

Propagation of a sausage soliton in the solar lower atmosphere observed by *Hinode*/SOT

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ABSTRACT

Acoustic waves and pulses propagating from the solar photosphere upwards may quickly develop into shocks due to the rapid decrease of atmospheric density. However, if they propagate along a magnetic flux tube, then the non-linear steepening may be balanced by tube dispersion effects. This may result in the formation of a sausage soliton. The aim of this Letter is to report observational evidence of a sausage soliton in the solar chromosphere. A time series of the Ca II H line obtained at the solar limb with the Solar Optical Telescope (SOT) on board *Hinode* is analysed. Observations show an intensity blob, which propagates from 500 to 1700 km above the solar surface with a mean apparent speed of 35 km s⁻¹. The speed is much higher than the expected local sound speed, therefore the blob cannot be a simple pressure pulse. The blob speed, length-to-width ratio and relative intensity correspond to a slow sausage soliton propagating along a magnetic tube. The blob width increases with height corresponding to the magnetic tube expansion in the stratified atmosphere. Propagation of the intensity blob may be the first observational evidence of a slow sausage soliton in the solar atmosphere.

Key words: shock waves – Sun: atmospheric motions – Sun: chromosphere.

1 INTRODUCTION

Energy transport from the solar photosphere towards the corona, which eventually may lead to coronal heating, is still an open problem. There are several possible ways of energy transport: waves, pulses or electric currents. Energy transport by waves has been recently observed through the oscillatory motions of plasma in the chromosphere (Kukhianidze, Zaqarashvili & Khutsishvili 2006; De Pontieu et al. 2007a; Zaqarashvili et al. 2007; Jess et al. 2009; Zaqarashvili & Erdélyi 2009). On the other hand, the dynamic photosphere may excite pulses due to convective shooting and/or magnetic reconnection, which then may propagate upwards. Several kinds of impulsive events are frequently observed on the solar disc: chromospheric bright grains (Lites, Rutten & Berger 1999), blinkers (Harrison 1997) and explosive events (Porter & Dere 1991). Recent observations by the *Hinode* spacecraft revealed various types of energetic events such as chromospheric jet-like structures (Katsukawa et al. 2007; Shibata et al. 2007; Nishizuka et al. 2008) and type II spicules (De Pontieu et al. 2007b). However, direct observational evidence of pulse propagation at the solar limb from the photosphere upwards, to our knowledge, has not been reported yet.

Upward propagating pressure pulses may quickly steepen into shocks due to the rapid decrease of density. However, if the pulses propagate along magnetic flux tubes, then tube dispersive effects may prevent the non-linear steepening. This may lead to the formation of a soliton, which is a stable structure propagating without significant change of shape. The formation of sausage solitons in magnetic tubes was first suggested by Roberts & Mangeney (1982). Since then, numerous papers have addressed the soliton formation problem (Merzljakov & Ruderman 1985, 1986; Roberts 1985, 1987; Sahyouni, Zheliazkov & Nenovski 1988; Ofman & Davila 1997; Zhugzhda & Nakariakov 1997; Nakariakov & Roberts 1999; Ballai, Thelen & Roberts 2003; Ruderman 2003; Erdélyi & Fedun 2006; Ryutova & Hagenaar 2007). Most of the studies consider a sausage soliton ($m = 0$ mode in magnetic tubes), but no observational support for the theory has been reported yet. On the other hand, some observations suggest the propagation of non-linear soliton-like kink waves ($m = 1$ mode in tubes) identified with moving magnetic features around sunspots (Ryutova & Hagenaar 2007).

Here, we report the upward propagation of a pressure blob in a time series of the Ca II H line obtained by *Hinode*/Solar Optical Telescope (SOT) (Tsuneta et al. 2008). Estimated parameters of the blob fit with a solution of a slow sausage soliton propagating along a magnetic tube. Therefore, we suggest that this is the first observational evidence of sausage soliton propagation in the lower solar atmosphere.

