DISCOVERY OF ALFVÉN WAVES IN THE SOLAR ATMOSPHERE

The University Of Sheffield.

SWAT Solar WAve Theory Group

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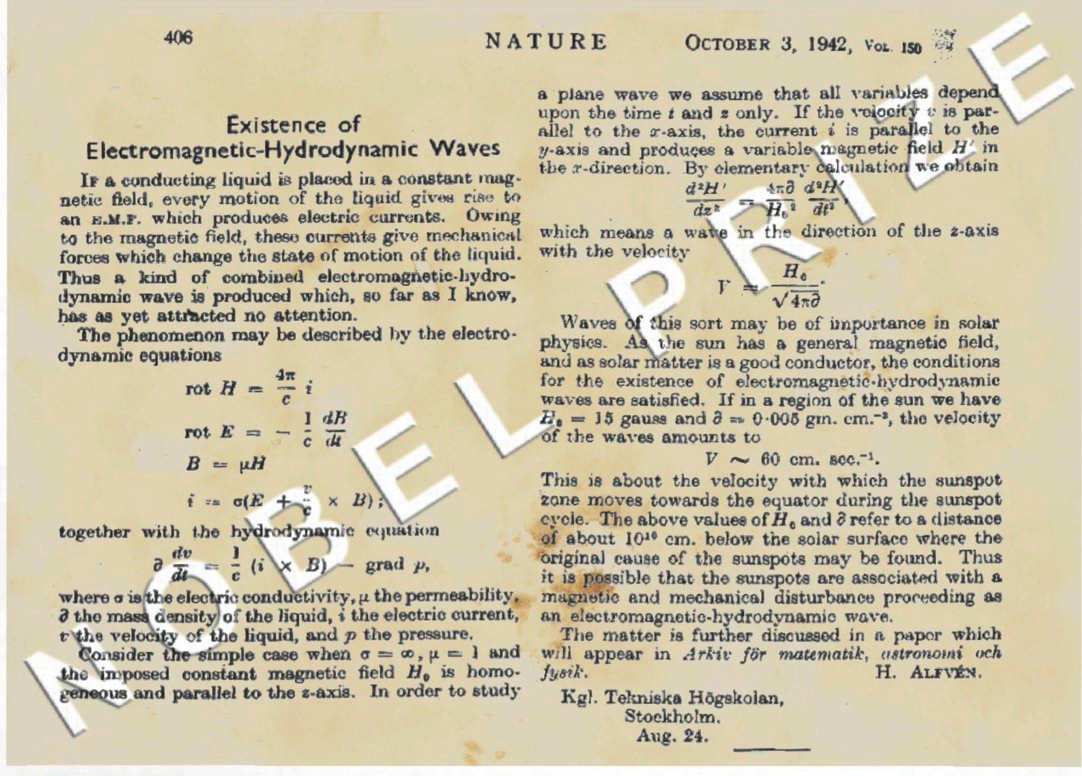
The Sun's outer layer, called the solar corona, has temperatures of the order of millions of degrees Kelvin. Surprisingly, this coronal temperature is about three orders of magnitude higher than the temperature of the visible solar surface. How this high temperature is maintained and what energy sources are involved continue to puzzle and fascinate researchers in astrophysics. Fantastic high-resolution data collected by the latest generation of ground-base and satellite instruments (ROSA, IBIS,SST, Hinode/EIS and SOT, SDO/AIA) reveal much about the role of solar magnetic field interactions and how magnetic plasma waves might transport energy from the deep solar interior to the upper corona and into the interplanetary space. These observations recently opened a new era in solar and space physics.



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Existence of Electromagnetic-Hydrodynamic Waves

If a conducting liquid is placed in a constant magnetic field, every motion of the liquid gives rise to an E.M.F. which produces electric currents. Owing to the magnetic field, these currents give mechanical forces which change the state of motion of the liquid. Thus a kind of combined electromagnetic-hydrodynamic wave is produced which, so far as I know, has as yet attracted no attention.

The phenomenon may be described by the electrodynamic equations

$$\text{rot } H = \frac{4\pi}{c} i$$

$$\text{rot } E = -\frac{1}{c}\frac{dB}{dt}$$

$$B = \mu H$$

$$i = \sigma(E + \frac{v}{c} \times B);$$

together with the hydrodynamic equation

$$\partial \frac{dv}{dt} = \frac{1}{c}(i \times B) - \text{grad } p,$$

where σ is the electric conductivity, μ the permeability, ∂ the mass density of the liquid, i the electric current, v the velocity of the liquid, and p the pressure.

