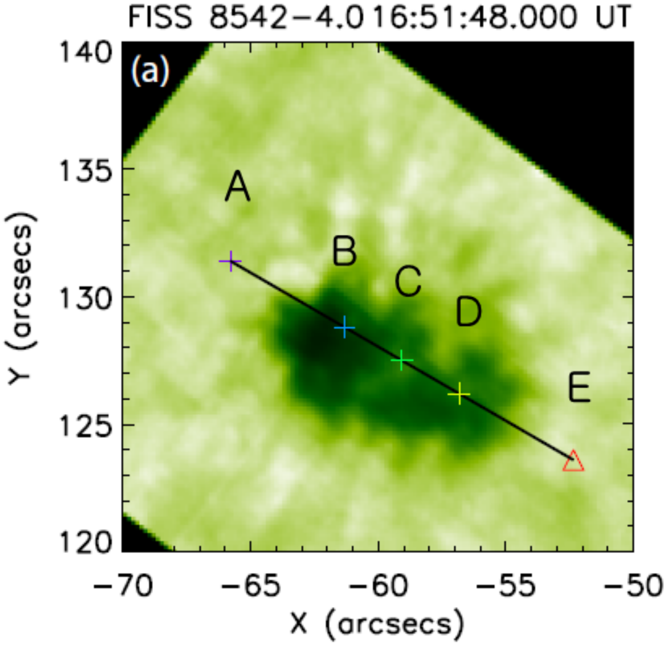


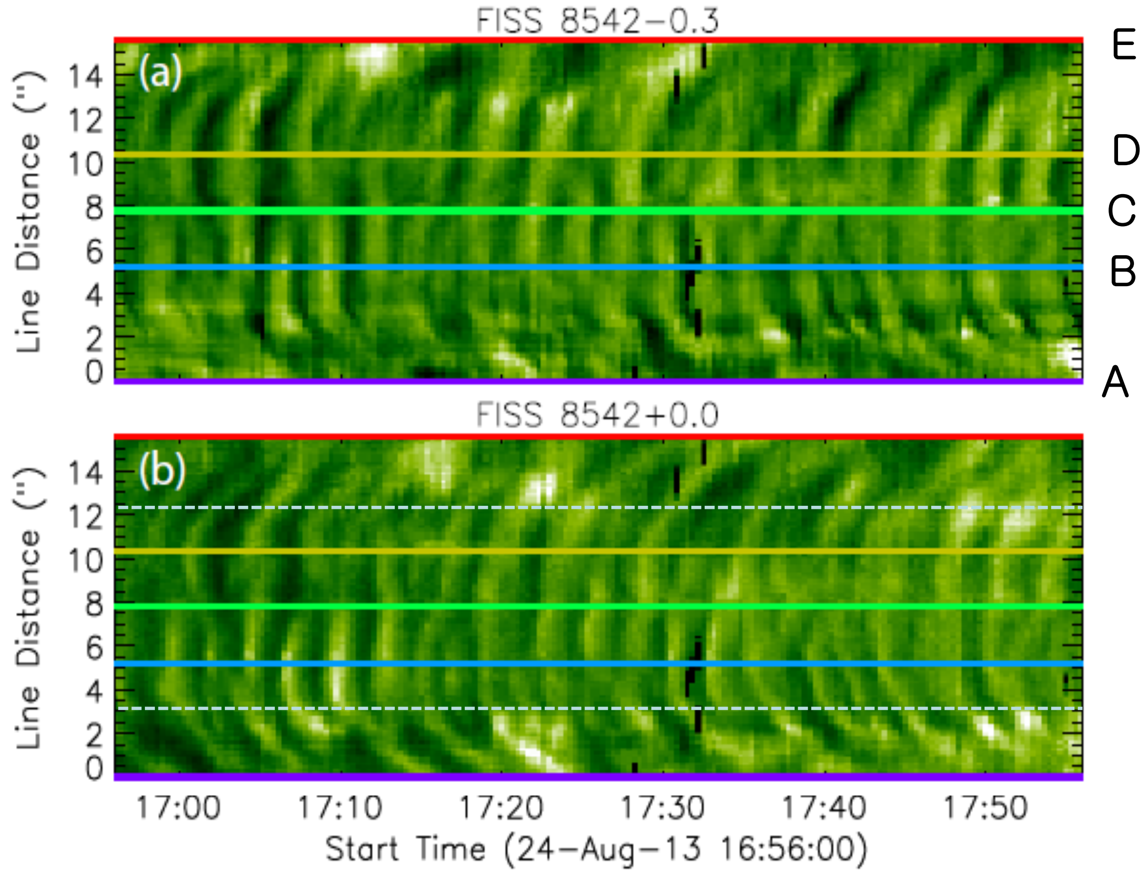
FISS is a unique system that can do imaging of H-alpha and Ca II 8542 band simultaneously, which is quite suitable for studying of dynamics of chromosphere.

