Alfvén Waves as an Energy Source in the Solar Corona

A.K. Srivastava
Department of Physics
Indian Institute of Technology (BHU), Varanasi-221005, India
X-ray, EUV, and solar wind confirm the existence of Million-degree hot solar corona
[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:

\[ k \cdot V = 0 \]

and

\[ V \cdot B_0 = 0 \]

Magnetic tension component of the Lorentz force generates it.
Alfvén Waves in Polar Corona: Early Detection in SUMER/SoHO Era

SOHO EIT, He II line, 304 Å, November 04, 1996 at 17:51

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

\[ \xi \propto B^{-1/2} \]

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

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

Where

\[ \epsilon \approx \frac{\omega^2 \eta}{2V_A^3} \quad \text{and} \quad k_0 \approx \frac{\omega}{V_A} \]

Harrison et al. (2002)
Alfvén Waves Along Coronal Jet: Impulsive Trigger by Reconnection


Example of Gaussian Fit
PERTURBATIONS DURING RECONNECTION

Governing MHD Equations

\[
\begin{align*}
\frac{D\mathbf{v}}{Dt} &= -\gamma\nabla\rho + j \times \mathbf{B} + \dot{\mathbf{e}}, \\
\frac{D\rho}{Dt} &= -\nabla p + j \times \mathbf{B} + \rho \dot{\gamma}, \\
\frac{DB}{Dt} &= \nabla \cdot \mathbf{B} = 0, \\
\frac{D\mathbf{E}}{Dt} &= -\nabla \mathbf{E}.
\end{align*}
\]

Alfven Wave Equation

\[
\frac{\partial^2 V_x(x,y,t)}{\partial t^2} = \frac{\partial^2 (x,y) \partial^2 V_x(x,y,t)}{\partial x^2}.
\]

Initial Plasma Conditions

\[
-\nabla p + j \times B + \dot{\mathbf{e}} = 0.
\]

Harris Current Sheet

\[
B = \nabla \times A,
\]

\[
A_y = B_0 w_{cs} \ln \left\{ \cosh \left( \frac{x}{w_{cs}} \right) \right\} \exp \left( -\frac{y}{\lambda} \right).
\]

\[
A_x = B_0 w_{cs} \ln \left\{ \cosh \left( \frac{x}{w_{cs}} \right) \right\} \exp \left( -\frac{y}{\lambda} \right),
\]

\[
A_y = B_0 \tanh \left( \frac{x}{w_{cs}} \right) \exp \left( -\frac{y}{\lambda} \right).
\]
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 Alfvénic Modes are:


Most of these studies found that such transverse waves carry substantial energy required to fulfill coronal losses.
RESONANCE BETWEEN Two Types of TRANSVERSE MODES


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 Alfvén Waves

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.
\[ V_\theta = A_V \frac{r}{w} \exp \left[-\frac{r^2 + (y - y_0)^2}{w^2}\right] \sin \left(\frac{2\pi}{P_d} t\right) \]
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.
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 timeline.
THANK YOU VERY MUCH