PART I

THE QUIET CHROMOSPHERE: LIMB PHENOMENA

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SPICULES AND THEIR SURROUNDINGS

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(presented by J. Rösch)

I have taken the liberty to change the title of this review from the one announced in the programme, because I intend to look at the empirical knowledge about spicules both from limb and disk observations, also because it does not seem feasible to discuss the problem of *relations* between spicules and their surroundings without starting by what is known about spicules themselves.

This introductory lecture has of course no ambition to be exhaustive. For more thoroughness one should go to the excellent reviews by Giovanelli *et al.* (1967), and and Beckers (1968, 1972). The 1972 review paper by Beckers was a great help to me in preparing this contribution.

Spicules were first extensively observed and described by Secchi one hundred years ago. Their name was, I believe, invented by Roberts in 1945, and it has been a very successful word.

At present, one can distinguish between three definitions of spicules:

– *Definition 1:* Spicules are jet-like features which, under good seeing conditions, can be seen through a broad band Hα filter to extend *above* the more or less continuous chromospheric Hα fringe of roughly 4000 or 5000 km thickness (see Figures 1 and 2).

– *Definition 2:* Spicules are elongated features present at all heights in the chromosphere above 1000 km and made observable by a variety of techniques, but mainly by narrow band Hα filters used at various wave lengths inside the line, both on the disk and at the limb. (See Figure 3).

Some attention will be given later to the following question: are spicules according to Definitions 1 and 2 the same physical phenomena? or in other words do the high level, jet-like spicules above 5000 km represent only a selection of the tallest, most favourably placed relative to the limb, among a larger population? And does this larger population (spicules according to Definition 2) represent the only fine structure of the chromosphere?

– *Definition 3:* Spicules are a 'dense component', sometimes hot, sometimes cold, used to improve the fit of model chromospheres to various spectral data which refuse to conform to the analysis done under the hypothesis of sphericl symmetry.

1. Spicules in the High Chromosphere (above 6000 km)

1.1. Size

According to the best observations by Dunn (1960) or more recent data from the Sacramento Peak vacuum telescope, the average diameter of spicules is 900 km with a real dispersion between 400 and 1500 km.

