MEASUREMENTS OF PLASMA MOTIONS IN DYNAMIC FIBRILS

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ABSTRACT

We present a 40 minute time series of filtergrams from the red and blue wings of the H$_\alpha$ line in an active region near the solar disk center. From these filtergrams we construct both Dopplergrams and summed “line center” images. Several dynamic fibrils (DFs) are identified in the summed images. The data are used to simultaneously measure the proper motion and the Doppler signals in DFs. For calibration of the Doppler signals, we use spatially resolved spectrograms of a similar active region. Significant variations in the calibration constant for different solar features are observed, and only regions containing DFs have been used in order to reduce calibration errors. We find a coherent behavior of the Doppler velocity and the proper motion that clearly demonstrates that the evolution of DFs involves plasma motion. The Doppler velocities are found to be a factor of 2–3 smaller than velocities derived from proper motions in the image plane. The difference can be explained by the radiative processes involved, as the Doppler velocity is a result of the local atmospheric velocity weighted with the response function. As a result, the Doppler velocity originates from a wide range of heights in the atmosphere. This is contrasted with the proper-motion velocity, which is measured from the sharply defined bright tops of the DFs and is therefore a very local velocity measure. The Doppler signal originates from well below the top of the DF. Finally, we discuss how this difference, together with the lower spatial resolution of older observations, has contributed to some of the confusion about the identity of DFs, spicules, and mottles.

Subject headings: Sun: atmospheric motions — Sun: chromosphere

Online material: mpeg animation

1. INTRODUCTION

The solar chromosphere owes its name to the reddish rim that appears above the lunar limb during solar eclipses. This reddish color mostly stems from the Balmer H$_\alpha$ spectral line, which makes this line one of the most important chromospheric diagnostics. Due to the highly dynamic state of the chromosphere and strong non-LTE (NLTE) effects, the line formation processes are still not yet fully understood (e.g., Carlsson & Stein 2002; Leenaarts & Wedemeyer-Böhm 2006). This is an important shortcoming in our interpretation tools that makes H$_\alpha$ observations traditionally difficult to interpret.

Due to the highly fibrilar structure of the chromosphere (Hale 1908), a strong influence from magnetic fields on the chromosphere has been suspected for about a century. The most common of these fibrilar magnetic fine structures are the jetlike structures known as spicules, mottles, and dynamic fibrils (DFs). In short, spicules are traditionally observed at the limb, mottles on the disk in the quiet Sun, and DFs in active regions.

Whether or not these structures are manifestations of the same phenomenon viewed at different angles has been the subject of a long-standing discussion (e.g., Beckers 1968; Grossmann-Doerth & Schmidt 1992; Tsiroupolou et al. 1994; Suematsu et al. 1995; Christopoulou et al. 2001; Rouppe van der Voort et al. 2007). One important argument against these structures being caused by the same mechanism has been the difference in the measured absolute velocities (Grossmann-Doerth & Schmidt 1992). Other authors have done direct measurements of mottles crossing the limb (Christopoulou et al. 2001). They also state that since both proper motions and Doppler motions are used in the comparisons, systematic errors are probably introduced. Such errors might also be amplified by the rather limited spatial resolutions of some of the data sets used.

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The detailed analysis of DFs has accelerated in recent years (e.g., De Pontieu et al. 2004; de Wijn & De Pontieu 2006; Hansteen et al. 2006; De Pontieu et al. 2007; Heggland et al. 2007) due to major advances in both observational techniques and simulation efforts. One of the main conclusions from these studies is that DFs are driven by magnetoacoustic shocks caused by $p$-mode oscillations and convective flows leaking into the chromosphere.

In a recent study, Langangen et al. (2008, hereafter Paper I) presented spectroscopic analysis of DFs as seen in one of the Ca ii IR lines. Numerical analysis of the line formation process showed a much lower DF velocity derived from Doppler measurements as compared to the proper-motion velocity. This was found to be due to both the low formation height and the extensive width of the contribution function of the Ca ii IR line. Furthermore, the DFs analyzed in Paper I showed mass motion, thus ruling out any excitation wave as the explanation model for the DFs (e.g., Sterling 2000 and references therein).

