SEARCH FOR HIGH VELOCITIES IN THE DISK COUNTERPART OF TYPE II SPICULES

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ABSTRACT

Recently, De Pontieu and coworkers discovered a class of spicules that evolve more rapidly than previously known spicules, with rapid apparent motions of 50–150 km s⁻¹, thickness of a few 100 km, and lifetimes of order 10–60 s. These so-called type II spicules have been difficult to study because of limited spatiotemporal and thermal resolution. Here we use the IBIS instrument to search for the high velocities in the disk counterpart of type II spicules. We have detected rapidly evolving events, with lifetimes that are less than a minute and often equal to the cadence of the instrument (19 s). These events are characterized by a Doppler shift that only appears in the blue wing of the Ca ii IR line. Furthermore, the spatial extent, lifetime, and location near network all suggest a link to type II spicules. However, the magnitude of the measured Doppler velocity is significantly lower than the apparent motions seen at the limb. We use Monte Carlo simulations to show that this discrepancy can be explained by a forward model in which the visibility on the disk of the high-velocity flows in these events is limited by a combination of line-of-sight projection and reduced opacity in upward-propelled plasma, especially in reconnection-driven jets that are powered by a roughly constant energy supply.

Subject headings: Sun: atmospheric motions — Sun: chromosphere

1. INTRODUCTION

The solar chromosphere, when viewed at the limb, is dominated by a variety of jet-like features that have been difficult to understand, mostly because the spatiotemporal resolution of previous observations has been insufficient to resolve much of the dynamics, which has led to a multitude of different interpretations (Sterling 2000). Recently observations at high resolution (100–200 km) and cadence (a few seconds) at the Swedish 1 m Solar Telescope (van Noort & Rouppe van der Voort 2006) and with the Solar Optical Telescope (SOT) on board Hinode (De Pontieu et al. 2007b) have provided unprecedented views of the complex mix of highly dynamic and finely structured features that dominate the chromosphere. A full understanding of chromospheric energetics and coupling to the transition region and corona requires a detailed study of what drives this plethora of features and how they are connected to one another.

Some progress in this direction has been made by De Pontieu et al. (2007b) who found that there are two fundamentally different types of spicules at the limb, with very different dynamic properties. The type I spicules evolve on timescales of order several minutes and seem to be driven by shock waves that form when oscillations and flows leak into the chromosphere along magnetic flux concentrations. These spicules seem to correspond to dynamic fibrils (active regions) and a subset of mottles (quiet Sun), when seen on the solar disk (Hansteen et al. 2006; De Pontieu et al. 2007a; Rouppe van der Voort et al. 2007). Hinode SOT observations revealed a second class of spicules ("type II") that occur on timescales of just a few tens of seconds during which they are seen to rise and then rapidly disappear, possibly because they are heated out of the bandpass. These newly discovered features, which dominate the limb in coronal holes and (to a lesser extent) the quiet Sun, remain mysterious since the line-of-sight projection makes it difficult to determine whether the high apparent velocities (50–150 km s⁻¹) are associated with real plasma flows of the same magnitude. There is a significant literature on the properties and relationship of mottles and spicules at various wavelengths. However, the enormous advances in spatial and temporal resolution of the Hinode data and the lack of high-velocity observations in the classical observations limit the usefulness of detailed comparisons with previous observational reports.

In this Letter we present a candidate for the disk counterpart of type II spicules. We observe short-lived blueshifted excursions in the line profile of the Ca ii 854.2 nm line that are not succeeded by an obvious redshift. Similar events have been reported earlier (e.g., Wang et al. 1998; Chae et al. 1998), but on temporally and spatially more extended features. To explain the differences observed between the limb and the disk we present numerical experiments using radiative transfer calculations and Monte Carlo simulations.

2. OBSERVATIONS

The observations were obtained using the Interferometric Bidimensional Spectrometer (IBIS) mounted at the Dunn Solar Telescope (DST) of the National Solar Observatory. For a more thorough description of the instrument see Cavallini (2006). The data used in this letter was obtained on 2004 June 2, during a period of good to excellent seeing conditions lasting about 55 minutes (UT 14:59–15:54). For a detailed description of the data set and the reduction routines we refer the reader to other observational reports (e.g., Cauzzi et al. 2008). The data was obtained with a scanning sequence of 27 steps in the Ca ii 854.2 nm line, with a step size of 8–16 pm and a spectral transmission FWHM of 4.4 pm. This scan covers a spectral region of −0.12 to about 0.16 nm from line center. The signal-to-noise ratio is about 130 in the line wing. The diffraction limit of the telescope at 854.2 nm is λ/D = 0.23," but with 2 × 2 binning the effective size is 0.165". The scanning of the Ca line takes 7 s and was repeated every 19 s pointing at an enhanced network very close to the boundary.
Fig. 1.—Snapshot of a line-center image showing an overview of the field of view. Crosses indicate the positions of the observed rapid blueshifted excursions, with the five examples seen in Fig. 2 marked as diamonds with the corresponding number.

disk center. The field of view (FOV) covers four rosette structures (see Fig. 1).

