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Chromospheric Alfvénic Waves Strong Enough to Power the Solar Wind

B. De Pontieu *et al.*

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track. Perhaps most important, De Pontieu *et al.* have also estimated the energy density of the observed waves, and for the first time it has been clearly shown that the energy associated with the waves is more than enough to accelerate the solar wind and heat the quiet corona. These pioneering results have serious consequences for solar and stellar coronal heating theories.

However, these observations also raise concerns about the applicability of the classical concept of a magnetic flux tube in the apparently very dynamic solar atmosphere, where these sliding jets were captured. In a classical magnetic flux tube, propagating Alfvén waves along the tube would cause torsional oscillations (Fig. 1A). In this scenario, the only observational signature of Alfvén waves would be spectral line broadening. Hinode does not have the appropriate instrumentation to carry out line width measurements. On the other hand, if these classical flux tubes did indeed exist, then the observations of De Pontieu *et al.* (*8*) would be interpreted as kink waves (i.e., waves that displace the axis of symmetry of the flux tube like an S-shape). More detailed observations are needed, perhaps jointly with STEREO, so that a full three-dimensional picture of wave propagation would emerge.

Solar prominences, heavy and cool elongated magnetic structures supported by mainly horizontal magnetic fields in the solar corona, also support a wide variety of MHD waves. Okamoto *et al.* (*14*) report for the first time, using SOT observations, the presence of Alfvénic perturbations in a prominence. Analyzing the properties of these waves can give unprecedented insight into the fine structure with detailed diagnostic information and a clue about the magnetic field strength of a prominence by means of solar magnetoseismology. However, again we must exercise caution in any interpretations, because perturbations only in the plane of the sky were reported. Numerical simulations of a two-dimensional stratified VAL atmosphere model embedded in a horizontal magnetic field mimicking solar prominences, driven by global photospheric motions, will also result in observational signatures very similar to those reported by Okamoto *et al.* (*14*) (see, e.g., Fig. 2 and movie S1). In particular, note the similarity between the time-distance plot (Fig. 2A) of the illustrative forward modeling simulations and figure 3 of Okamoto *et al.* (*14*). However, in the case of this numerical experiment the oscillations found are clearly not Alfvénic. Again, a joint Hinode/STEREO campaign may shed light on the full nature of the observed waves.

Hinode, with its three high-resolution and high-speed instruments on board, has opened new avenues for solar observation and theory. The unprecedented detection of numerous, highly dynamic fine-scale structures mainly following the magnetic field lines will serve as an impetus for explaining the dynamics and heating of the solar atmosphere. The new insights into the details of magnetic reconnection, the origin of solar wind, the direct and unprecedented proof of existence of Alfvénic waves in a wide range of solar magnetic structures (e.g., from sunspot penumbrae to coronal holes), and their role in coronal heating will surely generate further fruitful discussions in the solar and stellar community.

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REPORT

Chromospheric Alfvénic Waves Strong Enough to Power the Solar Wind

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Alfvén waves have been invoked as a possible mechanism for the heating of the Sun's outer atmosphere, or corona, to millions of degrees and for the acceleration of the solar wind to hundreds of kilometers per second. However, Alfvén waves of sufficient strength have not been unambiguously observed in the solar atmosphere. We used images of high temporal and spatial resolution obtained with the Solar Optical Telescope onboard the Japanese Hinode satellite to reveal that the chromosphere, the region sandwiched between the solar surface and the corona, is permeated by Alfvén waves with strong amplitudes on the order of 10 to 25 kilometers per second and periods of 100 to 500 seconds. Estimates of the energy flux carried by these waves and comparisons with advanced radiative magnetohydrodynamic simulations indicate that such Alfvén waves are energetic enough to accelerate the solar wind and possibly to heat the quiet corona.

The energy source driving the acceleration of the solar wind and heating of the quiet corona remains unknown. One promising candidate is Alfvén waves, transverse magnetohydrodynamic (MHD) waves that can propagate along the magnetic field over large distances and transport magnetoconvective energy from near the surface into the outer atmosphere (*1*–*7*). Alfvén waves of sufficient strength to drive the solar wind have never been directly observed in the lower solar atmosphere. This uncertainty has cast doubts on models of a wave-driven wind, because crucial model input parameters, such as the frequency spectrum and energy flux, are unknown (*6*).