FISS Ha Intensity



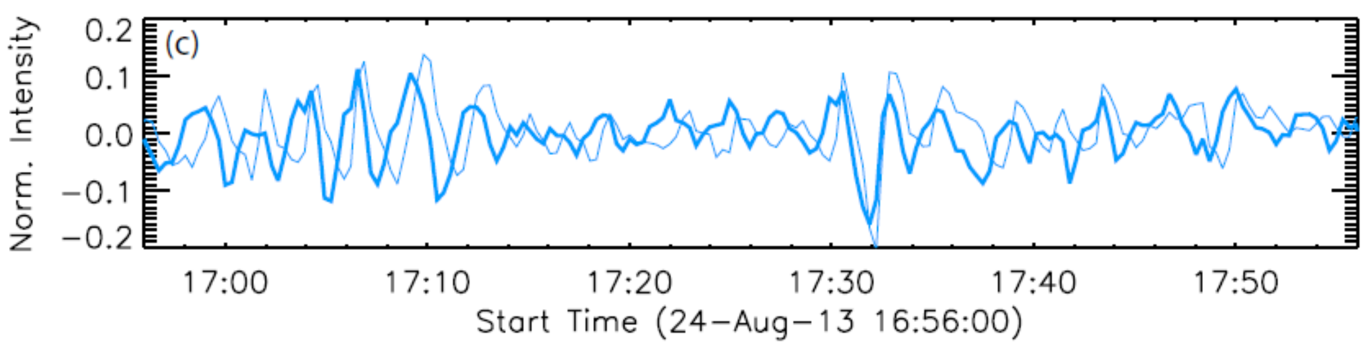
Wave source and propagation in CaII



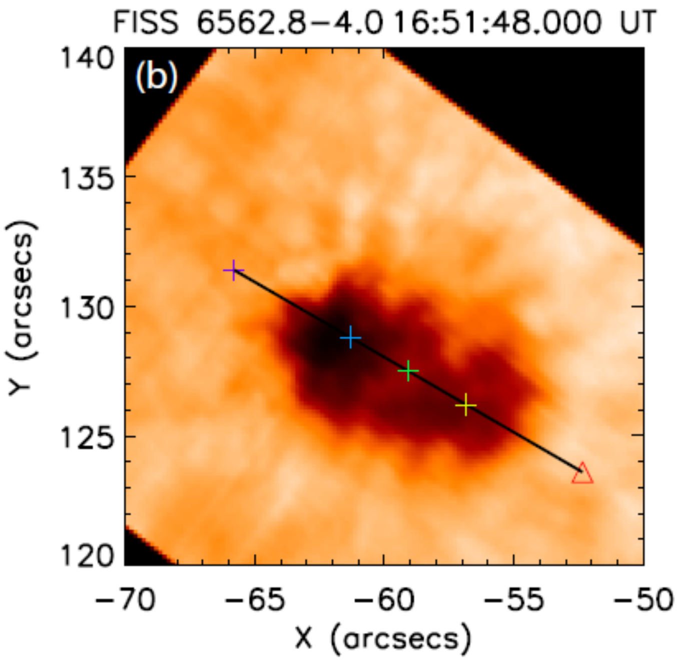


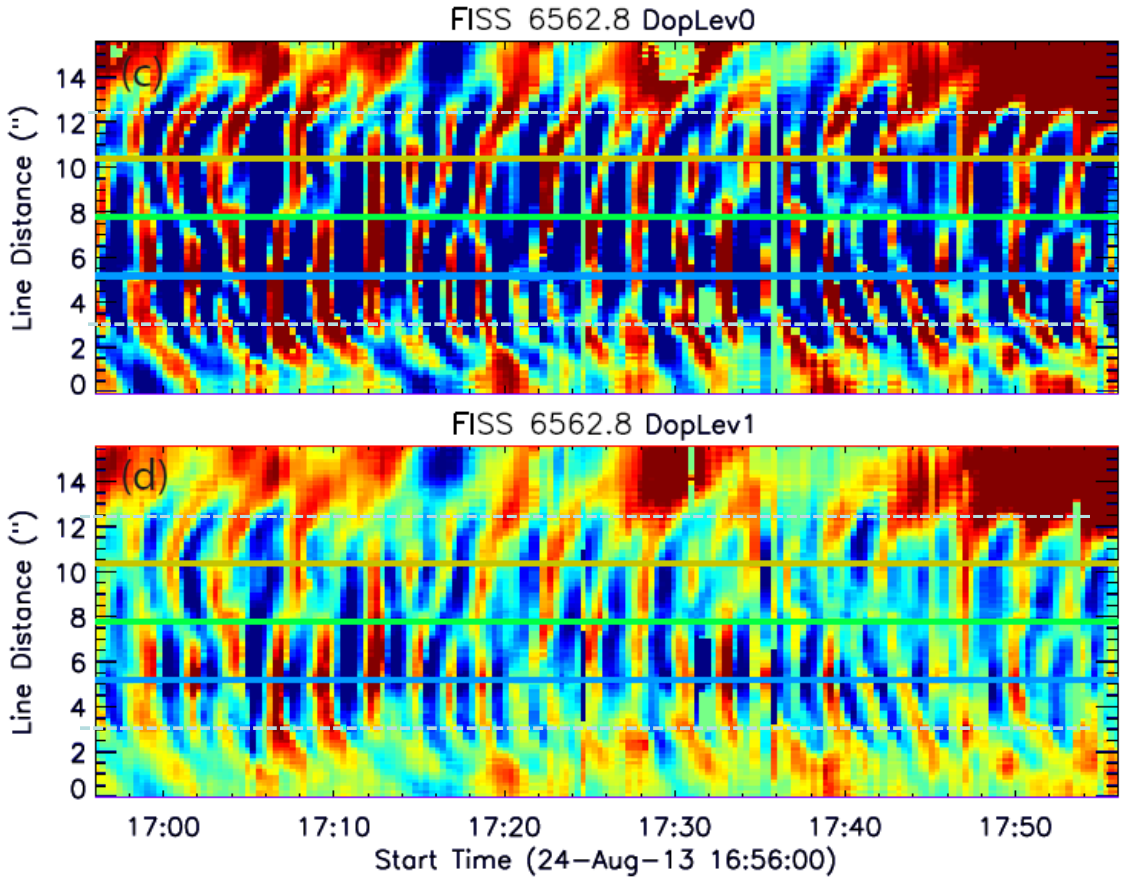
Thick line
: −0.3Å

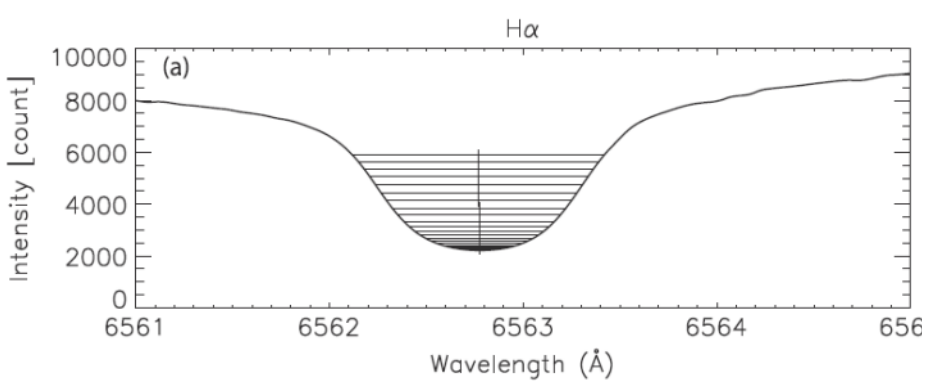
Thin line
: −0.0Å

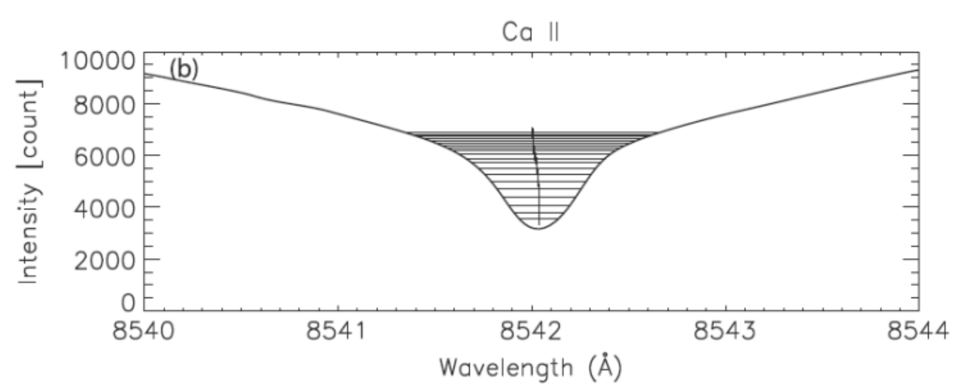


Wave source and propagation in Ha