3. DATA ANALYSIS

Visual inspection of the data set shows that the general dynamic behavior of the spectral line varies dramatically across the different regions in the FOV (e.g., network, internetwork [IN], and canopy; see Vecchio et al. 2007). The IN is cluttered with brightenings caused by the 3 minute shocks as explained by Carlsson & Stein (1997), while the centers of the rosettes are covered with mottles (with a spectral signature very similar to that of dynamic fibrils; Langangen et al. 2008). At the edges of the rosettes we observe a marked difference in the dynamic behavior of the line profile. The line is wider and there are no dominating shocks, as compared to the network and the IN. It is in this region at the edge of the rosettes that we find the blueshifted excursions (see Figs. 1 and 2).

The events have been identified in a semiautomatic fashion. First we perform a search for changes in the intensity on the blue side of the line at around 20 km s$^{-1}$. We then exclude all events that show a succeeding redshift, since these kinds of events are identical to the temporal evolution of the velocity in a dynamic fibril or an IN shock. Finally we exclude all events that occur during times of worse seeing quality. Such an automatic search results in a manageable number of events. The events found by the search routine were manually inspected, and only clearly blueshifted and short-lived events

Fig. 2.—Five examples of RBEs are shown. The top row shows the temporal evolution of the RBE (arrow). The detailed spectra (middle row) of the RBEs (solid line) is shown together with the mean profile (dotted line). The line-center image is shown in the bottom row. The contour (white line) shows the spatial extent of the RBEs. Note the alignment of the RBEs with the field lines; see also Fig. 1.
were chosen for further analysis. In this fashion we identified 87 blueshifted events distributed over the whole time series, from now on denoted as rapid blueshifted excursions (RBEs). We have done a visual search for separate downflows associated with the RBEs and have found no clear candidates.

To measure the spatial extent of the RBEs we calculate the spatial correlation of the dynamic behavior of the line profile at the semiautomatically flagged location with that of surrounding pixels. We choose the most pronounced time step in the RBE as anchor, subtract the mean line profile from the spectra, and calculate the correlation coefficient of the temporal evolution of the blue side of the RBE between neighboring pixels. The area covered by pixels with higher than 80% correlation to the anchor pixel is used as a measure of the spatial extent of the structure. The RBEs can be elongated (78%), round (8%), or have an irregular shape (14%); see Figure 2. The length of the elongated RBEs is usually 0.5–1.5 Mm with an average of 1.2 Mm, and the width is usually 0.3–0.6 Mm with an average of 0.5 Mm. The small round RBEs are often not more than 0.5 Mm in diameter. It is likely that some of the elongated shape of the RBEs is caused by the smearing due to the long scanning times (7 s) of the data.

From the measured RBEs we derive a mean lifetime of 45 ± 13 s. It is difficult to accurately measure plasma velocities in the RBEs, since many of the spectral profiles seem to consist of more than one component (but without any separation between components). However, a rough estimate of the velocity based on visual inspection and comparison to radiative transfer calculations suggests velocities of order 15–20 km s$^{-1}$ (see §4 for more discussion of this topic).

4. NUMERICAL EXPERIMENTS

The similarities in properties such as uniquely upward motion, rapid disappearance, lifetime, and location suggest a link between type II spicules and RBEs. However, there is an apparent lack of very high velocity RBEs, especially compared to the 50–150 km s$^{-1}$ velocities seen in type II spicules. To investigate these differences in the observed properties of type II spicules and RBEs we perform several numerical experiments. First we construct a toy model for the RBEs: a 100 km wide component with a line-of-sight velocity of 15 and 20 km s$^{-1}$ is introduced in a FAL C model (Fontenla et al. 1993), at a variety of different heights. We then use MULTI (Carlsson 1986) to calculate the impact of these higher velocity components on the Ca ii 854.2 nm line profile (as seen on the disk). While this may be unrealistic, it can give some insight into the effect of atmospheric motions on the line profile. A full understanding of the radiative transfer in these events will require a more sophisticated approach, e.g., a cloud model (Heinzel & Schmieder 1994) or more likely non-LTE radiative transfer from a 3D MHD model. This numerical experiment indicates that events that occur at the top of the chromosphere (where lower densities occur) are increasingly more difficult to observe.