Consider the simple case when $\sigma = \infty$, $\mu = 1$ and the imposed constant magnetic field H_0 is homogeneous and parallel to the z-axis. In order to study a plane wave we assume that all variables depend upon the time t and z only. If the velocity v is parallel to the x-axis, the current i is parallel to the y-axis and produces a variable magnetic field H' in the x-direction. By elementary calculation we obtain

$$\frac{d^2H'}{dz^2} = \frac{4\pi\partial}{H_0^2}\frac{d^2H'}{dt^2},$$

which means a wave in the direction of the z-axis with the velocity

$$V = \frac{H_0}{\sqrt{4\pi\partial}}.$$

Waves of this sort may be of importance in solar physics. As the sun has a general magnetic field, and as solar matter is a good conductor, the conditions for the existence of electromagnetic-hydrodynamic waves are satisfied. If in a region of the sun we have $H_0 = 15$ gauss and $\partial = 0{\cdot}005$ gm. cm.$^{-3}$, the velocity of the waves amounts to

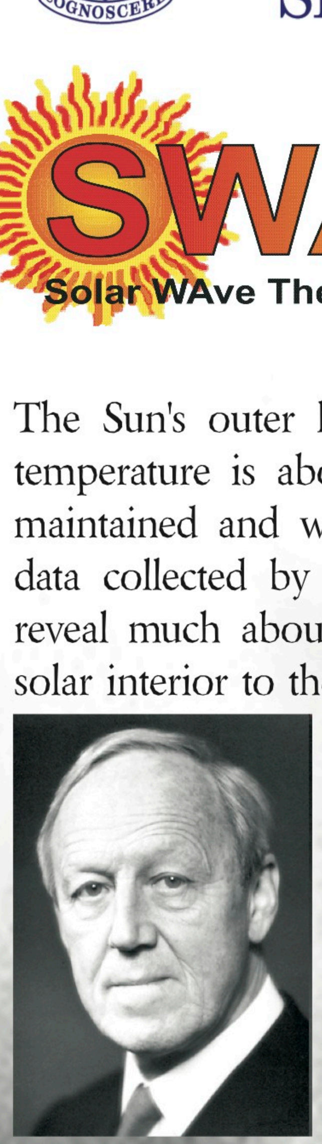
$$V \sim 60 \text{ cm. sec.}^{-1}.$$

This is about the velocity with which the sunspot zone moves towards the equator during the sunspot cycle. The above values of H_0 and ∂ refer to a distance of about 10^{10} cm. below the solar surface where the original cause of the sunspots may be found. Thus it is possible that the sunspots are associated with a magnetic and mechanical disturbance proceeding as an electromagnetic-hydrodynamic wave.

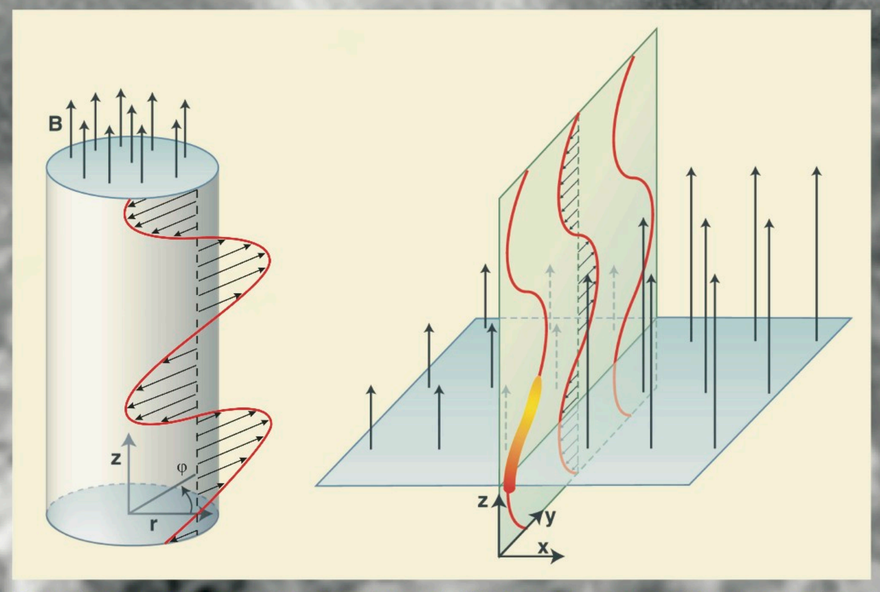
The matter is further discussed in a paper which will appear in *Arkiv för matematik, astronomi och fysik*.