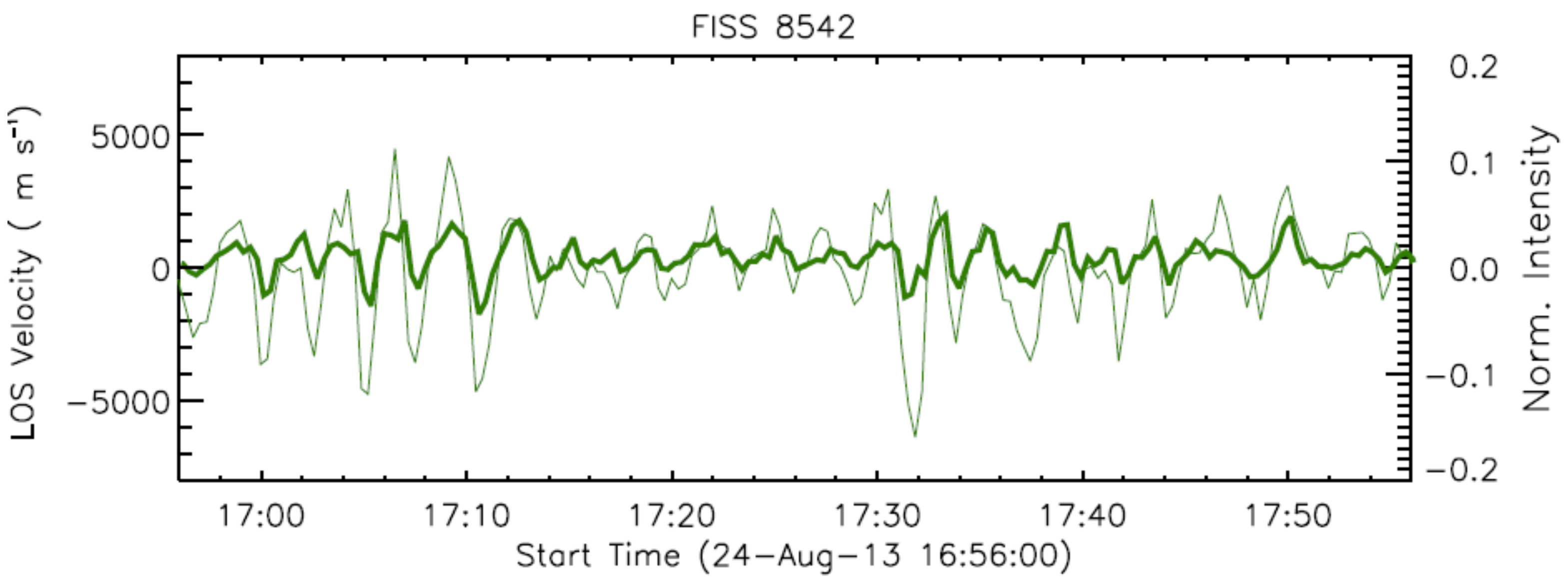






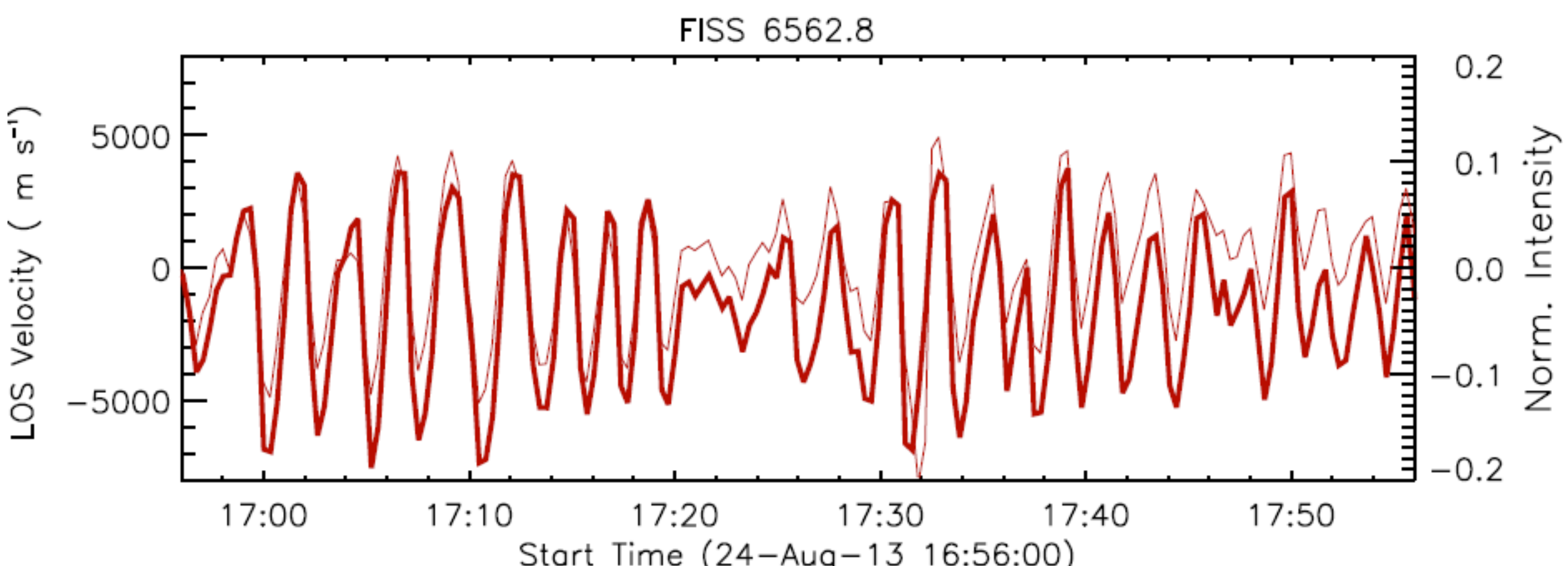


LOS speed and Intensity comparison at Ha (-0.3Å) and CaII (-0.3Å)



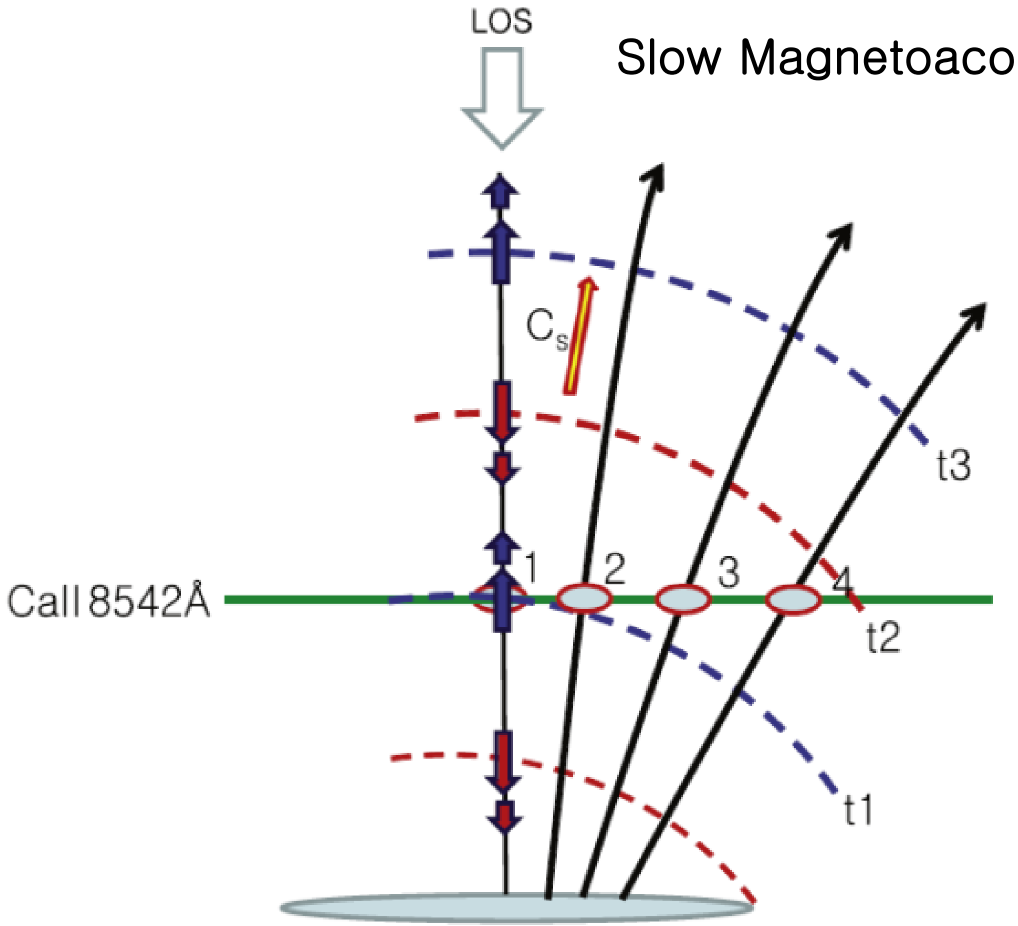
Thick line
: Doppler speed

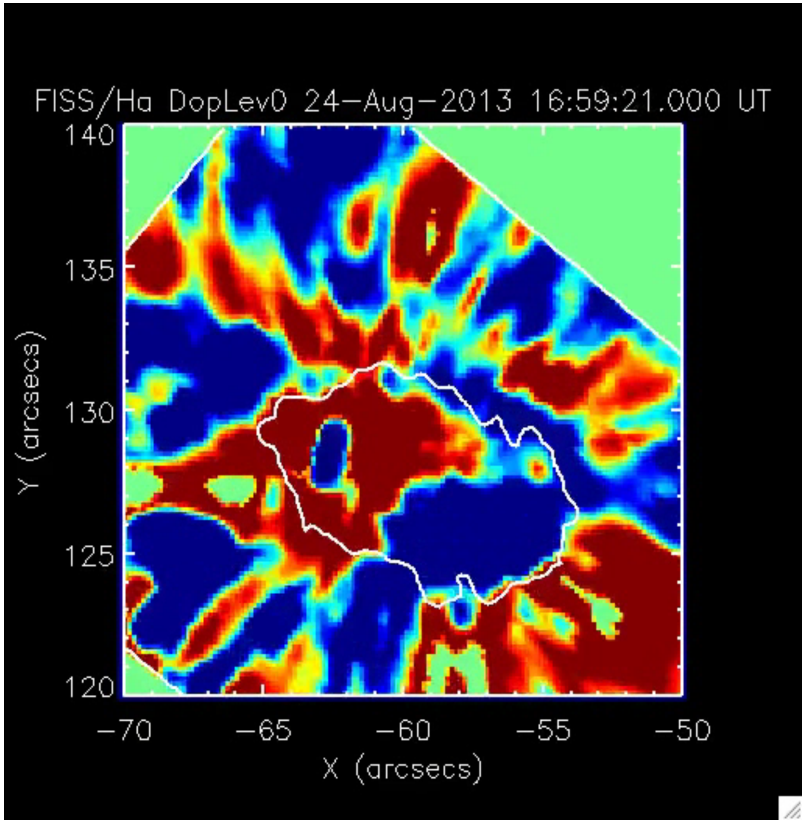
Thin line
: Intensity

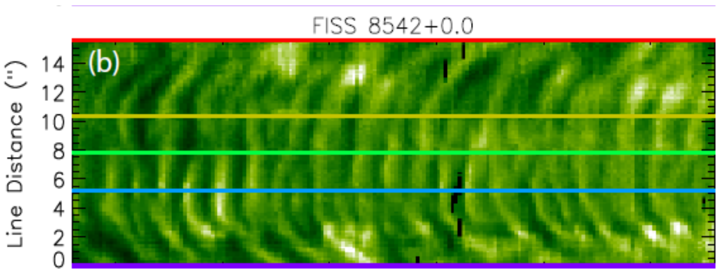


Conclusion (Cho et al., 2015)

