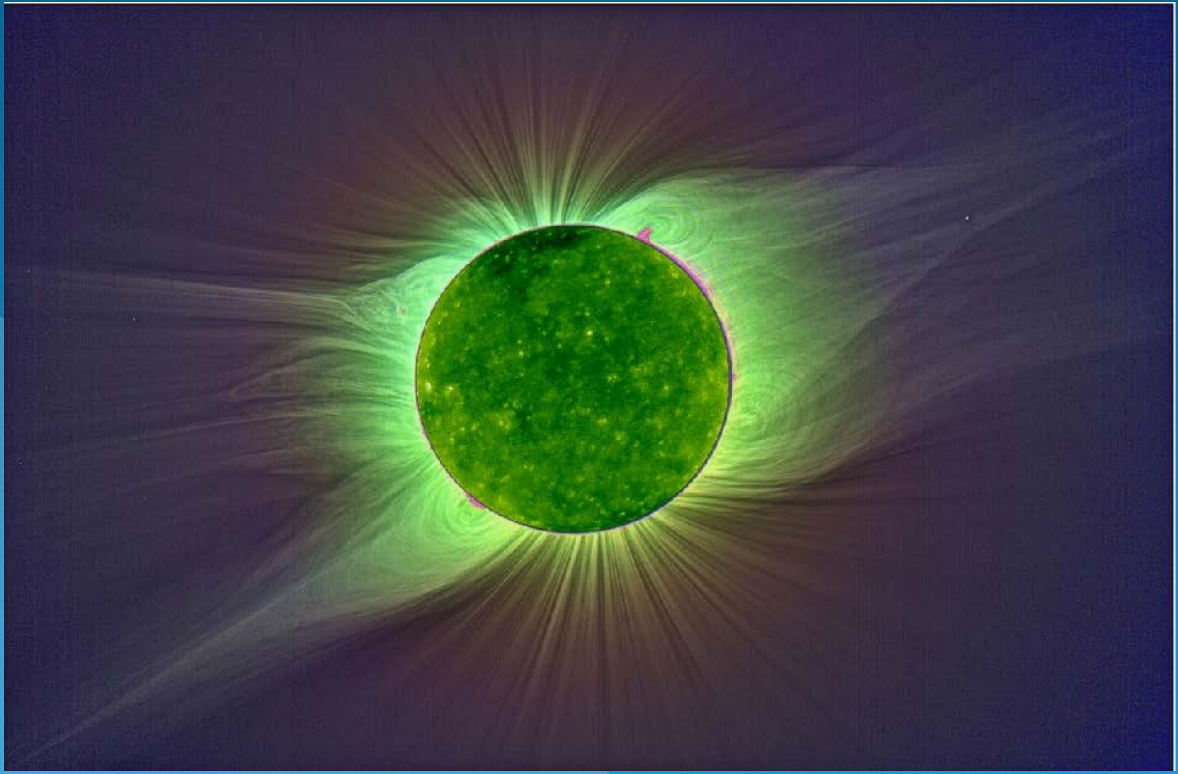
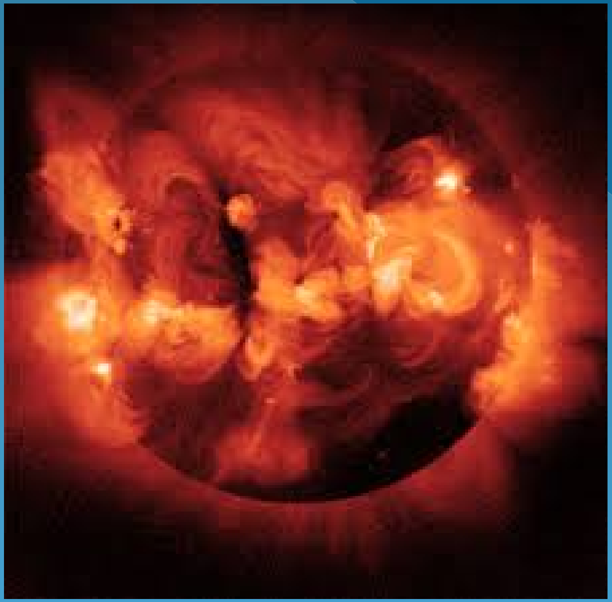
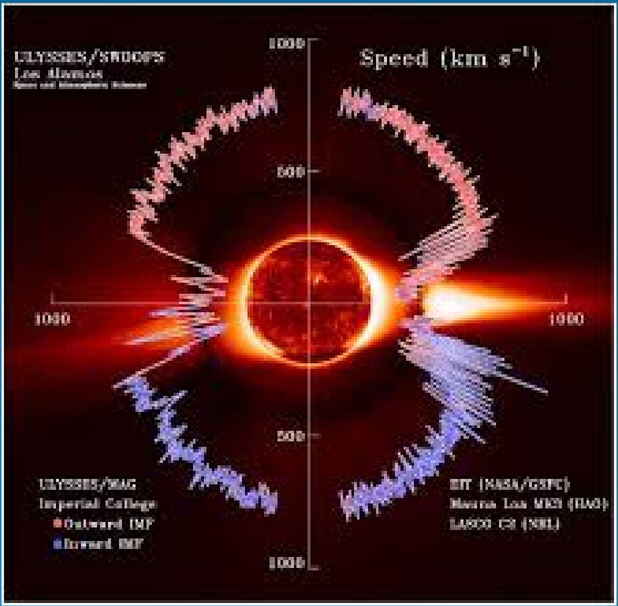
Alfvén Waves as an Energy Source in the Solar Corona



A.K. Srivastava
Department of Physics
Indian Institute of Technology (BHU), Varanasi-221005, India

Million-degree Hot Corona





X-ray, EUV, and solar wind confirm the existence of Milion-degree hot solar corona

Mechanism : Two Broader Prospective

[1] Direct Current (DC) Heating:

Magnetic Reconnection, i.e. dissipation of currents

Nanoflares Heating; First developed by Eugene Parker (1972)

[2] Alternating Current (AC) Heating:

Waves

Transverse Alfvén Waves are generated at the photosphere and travel up to the corona where they may dissipate their sufficient energy

First proposed by Hannes Alfvén (1947).

Random footpoint motion could be the driver otherwise they may also be generated *in situ* higher in the atmosphere

Other wave modes (slow and fast MAW) may also carry some fraction of energy.

Alfvén Waves along Magnetic Field Lines in Uniform Plasma : A candidate to transfer sufficient energy

$$\omega = k\,V_A \cos\theta,$$

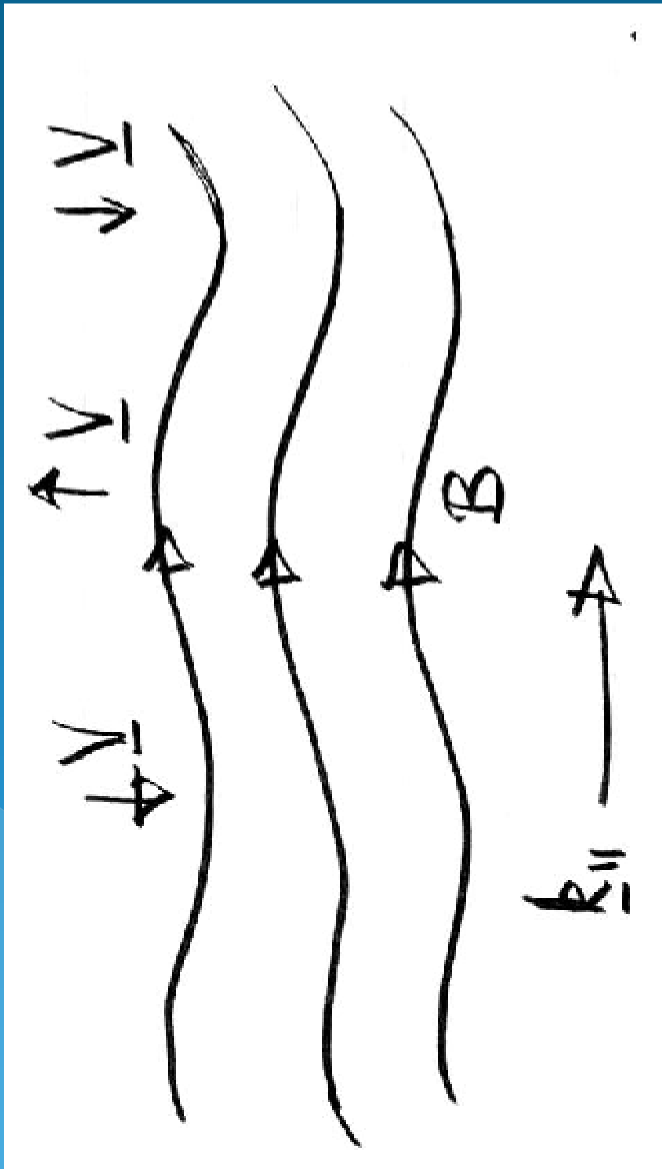
Following the conditions :

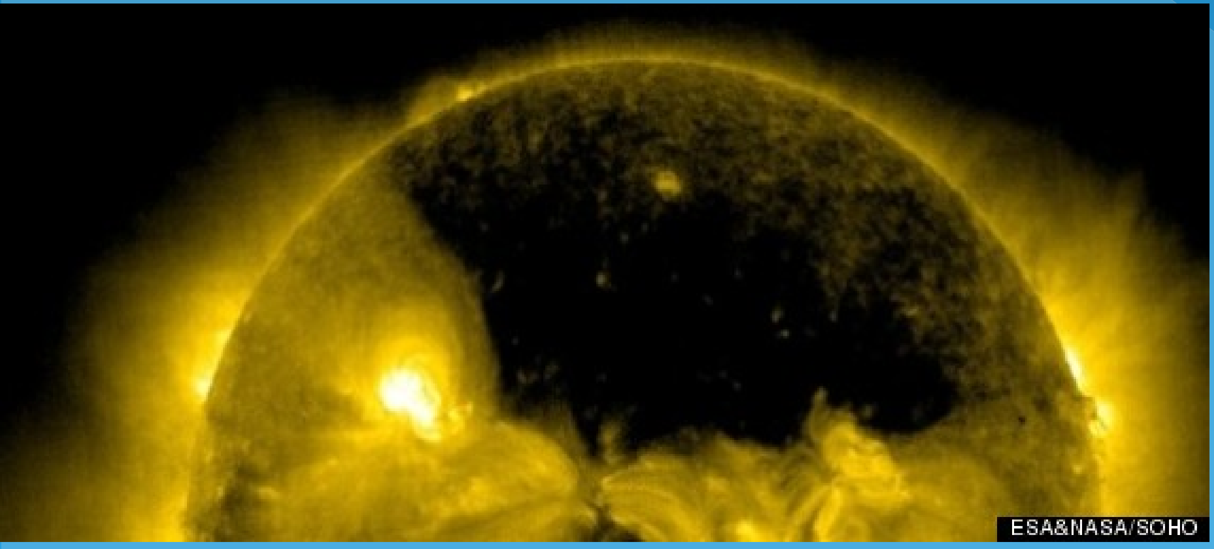
$$\mathbf{k} \cdot \mathbf{V} = 0$$

and

$$\mathbf{V} \cdot \mathbf{B}_0 = 0$$

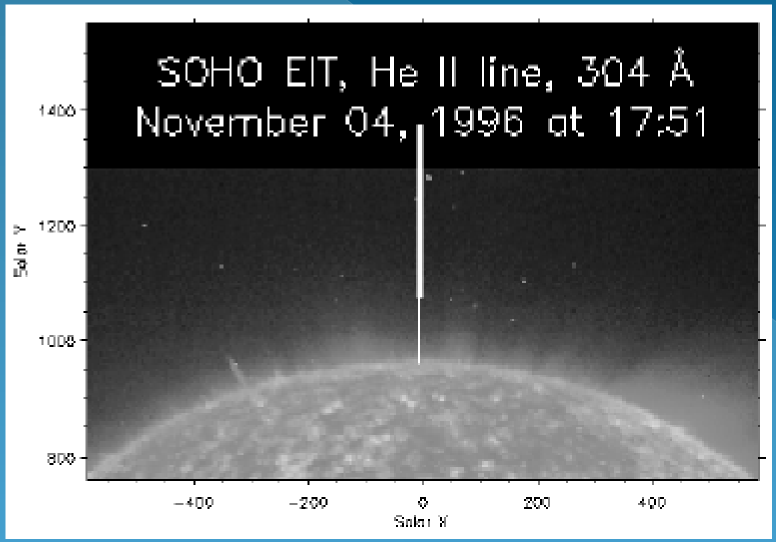
Magnetic tension component of the Lorentz force generates it





