Coronal heating by Alfvén waves

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In 1942 Hannes Alfvén proposed that waves can propagate through magnetized plasma under conditions similar to the Sun's atmosphere. After over six decades of this Nobel-prize winning discovery, scientists are still trying to figure out whether these waves are capable of heating the solar corona and accelerating the solar wind.

Observations of ultraviolet, X-ray and the wind from the Sun confirmed Bengt Edlén's[1] prediction of a million Kelvin hot solar atmosphere. This then posed a challenge to understand how the energy from the Sun's subsurface energy reservoir transports to its upper layers. Two competing theories have been extensively investigated, one invokes magnetic reconnection and the other magnetohydrodynamic (MHD) waves. The role of Alfvén waves has always been emphasized, at least in theory. The magnetic fields, which connect the solar photosphere with the corona, may guide the waves from the surface layers upwards. These waves may transport the energy of powerful photospheric motions into the corona leading to plasma heating. There now exists a few observational evidences of various kinds of MHD modes that can energize different parts of the magnetically structured solar atmosphere (e.g., kink, sausage, longitudinal, torsional waves). But the wave heating theory has so far been constrained with little direct observational evidence. High-resolution observations from *Hinode* now show the ubiquitous presence of magnetic waves from the chromosphere to the corona[2–5].

Alfvén and kink waves are transversal MHD waves which propagate along the magnetic field lines and carry magneto-convective energy from the Sun's subsurface to its outer atmosphere. The energy transported by these transverse waves can heat various solar structures and accelerate the solar wind. However, the long-period waves have remained undetected unambiguously in the lower solar atmosphere, and also without any satisfactory link between direct observations and theoretical interpretation. There is an indirect evidence of Alfvén wave propagation in the solar corona from observations of nonthermal broadening of spectral lines, but no direct evidence has been found as yet. These incompressible transverse MHD waves can carry non-thermal energy up to a long distance[6,7]. Some detection of Alfvén waves between the periods 100 and 500 s has been recently reported[2–5]. These studies show the direct excitation of Alfvén waves, which may carry enough energy to heat various solar structures and provide the momentum for transient events (spicules, X-ray jets). Recently, ubiquitous Alfvén waves have also been observed in the corona by Tomczyk *et al.*[8] using the coronal multi-channel polarimeter (CoMP) which has major implications in the context of coronal heating and coronal seismology. Van Doorsselaere *et al.*[9], however, favour kink waves over Alfvén waves in all these observations.

Alfvén waves are transverse magnetic waves which travel along the magnetic field lines. These waves can be excited in any electrically conducting fluid embedded in a magnetic field. In 1942, Hannes Alfvén[10] predicted their existence from the equations of electromagnetism and hydrodynamics. Alfvén calculated the properties of such waves, suggesting that they could be important in solar physics. Seven years later in 1949, while studying waves in liquid mercury, Lundquist[11] confirmed their existence. Alfvén waves are known to be an important mechanism for transporting energy and momentum in geophysical and astrophysical plasmas. They have been observed in Earth's magnetosphere, interplanetary and solar plasmas. Today, Alfvén waves and other related MHD waves take centre stage in the study of laboratory, space and astrophysical plasmas.

Let us look at a conducting fluid embedded in a uniform magnetic field as shown in Figure 1. The fluid flow will distort the magnetic field lines, which will in turn produce Lorentz force on the fluid, which will oppose further distortion in the magnetic field. The Lorentz force will change the momentum of the fluid and push it to minimize field line distortion. This will restore the system to its equilibrium state. Actually, this restoring force causes transverse oscillations of magnetic fields in conducting fluids. Increasing magnetic field distortion will result in the increase of the restoring force. As a result, the Lorentz force will reverse the direction of the fluid flow. Magnetic field lines are pushed back to their undistorted configuration and the Lorentz force weakens until the field lines become straight. The sequence of flow will repeat but in opposite direction. This cycle will continue if there is no dissipation. Figure 1 illustrates one complete cycle resulting from the push and pull between inertial and Lorentz force acceleration[12].

Making use of the chromospheric emission in Ca II H 3968 Å, observed by the solar optical telescope (SOT) on the

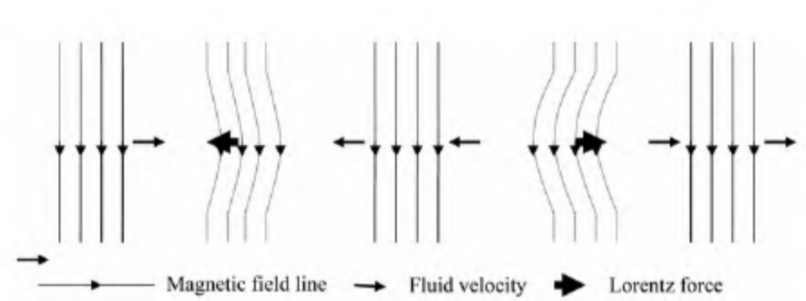

Figure 1. The fluid flow distorts the magnetic field lines which generates Lorentz force, which will then oppose further distortion, and will eventually restore the system. This restoring force provides the basis for transverse oscillations of magnetic fields. (Adapted from a figure by C. C. Finlay.)

