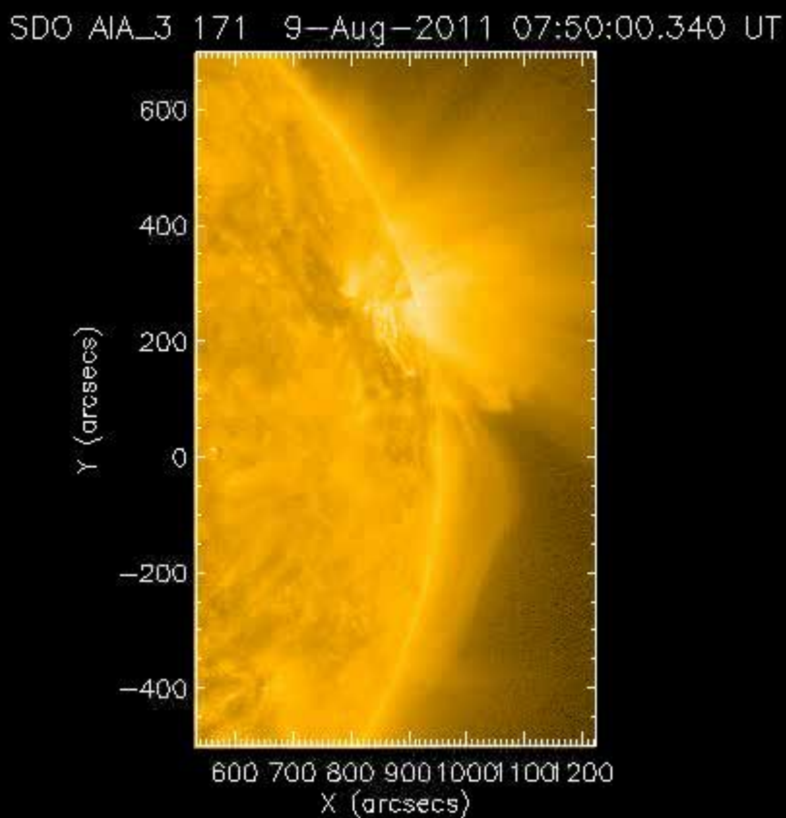
Observations and Modelling of X6.9-class Flare-induced Vertical Kink Oscillations in a Large-scale Plasma

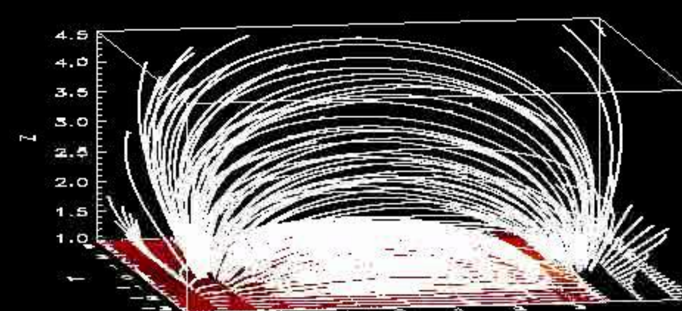
A.K. Srivastava
Department of Physics
Indian Institute of Technology (BHU), Varanasi-221005, India

Collaborators: Marcel Goossens; Leon Ofman; M. Parisi

Fast Magnetoacoustic Kink Waves in the Sun's Corona

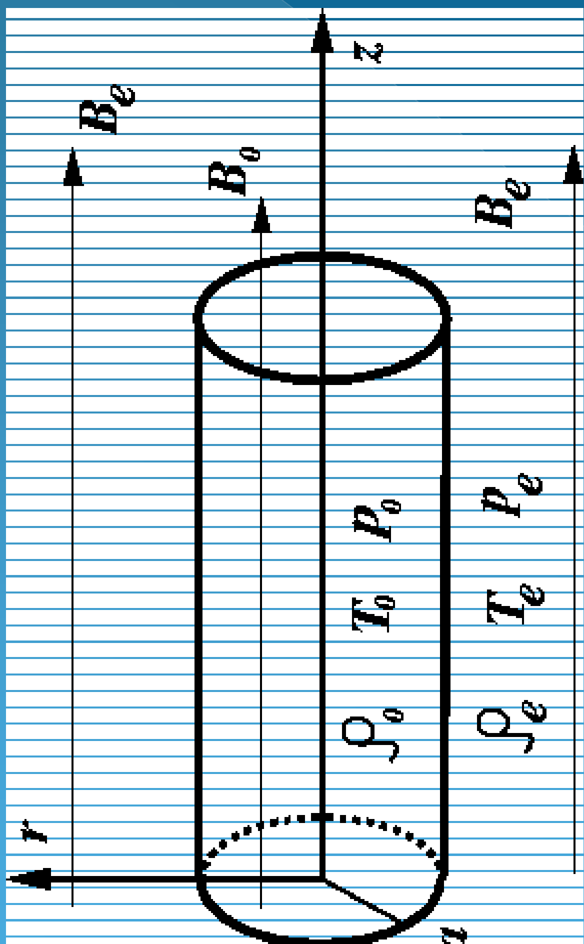


Perturbation of radial magnetic field and density in structured tubes.

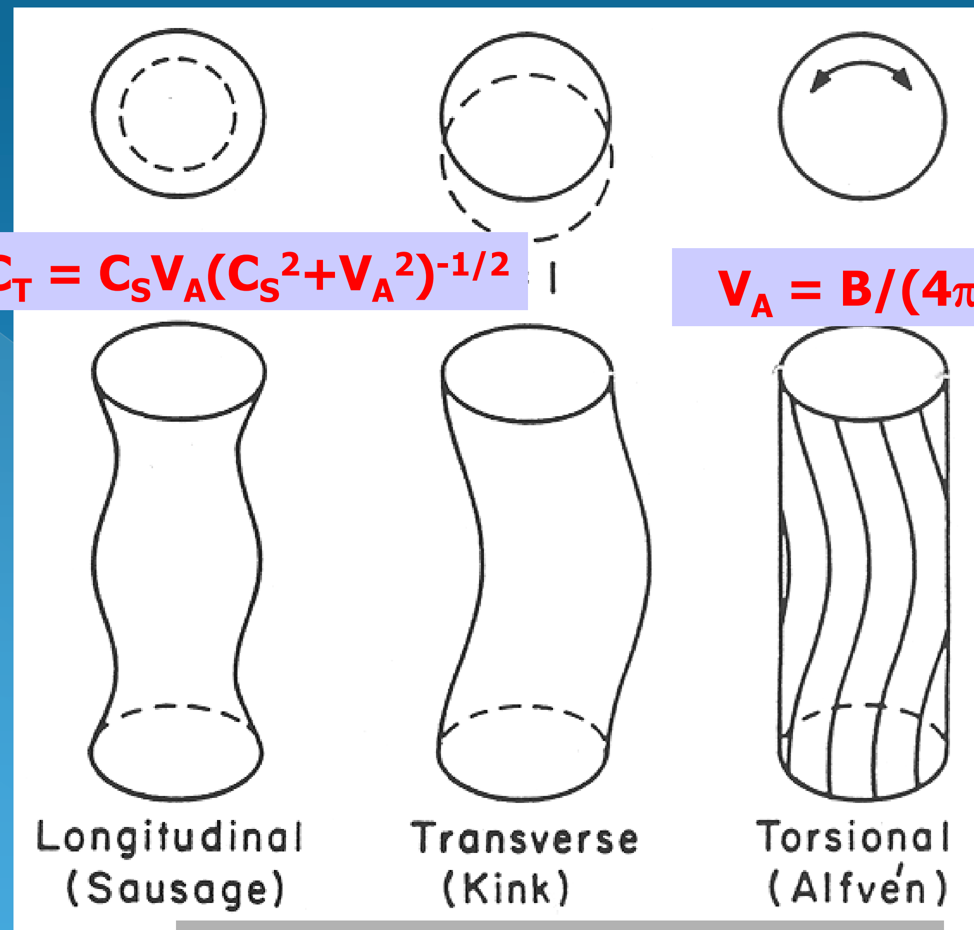


Modulation of axis of the coronal tube, and somewhat the density (thus intensity) in non-linear regime