R. Grant Athay (ed.), Chromospheric Fine Structure, 3–21. *All Rights Reserved.*

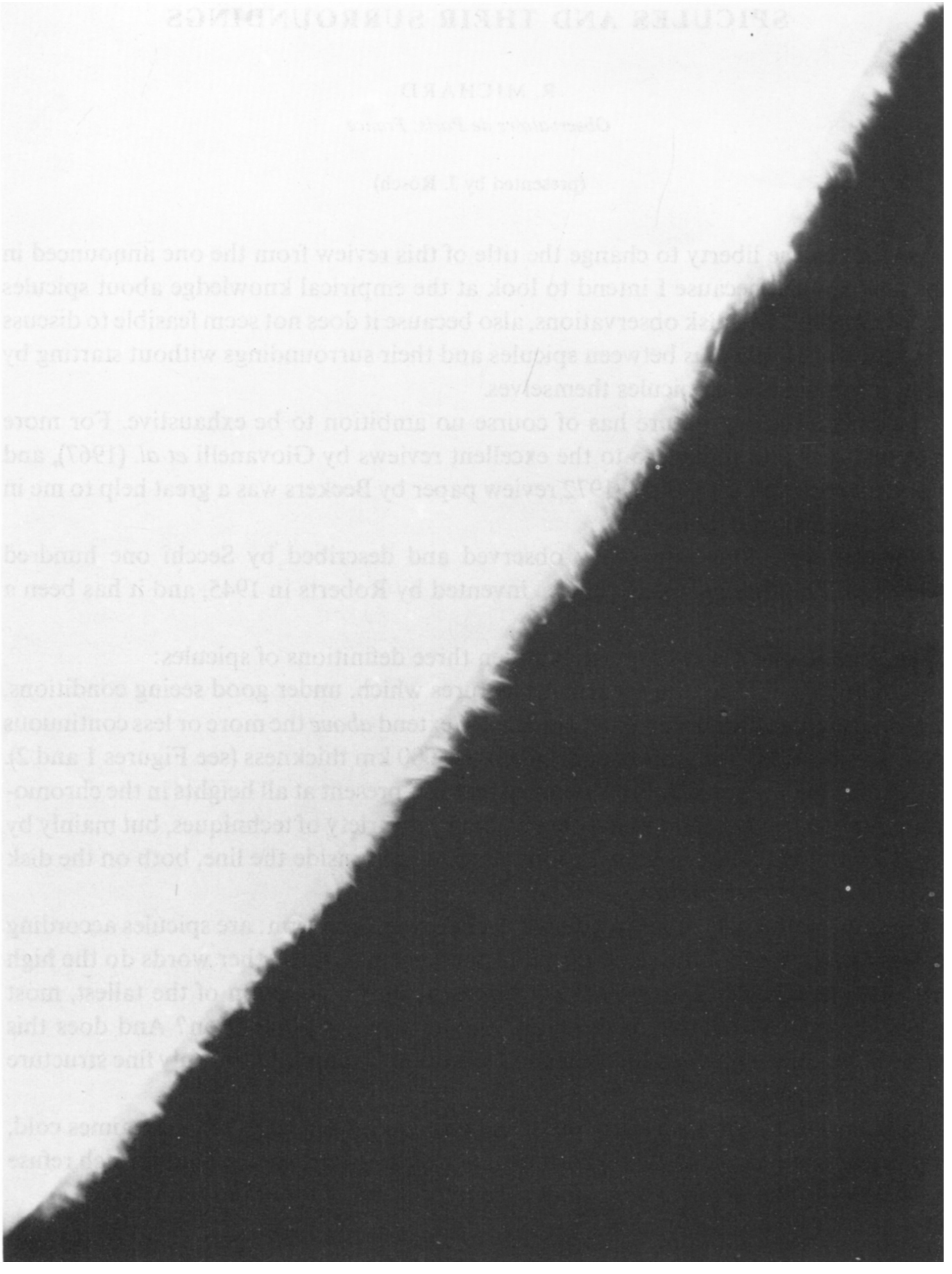

Fig. 1. Chromosphere photographed 0.9 Å in the wing of Hα with a 0.25 Å bandwidth filter, 1970, Oct. 14, Vacuum Solar Telescope, Sacramento Peak Observatory, Air Force Cambridge Research Laboratories.