With the advantage of well-sampled spectral line profiles, the number of analyzed DFs in Paper I was rather modest because of the limited spatial coverage of the spectrograph slit. With the current data, we exploit the wide spatial coverage of a tunable filter instrument, albeit at the expense of limited spectral resolution.

In this paper we add to the understanding of these jetlike structures by analysis of Dopplergrams obtained in an active region close to the disk center; hence, the observed jet structures are commonly known as DFs. In § 2 we describe the observational program and the instrumentation. The data reduction and the calibration method are explained in § 3. In § 4 we present the results of our measurements. We discuss our results in § 5, and finally, we summarize the results in § 6.

2. OBSERVING PROGRAM AND INSTRUMENTATION

The observations were obtained with the Swedish 1 m Solar Telescope (SST; Scharmer et al. 2003a) on La Palma. The degrading effects of seeing were minimized by use of the SST adaptive optics.
system (Scharmer et al. 2003b) and the multi-object multi-frame blind deconvolution (MOMFBD; van Noort et al. 2005) image restoration method. The Solar Optical Universal Polarimeter (SOUP; Title & Rosenberg 1981) provided narrowband images in the H<sub>α</sub> line (with a filter FWHM of 12.8 pm). The optical setup is described in detail in De Pontieu et al. (2007). Three fast Sarnoff CCD cameras, operating at a frame rate of 37 frames s<sup>−1</sup>, were simultaneously exposed by means of an optical chopper. One camera was operated as the SOUP camera, and the other two cameras were positioned as a phase-diversity pair on a beam that was split off from the main beam before SOUP but behind the prefILTER (with a FWHM of 0.8 nm). The latter cameras provided wideband photospheric reference images and operated as the MOMFBD anchor channel.

The target area (65<sup>0</sup>00<sup>″</sup>; 65<sup>0</sup>00<sup>″</sup>) was centered on a small pore in NOAA AR 10910, positioned at S11<sup>°</sup>, W11<sup>°</sup> (observing angle θ = 21<sup>°</sup>; μ = cos θ = 0.93) on 2006 September 23 (see Fig. 1). The time series comprises 40 minutes, starting at 10:56:57 UT. The pixel scale was 0.065<sup>″</sup>, and the SST diffraction limit (λ/D) at 656.3 nm is 0.14<sup>″</sup>, or 100 km.

A wavelength calibration was performed for SOUP in order to compensate for several offsets, such as solar rotation. An H<sub>α</sub> profile scan was obtained by stepping with 5 pm steps and averaging over a relatively quiet region in the vicinity of the target area. This profile scan was used to determine the line center shift in order to provide correct positioning in the wings. The profile scan is shown in Figure 2.

SOUP was alternating between the blue and red wings at ±30 pm from the H<sub>α</sub> line core. The total acquisition time for the two line positions was 10.6 s, which included 1.1 s to record 40 exposures for each line position and 8.4 s to change the line position. The line position change time of SOUP is relatively long and is the limiting factor for selecting the number of points to sample for the spectral line profile. We choose two line positions, which is the absolute minimum for obtaining Doppler information. Improving the spectral sampling would imply unacceptably long acquisition times, over which solar evolution changes would dominate the resulting line profile. Taking half a resolution element (approximately 60 km) as a limit, we expect that motions in the image plane with velocities faster than 6 km s<sup>−1</sup> cause false signals in the Dopplergrams.

3. DATA PROCESSING

3.1. Image Postprocessing

All images from each SOUP cycle were jointly processed in a single MOMFBD restoration, yielding three restored images: one wideband image, one H<sub>α</sub> red wing image, and one H<sub>α</sub> blue wing image. Each restoration is based on a total of 240 frames, 80 from each camera. The sequential recording of the wing images and the long time required for the line position to change imply that the seeing for the two positions is different. For the construction of a Dopplergram from unprocessed images, one would expect significant false signals due to misalignment. However, when we use the wideband cameras as the MOMFBD anchor channel, the restored H<sub>α</sub> wing images are guaranteed to be precisely aligned.