Various Modes of the Fluxtubes



Coronal Fluxtube



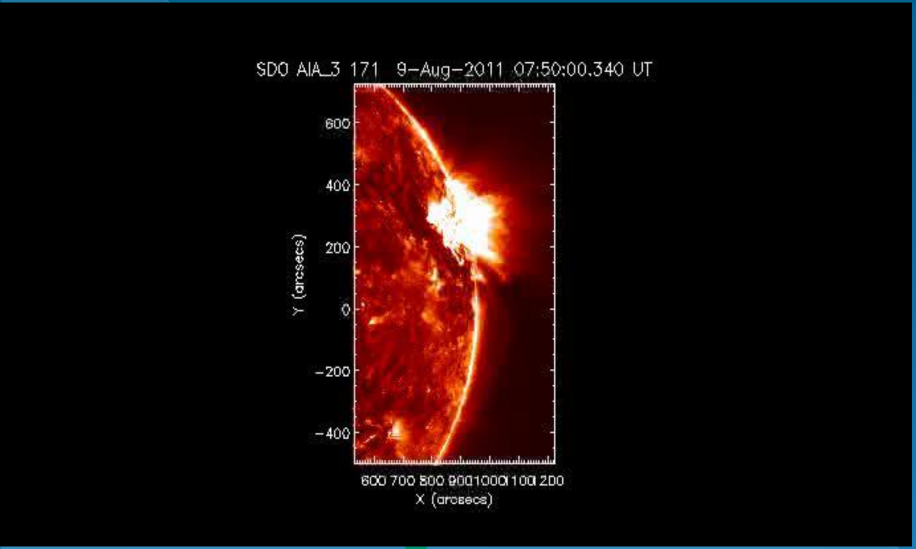
$C_T = C_S V_A (C_S^2 + V_A^2)^{-1/2}$

$V_A = B/(4\pi\rho)^{1/2}$

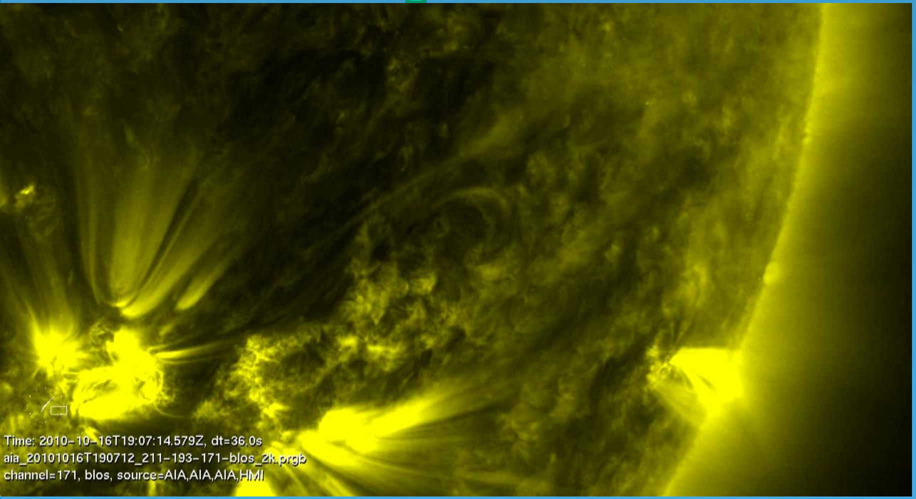
FMAW by Magnetic and thermal pressure

and TAW by Magnetic curvature force (tension)

Horizontal and Vertical Polarized Kink Waves

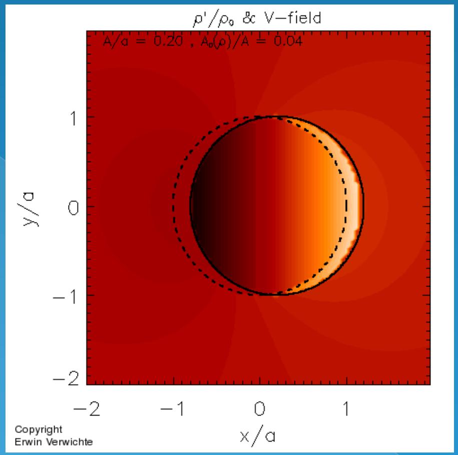


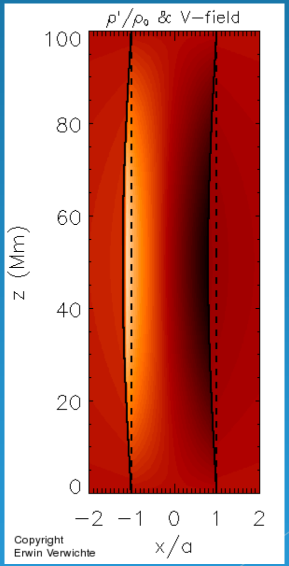
Straighten the curved loop and excite the perturbations