Slow Magnetoacostic Wave



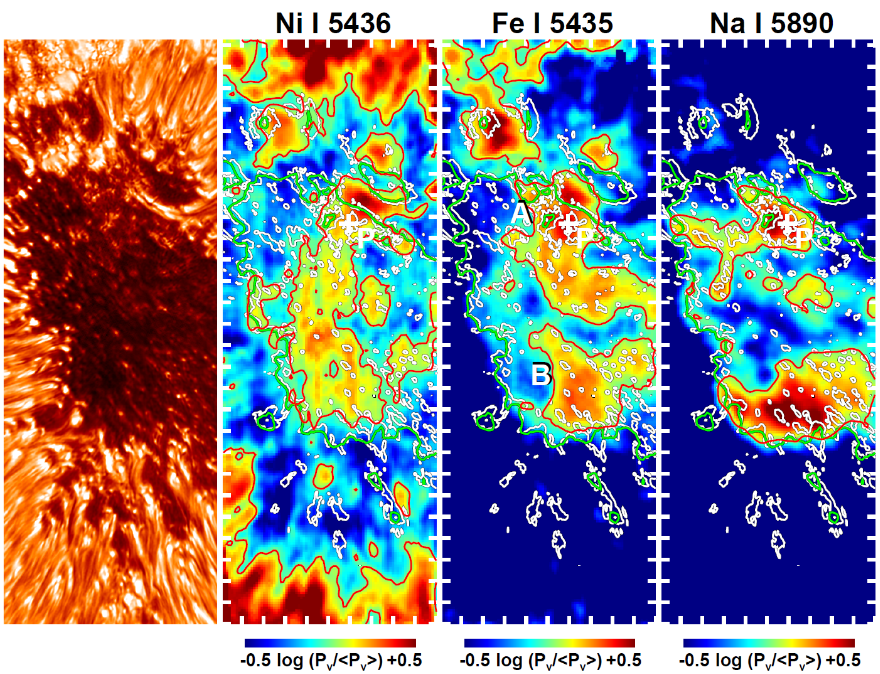




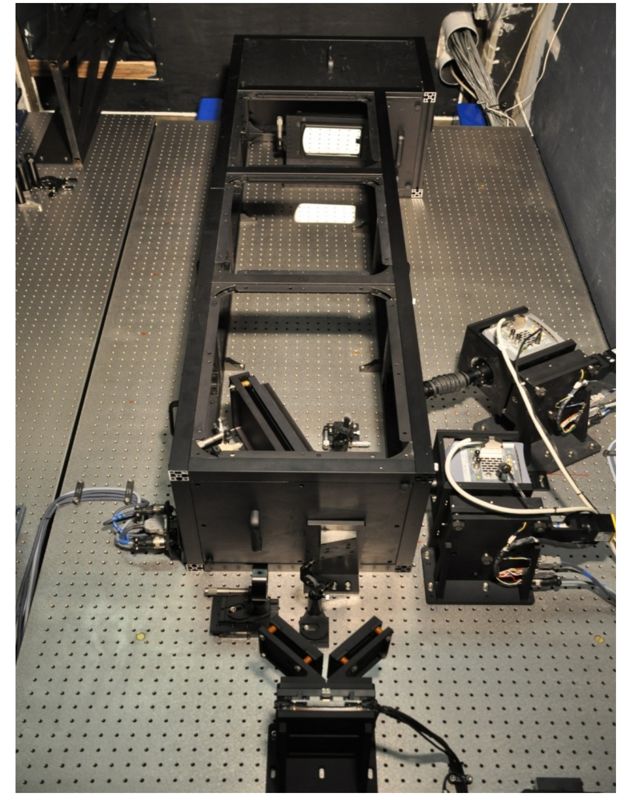
Sudden decrease of its speed beyond the pores can be explained by the projection effect caused by inclination of the magnetic field with a canopy structure.

Origin of 3-min UW (Chae et al.,2017)

The local enhancement of the 3-minute oscillation power in the vicinities of a light bridge and numerous umbra dots in the photosphere

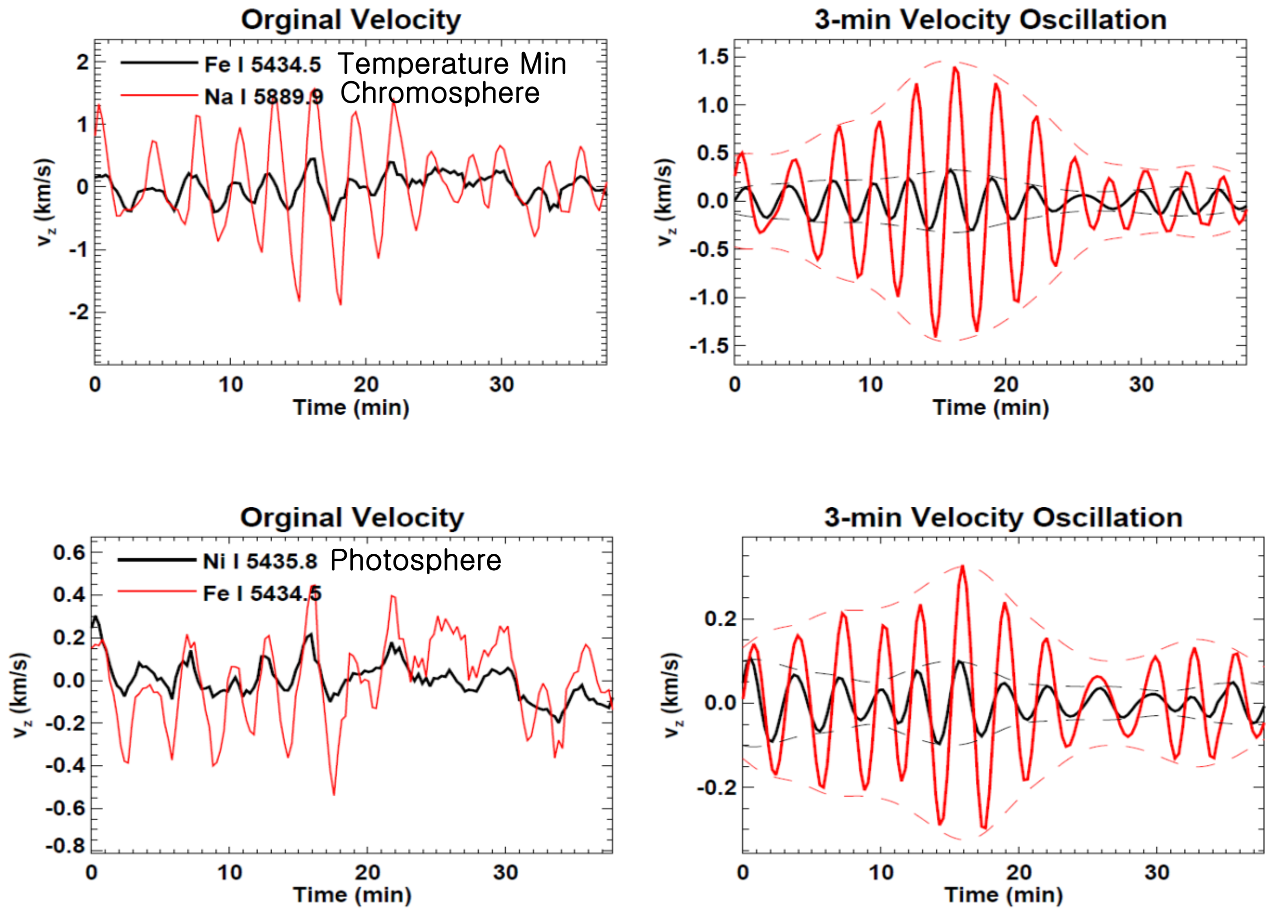


Fast Imaging Solar Spectrograph (FISS)



FISS recorded the Na I line on camera A and the Fe I line and Ni I line on camera B simultaneously, which is quite suitable for studying of wave propagation in chromosphere (Na I line), around the temperature minimum (Fe I line), and the photosphere (Ni I line)

Origin of 3-min UW (Chae et al.,2017)