H. Alfvén.

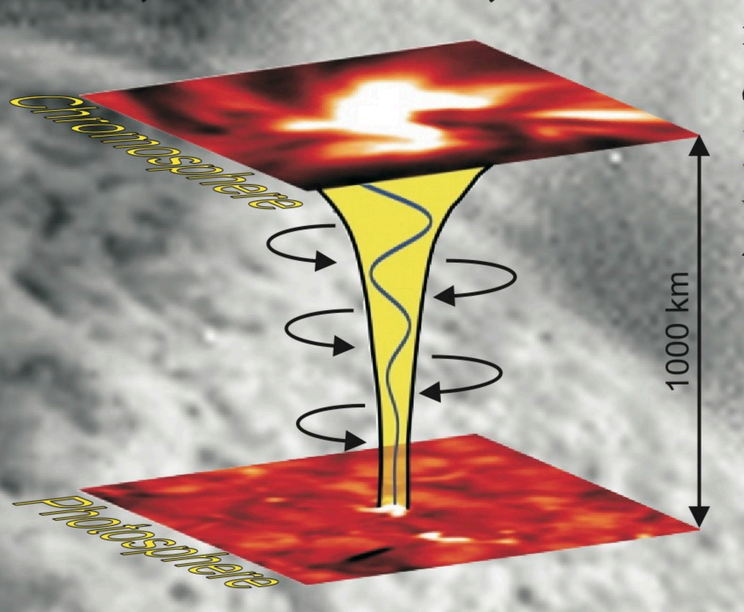
Kgl. Tekniska Högskolan, Stockholm. Aug. 24.



The heating processes that generate and sustain the hot corona have so far defied quantitative understanding, despite efforts spanning more than half a century. There are at least three fundamental questions that must be answered in order to understand the heating of solar and stellar atmospheres: Where is the energy generated? How does the generated energy propagate from the energy reservoir to the solar corona? How does the transported energy dissipate efficiently in the solar corona to maintain its multimillion-kelvin temperature? It is clear now that the crucial ingredient to understanding the corona is the ubiquitous magnetic field in the solar atmosphere. These fields can interact or reconnect with each other, resulting in energetic events. Among the many theories, perhaps the most compelling one involves the so-called **Alfvén waves**, predicted theoretically by **Hannes Alfvén**, for which he received a **Nobel Prize** in 1970.



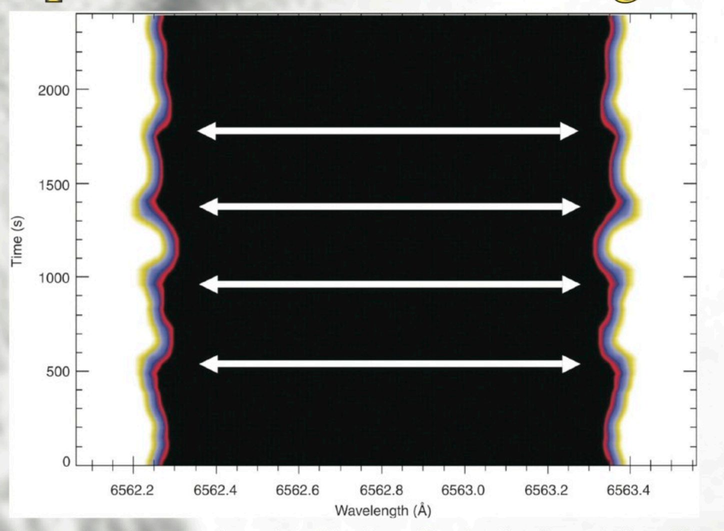
Magnetic flux tube showing snapshots of Alfvén wave perturbations propagating in the longitudinal z direction along field lines. At a given position, the Alfvénic perturbations are torsional oscillations (i.e., oscillations are in the φ direction, perpendicular to the background field). (B) Alfvén waves propagating along a magnetic discontinuity. The Alfvénic perturbations are within the magnetic surface (yz plane) at the discontinuity, perpendicular to the background field (y direction), whereas the wavesthemselves propagate along the field lines (z direction). (see R. Erdelyi, V. Fedun. Science, 2007)