Vertical Kink Modes

Srivastava & Goossens, 2013, ApJ



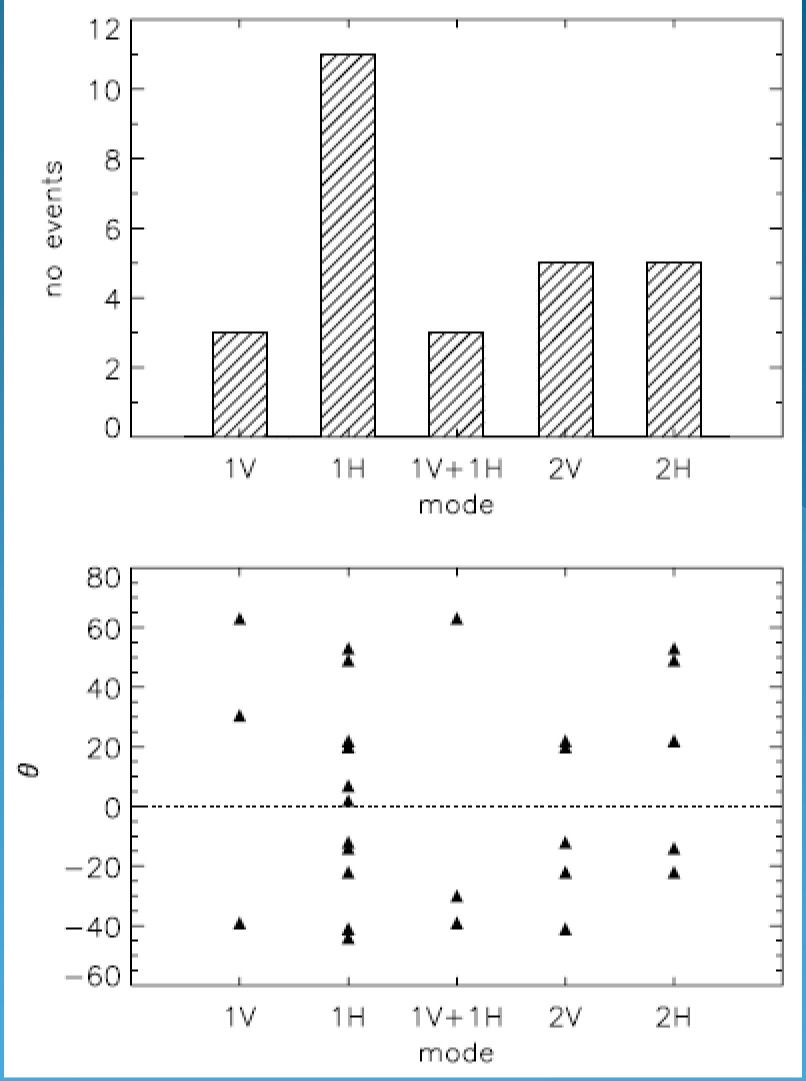


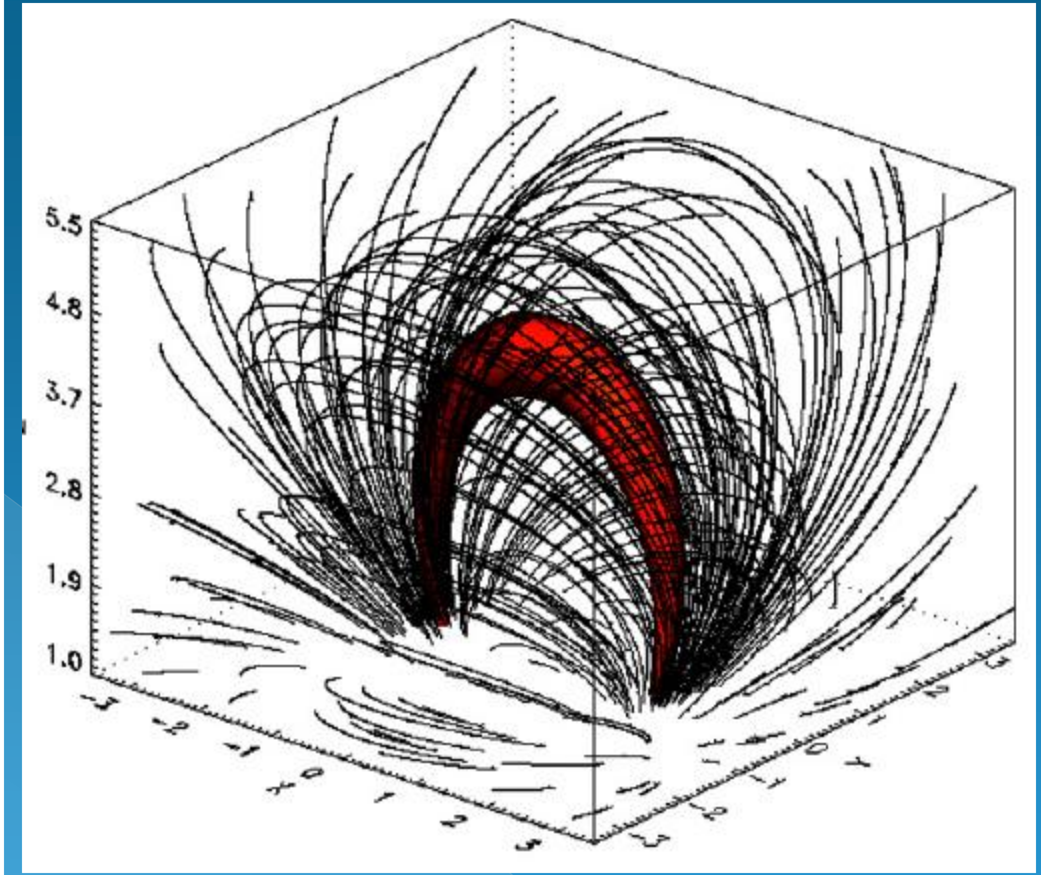
Credit : Erwin Verwichte, Univ of Warwick, U.K.

Horizontal Kink Modes

Aschwanden & Schrijver, 2011, ApJ

Vertical Kink Oscillations are Rare !

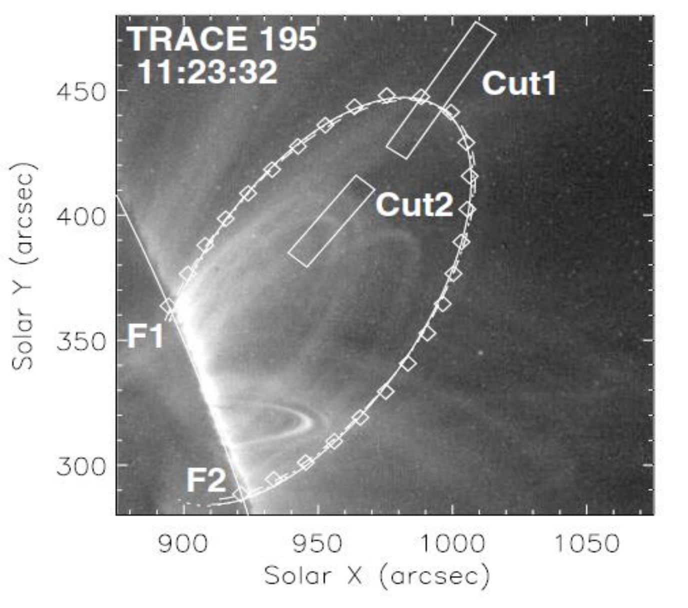


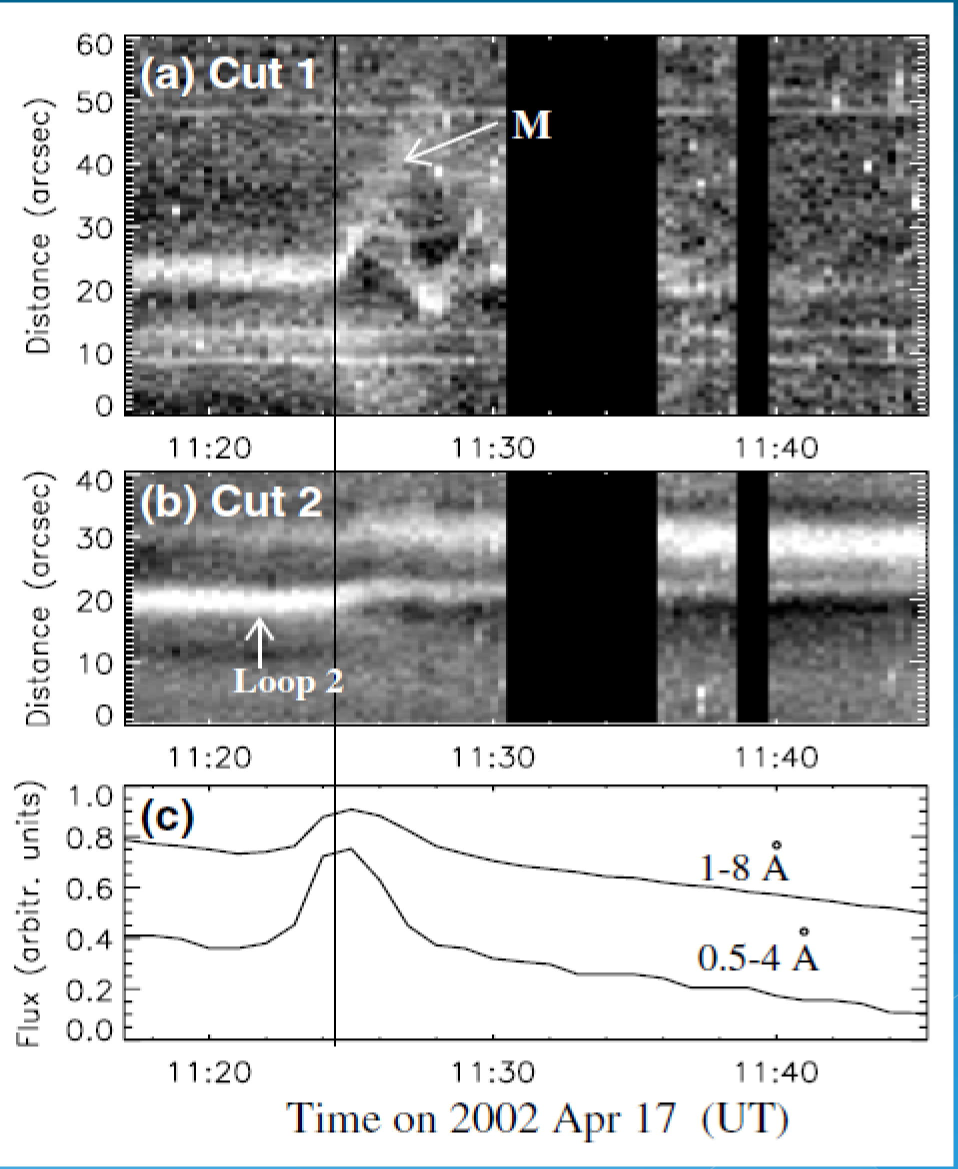


Selwa et al., 2011

For a central (symmetric) loop within the AR, the amplitude of vertical kink oscillations is significantly amplified in comparison to horizontal kink oscillations for exciters located centrally (symmetrically) below the loop. For pulses initiated further from such a symmetric loop a combination of vertical and horizontal oscillations is excited. For inclined loop (non-symmetric). In this case, vertical kink oscillations of any significant amplitude are not being excited, while horizontal ones can be easily detected.