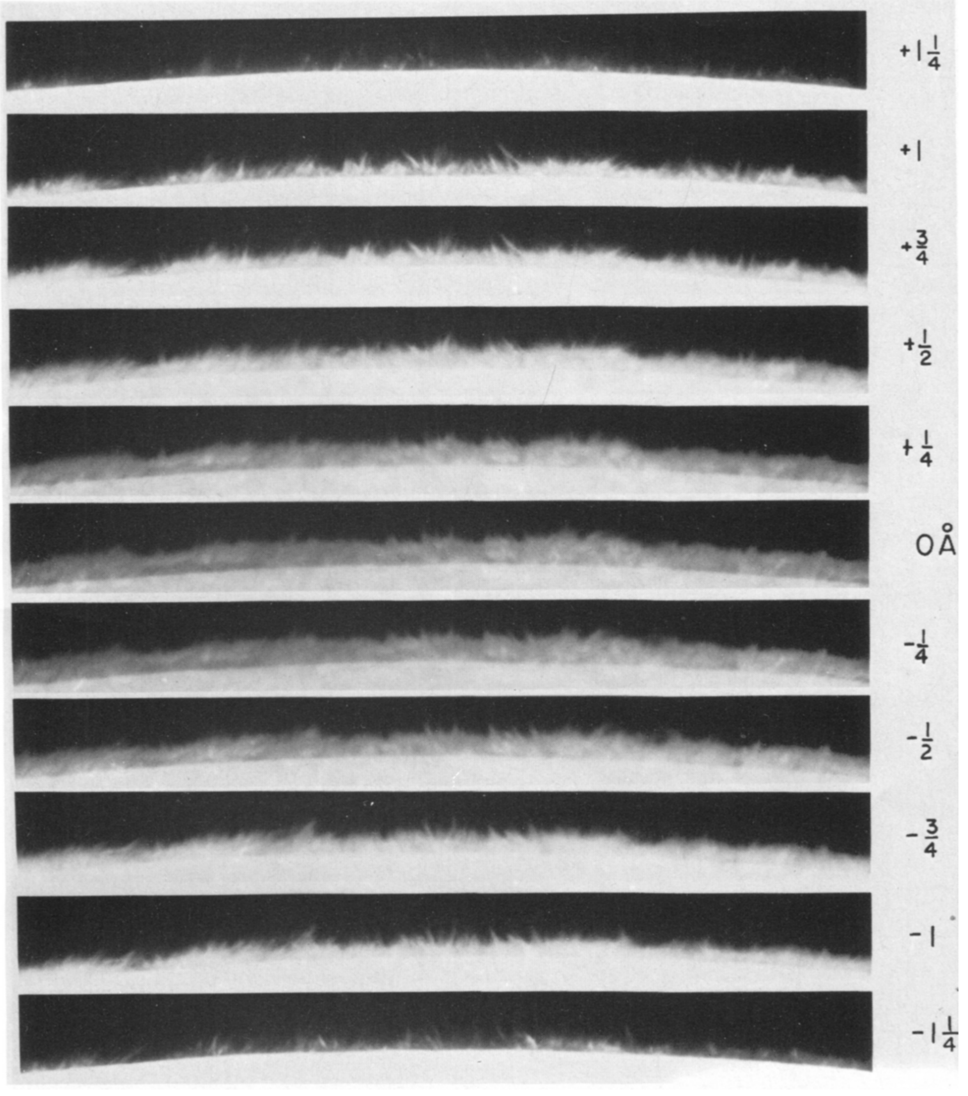

Fig. 2. A wavelength scan through Hα of the chromosphere. The birefringent filter has a bandwidth of 0.25 Å. A small amount of continuum light leaks through the filter causing the solar disk to show at the 0 Å position, 1970, Oct. 14, Vacuum Solar Telescope, Sacramento Peak Observatory, Air Force Cambridge Research Laboratories.

1.2. Counts

Above 6000 km the spicules are essentially isolated, and the countings along a given arc of the limb approximately give their actual distribution $S(h)$ in apparent height. According to various authors, $S(h)$ has a maximum of about 40 per 12 deg between 5000 and 6000 km; it decreases exponentially at greater heights: it also decreases sharply towards the limb until, somewhat below 3000 km, it becomes difficult to

Fig. 3. Spicules outline the edges of supergranule cells in this 0.25 Å bandwidth photograph taken 0.9 Å to the red of the Hα line. Dark absorption in the tops of loop prominences appears over the active region, 1971, Feb. 13, Vacuum Solar Telescope, Sacramento Peak Observatory, Air Force Cambridge Research Laboratories.

distinguish spicules (still with the broad band filter). Assuming this trend of the $S(h)$ function to be due to the mutual superposition of spicules, Athay (1959) corrected the counts to find the true number $N(h)$ of spicules intersecting a 12° arc of the limb; his corrections reach a factor of ≈ 3 at 5000 km and 15 at 3000 km and are quantitatively uncertain for many reasons.

In his review, Beckers concludes that the corrected counts can be fairly well represented by

$$N(h) = 10^3 \exp(-h/1950 \text{ km}) \text{ spicules per } 12°.$$

From this, assuming an even distribution of the spicules over the solar surface, we find their total number on the Sun to be

$$\Pi(h) = 10^6 \exp(-h/1750 \text{ km}).$$

These representations must not be used without caution in the ranges where they are mere extrapolations, in fact below 3000 km.

It should be noted that the observed function $S(h)$ depends on the distribution of spicules on the spherical solar surface, their distribution in lengths and in tilts to the vertical. Tilted spicules clustered in bushes, as shown by disk observations (Figure 3), are likely to overlap more often than vertical, evenly distributed, features.

Attempts have been made to evaluate the average proportion of spicule material along a given line of sight from spectral data, for instance by Michard (1959); these estimates very roughly agree with corrected counts, in showing that a tangential line of sight intersects in the mean more than one spicule below 3000 km.

1.3. Apparent Motions and Lifetimes

On successive Hα pictures, spicules appear to be 'ejected' from the Hα fringe, to ascend at an apparent velocity which is in the mean 25 km s^{-1}, to reach an average height of 9000 km; their top seems to remain stationary for a while; then the feature disappears, either by falling back along the same path (roughly half the cases) or by fading in brightness along its full length.