![Fig. 1.—Field of view (FOV) for one wideband image (left) and the corresponding sum of the two narrowband filtergrams (right). In the narrowband image, several fibrilar structures can be seen, and some DF axes are marked (solid white lines) for illustrative purposes.](image1)

![Fig. 2.—SOUP Hα profile scan of a quiet region used for the line offset calibration (plus signs). A solar atlas profile is shown for reference (solid line). Furthermore, the idealized filter profiles for the red and blue wing positions are plotted on an arbitrary scale (dashed lines).](image2)
The resulting Dopplergram is therefore virtually free from misalignment errors. This advantageous feature of restoring multiple objects with MOMFBD is discussed in detail in van Noort et al. (2005). Note, however, that significant changes in the amount of blurring can result in false signals after the subtraction process. For our data, we regard this as only a minor source of error, since the seeing was stable and homogeneous.

Dopplergrams $D$ are constructed following the standard method:

$$D = \frac{B - R}{B + R}.$$  

where $B$ and $R$ are the blue and red wing images, respectively. The measured pixel values in the Dopplergrams will hereafter be referred to as the Doppler signal. The sum of the wing images gives an image that is reminiscent of an H$\alpha$ line core image. We use these summed images as substitutes for line core images when measuring the DF trajectories.

The wideband and wing images form a time sequence with a cadence of 19.1 s. The frames in each time series are aligned and destretched, using the wideband images as a reference to determine the (local) offsets, which were then applied to the wing images. After alignment and destretching, the Dopplergrams and summed images are constructed from the wing images.

### 3.2. Dopplergram Calibration

The Dopplergrams were calibrated in order to interpret the signals as Doppler velocities. The main concern with such a calibration is the large variation in the shape of the H$\alpha$ line profiles from different regions of the Sun.

As a first-order approach, we use the H$\alpha$ atlas profile from the Kitt Peak solar spectral atlas (Brault & Neckel 1987). Artificial Doppler shifts are applied to the atlas profile, and the Doppler signals are measured, using the same procedures as for the observations. For low velocities, there is a linear correlation between the velocity and the Doppler signal (see Fig. 3, bottom). For velocities that approach 13.7 km s$^{-1}$, the velocity corresponding to a Doppler shift of 30 pm, the correlation starts to deviate from linear. Only for velocities that follow the linear correlation with the Doppler signal can a simple calibration constant be used. We estimate that for the line positions used, ±30 pm, this corresponds to a velocity of about 9 km s$^{-1}$, or a Doppler signal of ±0.4.

The atlas profile is derived from averaging observations from disk center of the quiet Sun. The calibration constant derived from this profile might not necessarily apply to Doppler observations from other solar structures. To investigate the effect of variations in the shape of H$\alpha$ line profiles on Doppler signals, we analyze spectrogram time series of both the quiet Sun and an active region.

The quiet-Sun spectral time series was obtained on the same day, 2006 May 4, as the active region time series described in Paper I. This time series covers an hour of a fairly quiet internetwork region at disk center, obtained during excellent seeing conditions. As for the spectral atlas, we measure both the Doppler velocity and the Doppler signal, but now we measure this in the resolved spectra. The observed H$\alpha$ line profiles are generally very wide and flat and therefore have a rather low Doppler sensitivity. To cope with these problems, the Doppler velocity was measured using the center-of-gravity (COG) shift of the 4% lowest intensity of the line. This method gives more weight to the Doppler velocities from the near wings, similar to the Doppler signal measurement. The resulting correlation between the Doppler signal and the Doppler shifts is shown in Figure 3b. It is clear that the result from the quiet-Sun series is very similar to the relation found for shifting the atlas profile. This is because the widths of the resolved line profiles in this region do not differ substantially from the atlas profile.