Alfvén Waves in Polar Corona : Early Detection in SUMER/SoHO Era

$$FWHM = \left[4ln2\left(\frac{\lambda}{c}\right)^2\left(\frac{2k_BT_i}{M}+\xi^2\right)\right]^{1/2}$$



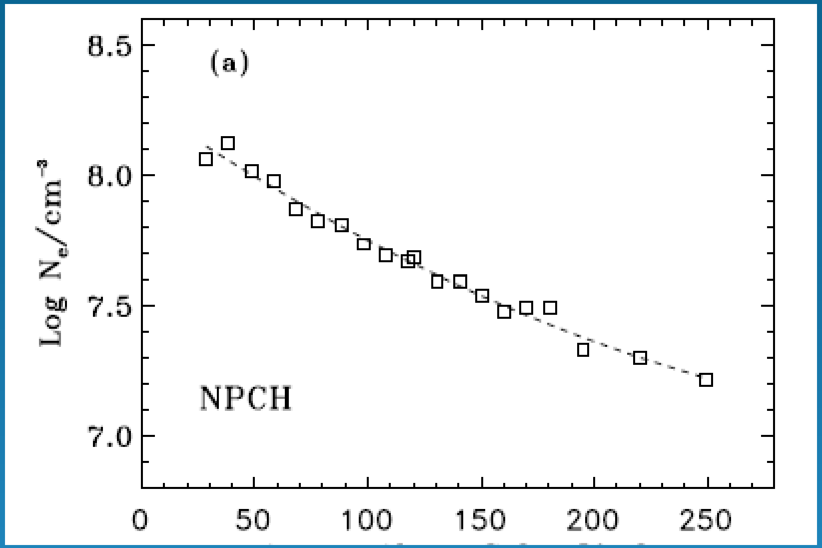
$$<\delta v^2>^{1/2} \propto \rho^{-1/4}$$

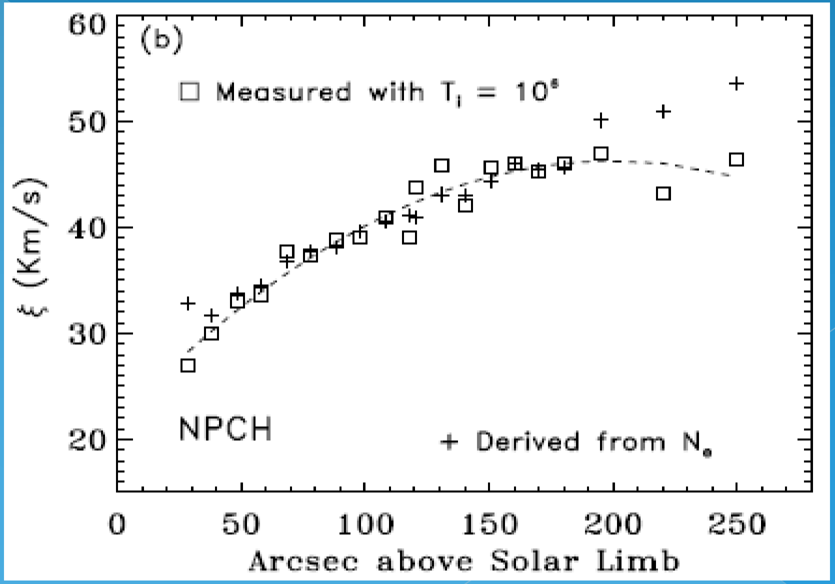
$$\xi \propto B^{-1/2}$$

Si VIII 144.5 nm EUV line

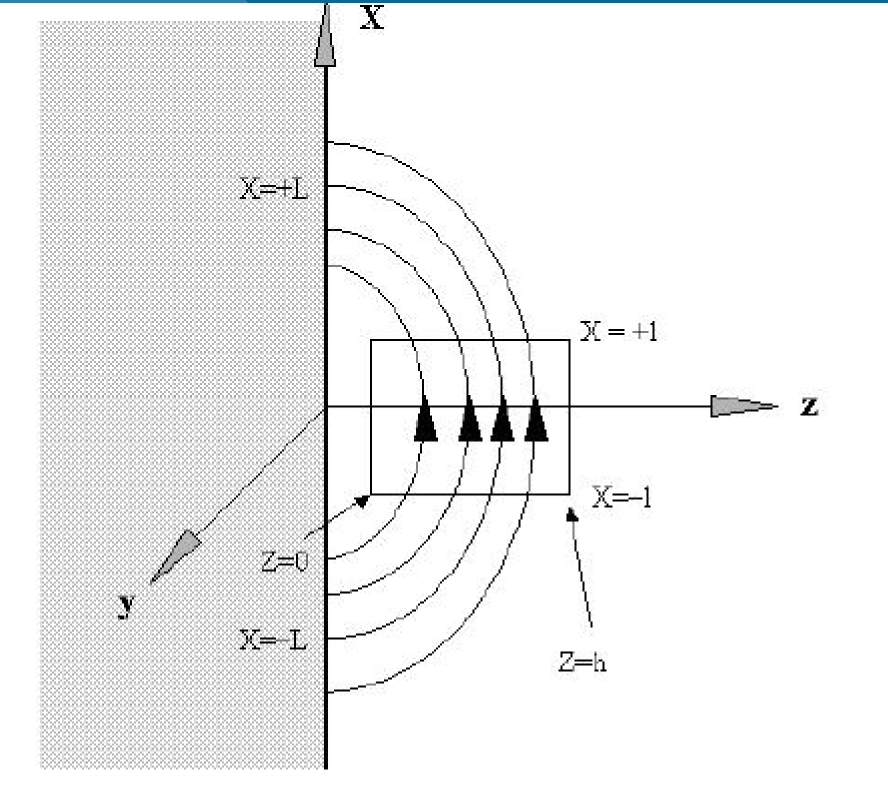
(Banerjee et al. 1998)

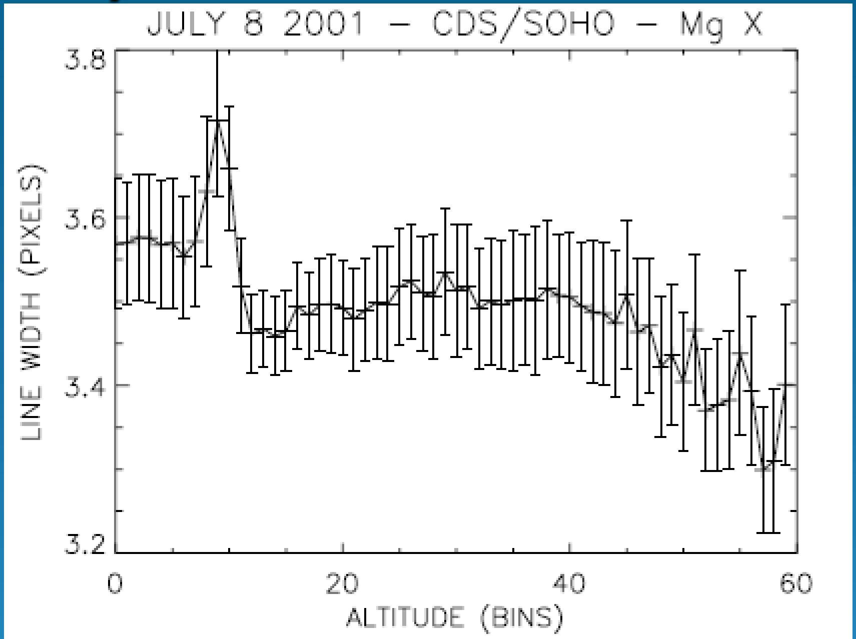
Other efforts on this line were by O'Shea et al. (2005); Dolla & Solomon (2008); Banerjee et al. (2008); Bemporad & Abbo, (2012)





Alfvén Waves Dissipation in Equatorial Corona : Observations by CDS/SoHO



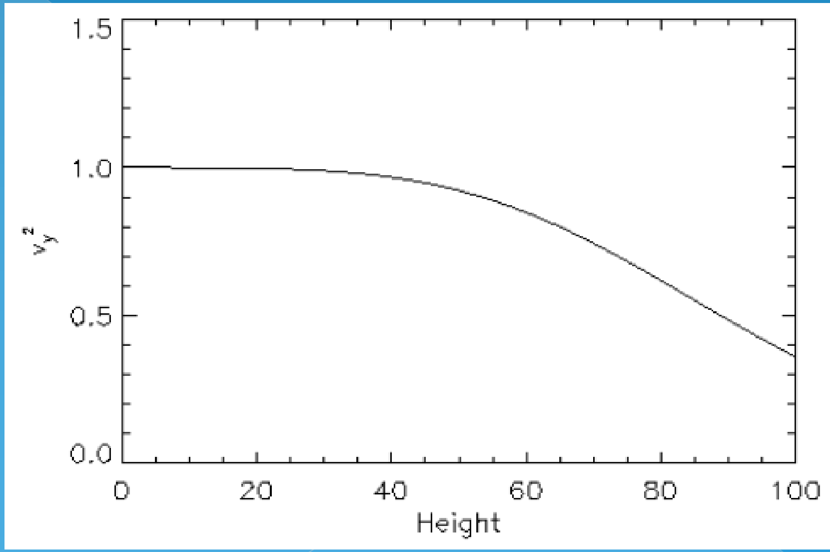


$$v_y = \frac{1}{\cos^2 k_0 L + \sinh^2 \epsilon L}$$

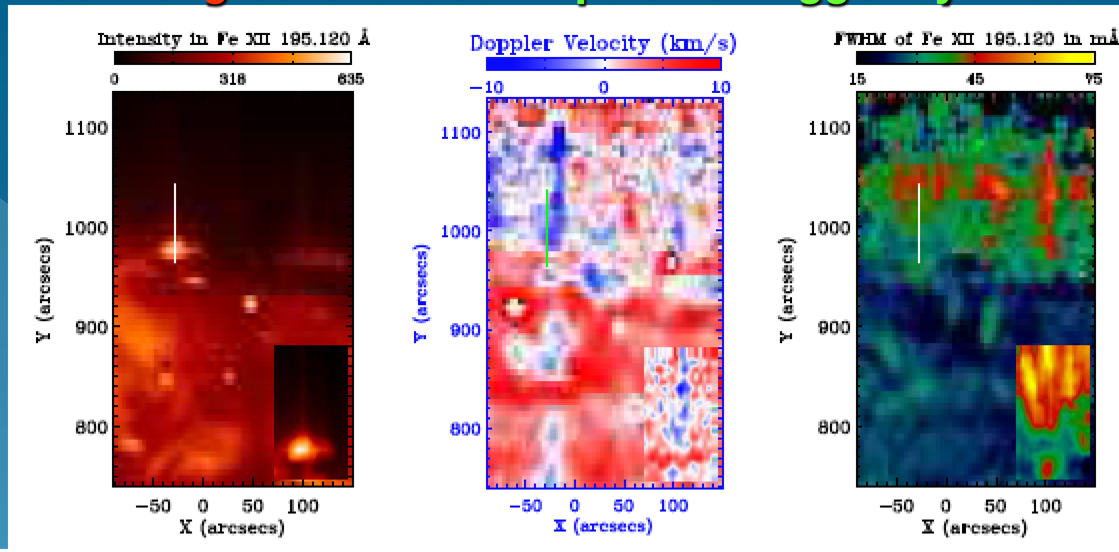
Harrison et al. (2002)