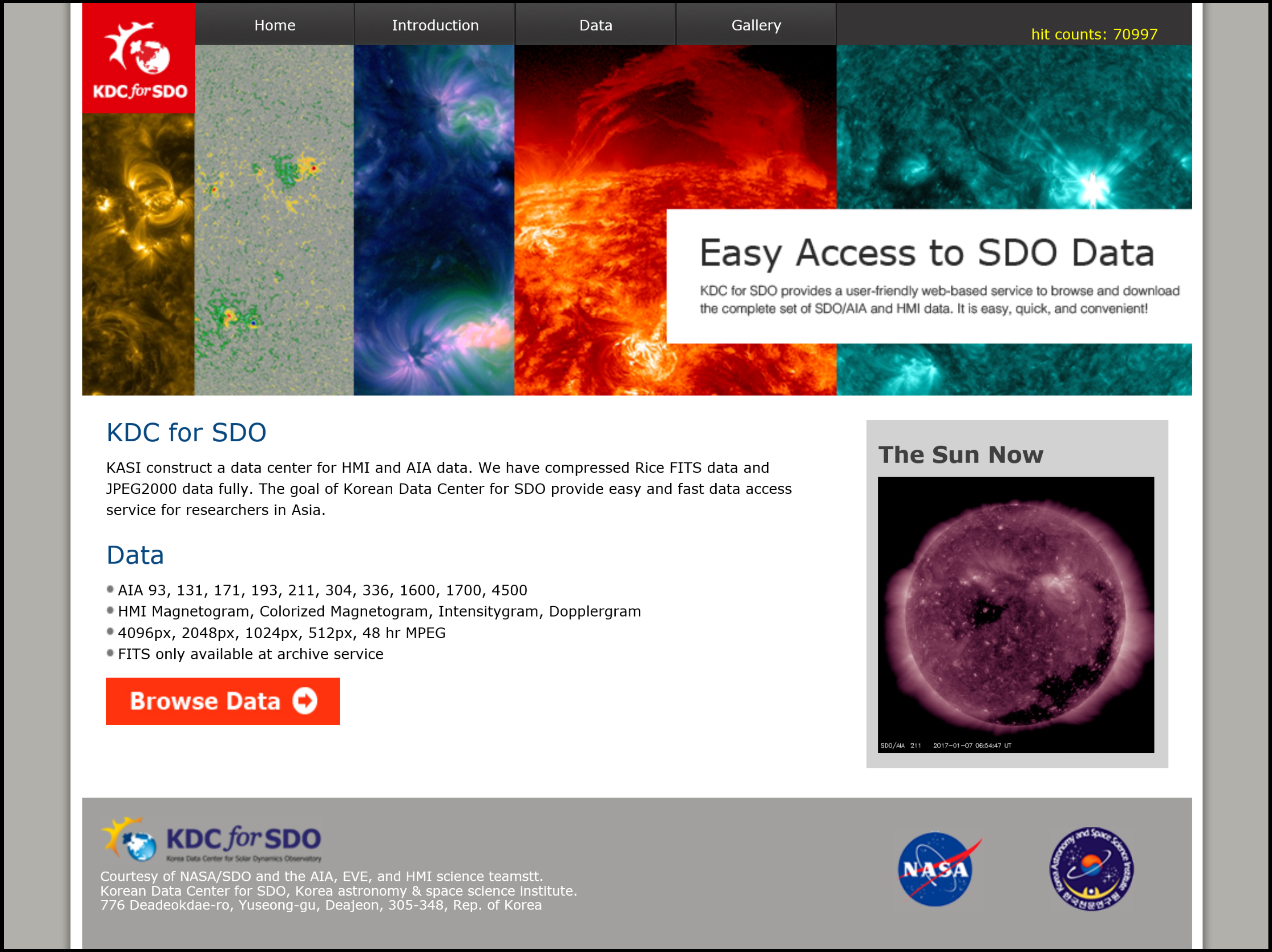


3−min band filtered velocity

(1) 3-min oscillation in the sunspot umbra are persistent in the low atmosphere, even down to the photosphere
(2) There exist systematic phase differences between different lines that are compatible with the upward propagation of the waves

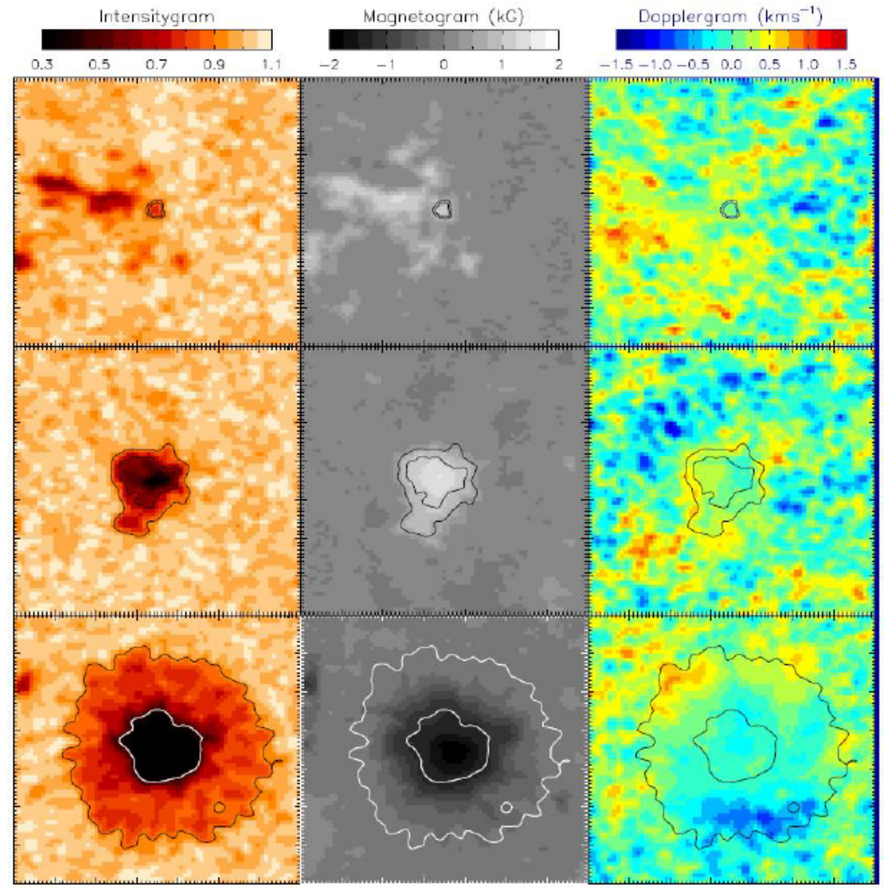
(2) Photosphere Observation using SDO/HMI

KASI SDO Website (http://sdo.kasi.re.kr)



Data and Process

- Daily (00 UT) *SDO*/HMI data (May 2010 – Feb 2015, 1663 images)



- Radial component

(1) Remove proper motion of the SDO satellite

(2) Use *cos μ* > 0.87

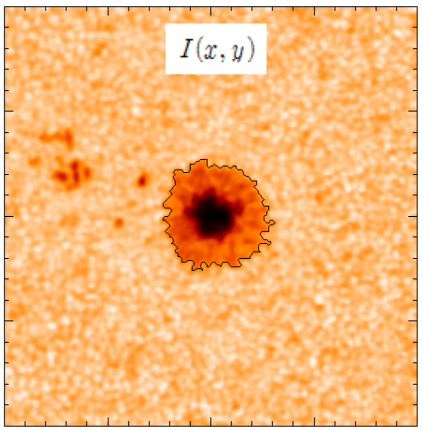
(3) Remove solar differential rotation

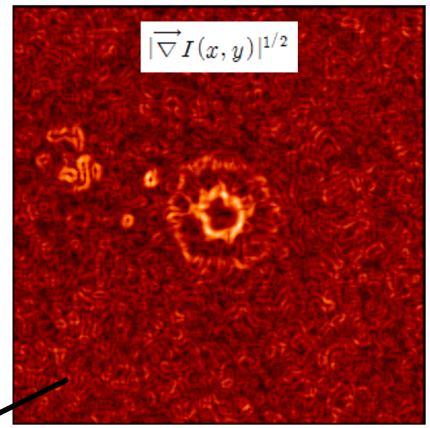
(4) de-projection

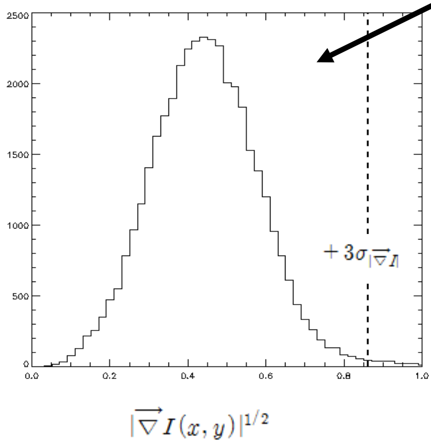
(5) remove supergranular vertical motion

