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On the detection of fast moving upflows in the quiet solar photosphere

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Abstract. In our studies of the dynamics and energetics of the solar atmosphere, we have detected, in high-quality observations from Hinode SOT/NFI, ubiquitous small-scale upflows which move horizontally with supersonic velocities in the quiet Sun. We present the properties of these fast moving upflows (FMUs) and discuss different interpretations.

Key words. MHD – waves – Sun: magnetic field – Sun: oscillations – Sun: chromosphere – Sun: photosphere

1. Introduction

Thanks to some remarkable advances in observational and theoretical techniques, our understanding of the dynamics and energetics of the lower solar atmosphere, in particular also of the quiet Sun magnetic field, has significantly evolved in recent years. Lites et al. (2008) have reported the ubiquitous presence of horizontal field in internetwork regions from observations with the spectropolarimeter on Hinode. Ishikawa et al. (2008) and Ishikawa & Tsuneta (2009) have detected transient horizontal magnetic field (THMF) to frequently emerge in both plage regions and the quiet Sun, which might be energetically important.

On the theoretical side, 3-D numerical simulations have reached a remarkable level of realism. The inclusion of radiative transfer allows direct comparison of observational signatures derived from the simulations with actual observations. Several groups have modeled the emergence of horizontal flux (e.g. Cheung et al. (2007), Cheung et al. (2008), Steiner et al. (2008), Martínez-Sykora et al. (2008)). The simulations of Martínez-Sykora et al. (2008) span the remarkable height range from the upper layers of the convection zone to the lower corona. Rosenthal et al. (2002) and

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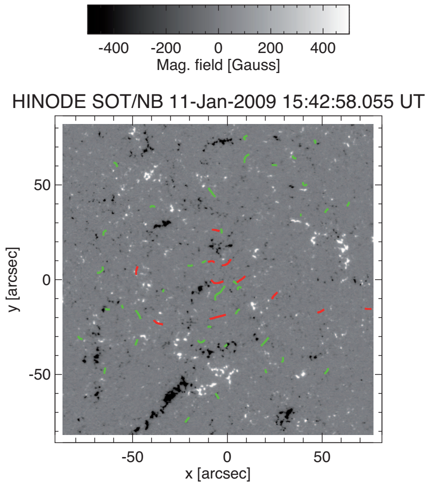

Fig. 1. Summary of the supersonic events analyzed in this work. The green paths mark events found in the last 10 minutes of the time series and are therefore nearly simultaneous to the magnetic field map obtained after the run. For greater clarity, we recommend viewing the online color version.

(Bogdan et al. 2003, hereinafter B03) have presented a detailed numerical model of the propagation of magneto-acoustic-gravity (MAG) waves in magnetic structures in the solar atmosphere.

Here we report the detection of fast moving upflows (FMUs) in the quiet solar photosphere. These approximately 1″ small elements appear in Dopplershift measurements, in the Mg b_2 line obtained with Hinode/NFI, to travel horizontally with supersonic velocities (10–45 km s^{-1}) in regions of low vertical magnetic field. Three possible explanations are discussed below: (a) the signature of emerging nearly horizontal flux ropes, (b) the signature of propagating MAG waves along a horizontal flux tube appearing in Dopplershift measurements in the Mg b_2 and Na D_1 lines, and c) supersonic flows in flux tubes.

2. Filtergram observations with SOT/NFI

A 2-hour filtergram time-series has been obtained with SOT/NFI onboard Hinode scanning 4 wavelength positions in the Mg b_2 line at 5173 mÅ on January 11th 2009, 13:28:34 – 15:36:13 UT. A similar time series has been obtained in the Na D_1 line on January 7th. A quick view of these latter data show similar features. For simplicity we discuss only the Mg b_2 data set in this short paper. The observational setup has been designed to study wave propagation between two different heights. The cadence achieved with this 4-wavelength scan is 32 seconds. The offsets of the working points relative to the nominal line center are ±68 mÅ (core) and ±188 mÅ (wing), respectively.

In order to calculate proxies of the velocities at two heights, the four different time series have been spatially coaligned removing instrumental jitter and interpolated to a common time frame using spline interpolation. During the latter interpolation, missing or defect data blocks have been interpolated. The red wing data set has been used as spatial reference for image stabilization as these images show the granulation pattern with highest contrast. During spatial coalignment, the red wing data set has been stabilized using a cross correlation algorithm comparing successive images. The blue wing and red core data sets have then been aligned to this stabilized red wing data set. Finally, the blue core data set has been aligned to the stabilized red core data set.