Vertical Kink Oscillations : First Detection with TRACE in 2002

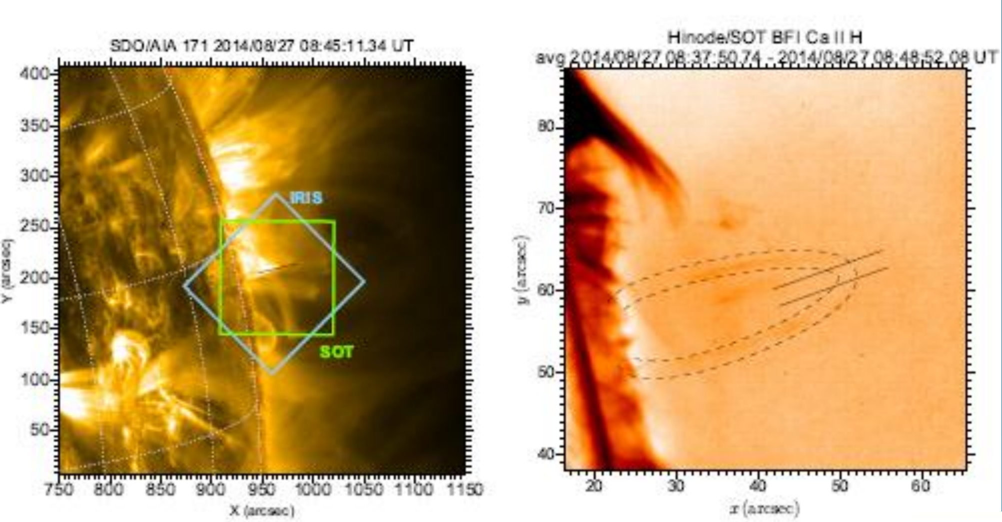




These oscillations were categorized by Swaying motion, change in loop length In vertical plain, and associated intensity variations

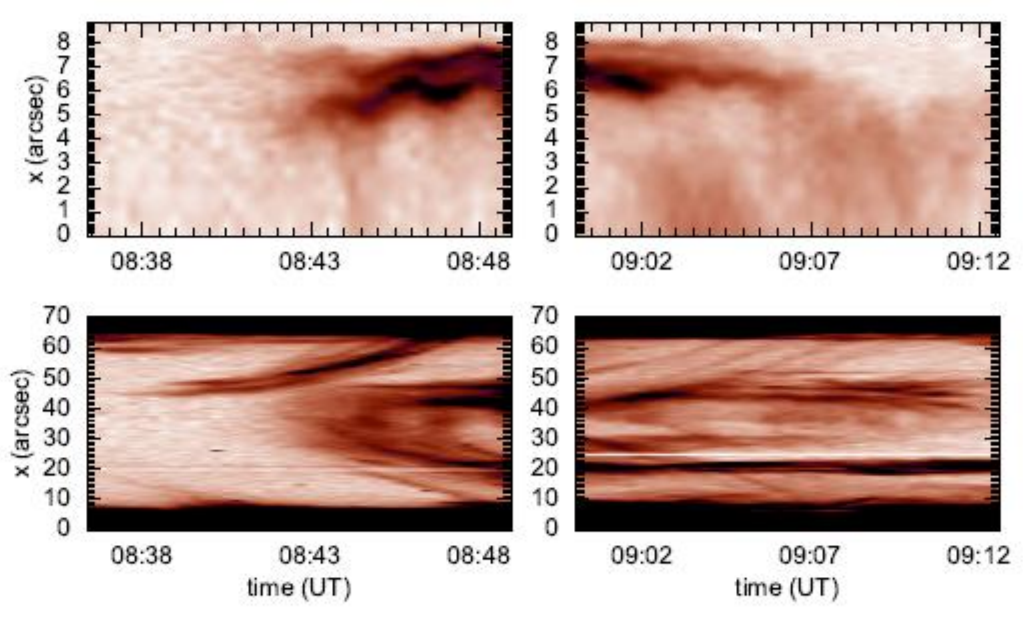
Wang & Solanki, 2002

Vertical Kink Oscillations : Recent Effort in SDO & IRIS ERA



Oscillations trigger due to the cooling of the coronal rain comprising the significant part of the mass of loop !

Coronal rains have found to generate the generated the vertical transverse oscillations in coronal loops.



Verwichte & Kohutava, 2017

Systematic Significant Development in 15 Years on the Study of Vertical Kink Oscillations in Post TRACE Era

[1] Detection of kink oscillations, detailed diagnostics of magnetic field, comparison with extrapolation --- Aschwanden & Schrijver (2011)

[2] Detection of kink oscillations due to failed flux-rope and stretching of the overlying loops --- Mrozek (2011)

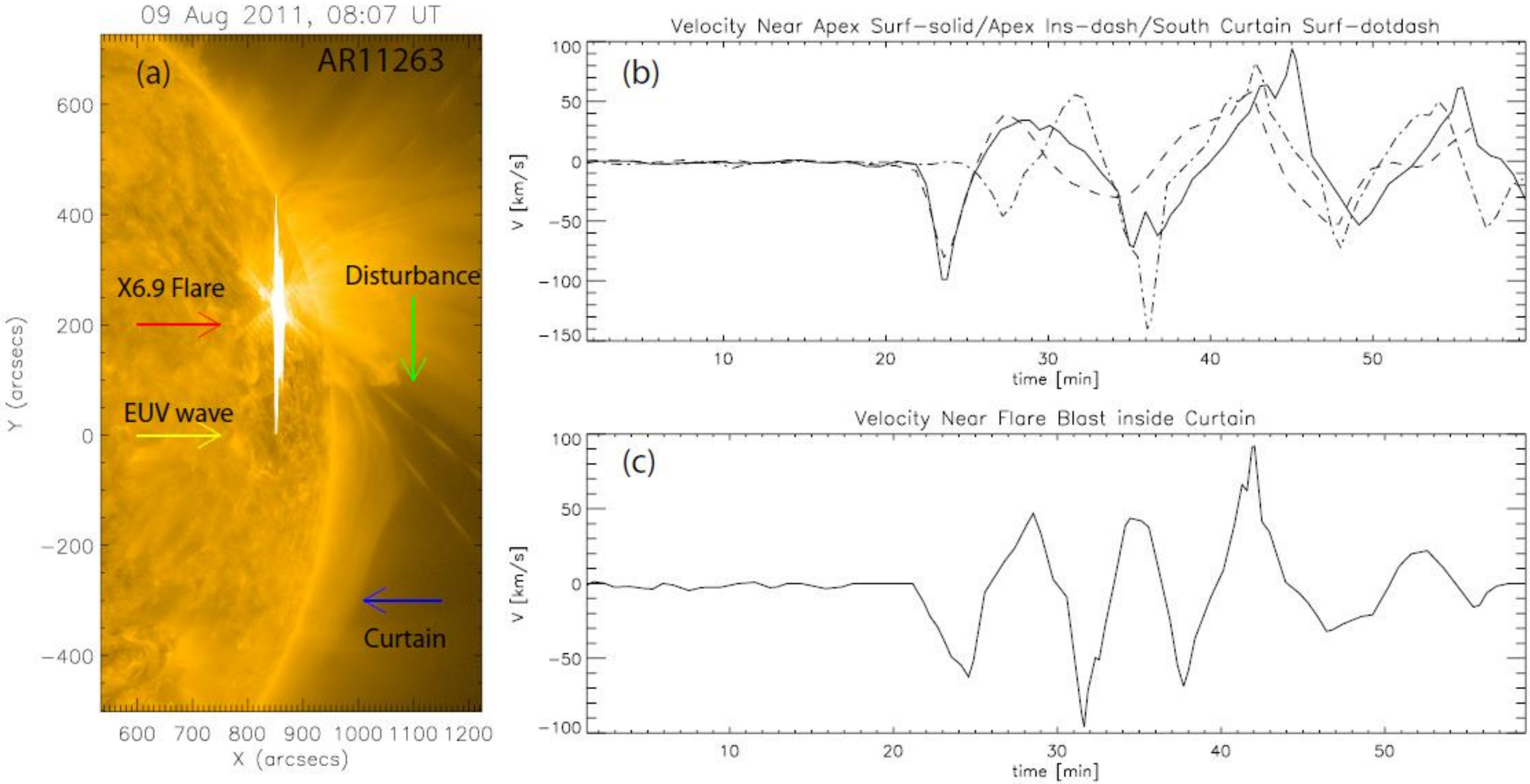
[3] Detection of vertical kink oscillations in the hot postflare arcades and diagnostics --- White et al. (2012)