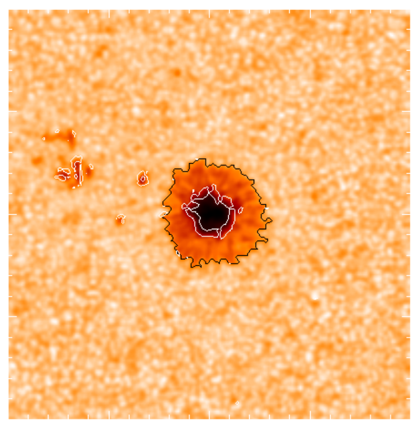
- <u>Sunspot boundaries</u>

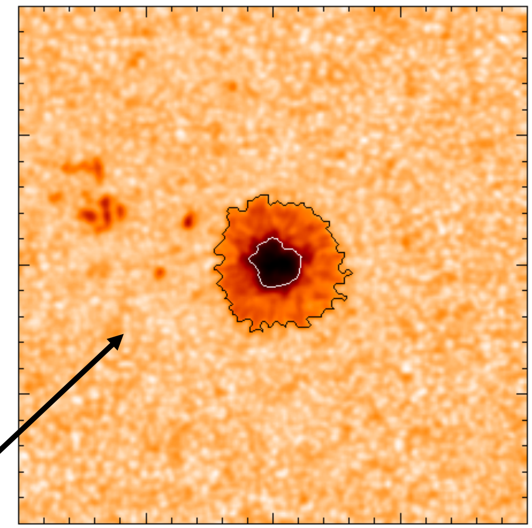
Sunspot boundaries











A_{Outer} I_{Outer} B_{Outer} V_{Outer}

A_{Inner} I_{Inner} B_{Inner} V_{Inner}

Result: Magnetic flux vs. Area

265,542 Dark holes

A_{Outer} I_{Outer} B_{Outer} V_{outer}

A_{Inner} I_{Inner} B_{Inner} V_{inner}

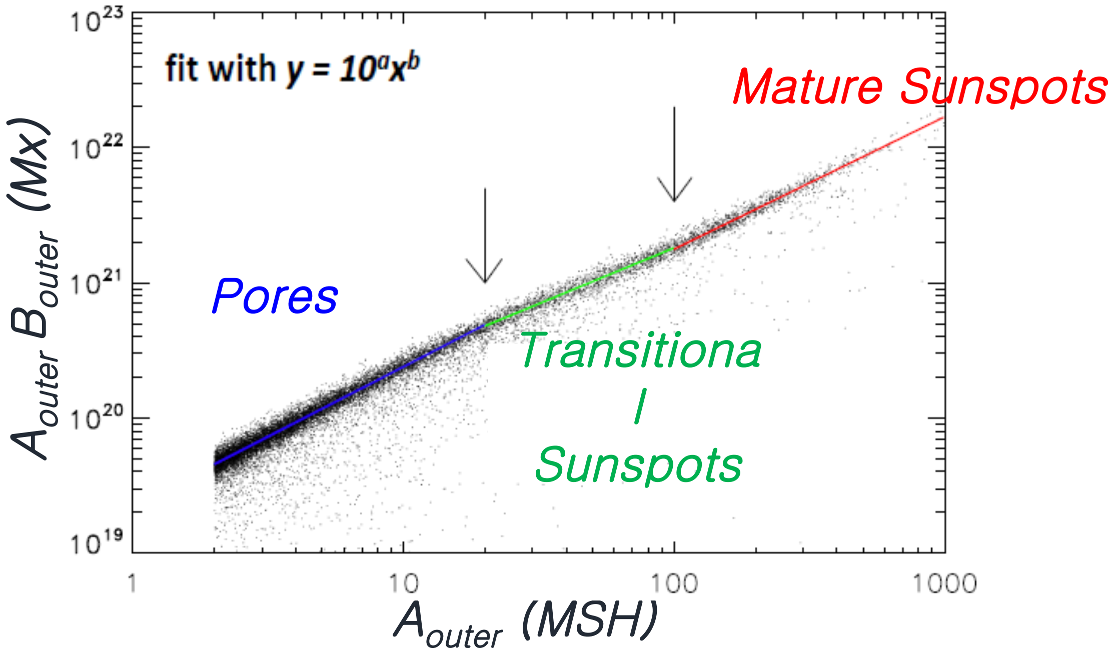
↓

9881 Sunspots

(A_{outer} >2 MSH, B > 500 G)

$1\ SH = 2\pi R_{Sun}^{2}$

(~3 Mm^2~1.7 × 1.7 km)



b = 1.0232 ± 0.0056

0.8089 ± 0.0165

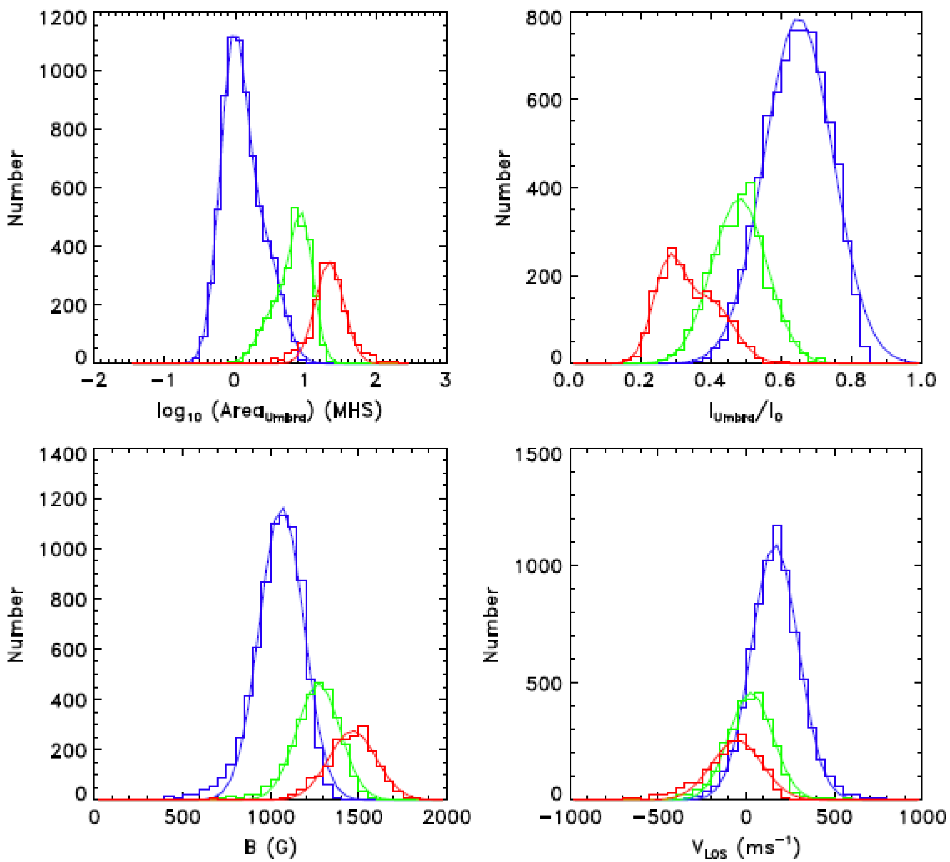
0.9989 ±0.0219

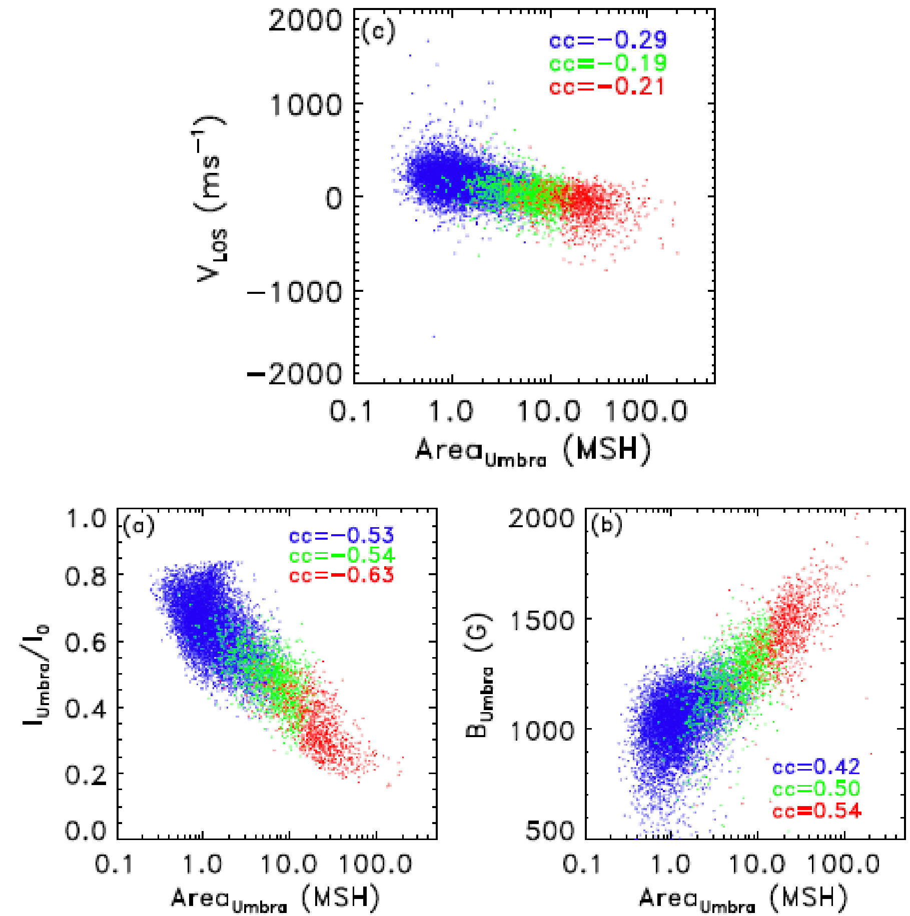
Classification: 20 – 100 MSH

Tlatov & Pevstov (2014)

MSH: **M**illionth of the **S**olar **H**emisphere

Results (Cho et al., 2016)