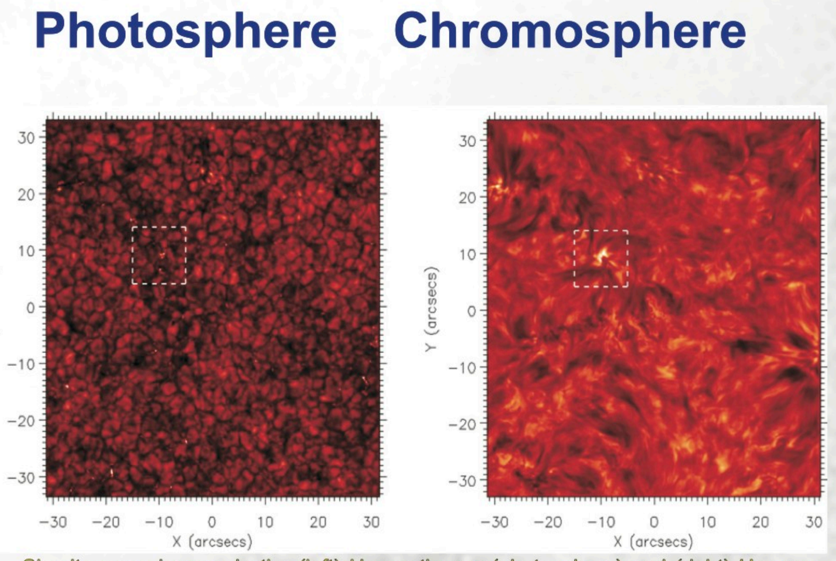
Expanding magnetic flux tube sandwiched between photospheric and chromospheric intensity images obtained with the SST, undergoing a torsional Alfvénic perturbation and generating a wave that propagates longitudinally in the vertical direction. At a given position along the flux tube,the Alfvénic displacements are torsional oscillation.

Recently in a landmark study of solar atmospheric magnetic field concentrations, labelled as chromospheric bright point groups, with the aid of the high-resolution Swedish Solar Telescope (Canary Islands) we have unambiguously proven for the first time the existence of the purely magnetic Alfvén wave mode (D. Jess, M. Mathioudakis, R. Erdélyi, P. Crockett, F. Keenan, D. Christian, Science, 2009). This is a major step in solar and astrophysics, as finally it became clear that these waves indeed exist under solar conditions and may be able to transport energy from the solar interior into the upper atmosphere of the Sun.

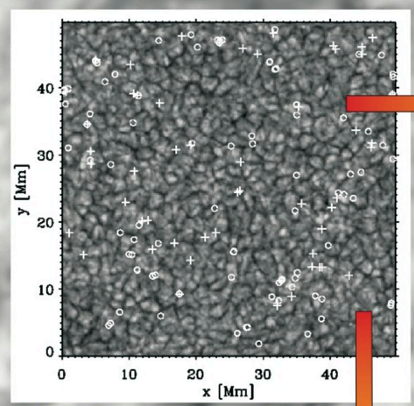
Torsional Alfvén waves incompressible so can be detected by periodic spectral line broadening.