Where

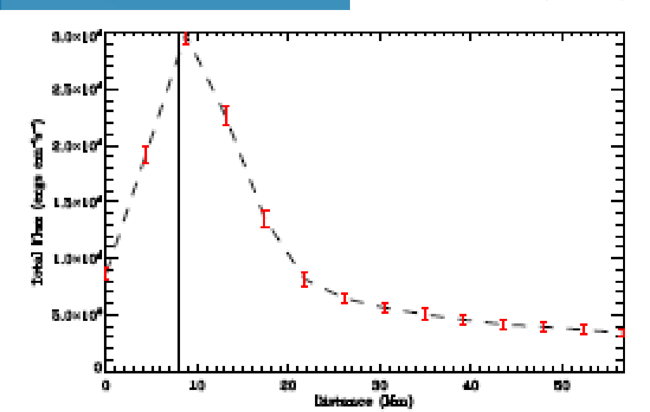
$\epsilon \approx \omega^2 \eta / 2V_A^3$ and $k_0 \approx \omega / V_A$

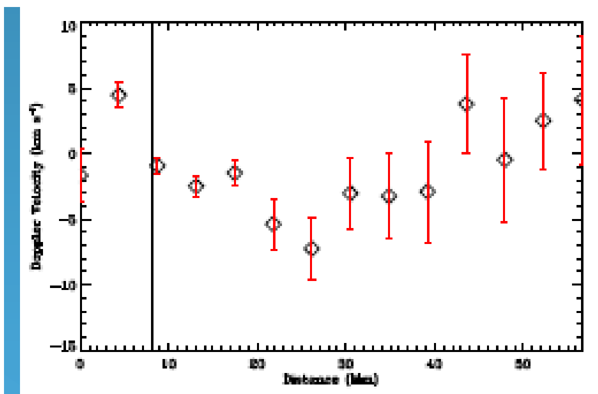


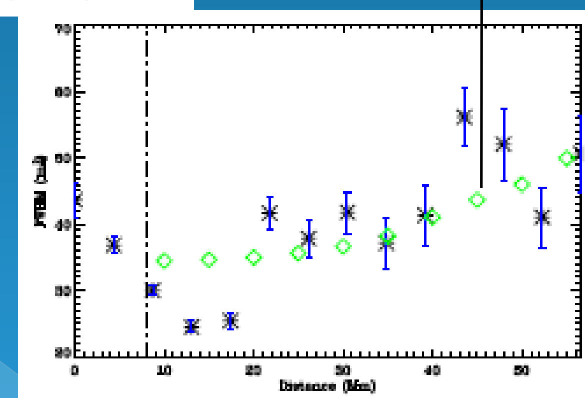
Alfvén Waves Along Coronal Jet: Impulsive Trigger by Reconnection



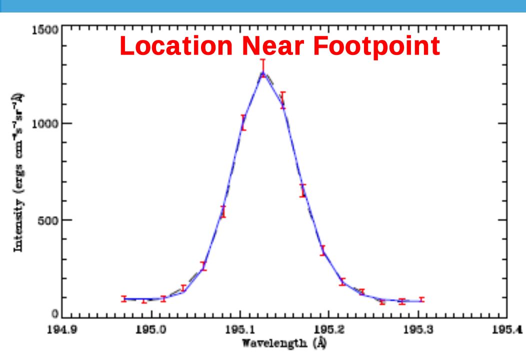
Green Diamonds : Synthetic Line Width derived by Spatio-temporily averaged Vz



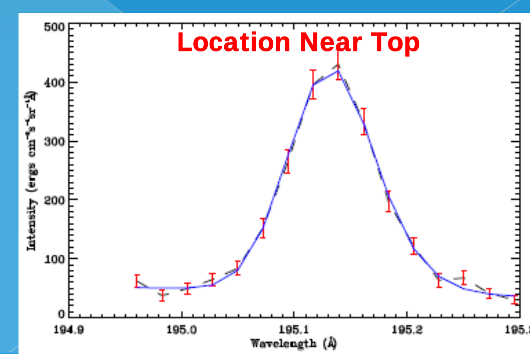


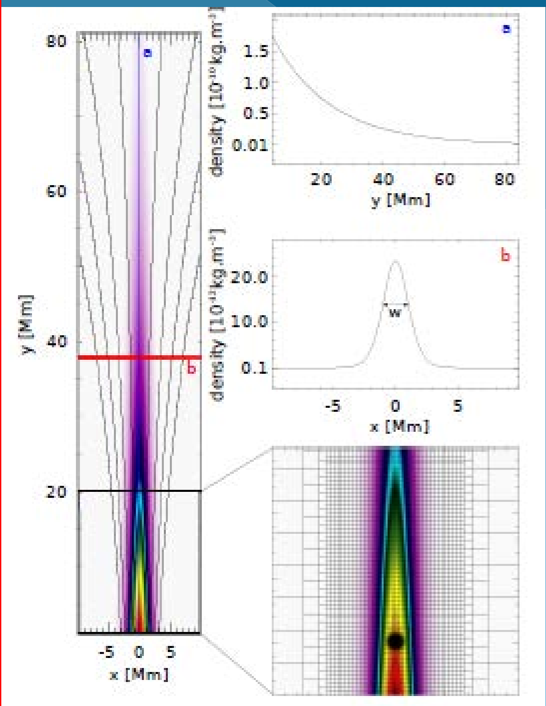


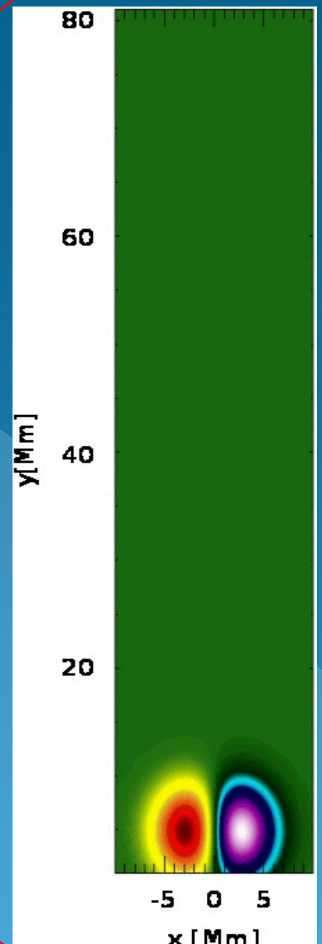
Jelinek, Srivastava, Murawski, Kayshap, Dwivedi, A&A, 2015



Example of Gaussian Fit







Governing MHD Equations

$$\frac{\mathrm{D}\varrho}{\mathrm{D}t} = -\varrho\nabla \boldsymbol{v},$$
$$\varrho\frac{\mathrm{D}\boldsymbol{v}}{\mathrm{D}t} = -\nabla p + \boldsymbol{j}\times\boldsymbol{B} + \varrho\boldsymbol{g},$$
$$\frac{\mathrm{D}\boldsymbol{B}}{\mathrm{D}t} = (\boldsymbol{B}\cdot\nabla)\boldsymbol{v},$$
$$\frac{\mathrm{D}e}{\mathrm{D}t} = -\gamma e\nabla\cdot\boldsymbol{v},$$
$$\nabla\cdot\boldsymbol{B} = 0.$$

PERTURBATIONS DURING RECONNECTION

$$V_z(x,y,t=0) = -A_0\cdot\frac{x}{\lambda}\cdot\exp\left[-\frac{x^2+(y-L_P)^2}{\lambda^2}\right]$$

Alfven Wave Equation

$$\frac{\partial^2 V_z(x,y,t)}{\partial t^2} = c_A^2(x,y)\frac{\partial^2 V_z(x,y,t)}{\partial s^2},$$