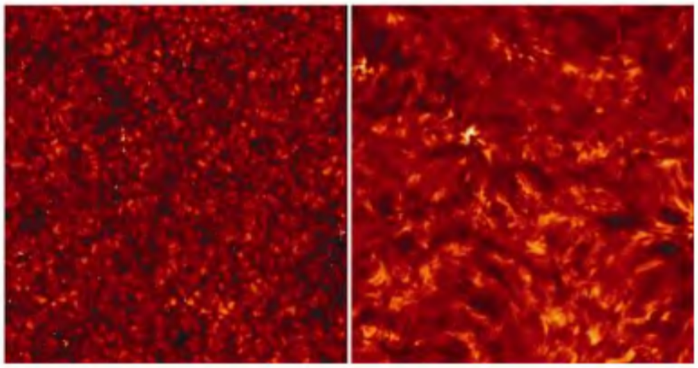

Figure 2. An image of the Sun's atmosphere (approximately 50,000 × 50,000 km) captured simultaneously at two different heights. The left image is the surface of the Sun, while the right image is at a height approximately 1000 km above the surface known as the chromosphere. The brightenings near the centre of the images are regions of strong magnetic field concentration, and are the structures which guide Alfvén waves. (Courtesy: D. B. Jess.)

spacecraft *Hinode*, He *et al.*[13] have recently identified high-frequency Alfvén (>20 mHz) waves propagating upward in the solar spicules. These waves are generated directly by the magnetic reconnection because the photospheric power does not contain enough energy beyond 20 mHz to drive high-frequency waves. Such high-frequency waves may be susceptible to the cyclotron resonance damping in the outer corona as a prominent candidate for the solar wind heating.

Using the Swedish 1 m Solar Telescope (SST) on La Palma in the Canary Islands, Jess *et al.*[14] took a closer look at a bright point group (BPG) on the Sun's surface. Figure 2 shows an image of the Sun's atmosphere (approximately 50,000 × 50,000 km) captured simultaneously at two different heights. The left image is the surface of the Sun, while the right image is at a height approximately 1000 km above the surface known as the chromosphere. The brightenings near the centre of the images are regions of strong magnetic field concentration, and are the structures which guide Alfvén waves. With adaptive optics to remove blurring due to Earth's turbulent atmosphere, they could resolve features as small as 110 km and detect spectral shifts around the wavelength of the hydrogen-alpha absorption. Analysing these bright spots (BPG) on the photosphere, they found distinctive oscillations in the motions of plasma revealed as Doppler shifts. They have interpreted these oscillations as Alfvén waves (<8.0 mHz) driven upward by the churning photosphere in the form of a flaring tube to the lower corona. Long hypothesized but never directly detected on the Sun, Alfvén waves are twisting oscillations along magnetic field lines formed as if one could grab the ends of the field lines and twist them one way and then the other, sending the energy out in the twists propagating along the field lines. They have calculated that there are enough bright point groups on the Sun for their Alfvén waves to heat the corona to its observed million degrees. The question is whether Alfvén waves are the only way to interpret it. Jess *et al.*s' interpretation is one. Their measurements must stand the test of time. Most other solar physicists agree. Even if powerful Alfvén waves exist, no one has explained how the waves break into the corona and dissipate their energy there. Many favour a different heating source, the tiny but abundant solar nanoflares.

Alfvénic fluxes are likely present at the bright point where the magnetic field concentration is high and associated with the inclined waveguide to channel the transverse waves in the upper atmosphere. The SST photospheric and chromospheric images of bright point (Jess *et al.*[14]) reveal an expanding magnetic flux tube sandwiched between these two layers, undergoing torsional Alfvénic perturbations and generating a wave that propagates longitudinally in the vertical direction towards the upper solar atmosphere. At a particular height in this flux tube, the Alfvénic displacements are torsional oscillations which are perpendicular to the direction of propagation and magnetic equipotential surface. However, due to the incompressible nature of such torsional waves, it was impossible to see the signature of density perturbations which can result in the intensity oscillations in the observations. Hence, this is the first most promising effort to catch such incompressible oscillations in terms of the periodic variations of full-width-at-half-maximum (FWHM) of H-alpha line profile. The largest FWHM is produced by the wave when the torsional velocity is at its maximum, while, also the vice-versa. The out of phase (180°) FWHM oscillations at the two opposite boundaries of a bright point of ~2200 km diameter, which act like a coherent waveguide, confirm the existence of torsional Alfvén waves in the lower solar atmosphere. If 1.6% of the Sun's surface is covered by the bright-points as observed by Jess *et al.*[14], then the average energy produced by them will be ~240 Wm^{-2}. Alfvén waves with an energy flux >100 Wm^{-2} within such waveguides may be sufficient to heat the corona locally, and to generate the momentum of supersonic winds.

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ACKNOWLEDGEMENTS. We thank D. B. Jess for reading the manuscript.

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