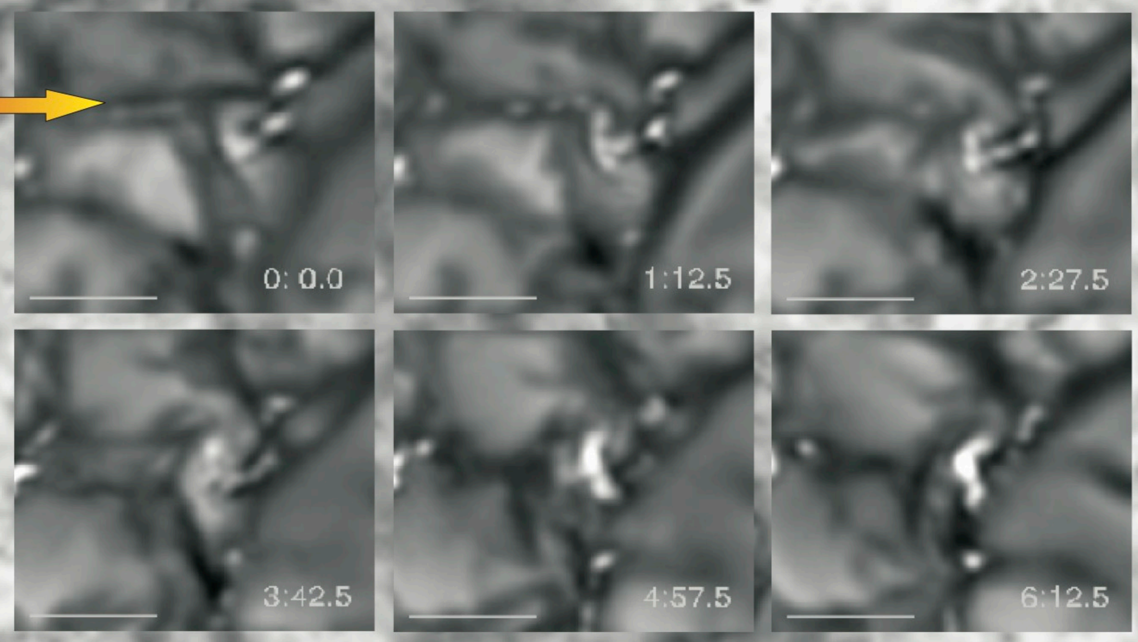
A wavelength-versus-time plot of the H profile showing the variation of line width at full-width half-maximum as a function of time. The arrows indicate the positions of maximum amplitude of a 420-s periodicity associated with the bright-point group.



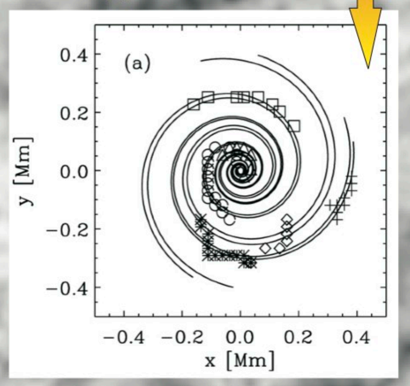
Simultaneous images in the (left) Hα continuum (photosphere) and (right) Hα core (chromosphere) obtained with the SST. The conglomeration of bright points within the region we investigated is denoted by a square of dashed lines. The scale is in heliocentric coordinates where 1 arc sec 725 km.



SST observed small scale rotational motion of magnetic bright points, counterclockwise (+) and clockwise (o).