[4] Detection of the vertically polarized kink mode in plasma curtain --- Srivastava & Goossens (2013)

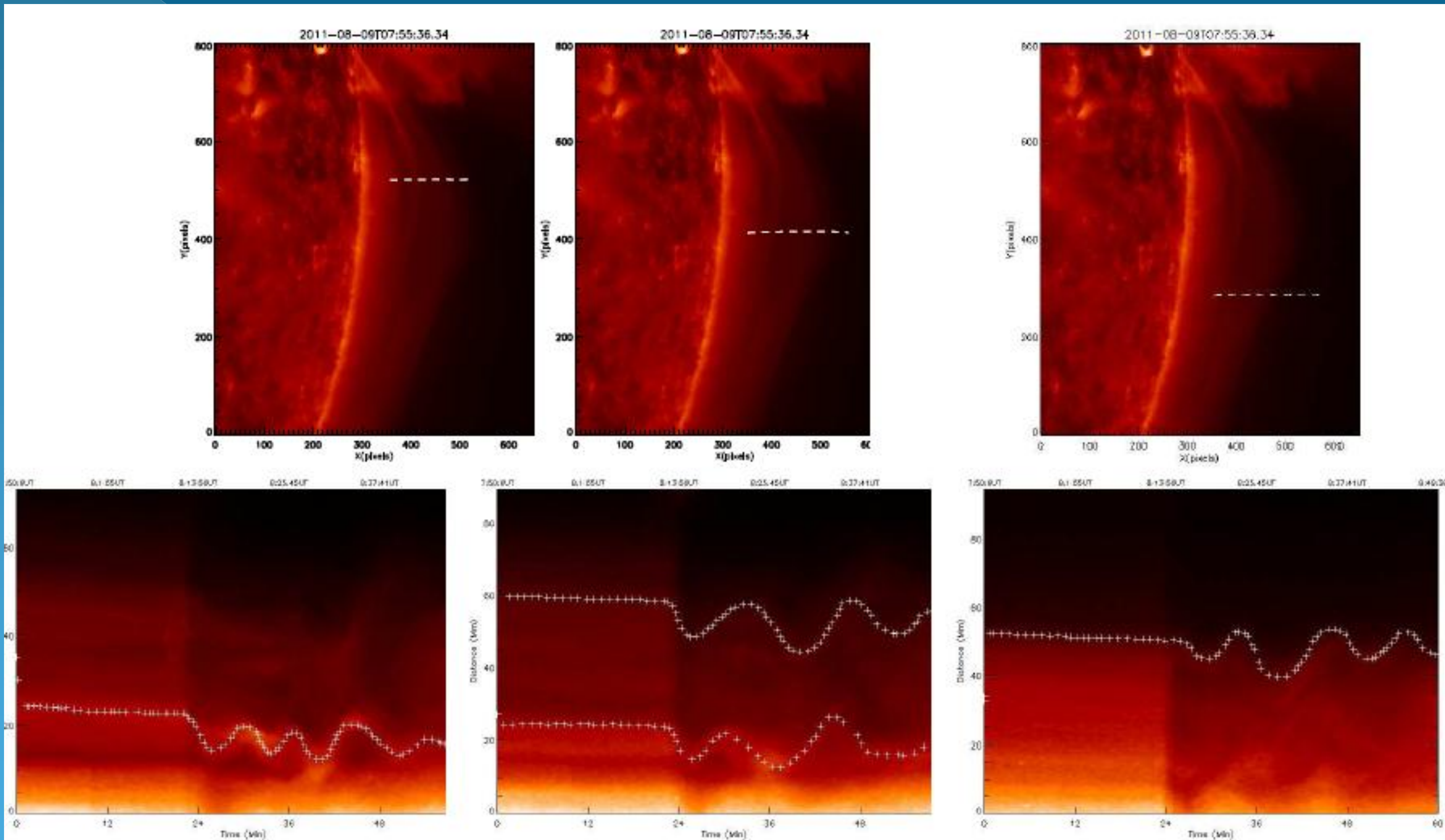
[5] Detection of the vertically polarized kink ode in magnetic flux rope --- Kim et al. (2014)

[6] Vertical kink waves due to coronal rains and its cooling – Verwichte & Kohutava (2017)

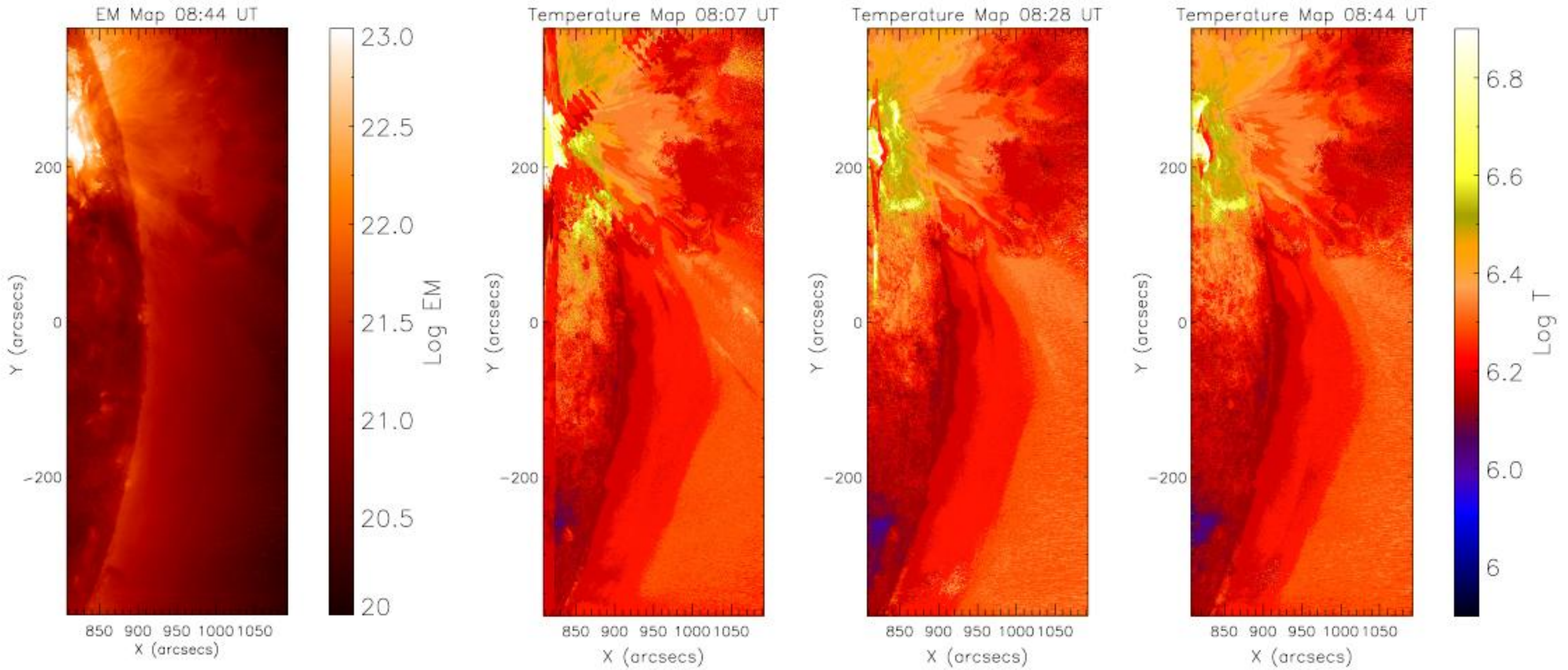
Case Study & Its Details: Vertical Kink Oscillations in Plasma Curtain due to EUV Waves during Strongest X6.9 Class Solar Flare of Solar Cycle 24



