Penetrating Waves along Spicules to the Corona

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Background

Alfvénic waves in coronal holes

- Most promising candidate for fast solar wind acceleration
- Propagation along open field lines in coronal holes

Energy flux of Alfvénic waves in chromosphere

- Propagatation along spicules
  ※ spicule: jet elongated along magnetic field line
- Enough energy flux to maintain corona & fast solar wind (e.g., De Pontieu+ 2007)
- Partial reflection in the transition region (TR) (Okamoto & De Pontieu 2011; Hollweg+ 1982)

→ Energy flux transported to corona is not clear.

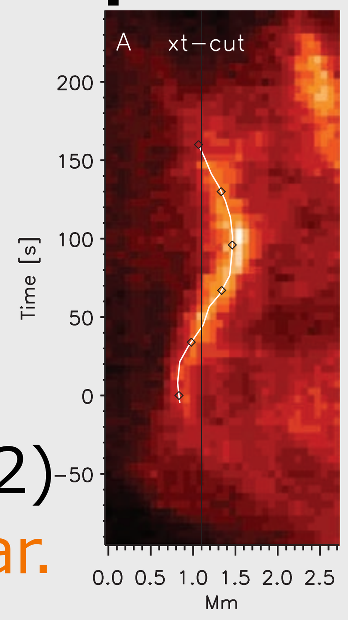


Fig 1. De Pontieu+ 2007

Purpose of this study

Estimate energy flux penetrating corona of Alfvénic waves propagating along spicules

To achieve our purpose, we need to…
- Detect ascending & descending waves along spicules
- Estimate energy flux **of each detected wave**

Observation

IRIS Si IV spectra (log T[K] ~ 4.9)
- Sit-and-stare mode
- Short cadence (5 ~ 6 s)

date	duration	cadence	position
2013/09/29	51 min	5.1 s	-3″, 971″
2014/09/10	65 min	5.4 s	-3″, 907″
2014/12/04	57 min	5.6 s	-53″, -952″
2015/01/10 ①	42 min	5.2 s	-9″, -996″
2015/01/10 ②	54 min	5.2 s	-9″, -997″

Tab.1 List of observations

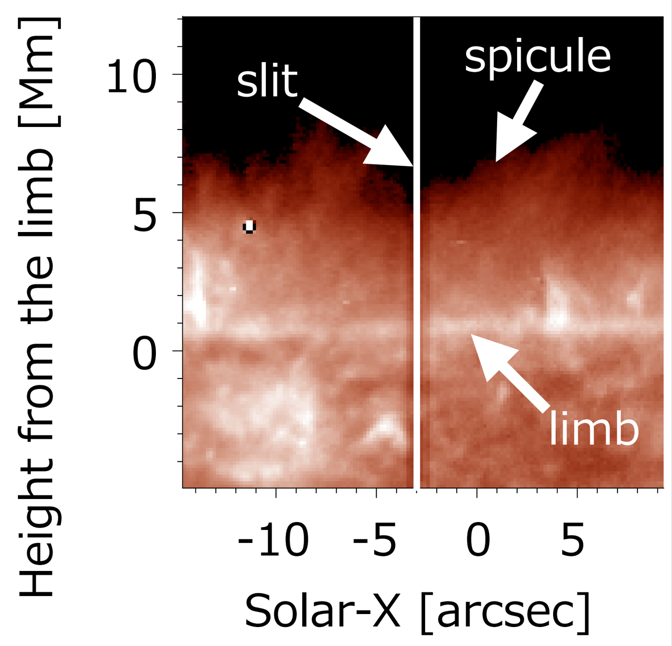


Fig 2. 1400 Å SJI (2013/09/29)

- Optically thin Si IV emission
  → Superposition of LOS velocity components

※Only one velocity component was assumed in this study.
  → Velocity amplitude would be underestimated.