After the coalignment, the velocity proxies have been calculated by $S_v = (R - B)/(R + B)$ where R and B denotes the measured intensities in the red and blue line positions, respectively, both near the core (offset 68 mÅ) and in the wing (offset 188 mÅ). In a realistic line profile the above defined signals are not perfectly proportional to Dopplershift but can be used as a good proxy. A detailed calibration to velocity is in progress for our study of the vertical propagation characteristics of waves between the two heights (Fleck et al. 2009). In this work we use uncalibrated proxy values instead. We also calculate a proxy of the intensity fluctuation as $S_I = (R + B)$, a calibration of which might be even more challenging as this measure may be largely contaminated by line profile changes due to velocities and magnetic flux. We can therefore use this last proxy only as a coarse indication of the intensity fluctuations.

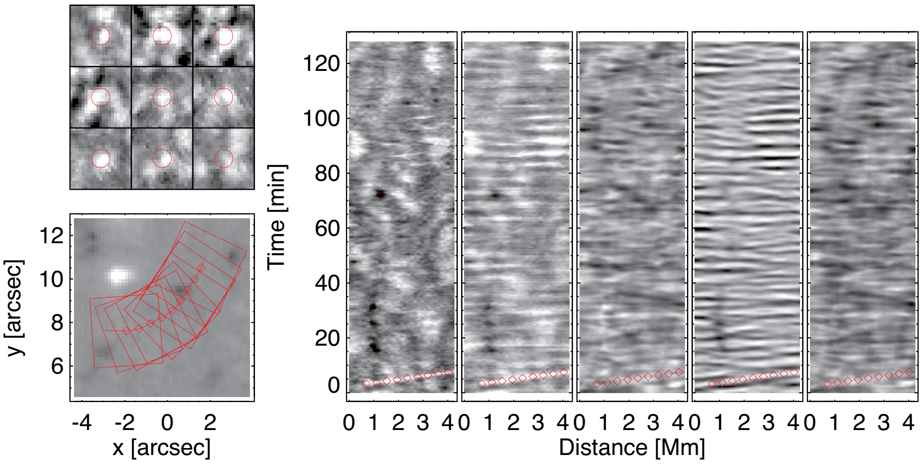

Fig. 2. Details of one of the events displayed in Fig. 1: the lower left image shows the details of the event path over the magnetic field strength as in Fig. 1. The squares indicate the picture areas following the event as displayed in the upper left sequence of images. There, the order of sequence is from top left to bottom right, and individual frames with 32 seconds cadence are shown. The circles indicate an ideal structure of 0.″96 diameter travelling at 13 km s^{-1} along the path. The direction of motion in these frames is always to the right. The 5 time-distance plots on the right side show (from left to right): wing velocity signal S_v filtered as discussed in the text, unfiltered wing velocity signal, wing intensity signal S_I, core velocity signal, and core intensity signal. The symbols indicate the position of the ideal structure element mentioned before. A color version of this figure is available online at the journal web site.

3. Results and discussion

A first inspection of the time series of S_v in the wing data set reveals frequent events of FMUs all over the field-of-view. By subtracting a spatially box-car averaged data set (with a spatial size of the filter of 2″) these events become even more evident. A movie of such a time series clearly reveals the ubiquitous presence of the FMUs (see online material). As the later analysis will show, these features appear to move horizontally with supersonic velocities up to 45 km s^{-1}.

To characterize these features, we hand selected a number of events, determined the propagation path and extracted time-distance diagrams along the features' paths. Figure 1 summarizes the paths of the analysed events on top of a map of the line-of-sight component of the magnetic field as measured by Hinode/SOT in the Na D_1 line 6 minutes after the time-series. This comparison is useful mainly for characterizing the physical context of the fast events, as we have access only to the line-of-sight component of the field and only after the run. However, the curved paths of the events we analyzed suggest a relation to magnetic fields (e.g. Fig. 2 and 3).

The FMUs have spatial scales of approximately 1″, can be followed in our high-cadence time-series for up to 5 minutes, and tracing paths as long as 4 Mm (see example in Fig. 2). They appear to be of rather impulsive character, although weak evidence of a quasi-periodical behavior is found in a few examples. They can be rather elongated in the direction of propagation (see Fig. 3). The shape of the FMUs is often evolving during the motion. A higher temporal cadence would be helpful to better identify their shape and evolution.

What are these FMUs? What drives them? We consider the following three scenarios: (a) the upflow signature of plasma surrounding an emergent THMF, (b) the manifestation of MAG waves propagating with supersonic velocities along a horizontal flux tube, and (c) a supersonic flow inside a flux tube.