The active region spectral time series is described in detail in Paper I. This series covers a plage region containing several pores. The viewing angle ($\mu = 0.96$) is approximately the same as the angle in the Dopplergrams from the present paper; hence, any systematic errors introduced by differences in the viewing angle are small. As above, both the Doppler velocity and the Doppler signal are measured in this time series. Significant differences compared with the spectral atlas calibration are found (see Figs. 3c and 3d). The calibration constant is in general higher in the active region, typically by a factor of 2. It is, however, clear from the spatially resolved calibration constants (Fig. 3c) that the variation is quite large. This variation is caused by the different spatial structures covered by the slit. The lower and middle parts of Figure 3c covered pores hosting running penumbral waves, whereas the upper part covered low-lying fibrils. In these regions, smaller calibration constants are found. In the boxed areas of Figure 3c, there is also some variation, but the lowest values are always substantially higher than those for the quiet Sun. These areas hosted several dynamic fibrils. Similar results were found in other time series, but with slightly lower calibration constants. We attribute this to the seeing conditions, which were less favorable.

We conclude that observed Doppler signals are very dependent on the shape of the H$\alpha$ line profile. The shape of the line profile varies significantly for different solar structures, and the calibration of Dopplergrams has to be done with care. The use of spatially resolved spectra is highly desirable, but even then the variations can be quite high. For the remainder of this paper, we adopt a calibration constant of 55 km s$^{-1}$ per Doppler signal, which is the mean value from the two boxes in Figure 3c. We argue that the calibration constant from these boxes is the optimal choice for our Dopplergrams, since we are interested in DFs. Numerous DFs were found in the region covered by the boxes in Figure 3c. The standard deviation of the calibration constants in these resolved spectra is 7 km s$^{-1}$. Note that this error should be multiplied by the Doppler signal, which gives a typical error of about 1–1.5 km s$^{-1}$.

### 3.3. Trajectory Measurement Method

For the measurement of the line-of-sight (LOS) Doppler velocity and the proper motion in the image plane, we follow the methods of Hansteen et al. (2006) and De Pontieu et al. (2007). The DFs are identified by visual inspection of the summed intensity time series, and the DF axes are manually defined. We see that individual DFs follow approximately straight trajectories. The right panel of Figure 1 shows examples of such axes; see also Figure 4 for a more detailed view of a DF. Data along these axes are extracted from both the summed and Doppler data cubes for further analysis. From the extracted data, we construct $x$-$t$ plots to measure the DF trajectories. Some examples of $x$-$t$ plots showing both the intensity and the Doppler signal can be seen in Figure 5.

The trajectory is defined by the position of the maximum change in the intensity between the top of the DF and the background, and a parabola is fitted to these data points. These parabolic fits give a good description of the temporal evolution of the length of the DFs (see Fig. 6). The velocity in the image plane is given by the time derivative of the fitted parabola.
The Doppler signal is extracted from the Dopplergrams, using the positions given by the parabolic fits obtained from the filter-grams. For a more robust measurement of the Doppler signal, we extract the Doppler signal 5 pixels (235 km) below these points along the DF axis; for further discussion, see the next section (§ 3.4). The Doppler data are fitted with a linear least-squares fit, which gives a good description of the time evolution of the velocity (see Fig. 6). The maximum velocity and deceleration are derived from the linear fit.

3.4. Error Estimation

In this section we summarize the different sources of error and discuss to what extent these affect our measurements of the DF trajectories. The uncertainty in the line center calibration through the SOUP profile scan affects the wavelength positioning of the SOUP filter (see Fig. 2). This could introduce an offset in the Doppler velocity, which affects the determination of the maximum Doppler velocity. To get a reasonable estimate of the error...
in this calibration, we have shifted the atlas profile relative to the observational points. Visual inspection of these shifted fits gives us an estimate of the error that is on the order of 1 km s$^{-1}$.