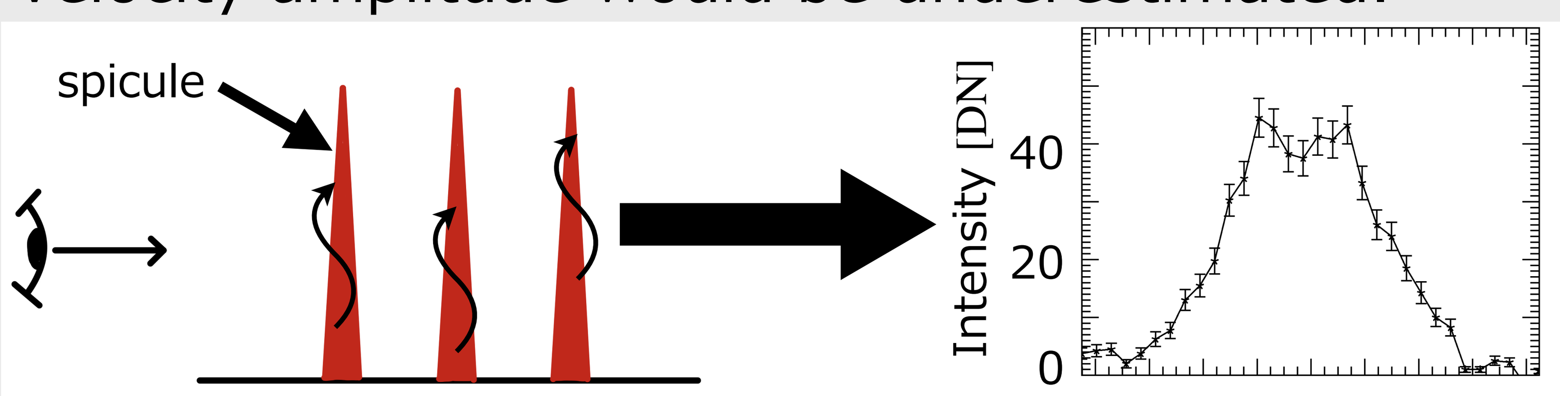


Fig 3. Schematic view of observed spicules & Si IV spectra with multiple velocity components

Method: Detection of wave packets

1. Emphasize 30~300s periodic motions of LOS velocity at each height step
2. Track sinusoidal time variation of LOS velocity taking cross-correlation
(until correlation coefficient becomes lower than 0.7)
3. Estimate energy flux $F = m_p\, n_e\, \delta v^2\, V_p$ for each detected wave packet

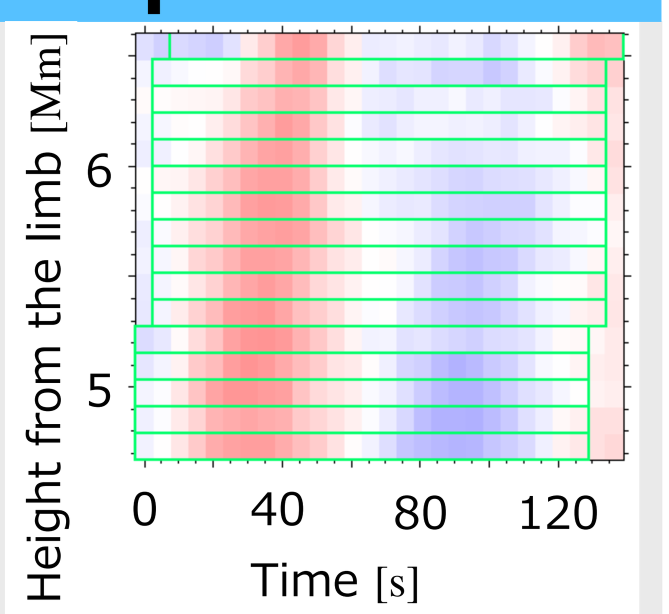


Fig 4. Space-time plot of LOS velocity during wave packet was detected

n_e electron density: time-averaged EM of Si IV emission at each height
δv velocity amplitude: sinusoidal fit for LOS velocity at each height
V_p phase velocity: linear fit for time lags of cross-correlation as a function of height

4. Determine mode of detected wave packets by taking correlation between LOS velocity & intensity
   correlation < 0.65: Alfvénic waves
   correlation > 0.65: acoustic waves (e.g., Liu+ 2014)

