PROPERTIES OF Hα SPICULES FROM DISK AND LIMB HIGH-RESOLUTION OBSERVATIONS

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ABSTRACT

We selected diffraction limited observations obtained at the NSO-Sacramento Peak VTT, in order to revisit the interpretation of the fine structure of Hα spicules both off the limb and on the disk, using a time series of narrow passband Hα filtergrams with better than 0.3" spatial resolution. Very high resolution off-limb spectra are also considered. We find common properties of Hα wing and disk spicules, as their multiple thread-like components, their aspect ratio, the detachment of material, their velocities. The bottom part of spicules at heights lower than 1500 km is not considered. The dynamical behaviour of the top parts suggests an impulsive phase with g>5g which explains the more extended out-of the network blue components, while the red components have longer duration.

1. INTRODUCTION

The interpretation of Hα center filtergrams is a very difficult task; good quality wing filtergrams show a pattern of elongated dark features, matching the properties of spicules. There is evidence, if one compares the geometrical distribution, the lifetimes and spectroscopic properties such as source function, Doppler width and optical depth, that dark mottles and off-limb spicules are the disk and limb manifestation of the same chromospheric structures. The difference in the value of upward velocity, which could be about four to five times higher in spicules (25-30 km s\(^{-1}\)) and more, may be the result of a more vertical direction of spicules compared to mottles. An attempt by Koutchmy and Macris (1971) to identify line wing spicules crossing the photospheric limb showed that they are seen in absorption on the disk, although at Hα center this is certainly not true and far more difficult, see Alissandrakis and Macris (1971), Alissandrakis et al. (1990). Concerning the off-limb spicules, Veselovsky et al. (1994) discussed some optical thickness effects due to their dynamical behaviour. Let us just additionally notice that the source function of rapidly (v > 40 kms\(^{-1}\)) moving chromospheric gas is greatly affected by the Doppler brightening effect, which makes the quantitative interpretation of intensity modulation of filtergrams and of line profile intensities very difficult.

Recently Herstchi and Mouradian (1992) found spicule line-of-sight velocities of the order of 40 km s\(^{-1}\) while the velocity from height variation was found to be 20 km s\(^{-1}\). The difference is suggested to be due to the ionization of the material as it penetrates into the corona, so the interpretation of Doppler velocities and apparent proper motions is not straight forward. We believe that the influence of the background atmosphere, which includes the coronal gas, is a main question which was also addressed by Gaizauskas, 1985. Moreover, when quantitative line profile intensities are interpreted, the Doppler line brightening effect should also be taken into account. Recent numerical simulations by Yokoyama and Shibata (1995) did show that the concept of rapidly emerging magnetic loops from the photosphere, which produce sudden energy release in the coronal environment through ejections, works to explain the phenomenon of chromospheric spicules (Sturrock et al., 1990, Tsap, 1994).

Much less work exists for features seen on the disk. Fine-structure chromospheric mottles are concentrated at the supergranular boundaries and they appear as dark or bright structures in projection onto the solar disk (Beckers, 1992). Their morphology depends strongly on the part of the spectral line in

which they are observed, as well as on their position on the disk, but they are best observed in Hα ground based filtergrams, provided the spatial resolution is good. They are sometimes organized into more or less symmetrical rosettes which are thought to be the manifestation of ‘diverging’ magnetic field lines of flux tubes, where the plasma is presumably injected from below (Marsh 1976; Rabin and Moore 1980, 1984). Strong magnetic flux which was analysed near the center of a rosette, (Dara and Koutchmy, 1983) shows correspondence with several bright points. Beckers (1963) found that dark mottles disappearing in the Hα–0.5 Å image became visible in the Hα+0.5 Å image. Bhavilai (1965) and Title (1967) found upflows and downflows in individual mottles but didn’t confirm a velocity reversal. Tsipropoula et al. (1993, 1994) found upflows at first, then downflows starting from the footpoints of dark mottles and expanding to their upper parts. They give typical line-of-sight velocities between zero and about 5 km s⁻¹ with their statistical distribution found to be rather symmetrical, which indicates that there is a similar amount of upflowing and downflowing material in chromospheric mottles. Heinzel and Schmieder (1993) studied both bright and dark mottles, showing rather low velocities. Tanaka (1974) has shown that, when the dynamical behaviour of the chromospheric fine structures on the disk is considered, the occurrence of multiple fine features, called by him ‘double dark mottles’, in each wing of Hα as well as the ‘very fast stretching’ of mottles cannot be ignored. Suematsu et al. (1995) have extensively studied the trajectories of seventy-six disk spicules in a region of enhanced network near the disk center and find a behaviour of inferred velocities compatible with ballistic trajectories, which means first upward and then downward velocities, but along the same apparent path. The initial ejection velocity is found to be 40 km s⁻¹. Reconstructed dopplergrams show that, sometimes, the entire spicule rises and falls as a whole, following the magnetic field lines. Finally, Zirin, in his most recent review on chromospheric structures (1996), calls for a radical revision of our conception of the modelling of the chromosphere, presenting qualitative observations.