We report here direct observations of Alfvén waves that carry an energy flux (100 W m^{-2}) into the corona that is sufficient to drive the solar wind. Until now, Alfvén waves had been difficult to observe by means of remote sensing of the solar atmosphere because of the limited resolution of available instruments. The high spatial (150 km on the Sun) and temporal (5-s) resolution of the Solar Optical Telescope (SOT) (*8*) on board the recently launched Hinode satellite (*9*) has allowed us to resolve some of the dominant spatial and temporal scales of the lower atmosphere, as well as the predicted amplitudes of the Alfvén waves (*6*). As a result, our observations suffer far less from the effects of superposition of many unresolved, independently moving structures along a long line of sight in an optically thin plasma that have plagued lower-resolution instruments in the past.

We analyzed several time series of chromospheric Ca II H-line (3968 Å) images taken with a broadband filter on board the SOT (full width at half maximum, 2 Å). These movies reveal how the chromosphere is dominated by a multitude of thin (~200 km wide), dynamic, jetlike extrusions called spicules. Spicules shoot upward at speeds between 20 and 150 km/s, reaching heights between 2000 and 10,000 km [for a description of their general properties, see (*10*)]. Here, we report that many of these chromospheric spicules undergo substantial transverse displacements on the order of 500 to 1000 km during their short lifetimes of 10 to 300 s (most are less than 100 s). Some longer-lived spicules undergo a swaying or oscillatory motion in a direction perpendicular to their own axis (Fig. 1 and movies S1 and S2), with the displacement varying sinusoidally in time (with a period of 3 min in Fig. 1 and movie S1). Spicules outline the direction of the magnetic field, because they are formed at heights where the magnetic field dominates the dynamics of the plasma (plasma $\beta < 1$, where β is the ratio of the gas pressure to the magnetic pressure). As a result, the oscillatory motion in a direction transverse to the long axis of the spicule implies the presence or passage of Alfvénic wave motions. Here, we use the term "Alfvén waves" to describe incompressible transverse MHD waves that propagate along the magnetic field in an inhomogeneous medium (*1*, *4*–*7*). The observed waves could also be interpreted as MHD kink-mode waves, should a stable waveguide exist in the chromosphere (*11*).

Our analysis of the Hinode data reveals that the Alfvénic motions are ubiquitous in the upper chromosphere. Because of the substantial line-of-sight superposition at the limb, these motions are best seen in data in which spatial scales on the order of 150 to 200 km (the typical spicule width) have been enhanced (using unsharp masking). A space-time plot along a cut parallel to the solar limb at a low height of 1000 km above the limb shows a myriad of mostly linear features (Fig. 2), which indicates that many spicules are moving transversely to their own axis at roughly constant speed. The predominance of linear motion, as opposed to full oscillatory swings, for what are in fact oscillations is not surprising if we consider the lifetime of spicules relative to the wave period. We have performed Monte Carlo simulations (*12*) that show that linear motion visually appears to dominate if the lifetime of the spicules carrying the Alfvén waves is much shorter than the wave period (fig. S2). The superposition of many independent bright features that carry Alfvénic motions with random phases leads to poor visibility of the extrema or swings in the sinusoidal motion (almost vertical in space-time plots), because many of the sinusoidal swings are superimposed on top of features that show little apparent lateral motion (e.g., because the polarization direction of the Alfvén wave is along the line of sight). Comparison of observations with simulations (Fig. 2, B and C) confirms that only the motions at high speed (which are almost linear for a sinusoidal path during the phase in between extrema of a sinusoidal motion) generate a space-time (xt) signal strong enough to catch the eye. Higher above the limb there are fewer spicules, so superposition is less of a problem. Many of these tall features also have longer lifetimes. As a result, cuts high above the limb reveal clearer swings, as