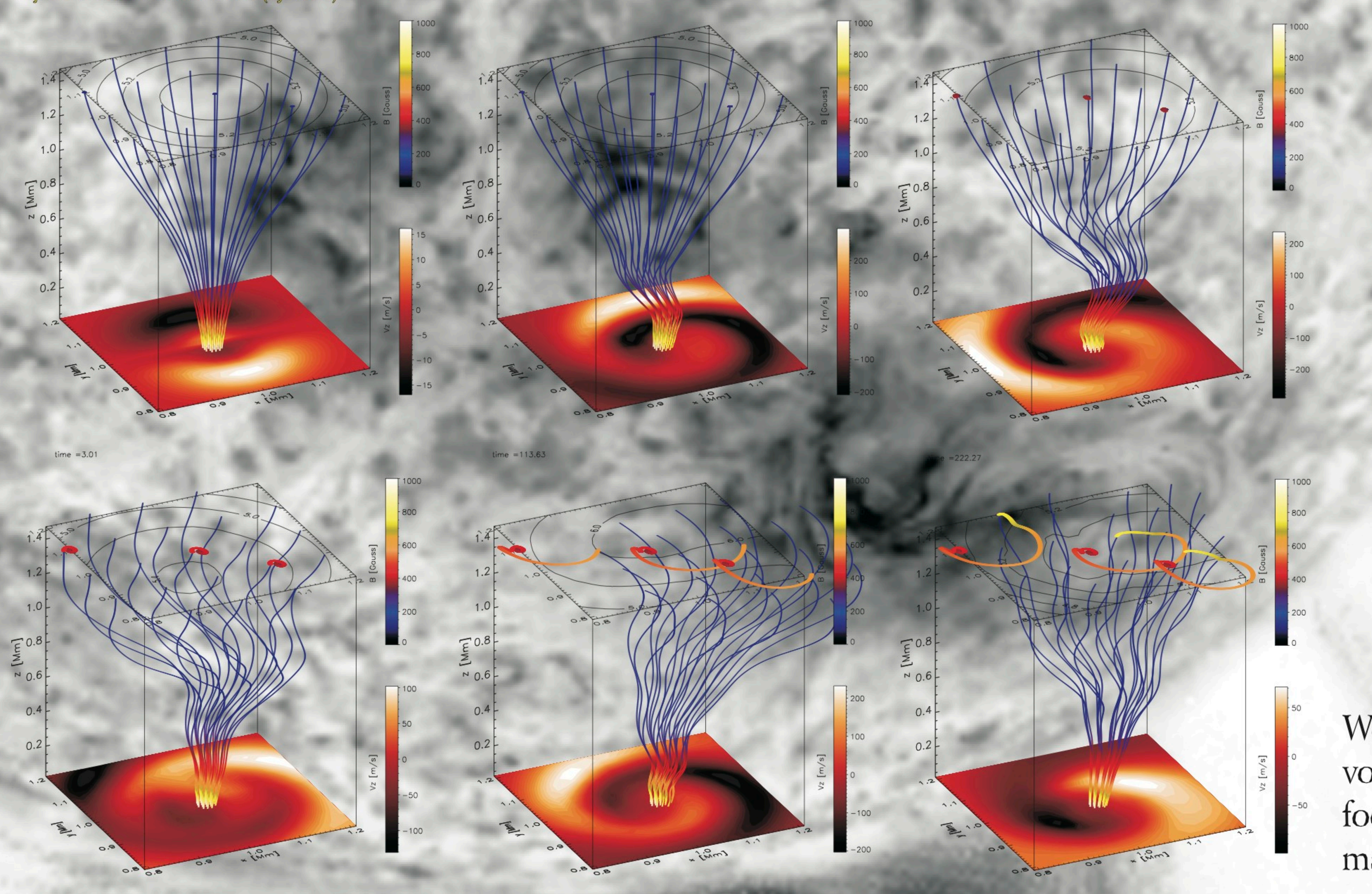
Sequence of snapshots corresponding to the event analyzed in detail by Bonnet et al (The Astrophysical Journal Letter, 2008). The bar corresponds to 1 Mm on the Sun. The bright structures in each snapshot depict a spiral pattern resembling the vortex derived from BP proper motions.



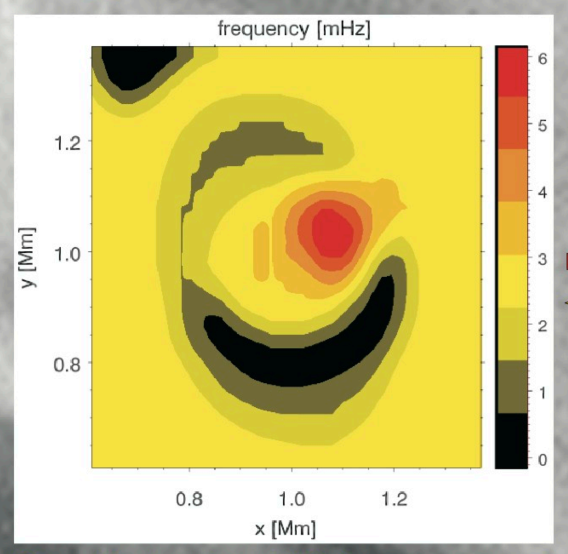
Logarithmic spiral (solid lines) that fits the trajectories of six observed BPs (symbols)

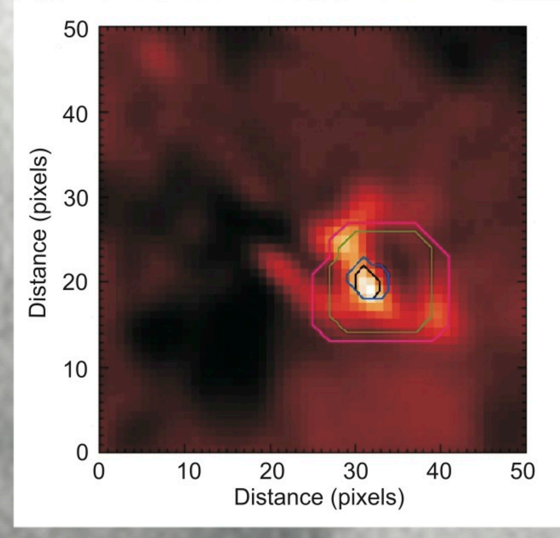
Now we know: TORSIONAL wave driver can cause such a distribution!!