Initial Plasma Conditions

$$-\nabla p + \boldsymbol{j}\times\boldsymbol{B} + \varrho\boldsymbol{g} = 0.$$

Harris Current Sheet

$$\boldsymbol{B} = \nabla\times\boldsymbol{A}.$$

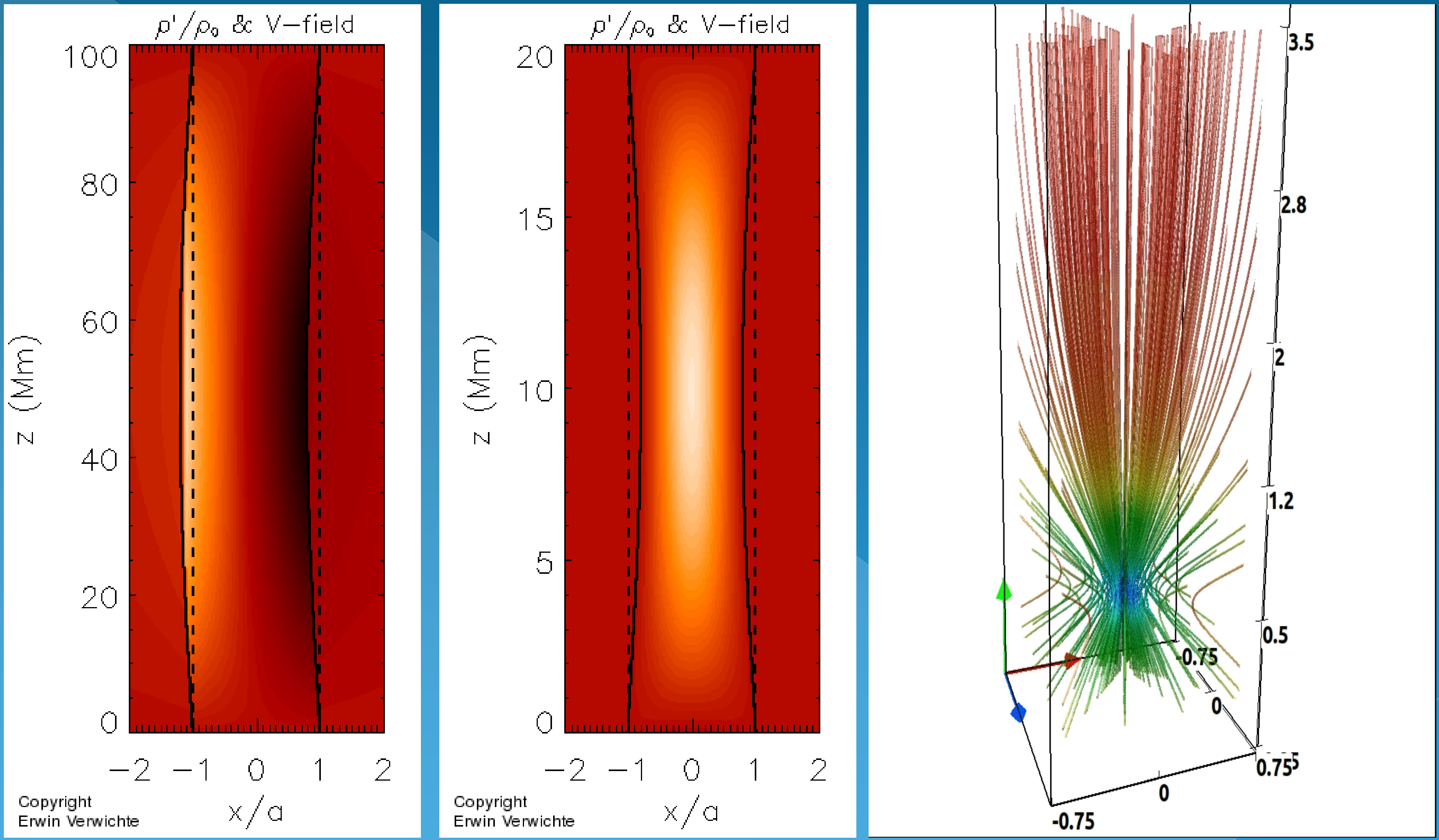
$$A_z = -B_0 w_{cs}\ln\left\{\left|\cosh\left(\frac{x}{w_{cs}}\right)\right|\right\}\exp\left(-\frac{y}{\lambda}\right).$$

$$B_x(x,y) = B_0\frac{w_{cs}}{\lambda}\ln\left|\cosh\left(\frac{x}{w_{cs}}\right)\right|\exp\left(-\frac{y}{\lambda}\right),$$
$$B_y(x,y) = B_0\tanh\left(\frac{x}{w_{cs}}\right)\exp\left(-\frac{y}{\lambda}\right).$$

$$\varrho(x,y) = \left\{\frac{B_0^2}{\mu_0 g\lambda}\left\{1+\ln\left[\cosh\left(\frac{x}{w_{cs}}\right)\right]\right\}\mathrm{sech}^2\left(\frac{x}{w_{cs}}\right) + \right.$$
$$\left. + \varrho_0\right\}\cdot\exp\left(-2\frac{y}{\lambda}\right),$$

$$p(x,y) = \left\{\frac{B_0^2}{2\mu_0}\mathrm{sech}^2\left(\frac{x}{w_{cs}}\right) + \frac{B_0^2 w_{cs}^2}{2\mu_0\lambda^2}\ln^2\left[\cosh\left(\frac{x}{w_{cs}}\right)\right] + \right.$$
$$\left. + \frac{\varrho_0 g\lambda}{2}\right\}\cdot\exp\left(-2\frac{y}{\lambda}\right) + p_0.$$

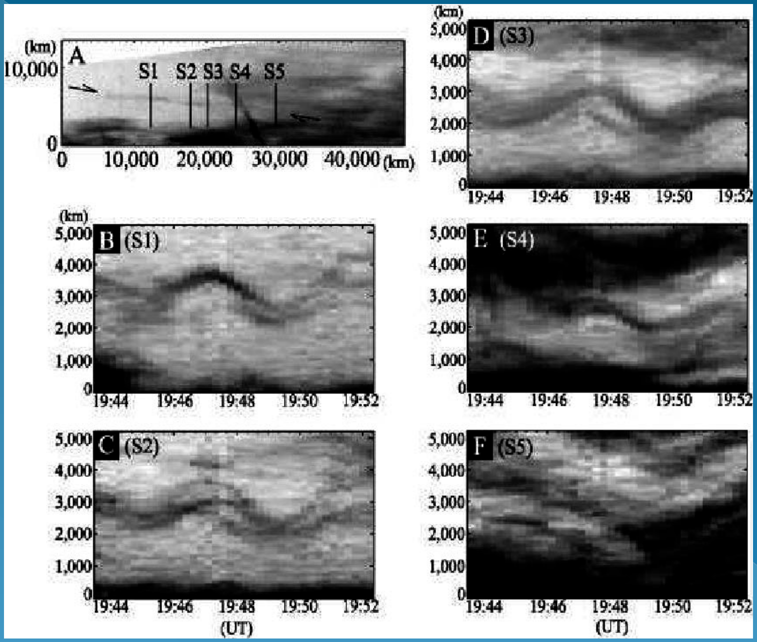
Initiation of New ERA after TRACE: MHD Wave Modes in Magnetic Tubes are Resolved



Apart from Fast Magnetoacoustic (kink and sausage) and Torsional Alfven Waves (presented here), the slow magnetoacoustic wave mode also present thre.

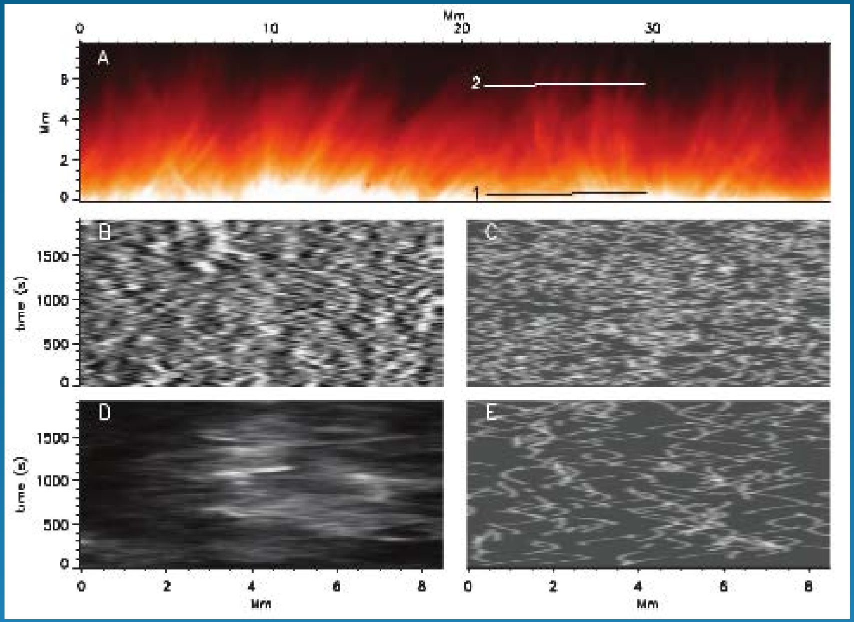
(Reference: Roberts, B. 1983,84; Nakariakov & Verwichte, 2005)

Alfvén(ic) Waves in Prominence



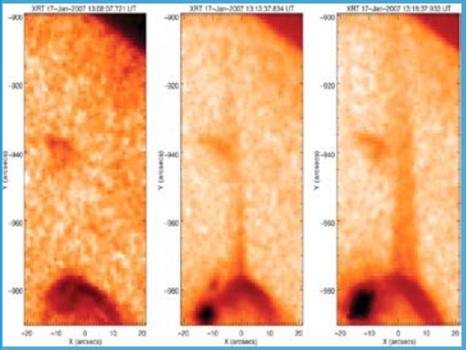
(Okamoto et al., 2007, Science)

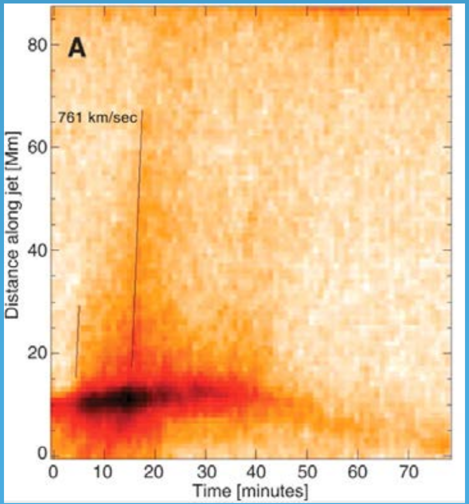
Alfvén(ic) Waves in Spicules



(De Pontieu et al., 2007, Science)

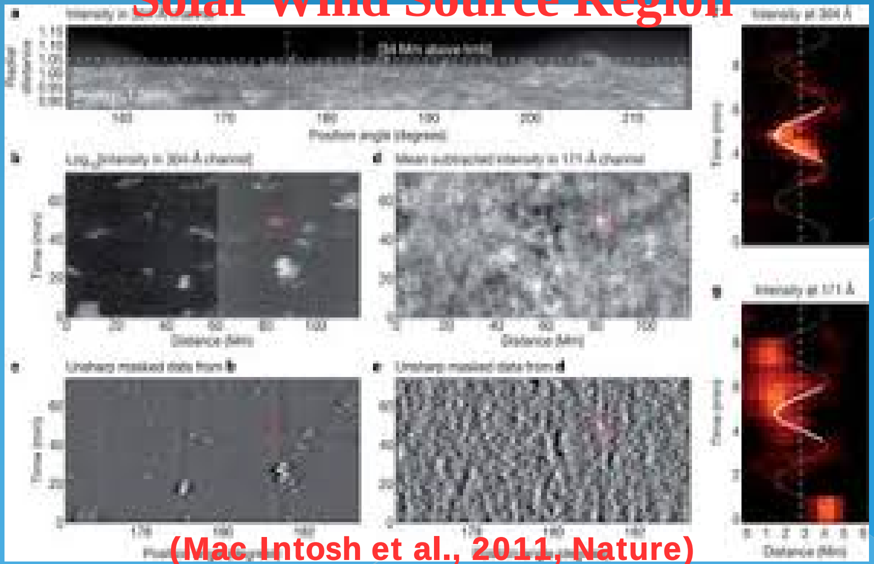
Alfvén(ic) Waves in X-ray Jets





(Cirtain et al., 2007, Science)

Alfvén(ic) Waves at Base of Solar Wind Source Region



(Mac Intosh et al., 2011, Nature)

Other recent significant efforts on detecting Alfvenic Modes are*:

[1] Tomzchyk et al. (2003; Science), “Alfvén Waves in the Solar Corona”.

[2] Richard Morton et al. (2007; Nat Com), “Investigating Alfvénic wave propagation in coronal open-field regions.

[3]Martínez-Sykora, J. et al. (2017, Science), “On the generation of solar spicules and Alfvénic waves”.