The difference of interpretation given by various authors is obviously a result 1) of the difference in the spatial and sometimes temporal resolution of observations, 2) of the fact they consider different positions in the line, as well as different passbands. The best resolution is obtained, provided we observe with a large aperture optically good telescope, when short exposure times are used and image selection made. This is possible only when a great number of filtergrams is available, even during moments of excellent seeing, because a field of view significantly larger than the isoplanetic patch should be considered.

The present work is a contribution to the comparative study of spicules using high resolution observations on the disk and at the limb. We consider the most ‘elongated’ and dynamical spicules as well as the part which seems to be detached from the ‘bottom’ of the spicule and we try to identify the phenomenon on the disk and better understand the origin of the whole phenomenon, being aware of the difficulty of considering the very bottom part of spicules which can easily be confused with the low chromospheric structures. We note that close to the feet of spicules or at the center of rosettes a pattern of bright points or filigrees is observed.

2. OBSERVATIONS

Among a great amount of available observational material taken in Hα, we have selected a few temporal sequences of the best quality (high spatial and temporal resolution). Sequences were mainly obtained at the focus of the VTT of NSO/Sac Peak using different methods and detection devices. We briefly summarise the parameters of observation.

2.1 On-disk observations: A sequence of high spatial resolution observations taken in a quiet-sun region at the disk center by R.B. Dunn, including the center as well as the wings (±5/8 and ±7/8 Å) of Hα, with the Vacuum Tower Telescope of the Sacramento Peak Observatory (SPO) and a 1/4 Å Zeiss filter, on April 9 1972. The image diameter is 38 cm. The exposure time was approximately 1/4 sec with the system diaphragmed down to approximately a 65 cm diameter. This film was never used to analyse disk spicules, although it was used for the identification of the filigrees.

2.2 Off-limb observations: a. Fast video imaging at very high resolution was carried out at the limb, near the solar poles (PA 165°), the region being centered at S 73.6° E 64.6°. A Sony video CCD camera was used with an effective exposure time of 1/60 sec at 30 frames/sec and a Super-VHS recorder with a resolution of 400 lines. The pixel size is 12.5 micron and the scale 3".75/mm. The diffraction limited spatial resolution is 0.178, or 130 km, at 6563 Å; a 30 mm free aperture Lyot filter was used in front of the camera without recollimating the F/80 beam. The FWHM was >1 Å near the center of the Hα line. A few frames were digitized after image selection among thousands of good frames of the video.

b. We also used UBF observations with an analog video CCD channel at the center of Hα to look for radially moving features. Due to the use of a very narrow passband, the scattered light is typically reduced by a factor of 10 compared to broad band observations, therefore we have got a contrast good enough to permit measurements of proper motions.
c. Fast CCD spectrography was also carried out at the Echelle Spectrograph (ESG) of the SPO VTT. We used a quite long curved slit parallel to the limb (h>1000 km) and observed at different heights up to 6 to 7000 km (top of spicules).

3. ANALYSIS

First we recognized the dark threads, which are well elongated components of spicules seen in absorption on the disk, far enough in the wings of Hα which show the same geometrical parameters as those seen in broad band observations above the limb, in emission. Their true diameter is barely resolved; we estimated its typical value of the order of 200 km. The typical apparent length is of the order of 5000 km, with a large dispersion of values which could reach 10000 km or more. This gives a typical aspect ratio a=25. On the disk, we focused our analysis on a time sequence which had a duration of 18 minutes and was the one with the best seeing.

In order to be able to follow the time evolution of dark threads the film was digitized and, using a suitable software, we were able to follow on the computer screen the evolution in each wing (±5/8 A), picture by picture. We were also able to make the addition and subtraction of the blue and red images; in a first approximation the results show respectively a picture where the whole feature can be seen, both its ascending and descending part, and a picture which is representative of the line-of-sight velocities, translated in intensity modulation.

Moreover we used well magnified pictures (0".7 /mm) to measure the length of dark threads in both wings, as well as their mean distance from the bright points, which are gathered either in a rosette center or in the center of elongated features. In either case threads surround the bright points and seem to emerge from them.