The long tuning time, 8.4 s, between the two spectral positions introduces errors due to changes in the seeing and solar evolution. In § 3.1, we argue that the error from the seeing is minimal because of the favorable conditions. Furthermore, the MOMFBD method guarantees precise alignment of the SOUP images. In § 2, we estimate that motions in the image plane that are faster than 1 km s$^{-1}$ cause false signals. This is a serious concern, since DFs have maximum velocities that are far greater than 6 km s$^{-1}$. For the summed images, this means that one would expect the top end for the DFs to be well defined during the beginning and end of their lifetime, when the velocity is largest. However, for the measurement of the DF trajectory, this is of less concern, since most of the measured points are found during the period close to maximum height, when the velocity is lowest. The deceleration and maximum velocity are determined from the parabolic fit. Also in the Dopplergrams, the changes due to solar evolution mostly affect the sharp edges of the DFs, and significant false signals can be expected during the periods close to maximum velocity. This is why we choose to measure the Doppler values a few pixels lower than the top of the DF. Since the DFs have a considerable linear extent that appears to be moving rather coherently, we estimate that this way we reduce the effect of solar evolution on the measured maximum Doppler velocity. As in the summed images, the deceleration is determined from a fit in which most of the fitted points are found when the velocity is lowest. In the same manner, using the linear fit reduces the impact of the increasing error for larger velocities when the velocity approaches the proper-motion velocities have an error of about 1 km s$^{-1}$. The proper-motion velocity measurements have an error of approximately 2 km s$^{-1}$. The proper-motion velocities have an error of about 1 km s$^{-1}$.

4. RESULTS

A total of 124 DFs are identified throughout the 40 minute time series. One example of a group of DFs can be seen in Figure 4. These DFs can be seen to move in a semicoherent manner, as illustrated by the Dopplergram, which displays downflow signal for the whole patch of DFs. Such semicoherent behavior of groups of DFs is also described in De Pontieu et al. (2007).

Using the methods described in § 3.3, we extract the lifetimes, maximum velocities, and decelerations of the 124 DFs, both in the image plane and along the LOS. For the Doppler measurements, we include only those DFs with an increasing velocity with time and with a change in velocity of more than 3 km s$^{-1}$ over the DF’s lifetime. Using these criteria, we remove 18 DFs, which means that more than 85% of the DFs display clear Doppler shifts together with proper motion. The statistical properties extracted for these DFs (124 based on proper motion and 106 based on Doppler motion) are presented in Table 1. The mean values are showed together with the corresponding standard deviations.

The deceleration and the maximum velocity show a strong correlation both in the image data and the Doppler data (see Fig. 7).

5. DISCUSSION

The correlation between the maximum velocities and decelerations found from the proper-motion measurements is similar to the correlation found by Hansteen et al. (2006) and De Pontieu et al. (2007). This is illustrated in Figure 7 by the gray-scale cloud shown in the background. This correlation between the deceleration and the maximum velocity is known to be the signature of shock waves being the driving mechanism of DFs (Hansteen et al. 2006; De Pontieu et al. 2007; Hegland et al. 2007).

Further support for this driving mechanism comes from the fact that we find a coherent behavior between the evolution of the Doppler signal and the proper motion for a large fraction of the DFs. This is a strong indication that there is actual plasma motion occurring during the lifetime of DFs. This supports the findings of Paper I, but based on a much larger sample.

The Doppler measurements show a similar correlation as those for the proper motion, but with much lower absolute values for both the decelerations and the maximum velocities. One possible explanation for these lower values could be high inclination angles of the DF trajectories with the LOS. One could expect to be able to derive the full trajectory vector by combining the two measured deceleration components. This naive method would give very high inclination angles, typically $\sim 75^\circ$. We know, however, that this cannot be the true inclination angle, since the Doppler velocity is a result of the local atmospheric velocity weighted with the response function to velocity over an extended height. In contrast, the measured proper motion is very local, due to the high-contrast boundary between the top of the fibril and the surroundings. Combining these two measurements leads to highly overestimated inclination angles. The difference in absolute values must be considered in the context of the results from Paper I. The lower Doppler velocities found from the Ca $\Pi$ IR line were explained by a combination of a lower formation height and an extended formation range. This is probably also the case for the H$\alpha$ line, but the formation height usually extends over a larger height range as compared to the Ca $\Pi$ IR line.