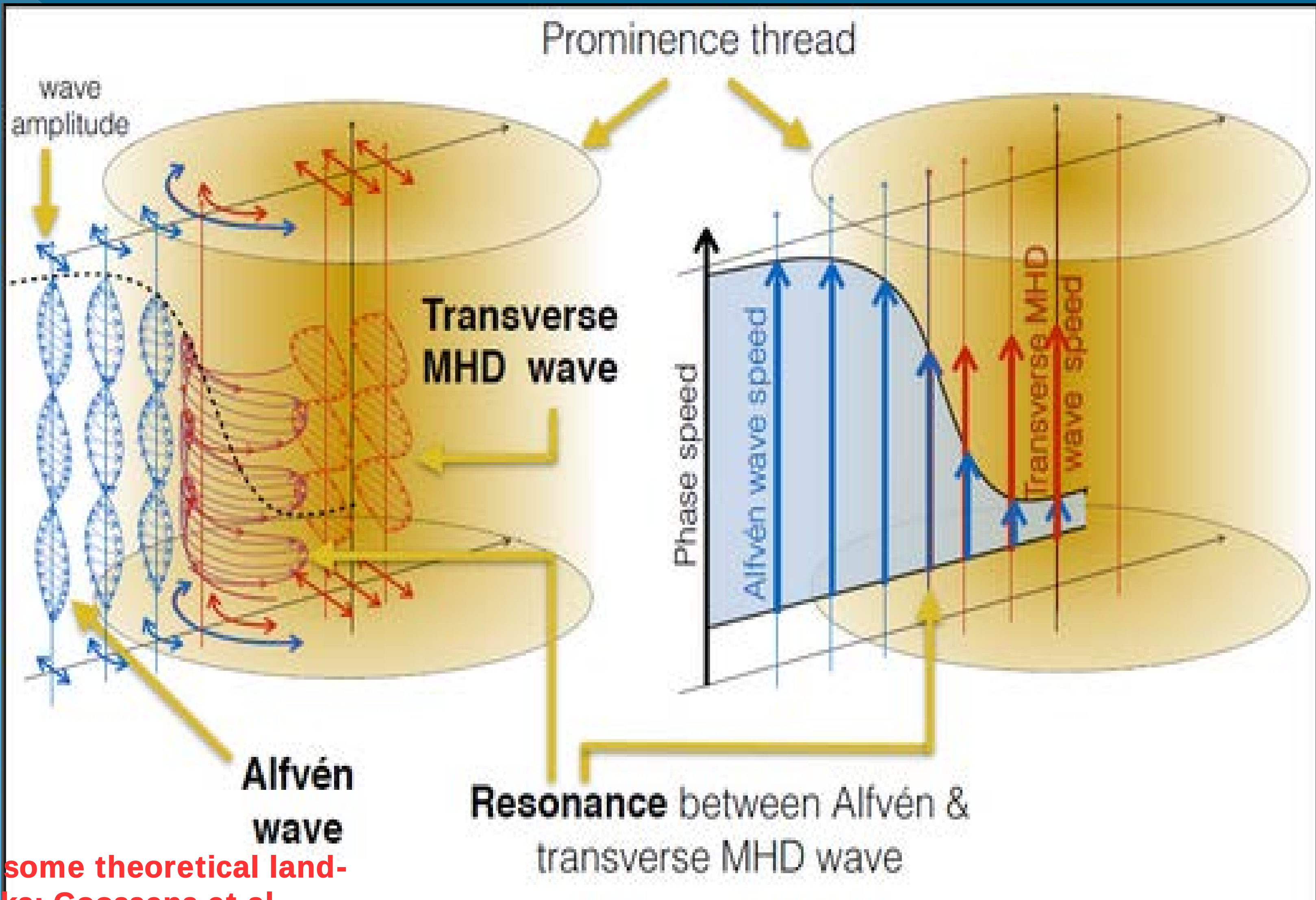
[4] Tian, Hui et al. (2012, ApJ), “Persistent Doppler Shift Oscillations Observed with Hinode/EIS in the Solar Corona: Spectroscopic Signatures of Alfvénic Waves and Recurring Upflows.”

[5] De Pontieu, B. et al. (2014, Science), “On the prevalence of small-scale twist in the solar chromosphere and transition region”.

[6] Okamoto et al. (ApJ, 2015), “Resonant Absorption of Transverse Oscillations and Associated Heating in a Solar Prominence. I. Observational Aspects”

Most of these studies found that such transverse waves carry substantial energy required to fulfill coronal losses

RESONANCE BETWEEN Two Types of TRANSVERSE MODES

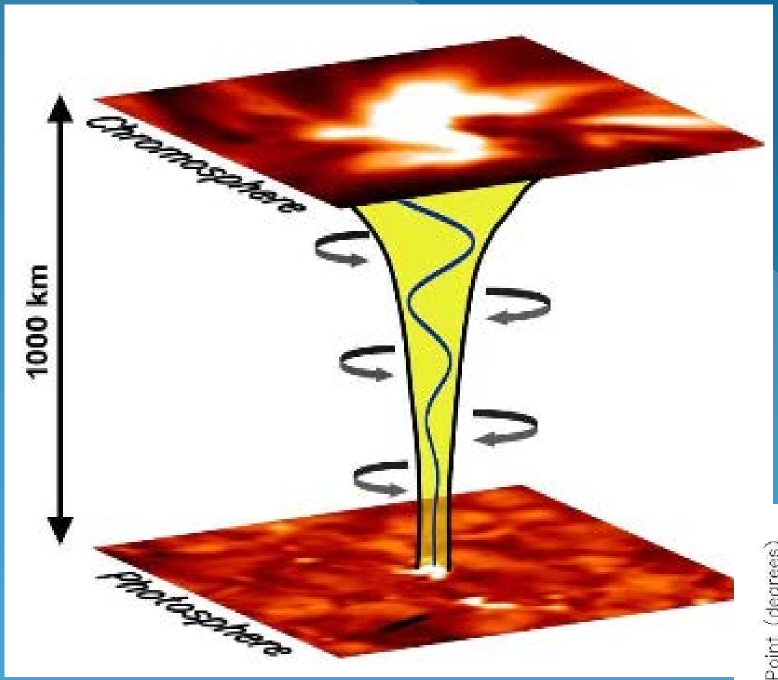


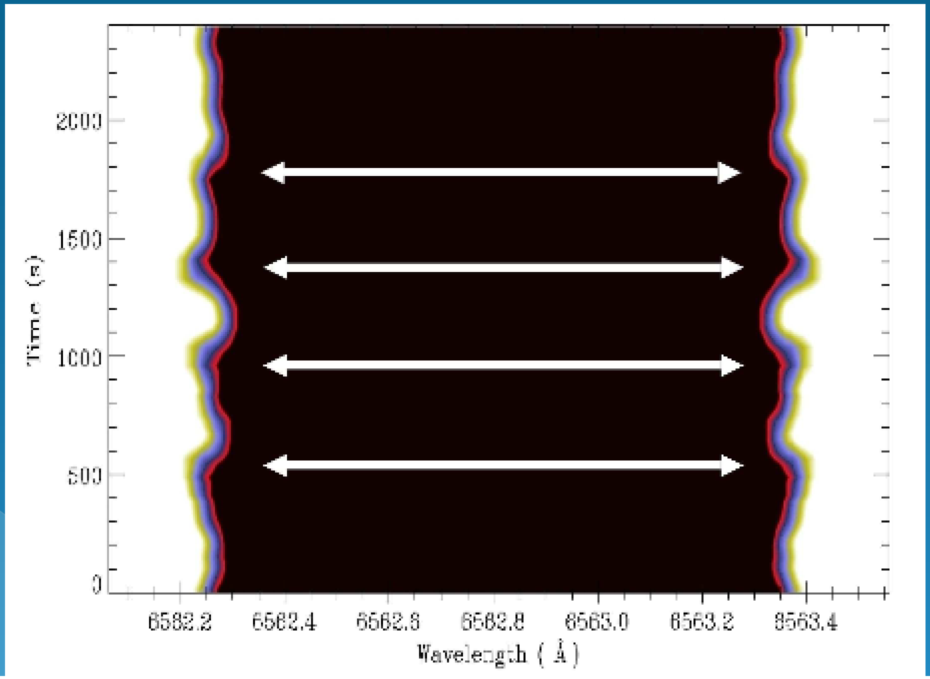
See some theoretical land-marks: Goossens et al., A&A (2002); RSPTA (2006); A&A (2009); ApJ (2012).