Vertical Kink Oscillations as reported by Srivastava & Goossens 2013



Srivastava, A.K. & Goossens, M., ApJ, 2013, 777, 13



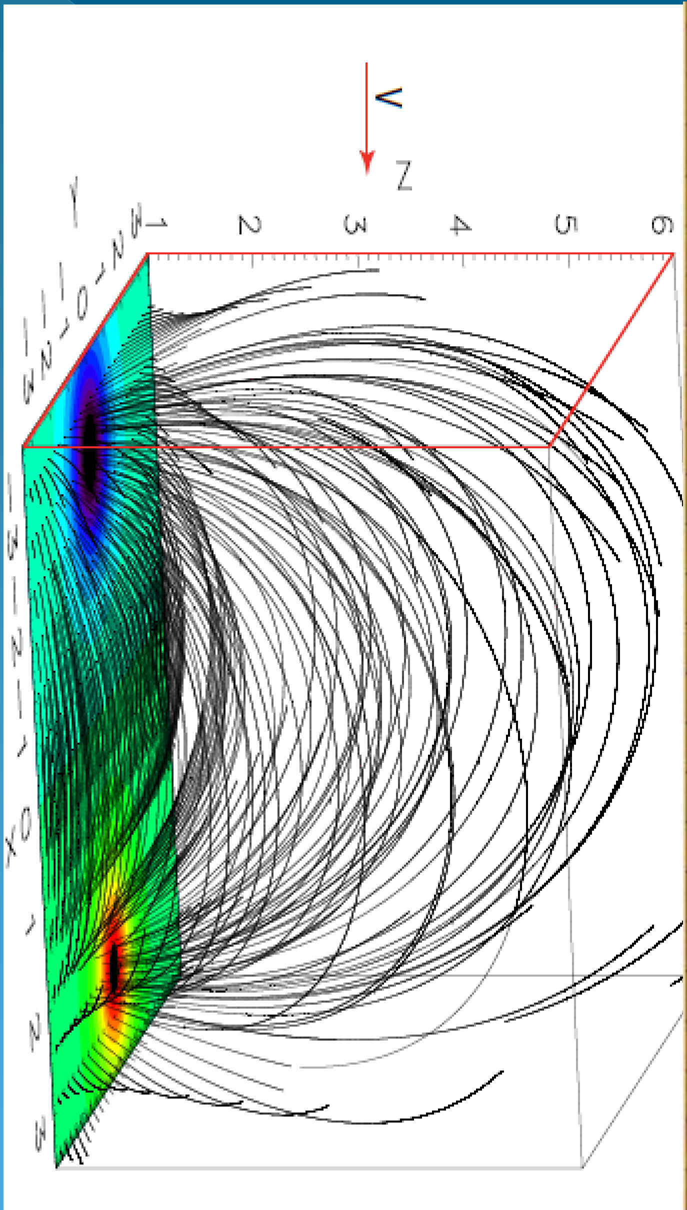
DEM analyses shows that during the oscillation the whole equator was Iike a uniform plasma curtain almost maintained at inner coronal temperature

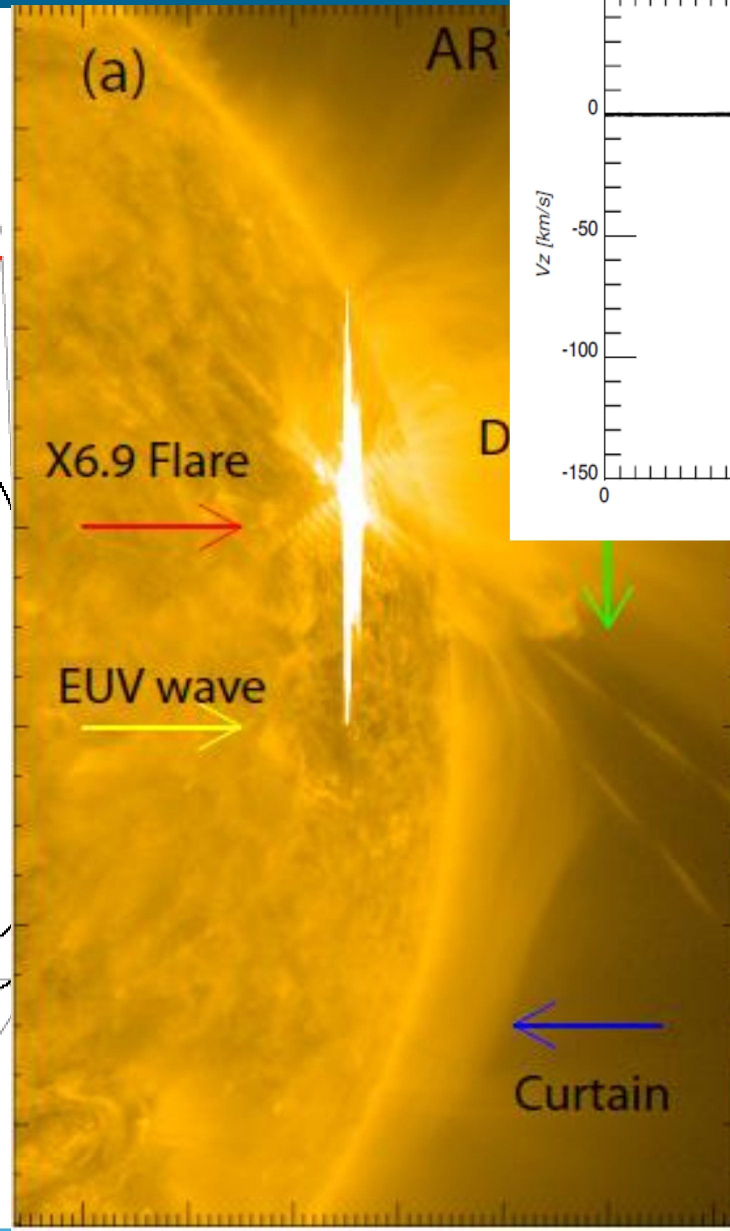
[1] Length of the oscillating segment of this rarely observed plasma curtain was L = 530 Mm that gives phase-speed of fundamental mode kink wave as (795 s) as 2L/P ~ 1332 km/s.