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2 OBSERVATIONS

We use a Ca II H time series of quiet Sun regions observed by *Hinode*/SOT. The spatial resolution of observation reaches 0.2 arcsec (150 km) and the pixel size is 0.054 arcsec (~ 40 km). The observational sequence runs on 2006 November 22 from 05:57:31 to 06:34:57 UT. The positions of the X-centre and Y-centre of the slot are, respectively, 960 and -90 arcsec, while the X-FOV and Y-FOV are, respectively, 56 and 112 arcsec. The exposure time for each image is 0.512 s. The integration time for each step of the time series is uniform and equal to 4.8 s.

We start with the raw (zero level) data, then use the standard SOT subroutines for calibration. The subroutines can be found in the SSWIDL software tree (<http://sohowwww.nascom.nasa.gov/solarsoft/hinode/sot/idl>). These subroutines correct the CCD read-out anomalies, bad pixels and flat-field; subtract the dark pedestal and current and apply the radiation despiking.

3 RESULTS

Analysis of the time sequence between 06:19:01 and 06:19:36 UT clearly shows an upward propagating pattern in the form of an intensity blob. Fig. 1 displays the corrected Ca II H image taken at 06:19:06 UT (the arrow shows the location of the blob propagation). Fig. 2 shows eight consecutive images of the sequence (left- to right-hand panels and top to bottom panels). The time interval between consecutive images is ~ 5 s. The blob is located at ~ 500 – 600 km above the surface (see the upper left panel of Fig. 2) at the moment of 06:19:01 UT, then it gradually propagates upwards. The blob is displaced by a distance of ~ 1200 km over a time interval of 35 s, therefore the mean apparent propagation speed is ~ 35 km s $^{-1}$. In the image, the blob propagates with a $\sim 35^\circ$ angle about the vertical. The propagation angle seems larger in Fig. 2, but this is due to the limb inclination (see Fig. 1). The blob may propagate also with some angle about the projected plane, then the real propagation speed may be higher. For an estimate, we may suppose the same angle of propagation, i.e. $\sim 35^\circ$, which gives the real propagation speed as ~ 42 km s $^{-1}$. The ratio between the blob and background intensities is ~ 1.4 . Therefore, the relative amplitude of the density enhancement is ~ 0.2 . The amplitude of the blob is strong enough and indicates its non-linear character. The strong amplitude of the pulse density excludes the possibility of a kink or Alfvénic pulse. Therefore, it should be a pressure pulse, which in magnetic tubes transforms into a sausage pulse. The ratio of blob length to width can be roughly estimated. Fig. 3 (upper panel) shows the ratio as a function of time.

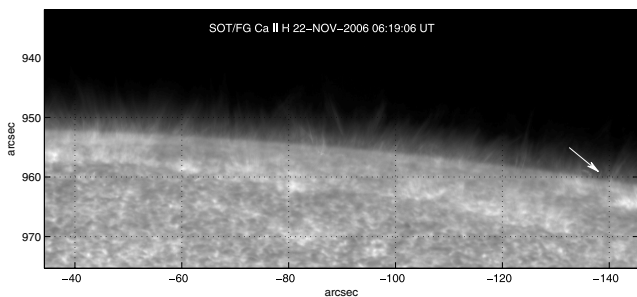


Figure 1. Corrected Ca II H image of the quiet Sun obtained by *Hinode*/SOT. The image was rotated by 90° , therefore the x-axis corresponds to the solar-Y and the y-axis corresponds to the solar-X. The white arrow shows the location of intensity blob propagation.

In the first four images (between 0 and 15 s, which corresponds to the location of the blob at lower heights), the ratio is approximately 3.5 and later it gradually reduces to ~ 2 , which gives ~ 3 on average.