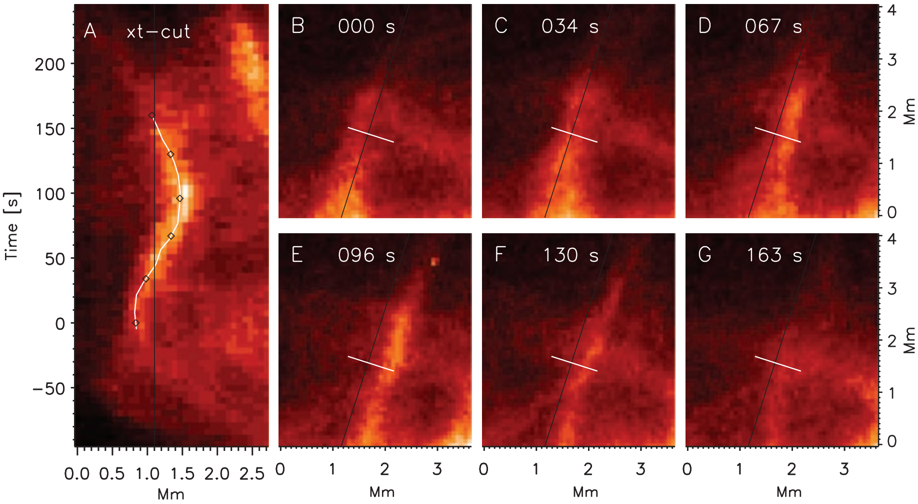

Fig. 1. Example of the transverse displacement of a spicule. (**A**) The intensity as a function of time (in seconds) along the spatial cut (in megameters) shown by the white line in (B) to (F) (space-time or xt plot). Black diamonds indicate the spicule location at the times shown in (B) to (F). The spicule sways from left at time (t) = 0 s to right at t = 96 s, and back to the starting position. These motions are compatible with the propagation along the spicule of an Alfvén wave with a large wavelength (>4 Mm). (**B** to **G**) A time series of Ca II H 3968 Å images from the Hinode SOT (movie S1). The white line shows the extent of the transverse displacement of the spicule (black guide line).

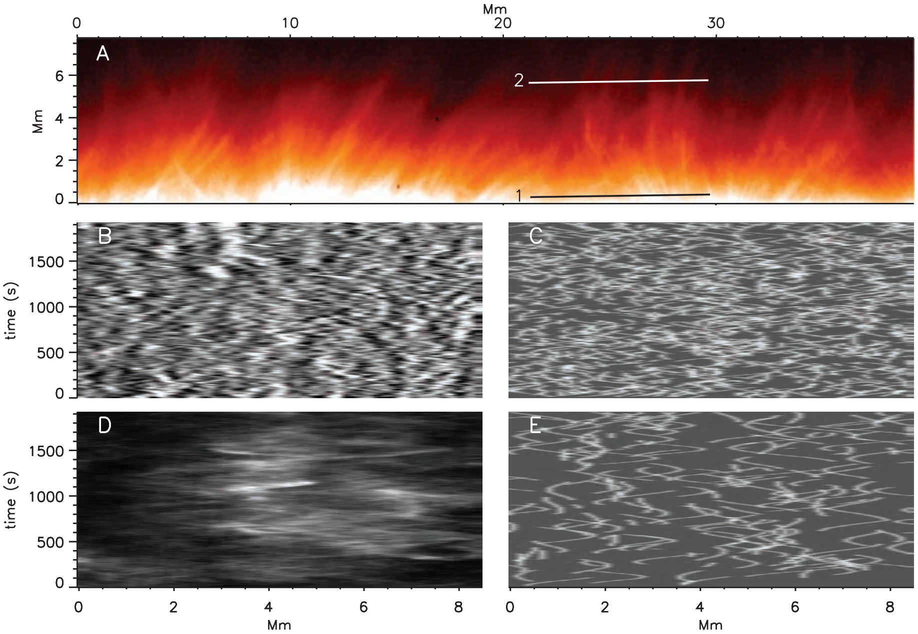

Fig. 2. Illustration of the ubiquity of Alfvén waves in the chromosphere. (**A**) A Hinode SOT Ca II H 3968 Å image showing how thin spicules that outline the magnetic field dominate the chromosphere. (**B**) A space-time plot [along the cut labeled 1 in (A)] of the Ca intensity processed to enhance 200-km-wide structures. The plot is dominated by a multitude of criss-crossed short linear tracks caused by spicular motion transverse to the magnetic field direction. (**D**) A similar cut for the line labeled 2 in (A). Image enhancement is unnecessary at these heights because of the smaller number of spicules. Similar linear tracks are visible, as well as swings. The general characteristics (linear tracks and swings) of (B) and (D) are well reproduced by cuts that are generated from Monte Carlo simulations [(**C**) and (**E**)] (*12*) in which spicules carry Alfvén waves.