The nondetection of Doppler shifts in $\sim 15\%$ of the DFs could be caused by very high inclination angles, or it could be the case...
that their driving mechanism is fundamentally different and the evolution of these DFs is not a result of mass motion. We believe that the combination of high inclination angles and the uncertainties in the measurements is a more plausible explanation for the fact that we do not detect Doppler signal. The identification method of DFs introduces a bias toward the more inclined DFs. There are a number of suggestive cases in which DFs are visible in the Dopplergrams, but no clear signature can be seen in the corresponding intensity images. We refrain from measuring these DFs, since this would complicate a comparison with other data sets. Furthermore, the identification of these DFs is not objective, and we expect the measurement errors to be unacceptably high, since low inclination angles would lead to potentially high Doppler velocities. Due to the coarse spectral sampling, this could lead to strong saturation effects in the measured Doppler velocities.

5.1. Spicules, Mottles, and Fibrils

The identification of the disk counterpart of spicules was already an important question 40 years ago (e.g., Beckers 1968). One of the main problems was to reconcile the velocities measured in spicules with those measured in mottles. This problem was also the main concern of Grossmann-Doerth & Schmidt (1992). They conclude that since the velocities are much larger in spicules than they are in mottles, the two could not be the same structure seen at different viewing angles. They, however, admit that the seeing might impair their results if the structures that were observed were smaller than
Later studies of mottles and spicule properties led to the conclusion that spicules and mottles are in fact the same feature seen at different angles (Tsiropoula et al. 1993, 1994). Tsiropoula et al. (1994) showed, using cloud modeling, that the proper motion and the cloud velocities were consistent. In a more recent work, Christopoulou et al. (2001) used a limb-darkening correction method to directly observe mottles crossing the limb. They argue that the main reason for the earlier confusion is caused by the low spatial resolution of the observations.

In our study, it is clear that the Doppler signal originates from spatially resolved structures. The excellent quality of the observations largely removes the errors that are due to low spatial resolution. Assuming reasonable inclination angles, i.e., that the mean angles are neither very large nor very small, we can conclude that the Doppler velocities are typically a factor of $\frac{1}{\sqrt{3}}$ smaller than the corresponding proper motion. A similar but larger difference was reported by Tsiropoula et al. (1994), and we believe that this difference can be attributed to the lower quality spatial resolution.

As discussed above, radiative transfer processes are the fundamental reason for the Doppler velocities to be lower than the proper motion. We argue that the fundamental differences between the Doppler and proper-motion velocities that we find for DFs are also valid for similar measurements on spicules and mottles. Besides the argument of the low spatial resolution, we believe that

| Parameter                          | Value       |
|------------------------------------|-------------|
| Lifetime (s)                       | $258 \pm 56$|
| Proper-motion velocity (km s$^{-1}$)| $18.6 \pm 6.6$|
| Proper-motion deceleration (m s$^{-2}$) | $142 \pm 64$|
| LOS velocity (km s$^{-1}$)         | $6.4 \pm 2.1$|
| LOS deceleration (m s$^{-2}$)      | $33.7 \pm 15.6$|
this difference was an important contributor to the earlier confusion about the unification of mottles and spicules. Similar work on spatially resolved limb spicules is needed in order to finally settle this discussion.

6. SUMMARY

With the SST, we have obtained a 40 minute time series of an active region observed in two line positions in the Hα spectral line. For the first time, the proper motion and Doppler velocity of DFs can be simultaneously measured in spatially resolved observations.

We find that most DFs, about 85% of our sample, show both cotemporal and cospatial Doppler motion and proper motion. The coherent behavior of the two velocity components shows that the evolution of DFs involves real plasma motion.

Both the proper-motion and Doppler measurements show a strong correlation between the maximum velocity and the deceleration. This is in agreement with earlier findings and supports the theory that DFs are driven by magnetoacoustic shocks.

We derive significantly lower values for the deceleration and maximum velocity from the Doppler measurements. We argue that this can be explained by the height extension of the response function. The Doppler velocity is a result of the atmospheric velocity weighted with the response function over an extended height. The proper-motion velocity is derived from the large contrast between the top of the DF and the background, which is a very local measure.

Using high-resolution spectrograms, we have demonstrated the importance of a rigid calibration method for Dopplergrams.

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FIG. 7.—Scatter plot of the decelerations and maximum velocities. The earlier reported values of Hansteen et al. (2006) are shown (scatter cloud). The image data results (plus signs) and the Doppler data results (diamonds) are superposed.