The propagation speed of the intensity blob is much higher compared to the local sound speed. Therefore, it cannot be a simple slow sausage pulse. One may compare the blob properties to new features observed by *Hinode*, such as chromospheric jet-like structures (Katsukawa et al. 2007; Shibata et al. 2007; Nishizuka et al. 2008) and type II spicules (De Pontieu et al. 2007b). The observed jets have different properties inside and outside sunspots. The chromospheric jets observed in the penumbral chromosphere have a length of 1–4 Mm, a width of 400 km and an apparent rise velocity of > 100 km s $^{-1}$ (Katsukawa et al. 2007). The anemone jets observed outside sunspots are 2–5 Mm in length and 150–300 km in width, and have an apparent velocity of 10–20 km s $^{-1}$ (Shibata et al. 2007). The type II spicules have a life time of 10–150 s, an apparent upward velocity of 50–150 km s $^{-1}$ and a width of 200 km (De Pontieu et al. 2007b). They are tallest, reaching 5000 km or more, in coronal holes, while in quiet Sun regions they reach lengths of several Mm. The length and apparent speed of our intensity blob do not coincide with either of these features: it is shorter than the observed jets, has a different upward speed and propagates as a pulse-like structure, not a jet. Therefore, we argue that the blob represents either a fast sausage pulse or a slow sausage soliton.

A fast sausage pulse may propagate much faster than the local sound speed for relatively larger external Alfvén speed (Edwin & Roberts 1983). However, fast sausage waves are leaky for the long-wavelength limit. Suppose that the radius of the tube where the fast sausage pulse (or wave trains) propagates is a , then we get $ka = 2\pi a/l = 2\pi/6 \approx 1$, where l is the characteristic length of the pulse (here the l/a parameter is taken from the observed length-to-width ratio of the blob). The fast sausage waves are leaky for this value of ka (see fig. 4 in Edwin & Roberts 1983). Therefore, the pulse should vanish rapidly before it can propagate upwards.

On the other hand, the observed blob propagates without a significant change of relative amplitude and form (at least in the first five images), which may rule out the possibility of a fast sausage pulse. The blob changes its shape in the last three images, becoming wider; however, the length-to-width ratio and relative amplitude remain more or less similar. The blob width is ~ 136 km at the lowest height and increases up to ~ 516 km at the greatest height (Fig. 3, lower panel). The observed broadening may reflect the magnetic tube expansion with height (we will discuss it later).

Another scenario of the intensity blob propagation is a slow sausage soliton, which is formed when non-linear steepening due to large amplitude is balanced by wave dispersion. The soliton propagates without significant changing of form and faster than the tube speed. The soliton solution should satisfy the parameters, which can be tested from observational properties of the pressure blob. The soliton solution in a structured magnetic field is well studied (Roberts & Mangeney 1982; Merzljakov & Ruderman 1985, 1986; Roberts 1985, 1987; Ruderman 2003). Therefore, there is no need to go for detailed calculation of the parameters; we just use the known theoretical properties of a slow sausage soliton and then compare them with observations. A slow sausage soliton can be either a surface or a body solution depending on its structure inside the tube (Zhugzhda & Nakariakov 1997). The quasi-homogeneous structure of observed blob suggests more a surface than a body soliton. Therefore, here we consider the slow surface sausage soliton; however, the body solution can also be tested in the future.