Credit: Okamoto & Antolin

Torsional Alfven Waves above Chromospheric Bright Points

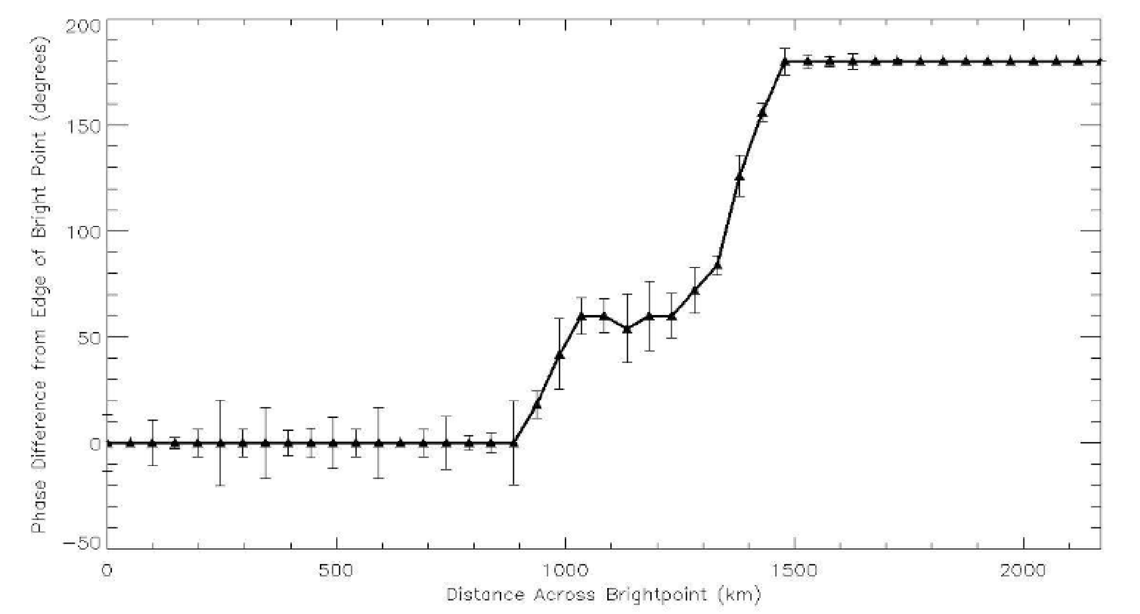
Period : 128-500 s



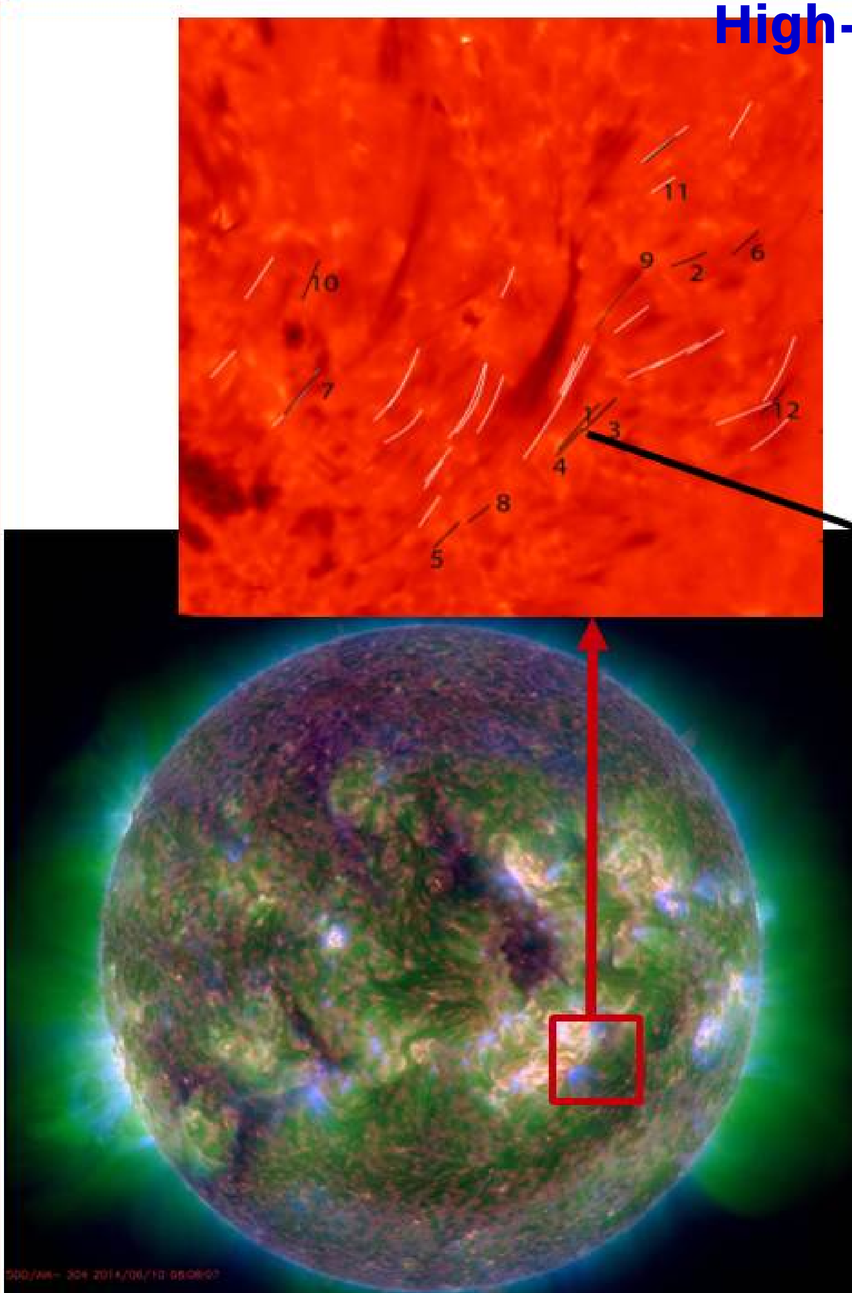


Jess et al., 2009, Science

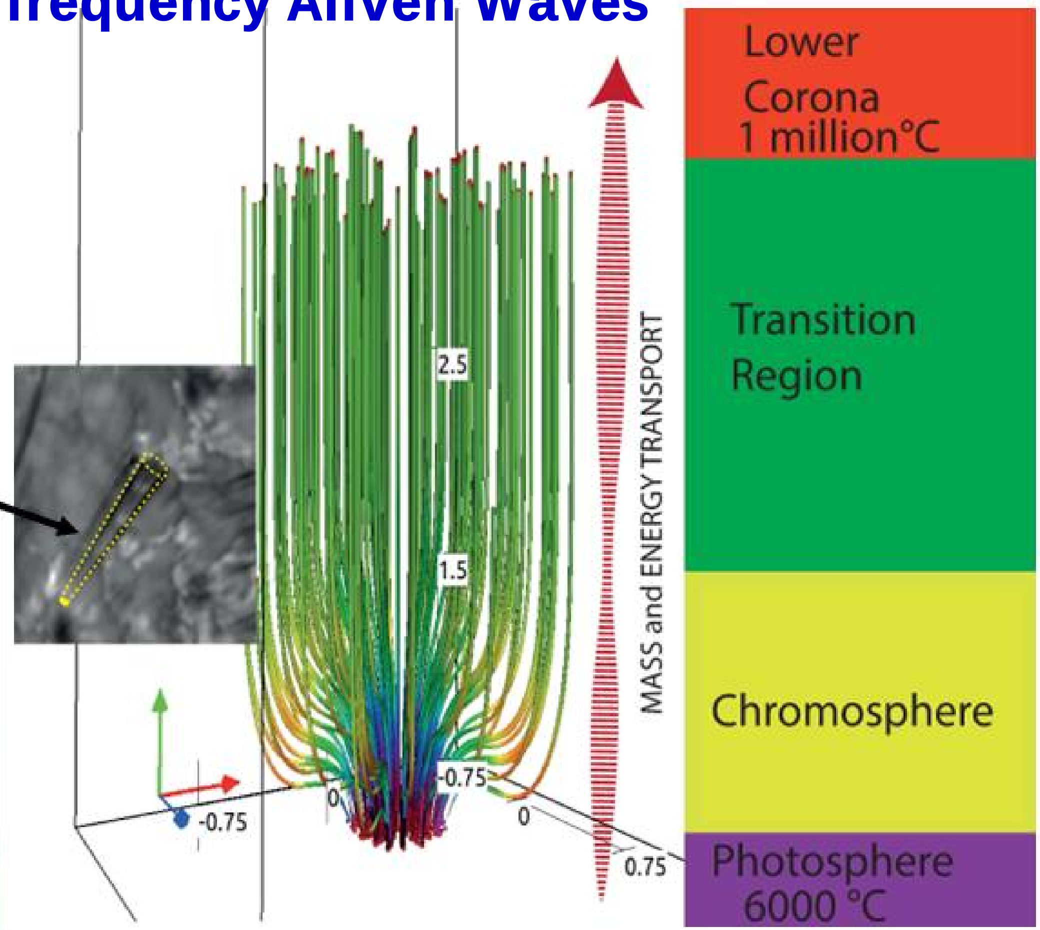
Authors quote: "The energy flux associated with this wave mode is sufficient to heat the solar corona."