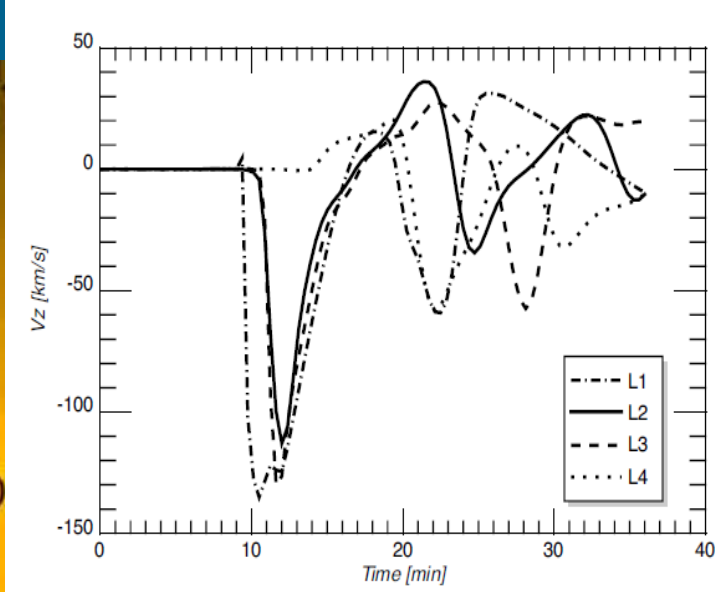
[2] This system is not a denser normal loop. It is not visible on-disk and implies that density contrast inside and outside is almost equal. This makes the fact that internal kink speed is almost equal to the localized Alfven speed. Benefits comes in the form that such system is diagnosed now for local Alfven speed depending upon the uncertainty in loop-length. It should be noted that coronal Alfven-speed is a non-measurable quantity by any standard method.

[3] Density-scale height is estimated as 88 Mm using the formula of McEwan et al. (2008) that relates the ratio of fundamental and Ist harmonics of kink waves (795 and 530 s here) to the tube half length and scale height. This is nearly equal to the hydrostatic scale height at 1.0 MK , i.e., ~80 MK. This derives the fact that large-scale corona is almost in equilibrium while it departs from it when we go towards the smaller spatial scales where localized dynamics and plasma structuring etc are dominant.

This is worth noting : In the typical solar atmosphere for μ=0.6 and γ=1.67, the magnetic Reynold number can be approximated as $R_m = 1.9 \times 10^{-8} l_o V_o T_o^{3/2} / ln\Lambda$ (Priest, 1982). For the portion of the observed plasma curtain that as a whole undergoes vertical kink oscillations, the length scale, Alfvén velocity, typical temperature for the formation of Fe IX emission are respectively 530 Mm, 1332 km s^{-1}, and 1.0 MK. For the typical inner coronal density of 10^9 cm^{-3} and temperature of 1.0 MK, the columb logarithm ($\log\Lambda$) is ~19.3 (Priest 1982). Therefore the magnetic Reynold number R_m is very high for the observed plasma curtain, which is ~7.0 $\times 10^{14}$. This is seven order of the magnitude higher than the Reynold number of the environment above a typical photospheric spot, i.e., the coronal loop plasma medium (Priest 1982). This clearly indicates that the collective motion of the plasma is tightly coupled with the magnetic field lines over the length-scale of the observed plasma curtain. Therefore, the numerical modelling of the kink oscillations in such plasma curtains need the very high magnetic Reynold number environment.