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illustrated in Fig. 2D. This is well reproduced by our Monte Carlo simulation (Fig. 2E) with fewer and longer-lived spicules (with lifetimes distributed around 100 s instead of around 40 s).

We also used Monte Carlo simulations to determine the properties of the observed Alfvén waves by comparing the maximum velocity and maximum transverse displacement of space-time tracks perpendicular to observed spicules with similar properties from simulated spicules (*12*). Our observations show that most spicules undergo some transverse displacement, usually between 200 and 500 km, and maximum transverse velocities of about 10 to 30 km/s, with a peak in the distribution around 15 km/s (Fig. 3). These observed distributions of maximum velocity and displacement are best reproduced by Monte Carlo simulations in which spicules carry Alfvén waves with velocity amplitudes that have a Gaussian distribution centered at 20 ± 5 km/s and a uniform distribution of periods between 150 and 350 s. The best fit agrees in almost all bins of displacement and velocity to within the estimated error bars (*12*). The fact that the observed distributions do not show an excess at 0 km displacement and 0 km/s velocity implies that our data are compatible with a model in which essentially all of the observed chromospheric features carry Alfvén waves. In addition, these comparisons are quite sensitive to the input velocity amplitude distribution: Higher average velocities (such as 25 km/s) or lower average velocities (such as 15 km/s) do not match the observed velocity amplitude distribution at either end (fig. S3).

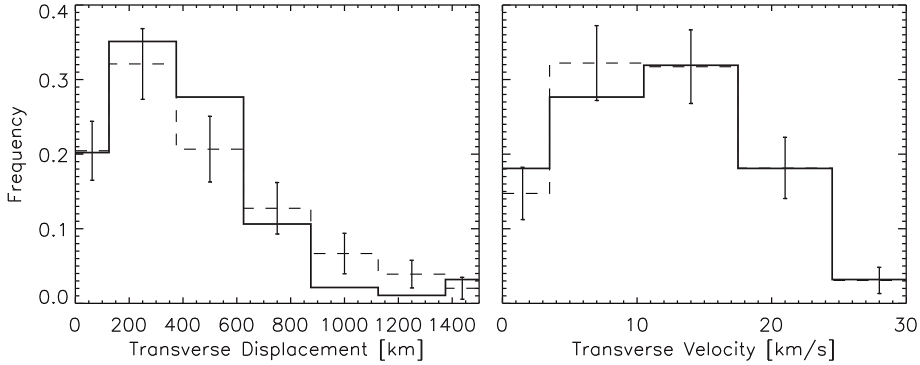

Fig. 3. Comparison between observed and simulated transverse displacements and velocity amplitudes. The left panel shows the distribution of measured transverse displacements of 94 observed spicules [full line (*12*)] and from a Monte Carlo simulation (dashed line) in which spicules carry Alfvén waves with periods randomly chosen from a uniform distribution between 150 and 350 s and velocity amplitudes from a Gaussian distribution around 20 ± 5 km/s. The simulated and observed distributions agree well, especially when taking into account the errors introduced by the poor statistics because of the low number of spicules measured [dashed error bars (*12*)]. The right panel shows a similar comparison for the observed and simulated transverse velocity amplitudes. The agreement between observed and simulated distributions indicates that our data are compatible with ubiquitous Alfvén waves that affect most observed spicules.