It is important to note that dark features, observed in the far wings as well as spicules on the limb, observed with high resolution, appear to have two or more quasi-parallel 'components', see Tanaka (1974), confirmed in Dara et al. (1996), therefore another parameter which is measured, both on the disk and at the limb, is the distance between threads or spicule 'components' respectively. By 'components' we mean the dark threads in which a spicule is analysed, when observed with high resolution. We make a comparison of the distance between them measured in the blue and in the red wing, as well as at the limb. As a rule, a long fine dark thread seen in one wing hardly ever appears at the same location in the other wing; the shift is systematically observed both across and along the structure. The shifts are consistent all along a time sequence so it isn't possible that they are due to seeing effects.

It is possible that bunches of dark threads are the classical dark mottles, at lower resolution. Putting together 2 or more quasi-parallel dark threads, which are indeed separated by a distance of at least 0".2, produces a pattern with a smaller aspect ratio and, additionally, gives the impression that the pattern obtained in one wing of Hα is similar to the one obtained in the other wing. The whole phenomenon has been called a spicule, although it contains many stretched components. Such behaviour is well confirmed by the examination of the off-limb movie. There, we also noticed the systematic occurrence of multiple components of spicules which are never exactly on phase during the ascending part of their life.

4. RESULTS AND DISCUSSION

a) The best blue and red frames, covering a 18-minute time series, were selected for the measurement of the length of dark threads. Figure 1 shows the distribution of their length in the blue and red wings. Assuming that the ascending and descending material follows field lines having the same inclination with the sun's surface, we conclude that there is a small but statistically significant difference between the lengths of ascending and descending material as seen in projection on the disk. Moreover the number of the measured threads in the blue wing (2837) is about the same (2702) in the red wing for the same region. The number of the measured threads depends on the quality of the picture, i.e. the spatial resolution; the better the quality the more threads can be distinguished. Since the time difference between red and blue wings is very small, their quality is comparable, therefore no difference in the measured number of threads in the two wings can occur because of that.

b) If we fit a curve to the bright points observed at the region where threads are converging and we measure the mean distance of the threads from this curve, we systematically find that the downward moving material of the mottle (appearing in the red wing) is closer to the bright points, that is closer to the footpoint of the thread, while the upward moving material (blue wing) is significantly further away from the region where we suppose it is ejected. The mean distance for 'red' threads is 5".2 ± 1".9 while for the 'blue' ones 7".2 ± 2".6. It should be noticed that the histogram width doesn't represent the error, but the real dispersion of the feature distance. Figure 2 gives the distance distributions for both blue wing and red wing threads. Our interpretation would imply: i) upward motion is occuring at larger velocities than the derived ones, ii) the length of the features reflects the dispersion of velocities along it, iii) the spicule may originate at high layers and descend to
much deeper layers than it originates. Accordingly, the ‘head’ of an upward moving feature will systematically be seen further than the ‘tail’ of a downward moving one; moreover, the lifetime of a descending feature is larger than the ascending one; its length will also be larger. This is what one can clearly see in Fig. 1a and b.

Figure 3 (a,b,c,d) shows selected images taken from the time sequence we have studied; the whole sequence extends over 18 min, which is a period longer than the mean lifetime. Altogether we give both wings \( \pm 5/8 \) A(top), their sum and their difference (bottom) for each time. The sum of the two wing images gives in fact the whole structure, descending and ascending part, while the difference is representative of the motion of the material. During the 18-minute period, we see great changes in the motion of the material, so by the end we aren’t able to recognize any pattern of its motion. In the dopplergrams of figure 3 we can also see that the corresponding to the dark feattures motion is strongly upward. Again, this is consistent with what we saw on the movie of the off-limb spicules.

c) Furthermore, to interprete on-disk observations of dark threads, we did not assume that the H\( \alpha \) profile can reliability be deduced for a single feature. First, from disk observations, it is rather hazardous to assume a ‘standard’ H\( \alpha \) profile of the background chromosphere: structures are everywhere present at high spatial resolution. More important, we showed that structures seen in one wing are never identical to those seen in the other one. This means that individual line profiles are narrow, result which is in excellent agreement with emission line profiles of the limb spectroscopic data given by Dara et al. (1996). Figure 4 shows four typical spectra at different times and different heights of the quiet chromosphere, obtained with the ESG of NSO-Sac Peak with a concentric curved slit parallel to the limb. The width of the spectra corresponds to 0.622 nm on the CCD chip and the height of each spectrum to 58.3 "'. Multiple line profile as well as very narrow ones can be clearly seen.

Moreover, considering the interspircular medium presumably at rest, there is a large difference in optical thickness between intensities observed in the line wings and those observed in the center of H\( \alpha \). Roughly, in the line wings we see high pressure but cool features which correspond to Doppler displaced structures, while at the line center low pressure ones are also seen, including the interspircular material of possibly higher temperature. The interpretation of our result is that spicules being systematically inclined, a blue shift would correspond to an outward motion from the ‘source’, i.e. from the center of the rosette or bright points, against gravity. At least a part of this gas, channeled by the magnetic field, will reach a distance larger than the ‘average’. On the contrary, the downflowing gas towards the rosette center is seen at a shorter distance. This interpretation is also in agreement with the most recent description of the spicule dynamics given by Suematsu et al. (1995).