Result: Energy flux of Alfvénic waves

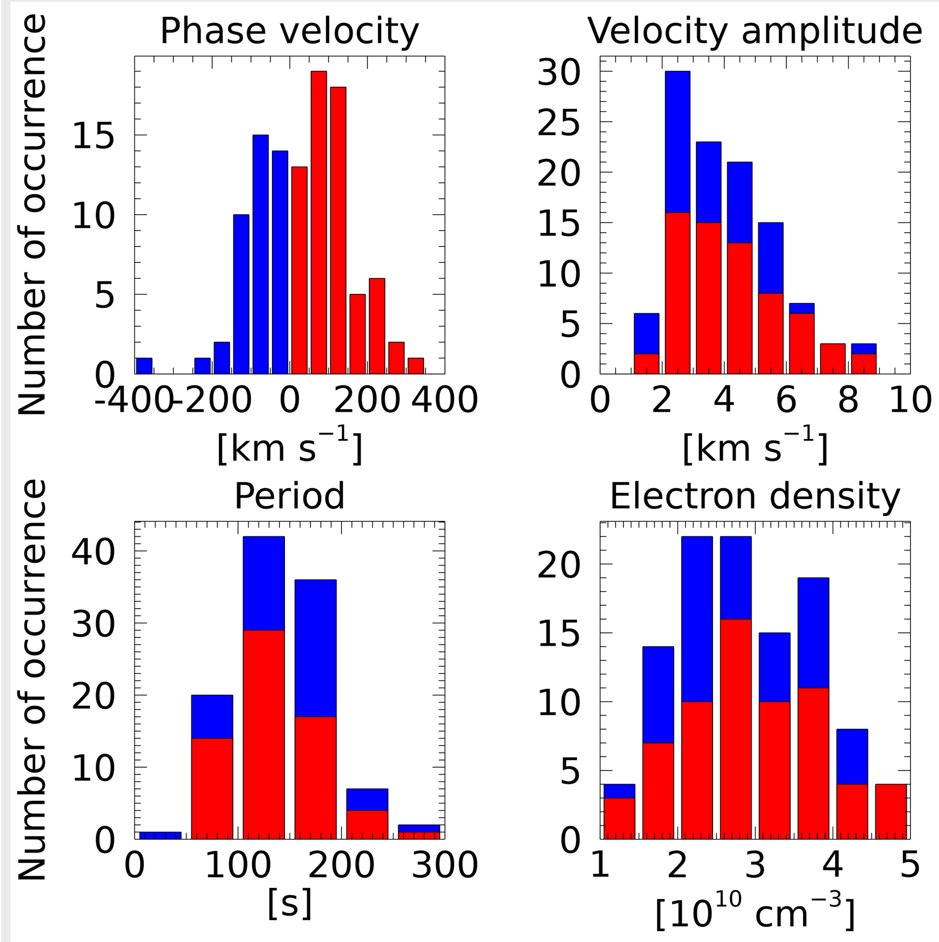


Fig.5 Parameters of ascending (red) & descending (blue) Alfvénic wave packets

- 120 wave packets were detected!
- 108 wave packets were classified as Alfvénic waves.

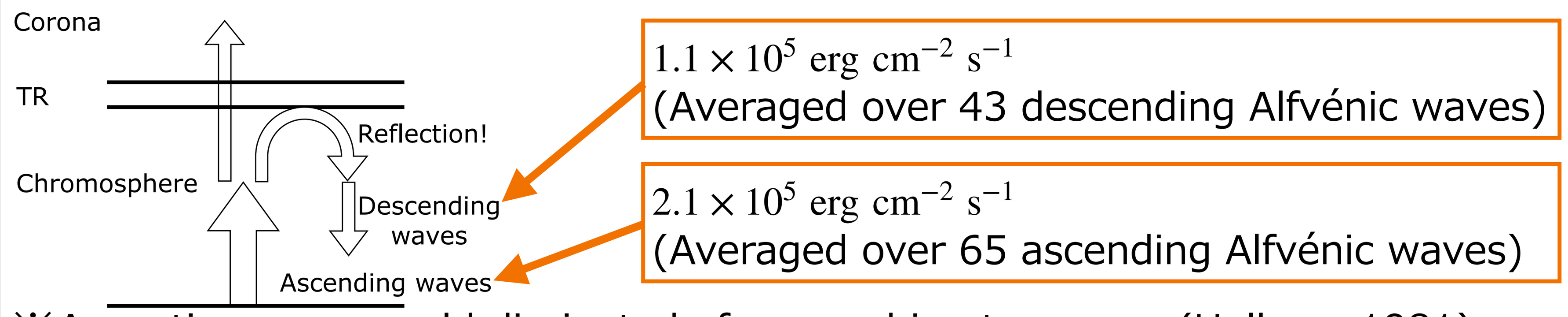
	Ascending	Descending
Alfvénic waves	65	43
Acoustic waves	6	6

Tab 2. Modes of detected wave packets

- Mean of the parameters
  V_p: 105 ± 75 km s^{-1}
  δv: 4.0 ± 1.6 km s^{-1}
  P : 141 ± 45 s ※ P: period
  n_e: $2.9 \pm 0.9 \times 10^{10}$ cm^{-3}

Energy flux of ascending Alfvénic wave: 1.1×10^5 erg cm^{-2} s^{-1}
decending Alfvénic wave: 5.5×10^4 erg cm^{-2} s^{-1}

Discussion: Energy flux transported to corona



※Acoustic waves would dissipate before reaching to corona (Hollweg 1981).
※Assuming randomly directional oscillations (δv would be multiplied by $\sqrt{2}$.)