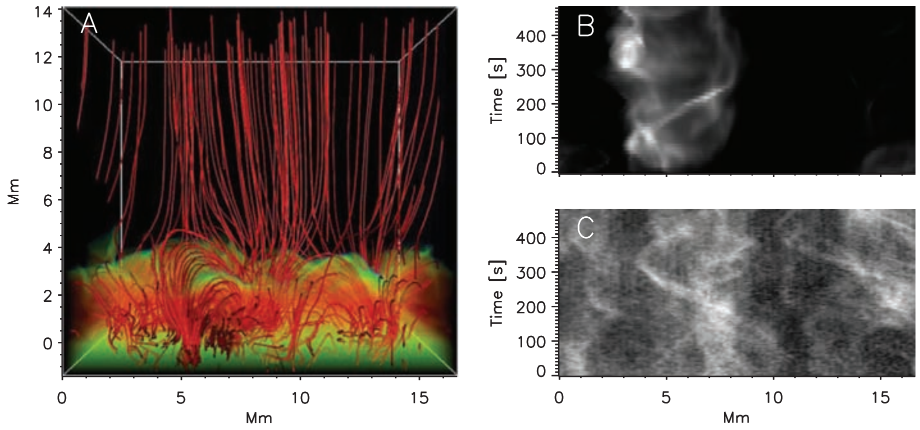

Fig. 4. Comparison between observations and simulations of Alfvén waves. (**A**) A snapshot from a self-consistent 3D radiative MHD simulation ranging from the convection zone up to the corona. Analysis shows that the field lines (red lines) in the corona, transition region, and chromosphere are continuously shaken and carry Alfvén waves (movie S5). The coloring shows the plasma temperature from lower chromospheric values (red) to higher transition-region temperatures (green). A space-time cut of the Ca II H 3968 Å synthetic intensity [(**B**), from simulations] shows similar half-sinusoidal and linear tracks as a space-time plot from the observations (**C**).

The wave periods are more difficult to determine because the lifetimes of the spicules delineating the waves are generally much shorter than the wave period. However, visual comparisons between the observations and simulated data limit the periods to between 100 and 500 s: Waves with very short periods on the order of 100 s or very long periods on the order of 500 s do not fit the data very well (fig. S4) (*13*). Our observations suggest that very long-lived macrospicules (lifetimes of >10 min and heights >10,000 km) show some evidence of Alfvén waves with longer periods between 300 and 600 s (fig. S5).

To study the propagation and impact on the atmosphere of these Alfvén waves, we turned to advanced three-dimensional (3D) radiative MHD simulations of a region on the Sun encompassing its convection zone, photosphere, chromosphere, transition region, and corona (*12*, *14*, *15*). Our simulations showed ubiquitous Alfvén waves with properties similar to those of the waves found in our observations, as illustrated in the xt cut of synthetic Ca II H emission at a height of 4.8 megameters (Mm = 10^6 m) in the MHD simulations (Fig. 4). Detailed analysis of the simulations makes it unequivocally clear that these are volume-filling Alfvén waves, with the magnetic field lines swaying back and forth as the waves pass (movie S5 and fig. S6). We do not see evidence for stable waveguides or MHD kink-mode waves. Our simulations show that despite reflections in the chromosphere and transition region, Alfvén waves with significant amplitudes propagate into the corona from below, with transmission coefficients from the chromosphere into the corona on the order of 3 to 15%. Similar values have also been obtained by 1.5D modeling (*5*–*7*, *16*–*19*).

This means that these waves are very important for the energy balance of the solar outer atmosphere. We estimate the energy flux in the chromosphere $E = \rho v^2 v_A = 4$ to 7 kW m^{-2}, with the Alfvén speed $v_A = B/\sqrt{(\mu_0 \rho)}$, with magnetic permeability μ_0. This estimate is based on the observed velocity amplitude $v \approx 20$ km/s, conservative values for the spicule mass density ($\rho = 2.2 \times 10^{-11}$ to 4×10^{-10} kg m^{-3}) (*20*), and measured spicule magnetic fields $B \approx 10^{-3}$ T (*21*). The implied Alfvén speeds are on the order of 45 to 200 km/s, which is compatible with our estimates of larger than 50 to 200 km/s based on the observed periods and minimum wavelength of the waves (*12*). The energy flux that reaches the corona is thus on the order of 120 W m^{-2} for a transmission coefficient of 3%, which is on the low end of what is expected theoretically. This energy flux is large enough to supply the energy necessary to heat the quiet Sun corona and/or drive the solar wind (~100 W m^{-2}) (*22*). This value is fully compatible with recent measurements with the coronal multichannel polarimeter (CoMP) instrument of coronal Alfvén waves with periods that are similar to those we report here (*23*). Although CoMP directly measures amplitudes that are only on the order of 0.5 km/s with a corresponding energy flux of ~0.01 W m^{-2}, Tomczyk *et al.* (*23*) point out that line-of-sight superposition in the optically thin corona can reduce the directly observed wave amplitudes and hide the remaining wave energy flux in the large nonthermal linewidths observed with CoMP.