High-frequency Alfven Waves

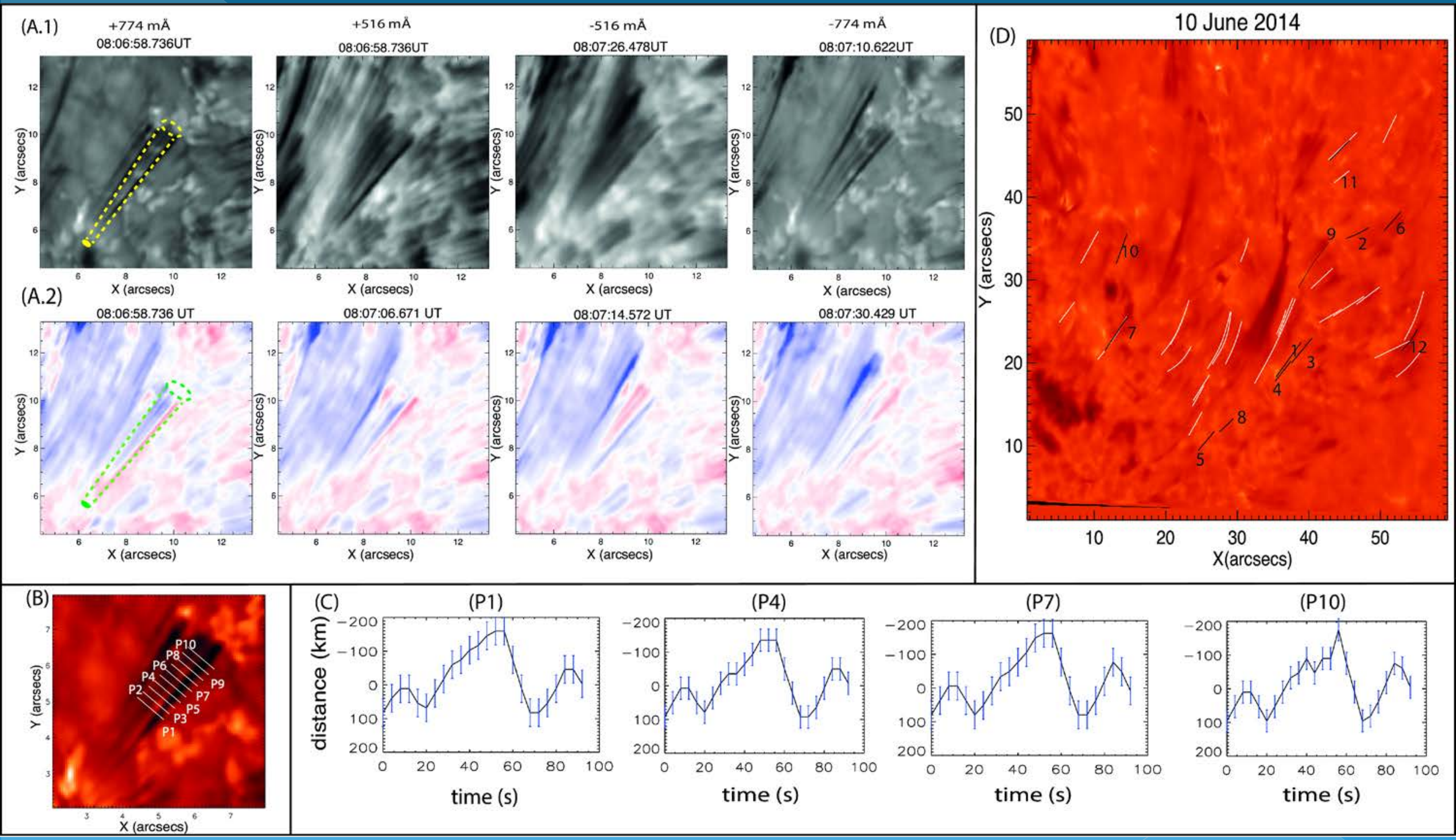


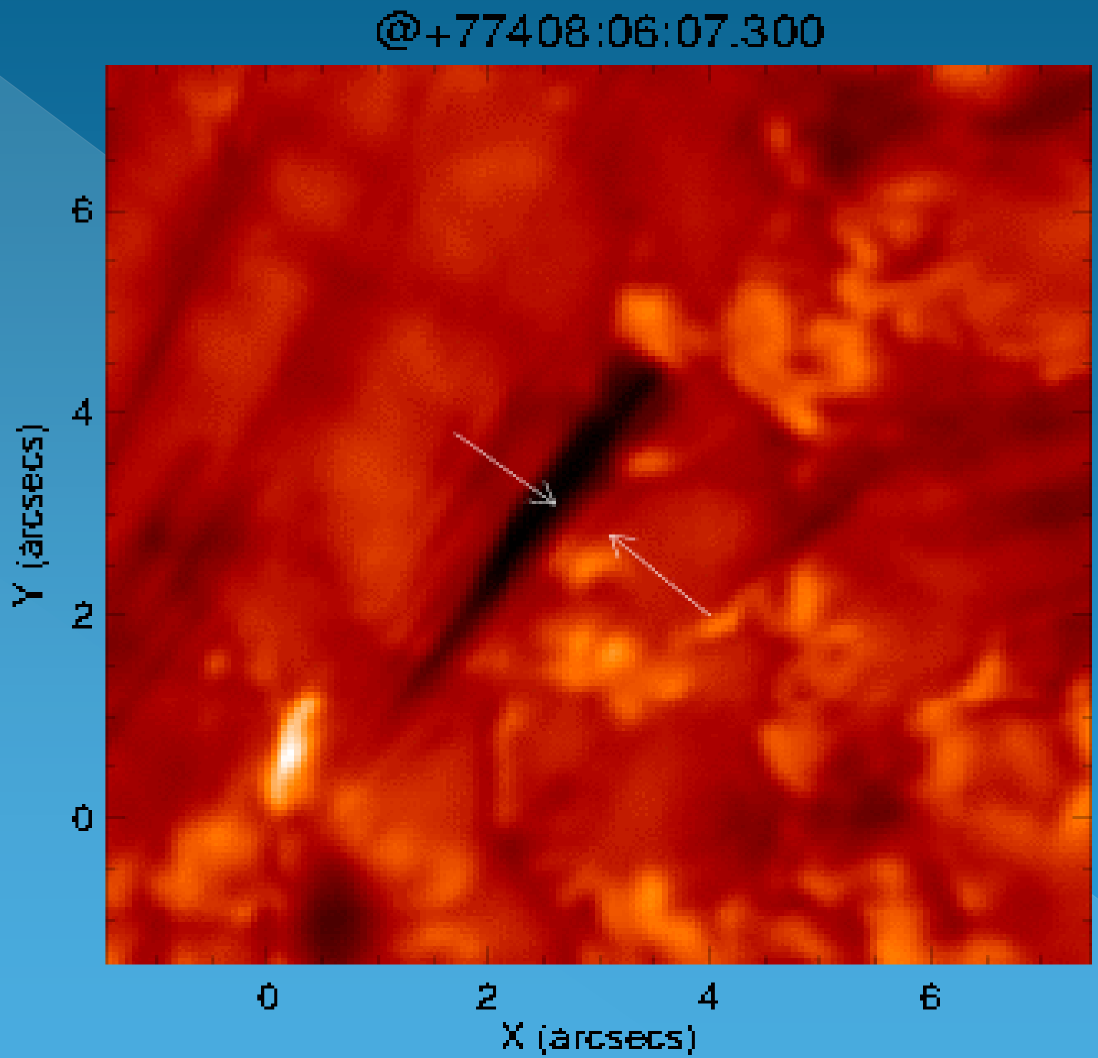
The Sun in 171 Å observed by SDO/NASA on 10 June 2014 at 08:00 UT

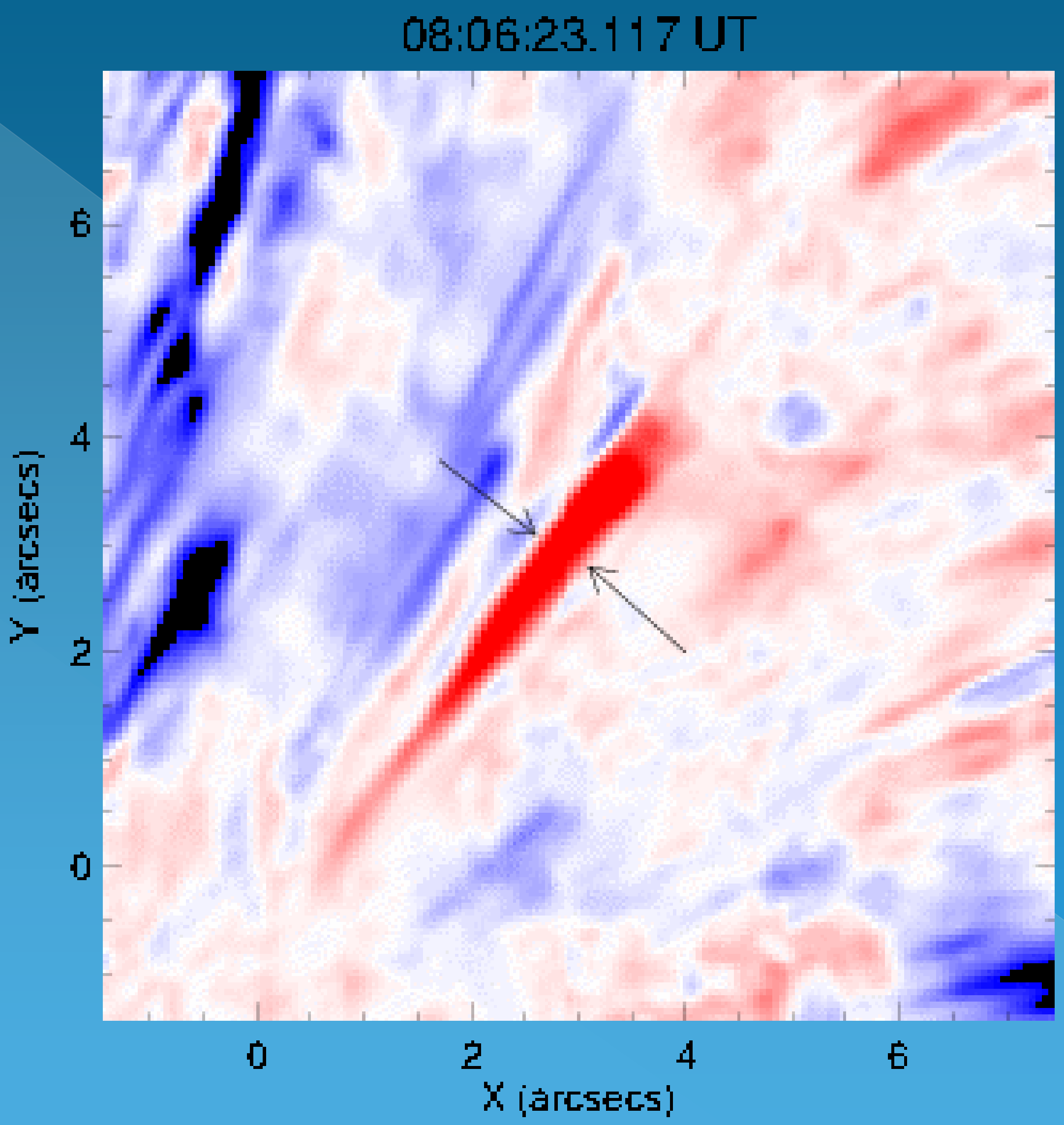


Srivastava et al. 2017, Nature Scientific Reports

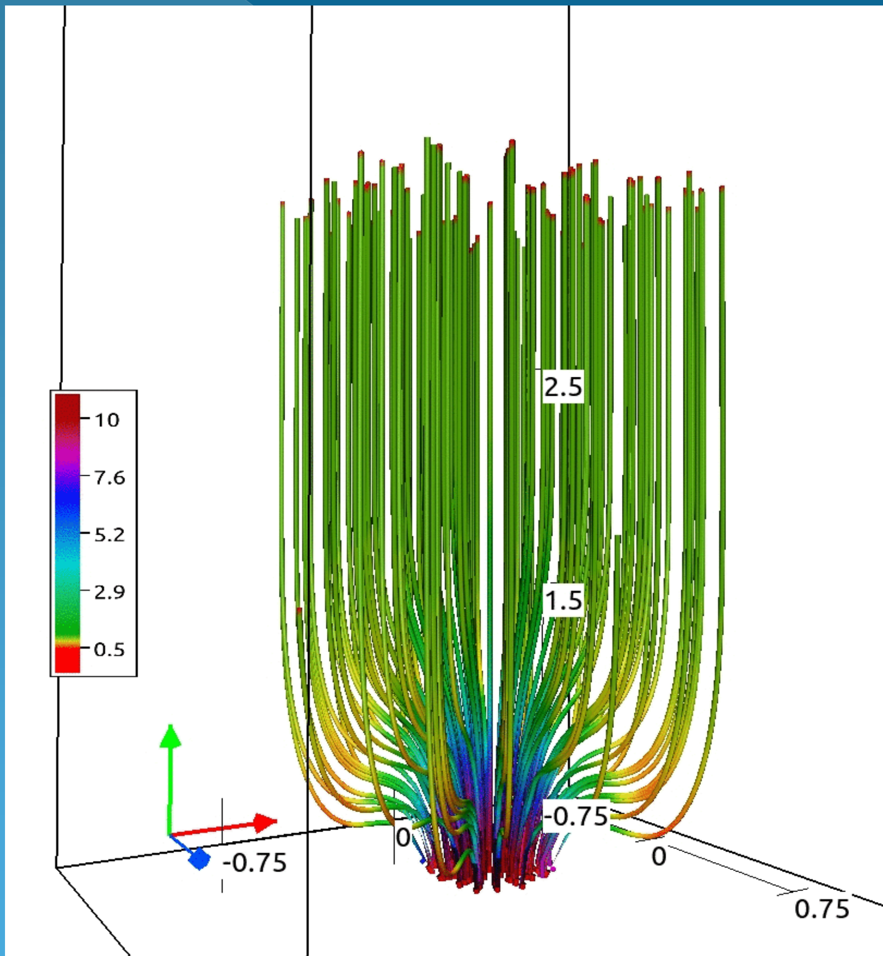
The Sun's heated corona on 10 June 2014 consists of fine structured flux tubes in the underlying chromosphere as observed by CRISP on the 1-m Swedish Solar Telescope (SST) at La Palma. The high-frequency torsional Alfvén waves (12-42 mHz) are discovered for the first time in these tubes channeling sufficient energy flux 10^3 W m^{-2} to heat the solar corona.