Regarding the measurements of the proper motion of off-limb large spicules, we considered material detached from a giant spicule. Observations were also carried out photographically, using a 0.1 nm FWHM H\( \alpha \) filter at the limb taken with the 16"-inche coronograph (Koutchmy and Loucif, 1991). Table I gives the velocities and the corresponding time.

<table>
<thead>
<tr>
<th>Time</th>
<th>Velocity</th>
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<tbody>
<tr>
<td>10:52:21</td>
<td>110 km s(^{-1})</td>
</tr>
<tr>
<td>10:52:41</td>
<td>100 km s(^{-1})</td>
</tr>
<tr>
<td>10:52:55</td>
<td>98 km s(^{-1})</td>
</tr>
<tr>
<td>10:53:15</td>
<td>62 km s(^{-1})</td>
</tr>
<tr>
<td>10:53:42</td>
<td>73 km s(^{-1})</td>
</tr>
</tbody>
</table>

As we can see the velocity is decreasing as the detached part is moving upwards. The mean velocity of the ascending material, about 80 km s\(^{-1}\), is large; velocities of this order have, however, already been reported for coronographic giant spicules by other observers.

It is noteworthy that in both off-limb and on-disk observations we find ‘multiple’ structures. As shown in Figure 5 double component spicules can easily be identified on the limb. Our broad band off-limb observations at H\( \alpha \) center show well Doppler-shifted spicules with both upward and downward motions. This is especially true for the nearby radial motions which are dominant in the polar regions chosen for our observations, so that Doppler shift effects are reduced in our passband. The smallest distance in the best broad-band high resolution images at the limb is close to the resolution limit which is about 0"'.2. One can see up to four components on the movie. Many examples of such multiple structures can be also identified on the disk filtergrams.

Spicules shown on figure 6 were observed over a quiet region, at low latitudes where spicules are inclined. There, we used a narrow passband shifted consecutively in the blue and the red part. Again multiple components, with large velocities(> 50 km s\(^{-1}\)) are observed well above the limb.

5. CONCLUSIONS

The above analysis has shown that we identify the same small-scale dynamical phenomena from on-disk and off-limb observations. We did not touch many aspects of the physics of spicules. Let us, at least, note that large accelerations are observed at
the spicule base. From the examination of the movie taken off-the-limb, with images similar to figure 6, we deduced an acceleration of typically >5g within the first Mm of the spicule ejection, where g is the solar gravity at the surface. On the other hand, from table 1, we readily calculate a deceleration of 2g, which means that, besides gravity, other forces are present. Watching carefully the movie made from on-disk digitized images, we were not able to measure the acceleration at the base of dark threads, which we believe are identical with spicules. This is mainly due to opacity effects resulting from the overlapping of structures, as well as, to the systematic appearance of bright mottles related to the bright magnetic features near the feet of the spicules. We intend to extend our study with spectroscopic observations. Moreover, it would be fundamental to observe also the transition region and the coronal emissions during the period of the spicule impulsive phase; such an observation could probably be carried out with one of SOHO coronal experiments, as well as in SXR with SXT on Yohkoh.

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Figure 1: Dark thread length distribution in the red (a) and blue (b) Hα wing.

Figure 2: Distance distribution of the ascending and descending features measured from the nearest bright points in the red (a) and blue (b) Hα wing.
Figure 3: Intensity maps at $H\alpha \pm 5/8$ Å (upper left and right) and the corresponding sum and difference (down left and right) at different times a, b, c, d.

Figure 4: Limb spectroscopic data in $H\alpha$. At top left: spectrum in the heart of the chromosphere near $H=2$ Mm; top right and bottom spectra: at the top of the chromosphere near $H=4.5$ Mm. Arrows show cases of i) well Doppler shifted profile of a thread at low height (white arrow at top left) ii) Y shaped profile (white arrow top right), ii) multiple line profile (white arrow bottom right) Very narrow (<48pm) line profile (black arrow at bottom left), and one without large Doppler shifts (black arrow at bottom right).
Figure 5: High resolution images selected from a video-CCD movie to show the ‘forest’ of spicules at the limb, starting from a distance of 0.35 Mm (photospheric limb). A detachment is also observed there on a single component of the spicule.

Figure 6: Spicules observed over a quiet region at low latitudes, on both \( \text{H}\alpha \) wings (upper left and right). Their sum and difference (velocity map) are shown below (upward is bright, downward is dark).