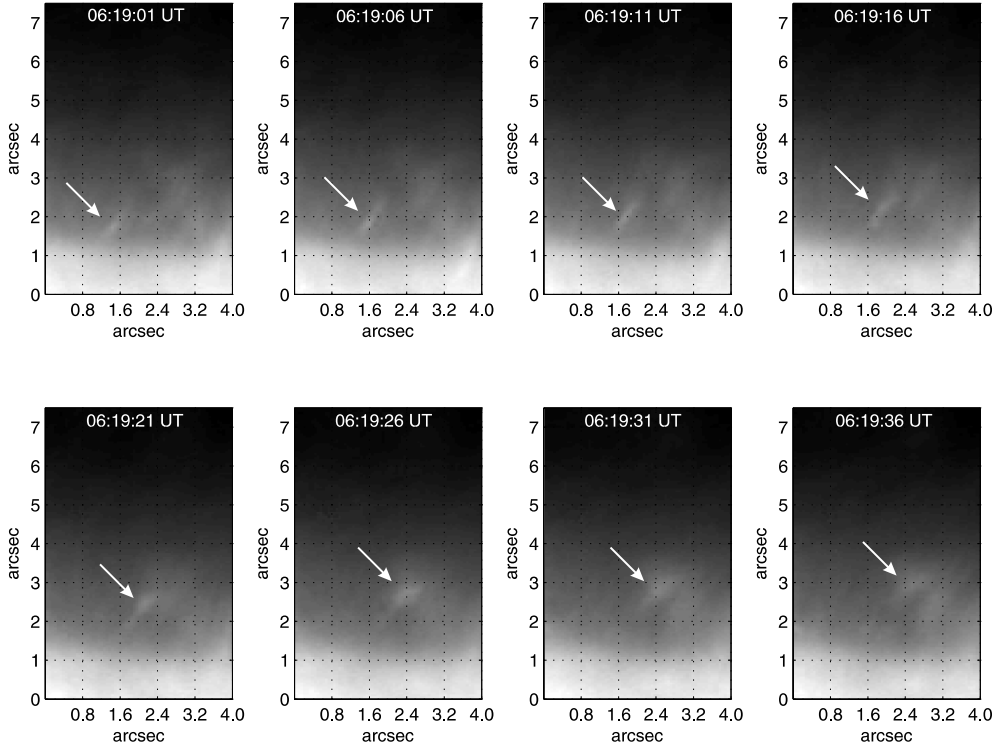


Figure 2. Eight consecutive images of the time sequence in the Ca II H line (left-to-right-hand panels and top to bottom panels). The intensity blob is located near $(x, y) = (1.4, 1.8)$ in the first image (upper left panel). The blob propagates upward with a mean apparent speed of 35 km s^{-1} . We identify it with a slow sausage soliton propagating along a magnetic flux tube.

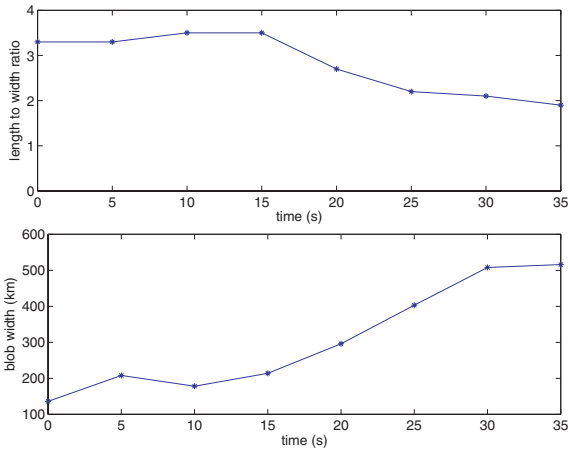


Figure 3. Length-to-width ratio (upper plot) and width (lower plot) of the intensity blob versus time from the sequence of Fig. 2.

4 SOLITON SOLUTION

Theoretical properties of a sausage soliton are more easily obtained for magnetic slabs rather than tubes. Numerical simulations of solitary waves in magnetic tubes (Ofman & Davila 1997) show the same properties of a slow soliton as derived by analytical calculations for a magnetic slab (Roberts & Mangeney 1982). Therefore, we consider a magnetic slab of width $2x_0$ embedded in a magnetized environment. Let us suppose that the magnetic field inside (outside) the slab is B_0 (B_e), the density inside (outside) is ρ_0 (ρ_e) and the plasma pressure inside (outside) is p_0 (p_e). The pressure balance condition at the slab boundaries is $p_0 + B_0^2/2\mu = p_e + B_e^2/2\mu$. The characteristic wave speeds inside (outside) the slab

are: the Alfvén speed $V_A = B_0(\mu\rho_0)^{-1/2}$ [$V_{Ae} = B_e(\mu\rho_e)^{-1/2}$], the sound speed $c_s = (\gamma p_0/\rho_0)^{1/2}$ [$c_{se} = (\gamma p_e/\rho_e)^{1/2}$] and the tube speed $c_T^2 = c_s^2 V_A^2 / (c_s^2 + V_A^2)$ [$c_{Te}^2 = c_{se}^2 V_{Ae}^2 / (c_{se}^2 + V_{Ae}^2)$]. An important parameter of wave propagation in magnetic slabs is $m_e = \sqrt{(V_{Ae}^2 - c_{Te}^2)(c_{se}^2 - c_T^2) / [(V_{Ae}^2 + c_{se}^2)(c_{Te}^2 - c_T^2)]}$, which plays the role of perpendicular wavenumber outside the slab. The waves may propagate in the slab only when $m_e^2 > 0$ (they are leaky if $m_e^2 < 0$).