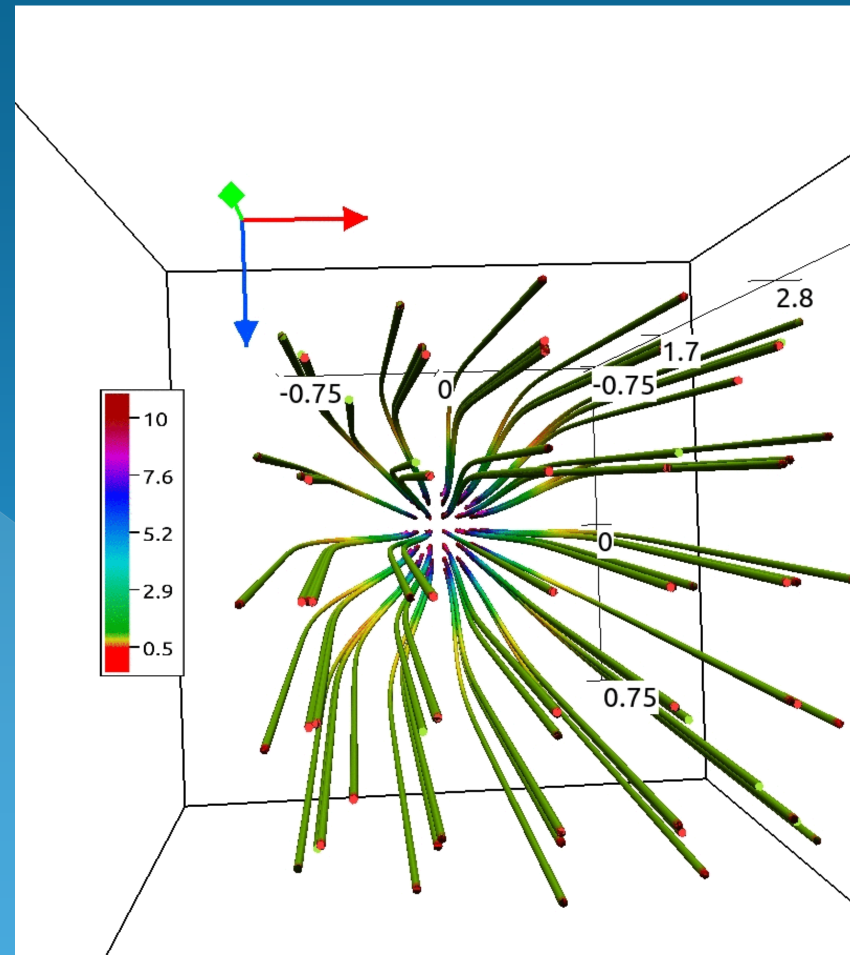

(A.1)
+774 mÅ
08:06:58.736UT
+516 mÅ
08:06:58.736UT
-516 mÅ
08:07:26.478UT
-774 mÅ
08:07:10.622UT
Y (arcsecs)
X (arcsecs)
(A.2)
08:06:58.736 UT
08:07:06.671 UT
08:07:14.572 UT
08:07:30.429 UT
(D)
10 June 2014
Y (arcsecs)
X(arcsecs)
(B)
P10
P8
P6
P4
P2
P9
P7
P5
P3
P1
(C)
(P1)
(P4)
(P7)
(P10)
distance (km)
time (s)


@+77408:06:07.300
Y (arcsecs)
X (arcsecs)
0
2
4
6
0
2
4
6

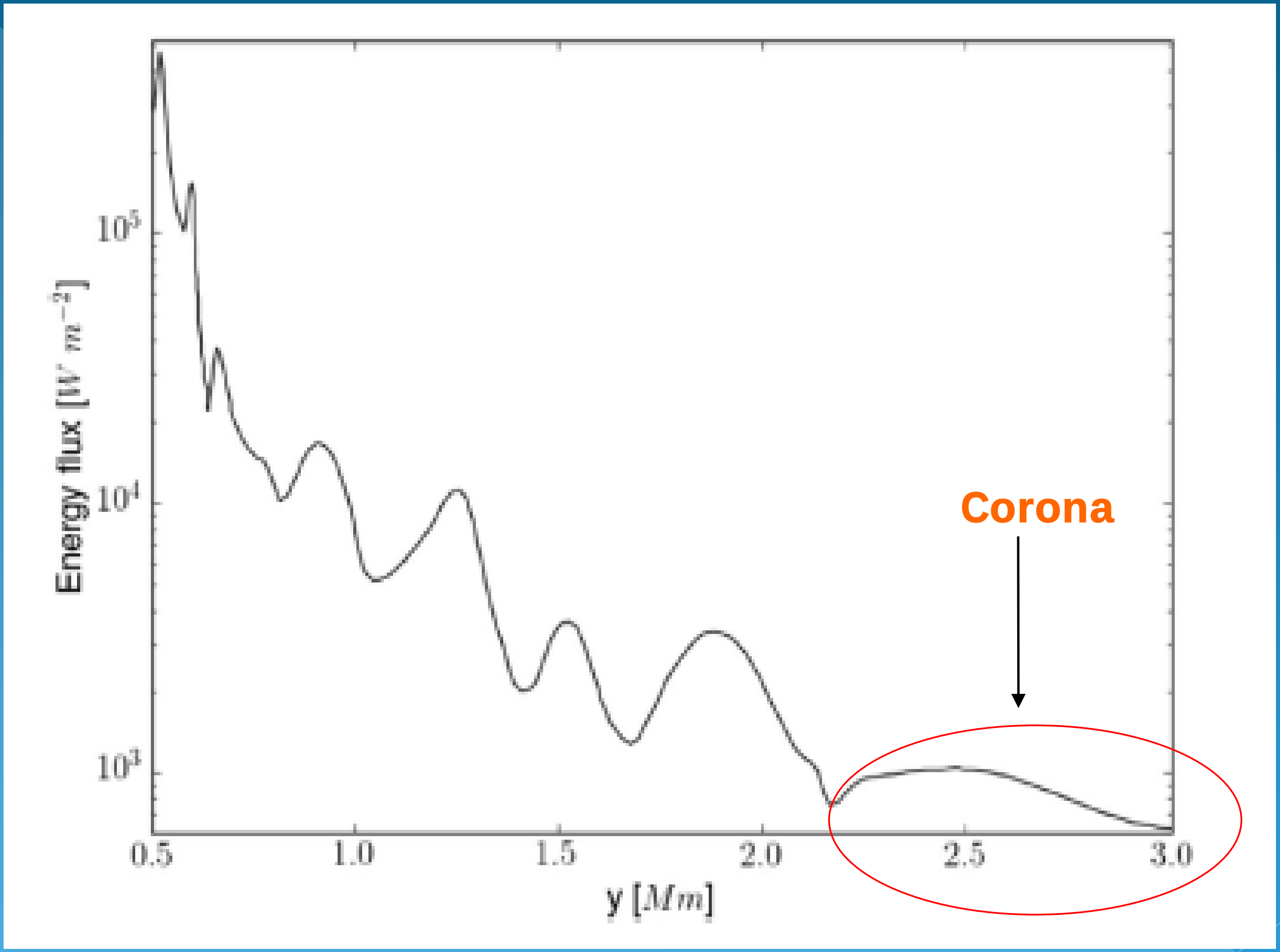


08:06:23.117 UT
Y (arcsecs)
6
4
2
0
0
2
4
6
X (arcsecs)





$$V_\theta = A_V \frac{r}{w} \exp\left[- \frac{r^2 + (y - y_0)^2}{w^2} \right] \sin\left(\frac{2\pi}{P_d} t \right)$$


Energy flux [$W\ m^{-2}$]
10^5
10^4
10^3
0.5
1.0
1.5
2.0
2.5
3.0
y [Mm]
Corona

Conclusions:

[1] Alfven waves are considered as an energy source that can possess and transport significant energy through the solar atmosphere.

[2] After 1995, especially in the SoHO era, the spectroscopic signature of these waves in the Sun's atmosphere was obtained. However, there were some early reports on line-width variations by Hassler, D. The signature of velocity and magnetic field fluctuations in solar wind were also already observed since a decade back by *in situ* observations.

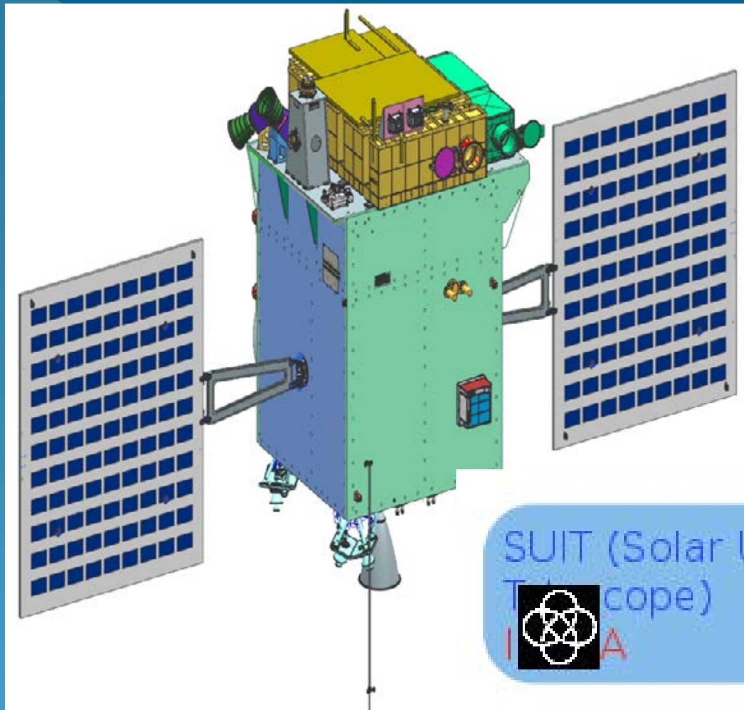
[3] It was known that these waves may carry substantial energy, but there was no direct detection in the solar atmosphere. Classical theories were not constrained.

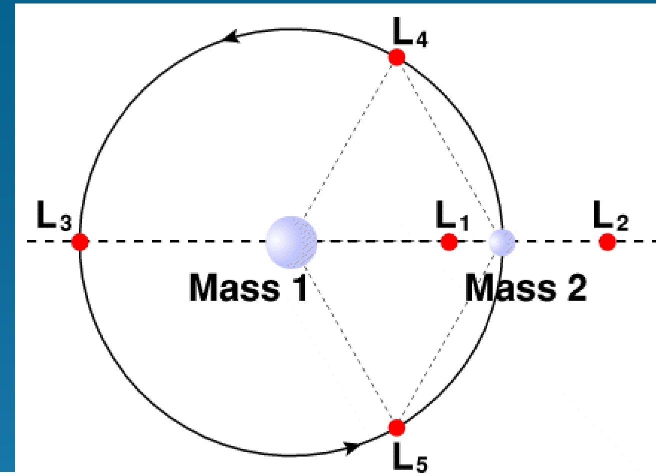
**[4] In Hinode and Post-Hinode era, the Alfvenic modes have been discovered through high-resolution ground based observations, while its theory was significantly developed by Marcel Goossens and colleagues. Their capabilities as an energy source, diagnostics agent, and probing on various physical processes (e.g., resonant absorption)
came in to reality in observational line.**

[5] However, the direct detection of true incompressible Alfven waves in localized fluxtubes (torsional waves) were still illusive until the detection by David Jess et al. (2009) who used SST H-alpha observations over bright points and found the opposite phase variation of FWHM on either edges of the fluxtube (128-400 s).

[6] State-of-art further went to the recent detection (in 2017) of the high-frequency oscillations in form of asymmetric Doppler-shift of H-alpha line over the surface of fine-structured tubes in the chromosphere. It was found that these waves possess substantial energy carrying upward.

Indian Aditya-L1 Space Mission (Time-Line: 2019)





SUIT (Solar Ultraviolet Imaging T cope)
I A

VELC (Visible Emission Line C onagraph)

SOLEXS (Soft X-ray Low rgy X-ray Spectrometer)
D - ISAC

HEL1OS (High Energy L1 ting X-ray Spectrometer)
D - ISAC

PAPA (Plasma Analyser oad For Aditya)
D - VSSC

ASPEX (Aditya Solar Wind cle Experiment)

netometer
D - LEOS

Future

Synergy at the core scientific level with the ground (e.g., DKIST, NLST, EST, SST), and space (e.g., Solar Orbiter, IRIS, SDO)observatories lying in the same time-line.

The University Of Sheffield.

northumbria UNIVERSITY NEWCASTLE

DYNAMIC SUN II. SOLAR MAGNETISM FROM INTERIOR TO THE CORONA