As a next step we investigate whether line-of-sight projection is behind the lower velocities (15–20 km s$^{-1}$) observed in RBEs on the disk compared to the high velocities of type II spicules at the limb. Perhaps the strong inclination from the vertical of the magnetic field lines at the edge of rosettes causes a reduction in observed velocities along the line of sight? For this purpose we perform a Monte Carlo simulation in which 50 type II spicules are allowed to occur (randomly) during a time period of 55 minutes (at 19 s cadence). Each spicule has a lifetime randomly chosen from a Gaussian distribution around 40 s with a standard deviation of 20 s. During their lifetime, the spicules are assigned an upward velocity chosen from a Gaussian distribution around 70 ± 15 km s$^{-1}$. The spicules have random orientation with a uniform distribution of angles between the spicule axis and local vertical between 0° and 90°. We then synthesize the impact of these spicules on the Ca ii 854.2 nm line by assuming each type II spicule is associated with a Gaussian absorption component with a depth of 10% of the continuum value, with a half-width of 10 km s$^{-1}$. The result of such a simulation (Fig. 3a) shows a large number of high-velocity events with Doppler shifts larger than 30 km s$^{-1}$, which we do not see in the IBIS data. We should note that assigning spicules orientations that are more inclined from the vertical (e.g., as in the inclined regions at the edge of rosettes) does lead to a reduction of high-velocity events in the simulated IBIS Dopplergrams. However, Hinode SOT data show that many type II spicules are more vertical, so a skewed angle distribution cannot be the reason for the mismatch in velocities between type II spicules and RBEs.

Next we investigate whether the decreasing density with

![Fig. 3.—Results from the Monte Carlo simulations: (a) a simulation with infinite scale height, (b) a simulation with a scale height of 1500 km, and (c) a simulation with a scale height of 1500 km and random height of energy input. The vertical dashed line is the limit of the IBIS observations.](Image)
height in spicules could lead to a reduced visibility of nearly vertical spicules in which the density rapidly decreases with height. A simple way of incorporating this effect is to decrease the absorption caused by each spicule as a function of height, using the observed intensity scale height (De Pontieu et al. 2007b). To test the maximal effect we use the lower observed scale height of 1500 km. The absorption component is then allowed to decrease in strength according to the fraction of the scanning time (7 s) and the cadence (19 s) the spicule occupies at the different heights. Highly inclined events (e.g., at the edge of the rosettes) do not reach high up, so do not suffer much attenuation of the default absorption. An example of such a simulation (Fig. 3b) shows that the visibility of events with high Doppler shifts is reduced significantly. However, it appears there are still a larger number of such events than we observe in the IBIS data.

A resolution to this problem comes when we assume that the spicules are caused by a local release of energy, such as in a reconnection event. If the reconnection events occur over a range of heights and each event is assumed to release a roughly constant amount of energy, then the drop-off in density with height will cause events that occur in the upper chromosphere to naturally lead to spicules with lower density and higher velocity than events driven by reconnection lower down. We incorporate this idea into the Monte Carlo simulations by allowing each spicule to be driven by reconnection at a random height chosen from a uniform distribution between 1000 and 2000 km (in the FAL C model). The velocity of the spicule caused by the reconnection is then assumed to be given by $v = \left(\frac{2U_p}{\rho}\right)^{1/2}$, where $U_p$ is the kinetic energy density in the event and $\rho$ is the density in the FAL C model at the height of the event. The energy density of the event is now a free parameter, but there is a whole range of values for this parameter (10–70 ergs cm$^{-3}$) that produce simulated Dopplergrams that are very similar to the RBEs in the IBIS data. One example of such a simulation with $U_p = 25$ ergs cm$^{-3}$ is shown Figure 3c. While this simulation produces a whole range of high velocity events, these are not visible against a bright background, and only visible at the limb (as type II spicules), where there is no background radiation. This can explain the lack of high-velocity RBEs on the disk and the predominance of high-velocity events at the limb (where there is a bias toward mostly vertical high-velocity events that reach greater heights).

5. CONCLUSIONS

We have presented a candidate for the disk counterpart of type II spicules: rapid blueshifted events (RBEs). The RBEs are found near the edges of the network. The lifetimes of the RBEs are about 45 s, which is very close to those of type II spicules (40 s). The length of the elongated RBEs is about 1.2 Mm and the width is 0.5 Mm. The length of the RBEs is shorter than the type II spicules, which might be caused by the intrinsic differences in visibility between the two kind of observations. Since RBEs are identified by a Dopplershift they are associated with mass motion. The magnitude of the mass motion in RBEs is lower than the apparent motion observed in the type II spicules. Monte Carlo simulations suggest that this discrepancy is to be expected if there is an inverse relationship between density and velocity of the events: high-density, low-velocity events show enough absorption to be visible in IBIS data taken on the disk, whereas low-density, high-velocity events are more clearly visible at the limb (since they reach greater heights), but have little visibility on the disk because they have little opacity. Such an inverse relationship would be expected if type II spicules are caused by reconnection events that occur over a range of heights in the chromosphere, and in which the amount of energy is roughly constant from event to event. Such a scenario is not unrealistic, and is supported by the presence of RBEs at the edge of rosettes where the relentless magnetoconvection pushes the ubiquitous IN flux into the strong network flux concentrations. Compounding factors that help explain the mismatch in observed velocities include the effects of variable line-of-sight velocity due to the magnetic field topology and the fall in intensity due to the decrease in density as the spicules reach greater heights. We show that a combination of these factors can explain the visibility of RBEs on the disk and type II spicules at the limb.

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