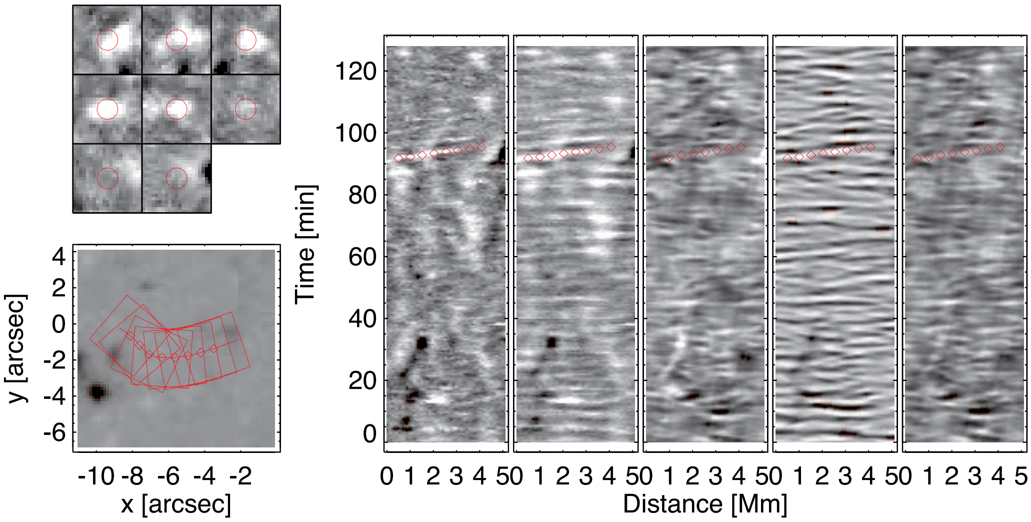

Fig. 3. Details of a different event displayed in the same order as Fig. 2. In this case, the ideal element was assumed to travel with 16 km s^{-1}. A color version of this figure is available online.

In the context of an emerging THMF one could explain the FMUs as the signature of the flows of the surrounding plasma driven at the point of emergence, comparable to a horizontal rope emerging out of water (see sketch in Fig. 5). In this analogy the water surface would represent the height where our velocity signal is formed. The position of emergence at this surface will move horizontally much faster than the emergence velocity if the rope is slightly inclined to the horizontal. The horizontal velocity could then exceed the sound speed even if the flux rope emerges much slower. The vertical velocity of the FMUs should then be approximately the velocity with which the flux rope emerges. This scenario can explain various properties of the observed FMUs. In fact, in this scenario we would expect to see only upflows at the center of FMUs, the spatial size of the features should be greater than the flux tube section and could be rather elongated. The apparent curved paths of the examples in Fig. 2 and 3 suggests curved flux tubes emerging. However, the geometry of such an emergence is not completely clear. There seems to be little evidence for the vertical "foot" points of these structures. One could also expect to see two emergence points propagating away from each other if the nearly horizontal structure is the central part of a loop. Interestingly, we could not identify any such case so far.

On the other hand, a quasi-periodic behavior would strengthen the hypothesis of a wave phenomenon along a horizontal flux tube. There is no evidence for rather long coherence times like those of the MAG waves studied by B03. As shown in the histograms of Fig. 4, roughly half of the cases show some evidence for wave trains of a couple of periods of the order of 4 minutes.

An interesting example for the following discussion of waves along or flows inside a horizontal flux tube is shown in Fig. 2. This FMU is moving horizontally at 13 km s^{-1} and can be followed along the clearly curved path over a distance of nearly 4 Mm for nearly 5 minutes. In the simplified picture of the wing signal being formed within a few hundreds of kilometers in the low photosphere, this suggests a nearly horizontal motion, otherwise the event would disappear quite rapidly in the wing Doppler signal. It is interesting to recall here the recent finding that nearly 80% of the Sun's magnetic flux appears in horizontal fields (Lites et al. 2008). However, in the case of an extremely cool cloud which makes the gas optically thick in the Mg line, the signal would form essentially inside the cloud and

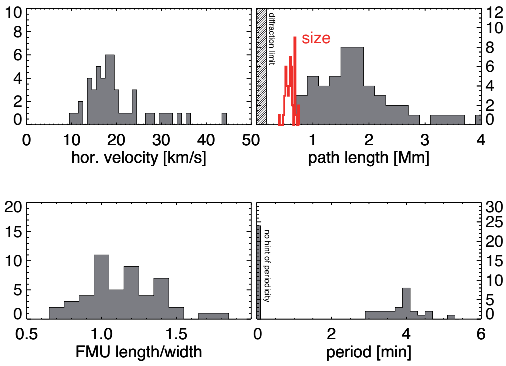

Fig. 4. Histogram of properties of the 49 events shown in Fig. 1.

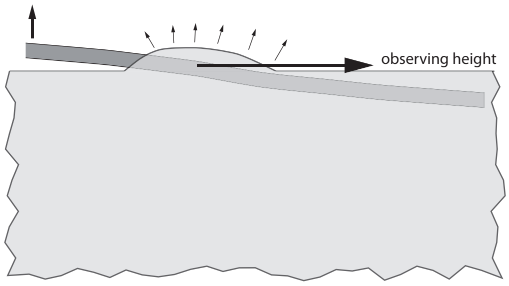

Fig. 5. A schematic sketch of the scenario of an emerging horizontal flux tube that could explain the apparent super-sonic velocities.

could therefore follow large height differences, though this hypothesis seems to be incompatible with the results of our intensity proxy.