Once in the corona, Alfvén waves propagate quite freely, and although modelers disagree on which dissipation mechanism dominates, they agree that Alfvén waves with an energy flux of 100 W m^{-2} are vigorous enough to launch the solar wind when, inevitably, their energy is thermalized and their momentum flux is added to the wind (*5*, *6*). Our observations of vigorous low-frequency waves obviate the need for high-frequency models in which Alfvén waves are assumed to be generated by reconnection processes in the low corona and dissipated through resonant absorption as the wave frequency becomes equal to the gyrofrequencies of the various ions in the plasma (*2*, *3*, *24*, *25*). The observational support for such models has recently been challenged (*26*, *27*). Our data, on the contrary, strongly support the recent models that are based on the dissipation of low-frequency waves; for example, because of self-interference from reflection (*4*, *28*), compressible effects (*7*), or parametric decay (*29*, *30*). Both the observed amplitudes and periods are consistent with those in comprehensive simulations that describe the generation, propagation, and dissipation of Alfvén waves from the photosphere to Earth orbit (*5*, *6*).

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Supporting Online Material

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Figs. S1 to S6
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Movies S1 to S5

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REPORT

Coronal Transverse Magnetohydrodynamic Waves in a Solar Prominence

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Solar prominences are cool 10^4 kelvin plasma clouds supported in the surrounding 10^6 kelvin coronal plasma by as-yet-undetermined mechanisms. Observations from Hinode show fine-scale threadlike structures oscillating in the plane of the sky with periods of several minutes. We suggest that these represent Alfvén waves propagating on coronal magnetic field lines and that these may play a role in heating the corona.

Solar prominences are classified as either quiescent or active region (AR), the latter referring to material suspended above sunspot magnetic regions. Quiescent prominences often exist for many weeks at high solar latitudes, whereas AR prominences can be dynamic and short-lived. They are the most enigmatic of solar structures supported by coronal magnetic field lines, sometimes erupting as the source of coronal mass ejections, large-scale eruptions of plasma from flaring solar active regions, that can have major impacts on the terrestrial magnetic environment. Recent ground-based observations have revealed that AR prominences have numerous small threadlike features (*1*), with continuous flow of material along the threads (*2*–*9*). Observations from space (*10*, *11*) confirm these findings and show additional dynamics related to coronal structure.

We report Hinode Solar Optical Telescope (SOT) (*12*, *13*) observations of an AR prominence in a 0.3-nm broadband region centered at 396.8 nm, the H-line spectral feature of singly ionized calcium (Ca II). Radiation in this bandpass typically has a temperature of less than 20,000 K.

We obtained over 1 hour of continuous SOT images of NOAA AR 10921 on the west solar limb on 9 November 2006. The images show a multithreaded AR prominence suspended above the main sunspot (Fig. 1). Although no simultaneous Hα images were taken, the Ca II H-line prominence structures are consistent with the structures seen in lower-resolution Hα observations (*14*). The Ca II H-line movie (movie S1) shows ubiquitous continuous horizontal motions along the prominence threads. The origins of these flows remain unknown. Some of the flows had constant speeds of about 40 km s^{-1}, whereas others accelerated monotonically in a more complicated fashion.

The Hinode SOT movies also reveal that many of the threads in the prominence underwent vertical (i.e., in the plane of the sky) oscillatory motions (Fig. 2) at periods of 130 to 250 s. The

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