It is my opinion that the difficulty of observations are such, that the given description does not necessarily imply that two different mechanisms of disappearance are really at work. The observers note that the descent is much more poorly defined than the ascent.

On Dunn's films, Mouradian (1967) detected a tendency for many spicules to broaden or explode as they are fading. Although more recent data do not corroborate this result, according to Beckers (1972), it remains likely that spicules decay by a combined mechanism, part of the material falling back and part dissolving in the corona.

The 'lifetime' defined as the average duration of visibility above the inner Hα fringe is 5 min. There appears to be a genuine dispersion in the velocities, maximum heights and life-times. It is also interesting to note the reported positive correlation between velocity and maximum height and between life-time and maximum height: they are suggestive of a motion primarily governed by gravitational forces.

It is not yet certain that the apparent displacements of spicules tops are entirely due to material motions: we shall return to this in discussing observed Doppler effects.

1.4. Grouping of Spicules

Large scale configurations have been recognized in the occurrence and orientation of spicules by Lippincott (1957) and more recently by Platov and Shilova (1969, 1971).

The name of 'porcupine' was given to a fan-like pattern of about 10000 to 20000 km extent along the limb, in which spicules seem to radiate outward from an origin buried inside the Sun, 10000 to 30000 km deep. These formations should be related with the 'bushes' or 'rosettes' of dark Hα features on the disk to be described later.

Other systematic groupings in inclination to the limb are observed. At high solar latitude, the spicules have systematic inclinations, paralleling those of the polar plumes of the corona.

The local magnetic fields seem to be the only possible agent likely to give a non-random orientation to spicules, whatever their physical mechanism; it is thus believed that spicules trace magnetic lines of force.

Systematic equator-pole variations in spicule properties have been reported: polar spicules are less inclined, somewhat taller and faster and less numerous.

2. Spicules in the Inner Chromosphere

2.1. Evidence for an 'Interspicular Medium'

By using graded height sequences of high resolution spectrograms, Michard (1959) showed that all spicules seen above 5000 km can be traced much lower in the chromosphere in *the wings of the line* (Figure 2). This improved visibility arises from two reasons:

(1) Spicules with violet-shifted emissions are not masked by spicules with red-shifted profiles and conversely,

(2) While at the line center most of the spicules are likely to be obscured by an absorbing *interspicular* medium, this absorption is much reduced in the wings.

Michard developed a model for the interpretation of spicule spectra in the presence of a postulated interspicular medium. The local profile on a spicule should be represented by

$$\Delta I_{s,\lambda} = B_s [1 - \exp(-\tau_{s,\lambda})] \exp(-\tau_{is,\lambda}), \tag{1}$$

where $\Delta I_{s,\lambda}$ represents the difference of emission on a line of sight crossing the spicule and a nearby line of sight 'between' spicules, B_s is the source function and $\tau_{s,\lambda}$ the optical thickness of the spicule and $\tau_{is,\lambda}$ is the optical depth of the interspicular medium along the line of sight to the spicule.

A coherent interpretation of the data about spicules and the averaged spectrum of the chromosphere, is obtained by assuming that the source-function and the line-broadening parameter are both larger in the measurable spicules than in the interspicular medium. The main proof for the existence of an interspicular medium of significant optical thickness is the presence of a central reversal in the profiles of spicules below 5000 km; and the fact that this central reversal remains at the average wavelength of Hα, even when the spicule profiles are Doppler shifted.

According to Michard the total optical thickness of the chromosphere *between spicules* for a tangential line of sight and for the center of Hα increases from zero at 6000 km to $\simeq 10$ at 2000 km; below it increases to large and poorly determined values. The visibility of spicules is due to their larger broadening parameters and to their Doppler effects.

The arguments for an interpsicular medium of significant opacity in very strong lines have been further checked by Pasachoff *et al.* (1968) using high quality spectrograms in various lines.