Fig 6. Schematic view of transported energy flux to corona

Energy flux transported to corona: 1.0×10^5 erg cm^{-2} s^{-1}

1/5 of required energy flux for fast solar wind acceleration (5×10^5 erg cm^{-2} s^{-1}; c.f., Withbroe 1988)

Discussion: Underestimate of velocity amplitude

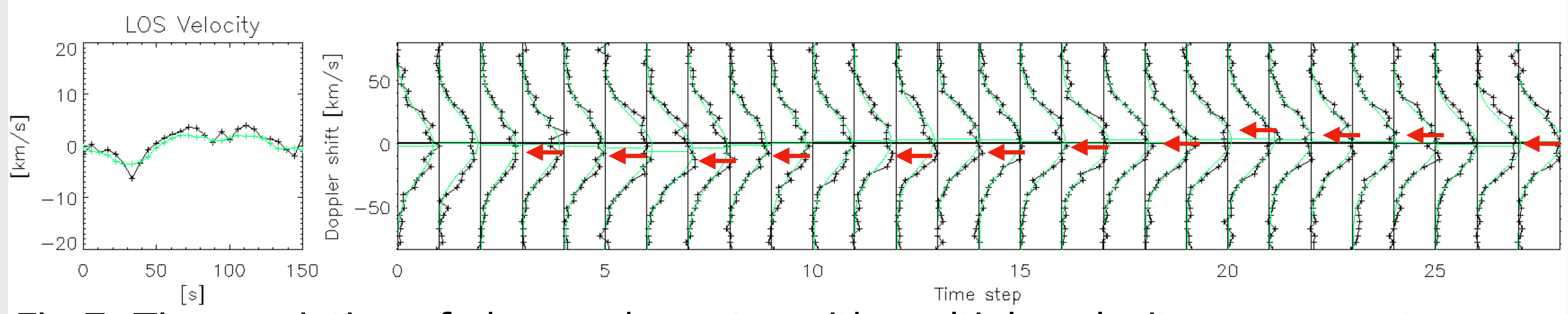


Fig 7. Time variation of observed spectra with multiple velocity components
Green line in left panel: LOS velocity emphasized with 30~300s motion
Green lines in right panel: results of single Gaussian fit

- One of the components (red arrow) shows periodic variation with 10 km s^{-1} (twice the velocity amplitude assumed one velocity component existed).

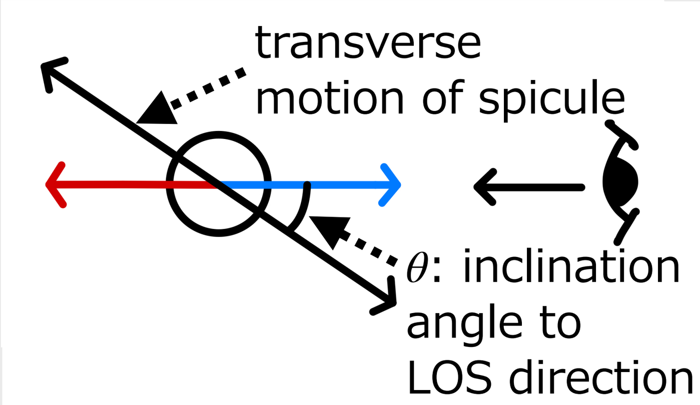


Fig 8. Schematic view of transverse motion of spicule

- θ cannot be obtained only by LOS velocity.
- Waves with amplitudes larger than slit width cannot be detected.

→ Tracking transverse motion in plane of sky is important.

Conclusion

We have estimated **energy flux for both ascending & descending Alfvénic waves** propagating along spicules for the first time.

Energy flux transported to corona: 1.0×10^5 erg cm^{-2} s^{-1}

※ Assuming all descending waves are due to ascending waves partially reflected in TR

1/5 of required energy flux for fast solar wind acceleration

→ The key is to resolve the underestimate of δv ($\delta v^2 \propto F$).

Future work

- Separation of multiple velocity components
- Tracking transverse motion in 2 directions (in LOS direction & plane of the sky)