Bimodal distributions of I, B, Vlos

Pores: redshifted
Sunspots: blueshifted

Determination of V_A and plasma- β

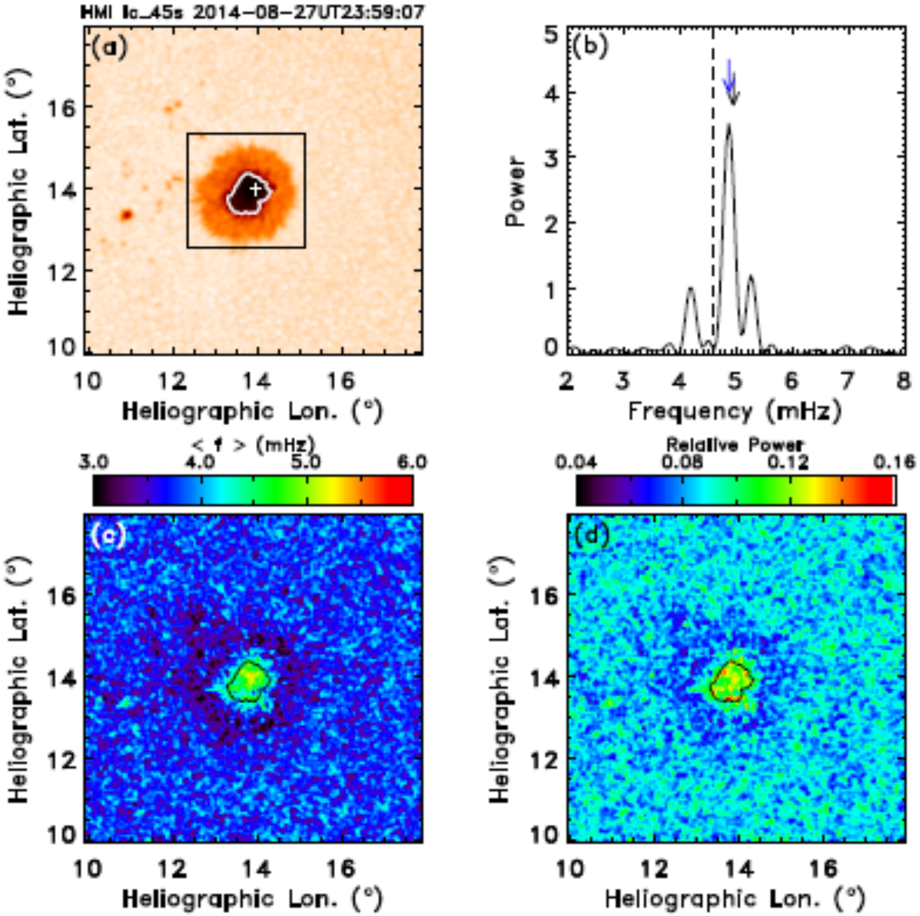
- Applying seismology based on the theory of slow magnetoacostic waves in the non-isothermal stratosphere with a uniform verical magnetic field, we estimated the Alfven speed, plasma beta, and mass density within umbra.

- Select 478 central (cos μ >0.954) sunspots cubes (1-hour) with Area > 5 MSH

- $I = I_{obs} / I_{quiet}$ with even spacing by using the bi-linear interpolation
  $(I_{xy} = I_{00} (1-x)(1-y) + I_{10}\, x(1-y) + I_{01} (1-x)y + I_{11}\, xy)$

KASI

Weighted Mean Frequency



$<f> = \Sigma P(f)\, f \,/\, \Sigma P(f)$

Using $<f>$ rather than f_{Peak}
- Multiple peaks
- Spatial dependency of dominant frequency (Reznikov et al. 2012, Kobanov et al. 2011)

Method: Seismology

-Non-isothermal, stratified atmosphere with a uniform vertical magnetic field

(Roberts 2006)

$$\Omega^2 = (2\pi f_{cutoff})^2 = c_T^2\left\{\frac{1}{4\Lambda_p^2}\left(\frac{c_T}{c_s}\right)^4 - \frac{1}{2}\gamma g\left(\frac{c_T^2}{c_S^4}\right)' + \frac{1}{c_A^2}\left(\omega_g^2 + \frac{g}{\Lambda_p}\frac{c_T^2}{c_S^2}\right)\right\} \qquad \omega_g^2 = g/\Lambda_\rho - g^2/c_S^2, \qquad \Lambda_p = c_S^2/(\gamma g)$$

Reformulating above equation with respect to X

$$\Omega^2 = (2\pi f_{cutoff})^2 = \frac{3\gamma g}{4\Lambda_p}X^3 + \left(\frac{\gamma g}{2\Lambda_\rho} - \frac{\gamma g}{\Lambda_p} - \frac{g}{\Lambda_p}\right)X^2 + \left(\frac{g}{\Lambda_p} - \frac{g}{\Lambda_\rho} + \frac{g}{\gamma\Lambda_p}\right)X + \frac{g}{\Lambda_\rho} - \frac{g}{\gamma\Lambda_p} \qquad X \equiv c_T^2/c_S^2$$

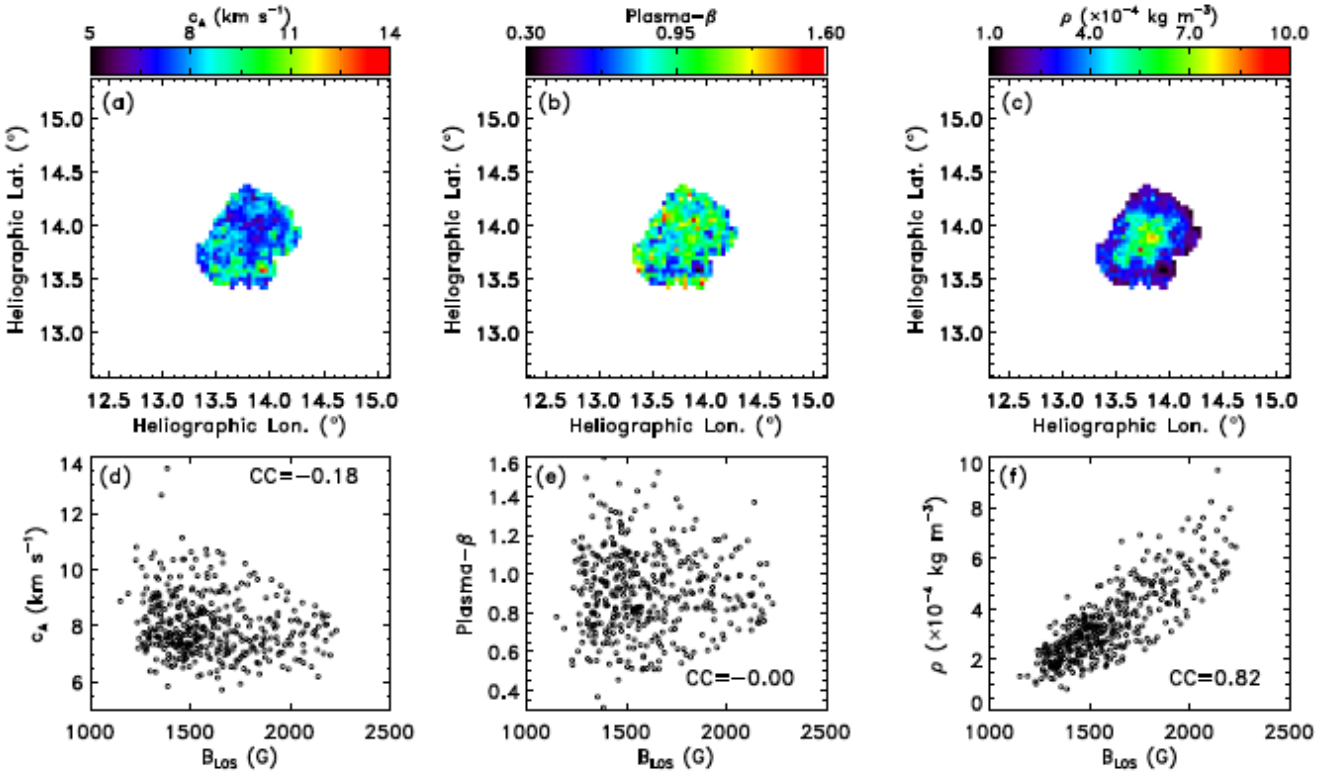
I / I_0 → T (Plank's law)

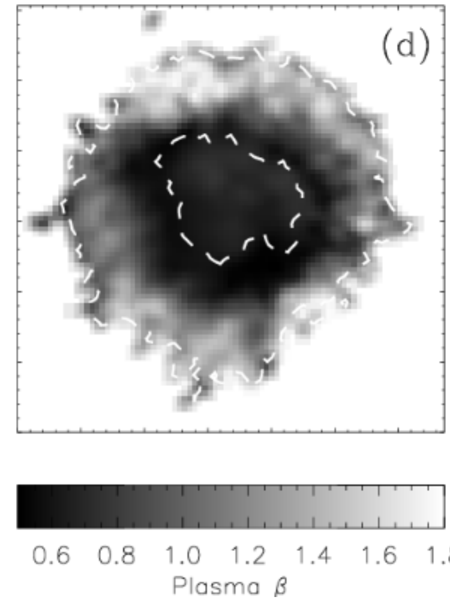
→ $c_S = [\gamma k_B T/(\mu m_H)]^{1/2} = 103.26\,[T]^{1/2}$, $\Lambda_P = c_S^2/(\gamma g)$,
$\gamma = 5/3$, $\mu = 1.3$, $\Lambda_\rho = \gamma\Lambda_P$

→ $\Omega = \Omega(c_S, c_T) = \Omega_{obs}$, $f_{cutoff} = 0.55\,\langle f\rangle$

We found that positive solutions for all pixels inside the umbra exist when the scaling is in 0.5–0.55. Thus we take 0.55 as the upper limit of the scaling.