Filtergrams of superior quality have been obtained by Dunn at the Sacramento Peak tower, using a filter of pass-band 0.25 Å shifted throughout the Hα line. A first analysis was recently reported by Lynch *et al.* (1973). An enormous number of spicules (according to definition 2!) are seen in the low chromosphere, sufficiently away from the line center: direct counts on the original negatives give $S(h) = 110$ per 12° at Hα± 0.75 Å and ± 1 Å, for $h \simeq 4000$ km. Since the structures are very different in opposite wings, the true number should be increased by a factor of nearly 2, and still larger to take account of the chance overlaps of features with similar Doppler shifts.

There is some inconsistency between these very large counts and the value of 950 km for the true spicule diameter, reported in the same paper. An arc of 12° at the limb contains only 155 times this spicule diameter: according to the Athay and Thomas (1961) analysis, if any number of spicules are projected on an arc of 155 times the spicule diameter, the maximum number of isolated features is $155/2e \simeq 28$.

A more quantitative, and perhaps more objective study of spicule abundances is presented in the same paper from counts of intensity enhancements on microphotograms at a given intensity threshold. The numbers of features at $I = 2\%$ (in percentage of the Hα continum at the disk center) reach maximum values $S \simeq 30$, at lower and lower heights when observing farther and farther from the center of Hα (Figure 4).

Although a quantitative interpretation of these fine data is still lacking, we suggest that the very fast increase of the number of features when going from the center of the line towards the wings is due to the decrease of interspicular absorption.

2.2. Doppler shifts and velocity field of spicules

As shown by spectrograms and by the recent narrow band filtergrams, many spicules show significant Doppler shifts. Among others Mouradian (1965) obtained extensive observations of spicules emission profiles carefully corrected for the influence of the 'interspicule medium'. His data are shown in Figure 5. *Above 6000 km* the rms line of sight velocities is about 10 km s^{-1}; the average velocity being zero. These results are confirmed by others, such as Nikolsky and Sasanov (1966), Athay and Bessey (1964) who also find a decrease of spicule velocities near the pole, and Pasachoff *et al.* (1968). As noted by Beckers, the Doppler data are consistent with the idea that the apparent displacements of spicule tops, are indeed due to genuine motions at the same

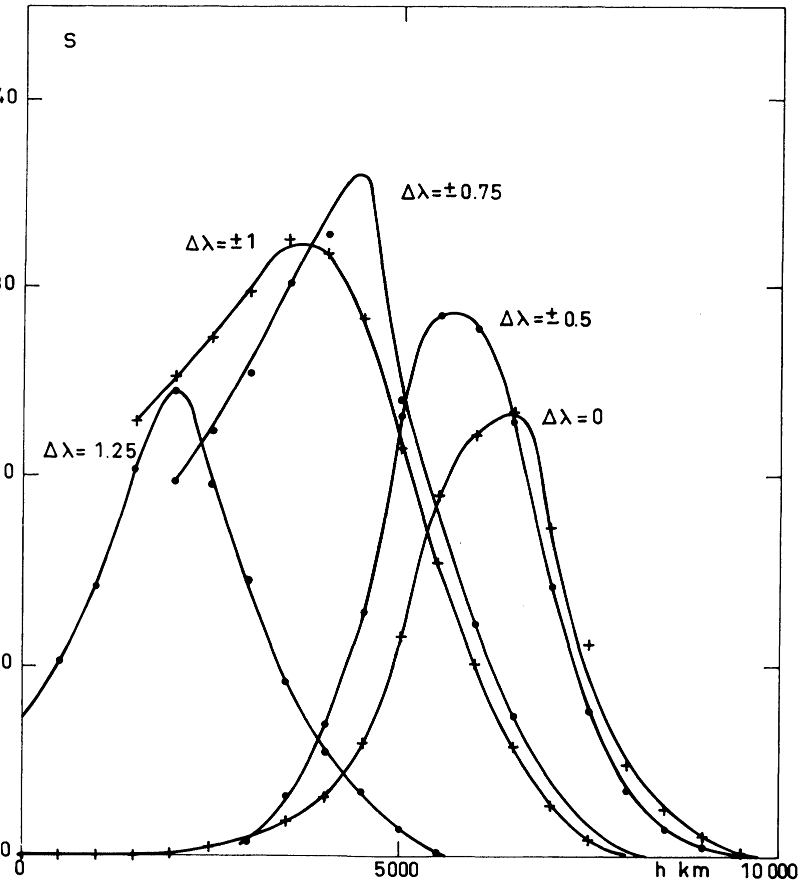

Fig. 4. Counts of spicules of treshold intensity 2% of the Hα continuum at the center of the disk, for various wavelengths $\Delta\lambda$ throughout the Hα line. The figure is drawn from the results of Lynch *et al.* (1973).