Alternative interpretations of the FMUs are the propagation of a wave along a static horizontal flux tube, or a flow inside such. To test the compatibility of the various wave types with our observations we searched for evidence of the events in the different observables (see time-distance plots in Fig. 2 and 3). The events are mainly visible as upward velocity in the wing data set. Our filter removes a large part of the p-mode signal in the time series and makes the events more visible. However, the events are clearly visible also in the unfiltered wing velocity. This suggests a transverse wave. On the other hand, their signature in the intensity proxy is very weak, if detectable at all. The expected velocity cross talk in S_I makes any spurious intensity signal even more questionable. A Doppler signal of the events is visible simultaneously in the higher-formed core signal although the events are hard to isolate at that height, which is dominated by the 3–5 minute oscillations. This could also be caused by the broad contribution function of the core signal (Straus et al. 2009) which has some overlap with the wing signal.

B03 have shown that slow MAG waves in a vertical magnetic flux tube can produce apparent horizontal propagation at supersonic speeds due to a projection effect in case of a slightly inclined wave, even if slow waves are limited to sonic speeds. However, to explain the event of Fig. 2 that travels over nearly 4 Mm such an explanation would require a plane wave extending over that distance in a vertical flux element. Furthermore, the slow MAG waves should be visible in intensity, for which we have no evidence. We therefore exclude slow MAG waves as possible explanation for FMUs.

As for fast MAG waves, we would like to refer to the time-distance plots of $\Delta\rho/\rho_0$ and v_z/c_0 in B03, who studied MAG waves in a rather different geometry in a Sun-like atmosphere. These diagrams indicate that fast waves should be visible in both vertical velocity and intensity, except in the case of low-β. In the latter case, only interference effects between different waves make a weak signature in the intensity fluctuations. These effects, however, are not relevant here, because of the impulsive character of the FMUs.

Flows inside flux tubes can reach real supersonic velocities. The signature of the vertical velocity could then be interpreted as a rising flux tube, or as the vertical component of the flow in an inclined flux tube. However, it is unclear why the driving vertical flows at the foot points of the flux tube are not visible.

4. Conclusions

We report the detection of ubiquitous fast moving upflows (FMUs) in the quiet Sun with SOT/NFI. These events show up in the Doppler signal in the wing of the Mg b_2 line. This signal is formed in the low photosphere at about 150 km (Fleck et al. 2009).

The small features of approximately 1″ size travel horizontally with apparent supersonic velocities. Some of them show curved paths. The elements can be followed up to 4 Mm and reach horizontal velocities of up to 45 km s^{-1}. We discuss three mechanisms that might explain these features: a) the emergence of nearly horizontal flux tubes, b) MAG waves in horizontal magnetic fields, and c) supersonic flows in flux tubes. The presently available observational material does not allow us to distinguish between these options, and there might be other explanations. For instance, one might speculate about a possible link to the recently discovered "rapid blueshift events" (Rouppe van der Voort et al. 2009), which were identified as the on-disk counterparts of type-II spicules (de Pontieu et al. 2007).

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References

Bogdan, T. J., Carlsson, M., Hansteen, V. H., et al. 2003, ApJ, 599, 626

Cheung, M. C. M., Schüssler, M., & Moreno-Insertis, F. 2007, A&A, 467, 703

Cheung, M. C. M., Schüssler, M., Tarbell, T. D., & Title, A. M. 2008, ApJ, 687, 1373

de Pontieu, B., McIntosh, S., Hansteen, V. H., et al. 2007, PASJ, 59, 655

Fleck, B., Straus, T., Carlsson, M., et al. 2009, MmSAI, this volume

Ishikawa, R. & Tsuneta, S. 2009, A&A, 495, 607

Ishikawa, R., Tsuneta, S., Ichimoto, K., et al. 2008, A&A, 481, L25

Lites, B. W., Kubo, M., Socas-Navarro, H., et al. 2008, ApJ, 672, 1237

Martínez-Sykora, J., Hansteen, V., & Carlsson, M. 2008, ApJ, 679, 871

Rosenthal, C. S., Bogdan, T. J., Carlsson, M., et al. 2002, ApJ, 564, 508

Rouppe van der Voort, L., Leenaarts, J., de Pontieu, B., Carlsson, M., & Vissers, G. 2009, ApJ, 705, 272

Steiner, O., Rezaei, R., Schaffenberger, W., & Wedemeyer-Böhm, S. 2008, ApJ, 680, L85

Straus, T., Fleck, B., Carlsson, M., et al. 2009, in 3rd Solar Orbiter workshop held in Sorrento