Here we report our successful attempt to accurately model the generation of Alfvén waves in the lower solar atmosphere using state-of-the-art three-dimensional numerical simulations of the Sun's very complex and dynamic atmosphere. We also show how, in the magnetic building blocks of the Sun called magnetic flux tubes, Alfvén waves propagate and transport a massive amount of energy. Further, by using self-similar analytical solutions for magnetic field modelling we have developed a three-dimensional magneto-hydrostatic representation describing accurately solar magnetic fields. These configurations are then used as the basis for complex, non-linear MHD simulations. Using these simulations as a source to generate Alfvén waves, we have used modelling of recent high-resolution ground-based observations of magnetic bright points to provide clear evidence for the existence of photospheric swirls in and around magnetic flux tubes.



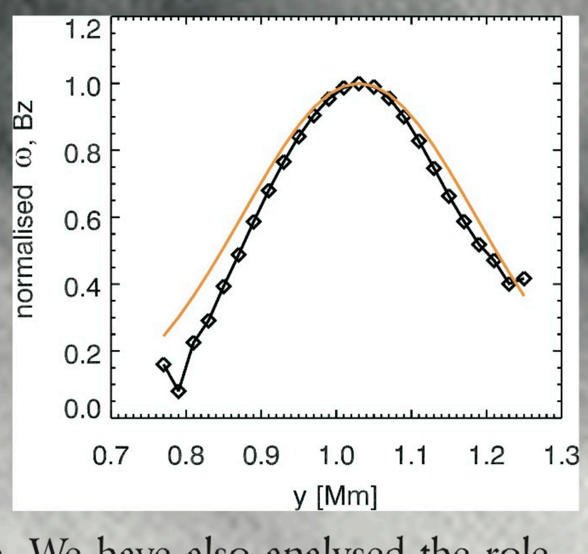
Magneto-seismology

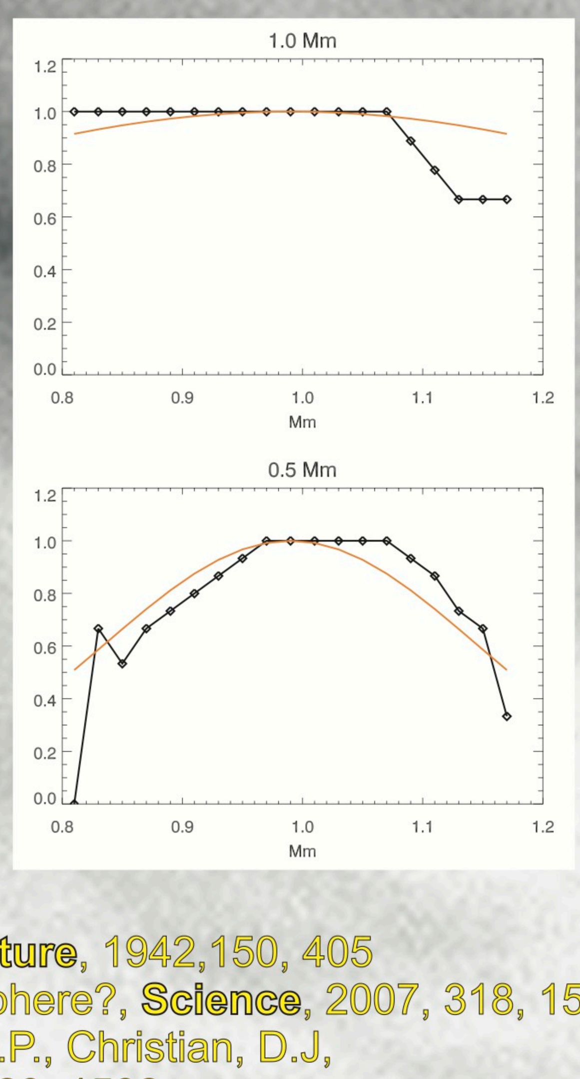