The solution of a slow sausage surface soliton in magnetic slabs can be given by the following expression (Ruderman 2003):

$$\eta = \frac{al^2}{l^2 + [z - st]^2}, \quad (1)$$

where η is the displacement of the slab boundary, a is the maximal value of the displacement η (i.e. the soliton amplitude) and

$$s = c_T + \frac{1}{4} \frac{ab}{x_0}, \quad l = 4 \frac{\kappa x_0}{ab} \quad (2)$$

are the soliton speed and the spatial scale, respectively.

The parameters b and κ are expressed as

$$b = \frac{V_A^4 [3c_s^2 + (\gamma + 1)V_A^2]}{2c_T (c_s^2 + V_A^2)^2}, \quad \kappa = \frac{x_0 \rho_e c_T c_s^2 (c_T^2 - V_{Ae}^2)}{2 \rho_0 m_e V_A^2 (c_s^2 + V_A^2)}. \quad (3)$$

Let us check if the observed parameters of the intensity blob satisfy the requirements of a sausage soliton. The observed blob propagates in the chromosphere, where the sound speed can be taken as $c_s = 10 \text{ km s}^{-1}$. We assume the density ratio outside and inside the slab as $\rho_e/\rho_0 = 0.9$. Then, the propagation speed of the soliton, s , is determined by the soliton relative amplitude, a/x_0 , and the Alfvén speed V_A (see equation 2). The observed relative amplitude of the blob is estimated as $a/x_0 = 0.2$, then the Alfvén speed stays as a free parameter. In order to obtain the observed

apparent propagation speed, i.e. 35 km s^{-1} , the Alfvén speed needs to be $\sim 70 \text{ km s}^{-1}$.

Another important parameter of the sausage soliton is its length-to-width ratio. Observations show that the blob has elongated form: its mean length is approximately three times larger than its width. Then the parameter associated with the soliton length is $l \approx 6x_0$. This will be achieved when $m_e \ll 1$, which in turn requires $c_{se} \rightarrow c_T$ or $c_{se} \rightarrow c_s$ (as the Alfvén speed is much higher than the sound speed). Thus, the soliton may have the observed elongated shape if the electron temperatures inside and outside the tube are approximately similar.

5 DISCUSSION

The brief conclusion of the previous section is that the observed intensity blob may represent a slow sausage soliton in a chromospheric magnetic tube, which has an Alfvén speed of $\sim 70 \text{ km s}^{-1}$ and temperature balance with the surroundings. Note that both requirements are quite typical of the chromosphere. Possible inclination of the tube along the line of sight may cause an additional correction to the estimated Alfvén speed. 35° inclination leads to a blob propagation speed of $\sim 42 \text{ km s}^{-1}$, which then causes a slight increase of the required Alfvén speed.

It is interesting to note that the blob form remains almost unchanged in the first four images of Fig. 2. However, in the last four images the width of the blob is significantly increased. Fig. 3 (lower panel) shows the variation of the blob width with time. The gradual increase of the blob width is probably due to the expansion of the magnetic tube with height due to the stratification of the solar atmosphere. In the thin flux tube approximation, magnetic field strength varies as $B_0(z) = B_0(0) \exp(-z/2h)$ in the simplest case of isothermal atmosphere, where h is the scaleheight. Conservation of magnetic flux yields $B_0(z)A(z) = \text{const}$, where $A(z)$ is the tube cross-section. Then, the dependence of the tube diameter on height should be as $\sim \exp(z/4h)$. This dependence can be used up to 1200 km , where the thin flux tube approximation is valid (Hasan et al. 2003). The scaleheight of $\sim 220 \text{ km}$ (estimated for the sound speed of 10 km s^{-1}) yields an increase of the tube diameter by ~ 2.2 times between 500 and 1200 km heights. The observed width at 500 and 1200 km is 136 and 300 km , respectively. The ratio between the two parameters gives exactly the suggested value. Thus, the blob propagates along the magnetic tube, which is expanded upwards as modelled by the stratified atmosphere. The rapid broadening of the blob in the last images (i.e. greater heights) may correspond to the rapid increase of the tube cross-section (see fig. 1 in Hasan et al. 2003).