Result: Map of plasma- β



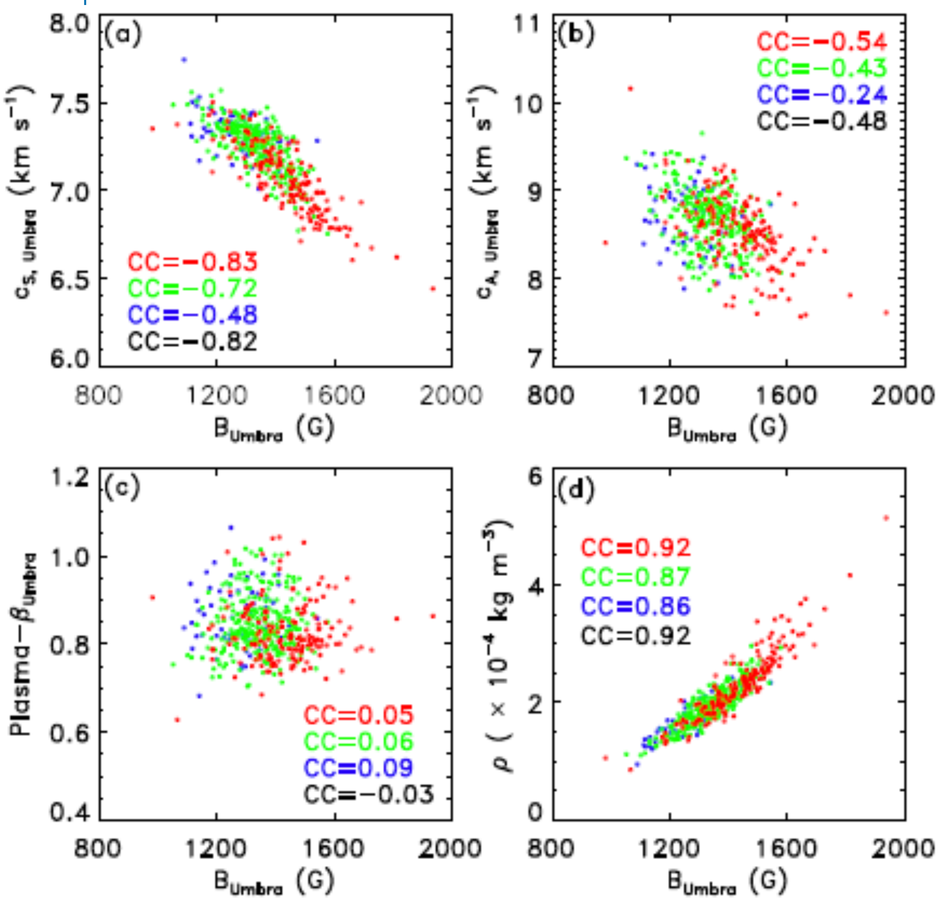


c.f., Mathew & Solanki (2004)

$X \equiv c_T^2/c_S^2$ ⇨ $c_A = c_S c_T/[c_S - c_T]^{1/2}$, $\beta = 2\, c_S^2 / (\gamma c_A^2)$, $\rho_o = B_o^2 / [\mu\, c_A^2]^{1/2}$

Result: plasma *β and C_A vs. B*

Result – Average *Plasma-β and c_A vs.* B for 478 umbrae



- Pores (< 20 MSH)
- Transitional susnpots (20 – 100 MSH)
- Mature sunspots (> 100 MSH)

→ ***c_A*** are negatively correlated with B, which might be due to significant increase of density

→ Plasma-β in umbra seems to be independent of B

→ Density inside the umbra is highly dependent on the field strength.

=

Conclusion

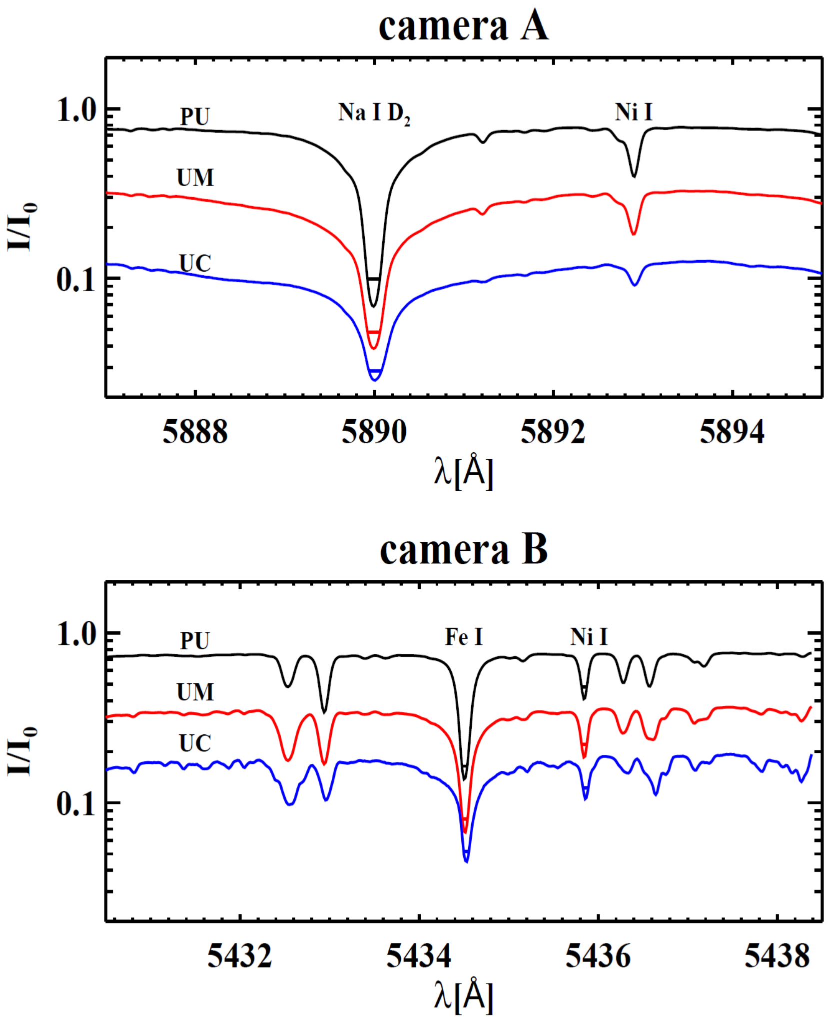
(1) High resolution imaging spectrograph observations using NST/FISS shows that the observed wave inside umbra is a slow magnetoacoustic wave propagating along the magnetic field lines in the pores.

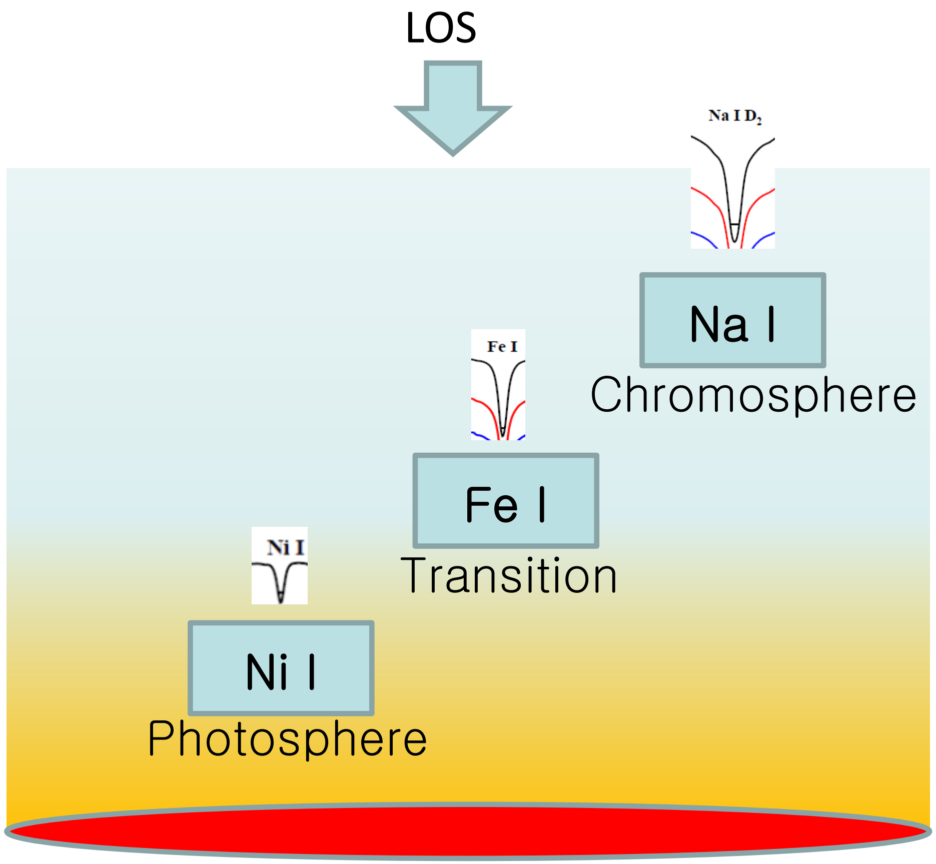
(2) Three groups of pores, transition sunspots, and mature sunspots have different characteristics in their area, intensity, magnetic field, and LOS velocity as well in their relationships.

(3) Deduced Alfven speed and sound speed inside sunspot umbra is negatively correlated with average magnetic field strength, which might reflect a depression of the continuum forming height.

Thank you
for your attention

Line formation height





Usually the lower the core intensity of an absorption line is, the higher the line formation region is.