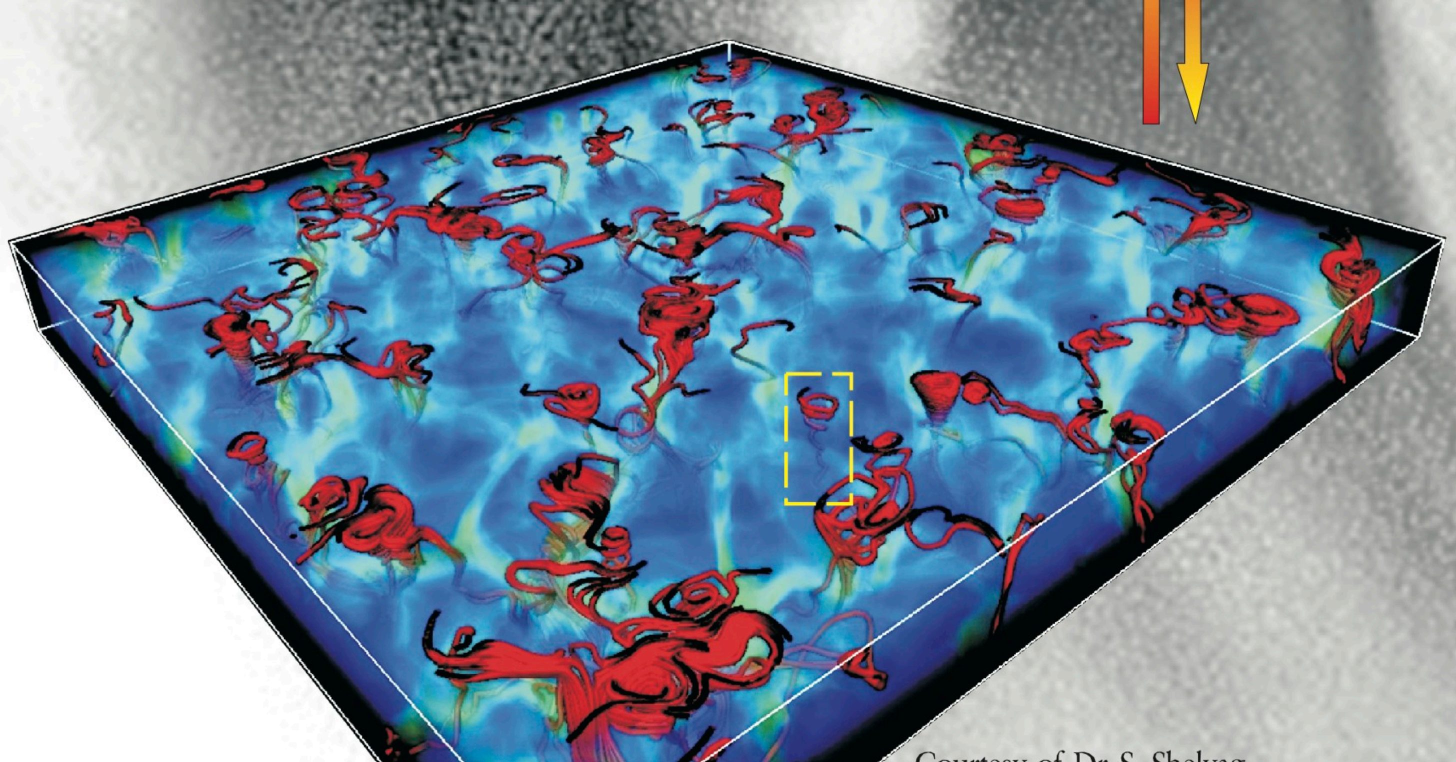
Since the torsional Alfvén waves can be generated independently on each magnetic surface, for the first time we can resolve the frequency as a function of radius in the chromospheric flux tube!

Reconstruction of the magnetic field !





We also found that simulating these vortex-type swirling motions at the foot-point region of open solar magnetic flux tubes results in outstanding agreement between modelling of Alfvén wave propagation and the observational data. Most importantly, the energy flux associated with these Alfvén wave modes is found to be more than sufficient to heat the solar corona. We have also analysed the role of various observed vortex type drivers and the excitation of other permitted magnetic plasma wave modes of (kink, sausage, higher harmonic oscillations) allowing us to gain an unprecedented insight into the dynamical processes taking place in the atmosphere of a proxy star, the Sun.



Courtesy of Dr S. Shelyag

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