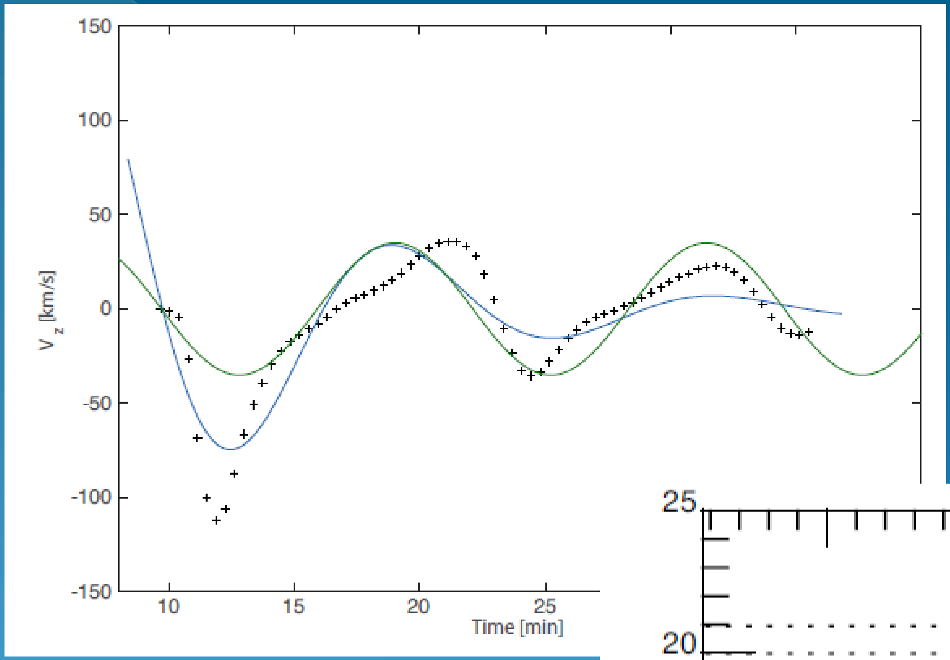


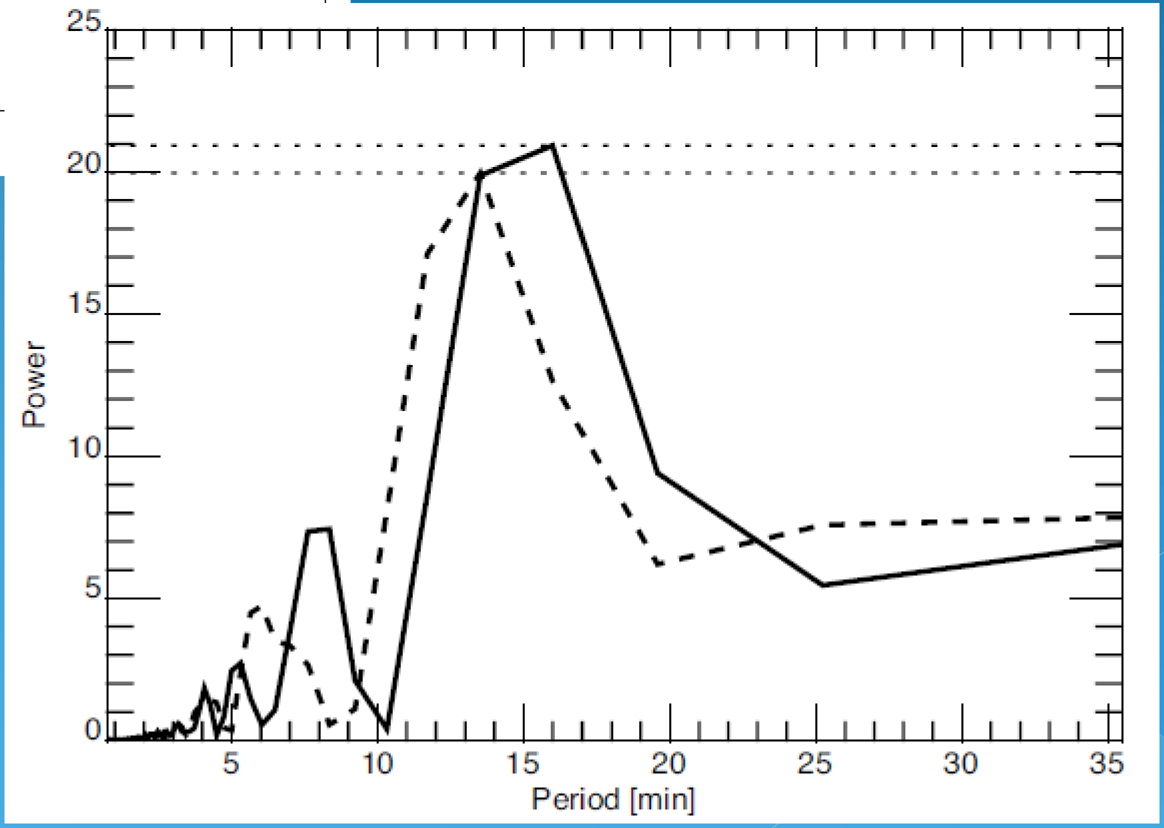




Ofman, Parisi, Srivastava, 2015

Analyses at the detection point within the model atmosphere



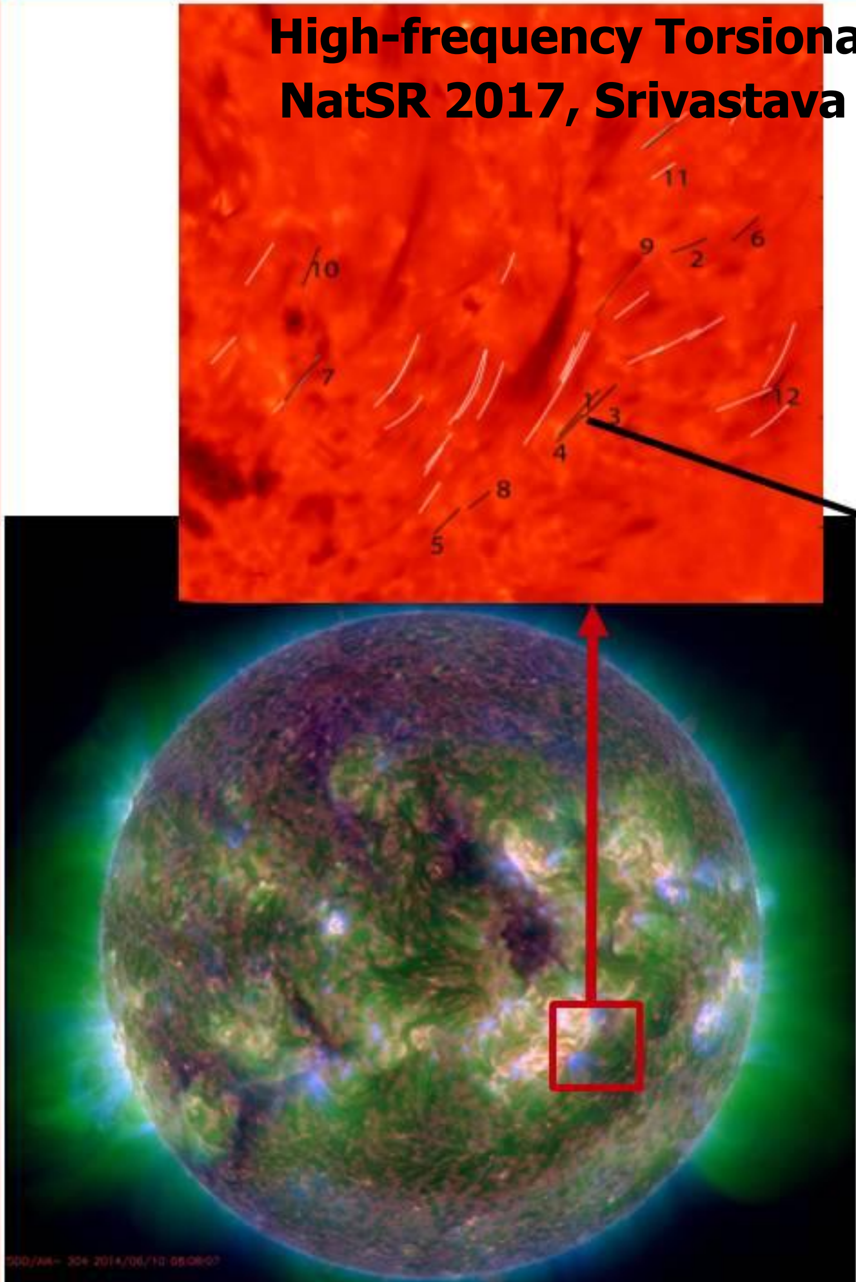


Comparison of the model devised result with Coronal Seismology

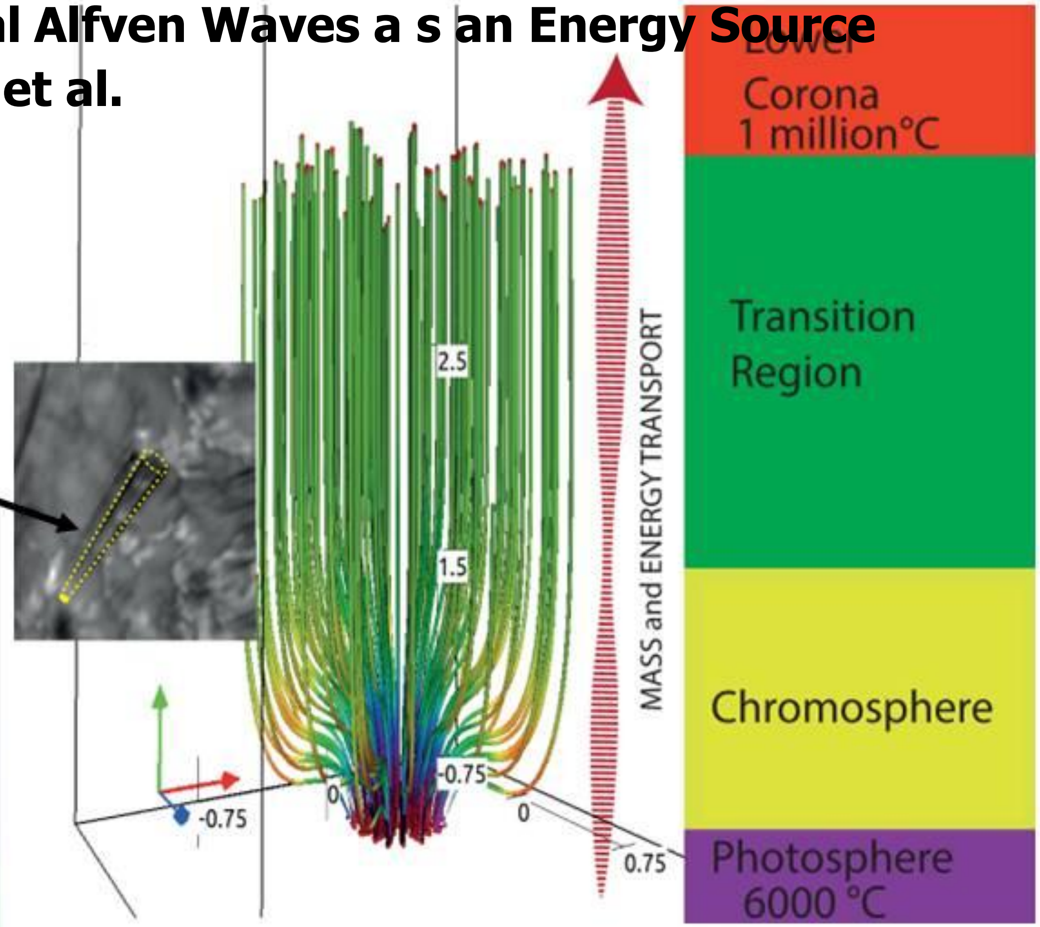
Location of observation	Observed periods [min]	MHD period [min]	B_{MHD} (G)	B_{CS} (G)
Flare Blast (L1)	8.9	9.2	2.2	8.4
Apex Inside (L2)	13.3	13.5*	3.1	4.3
Apex Surface (L3)	14.9	14.8	2.9	4.3
Southward Surface (L4)	12.7	11.7	3.4	4.9

The analyses depicts that realistic 3-D model atmosphere description will be needed to appropriately estimate the magnetic field .

High-frequency Torsional Alfven Waves a s an Energy Source
NatSR 2017, Srivastava et al.



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



THANKS

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.