The blob begins to disappear after a height of $\sim 1700 \text{ km}$ probably due to the changed conditions for soliton formation. Due to the mathematical difficulties, all known theoretical properties of a slow surface sausage soliton were calculated for magnetic tubes with constant cross-section. Therefore, it is unclear what happens when the soliton propagates along tubes with varying cross-section. Intuitively, one may suppose that the soliton parameters also slowly vary during the propagation. It also should be mentioned that the soliton solution, which we use to model the blob propagation, was obtained without taking into account the stratification, which is important in this part of the solar atmosphere. These problems need further detailed study theoretically and numerically.

The length and apparent speed of the intensity blob are quite different from chromospheric jet-like structures (Katsukawa et al. 2007; Shibata et al. 2007; Nishizuka et al. 2008) and type II spicules

(De Pontieu et al. 2007b). Interpretation of the blob as a plasmoid propagating after a magnetic reconnection can be also ruled out as no explosive event is detected in the upper photosphere during the observations. If magnetic reconnection took place in subphotospheric layers, then the plasmoid should have much higher density than is observed. The propagation speed of the blob can be modelled by a transverse kink or fast sausage pulses as well. The second possibility is unlikely to occur as the observed spatial scale leads to the leaky regime of fast sausage waves. The first possibility needs further discussion as a kink pulse may lead to intensity enhancement in inclined magnetic tubes (Cooper, Nakariakov & Tsiklauri 2003). However, it requires a very large amplitude and the pulse may have a significantly curved form, which is not observed. Therefore, the kink pulse is unlikely to be the reason for the intensity enhancement.

Following the discussion above, it seems that the slow sausage scenario has a strong background. We suggest that this is the first observation of a sausage soliton in the solar atmosphere. We believe that careful analysis of SOT time series will reveal other similar cases, which may enhance interest in soliton physics in the solar atmosphere.

Of additional importance for the quantitative interpretation of the observed phenomenon as a propagating solitary wave would be taking into account the plasma partial ionization effects in the solar chromosphere. The presence of even a small amount of neutral atoms in plasma is known to change its dynamical and physical properties significantly (Braginskii 1965; Khodachenko & Zaitsev 2002; Khodachenko et al. 2004). Different interaction of electrons, ions and neutral atoms with the magnetic field and each other causes the main specifics of the partially ionized plasma magnetohydrodynamics, which differ significantly from the fully ionized plasma case. The inclusion of ion–neutral collision effects in the scope of the proposed interpretation requires a special theoretical study of solitary wave behaviour in partially ionized plasmas, which represents a subject for future work.

It would be interesting to search for an analogy of soliton-like formations on the solar disc. Possibly, chromospheric bright grains (Lites et al. 1999), which were often associated with the shocks, represent soliton formations in magnetic tubes. Future detailed study is necessary to identify these features.

6 CONCLUSIONS

(i) A time series of the Ca II H line obtained by *Hinode*/SOT at the solar limb shows an upward propagating intensity blob. The blob appears at $500\text{--}600 \text{ km}$ height above the surface and reaches a height of $\sim 1700 \text{ km}$ after 35 s . Therefore, the mean apparent propagation speed is 35 km s^{-1} . The blob has elongated form and the length-to-width ratio is ~ 3 on average. The length-to-width ratio, the relative intensity and the propagation speed change slightly during the propagation.

(ii) The observed parameters fit with the theoretically expected properties of a slow sausage soliton propagating along a magnetic flux tube, which has an Alfvén speed of $\sim 70 \text{ km s}^{-1}$ and is in temperature balance with the surroundings (note that an inclination of the tube along the line of sight may slightly increase the value of the Alfvén speed). Therefore, we suggest that this is the first observational evidence of a slow sausage soliton in the solar atmosphere.

(iii) The width of the blob increases with height, which coincides with the expected expansion of magnetic tubes in the stratified atmosphere.

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