velocities: assuming a constant velocity of 25 km the rms line of sight somponent of 10 km s^{-1} would correspond to a rms tilt of 24° to the vertical. The rms tilt observed by Beckers is 19° and he assumes this to be a lower limit.

While many spicules, particularly those with the largest Doppler shifts, show an increase of Doppler shift with height, there appears to be no significant systematic variation of the rms Doppler shift with altitude above the limb.

During the time of spicule visibility their Doppler shift increases progressively, goes through a maximum and decrease rather abruptly, as first reported by Mouradian. This author did not find spicules reversing their Doppler motion, and suggested that the material does not fall back in the physical state and trajectory of its ascent. However Nikolsky *et al.* at Izmiran, Pasachoff *et al.* at Sacraments Peak, find a number of spicules actually reversing their Doppler motion before disappearing. However a majority of 80% conform with Mouradian's description, according to Pasachoff *et al.*

As already found for the apparent motions, the Doppler motions seem to indicate

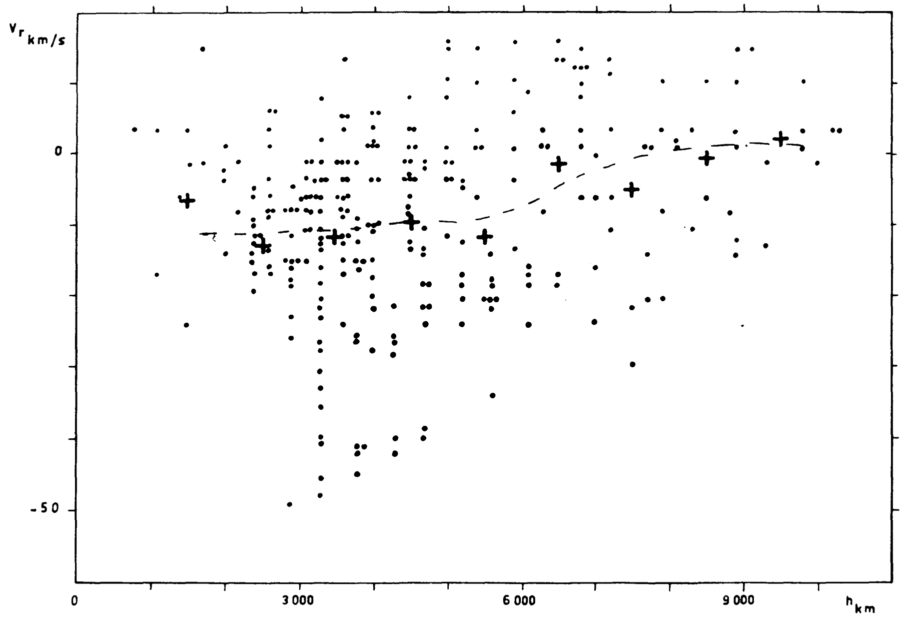

Fig. 5. Line-of-sight velocities of spicules as a function of height, from the analysis of Pic-du-Midi spectrograms (Mouradian, 1965). In the lower chromosphere, the Doppler shifts are systematically towards the violet, a result questioned by other observers. (Reprinted from *Ann. Astrophys.* 1965).

that the spicule material falls back in part in spicular form, and in part after 'dissolution' in the corona. It is possible that the two mecanisms are simultaneously at work, with a different relative importance in each spicule. Although direct correlations between the Doppler curve and brightness curve of spicules have not been presented, it seems likely that the large velocities occur during the youth and ascending phase of spicules; therefore ascending spicules should be brighter.

In the *low chromosphere*, Mouradian found the Doppler effects of spicule to have an rms value of the same order of magnitude as above, but to scatter around a mean of -10 km s^{-1}, i.e. spicules have systematic violet shift. This systematic effect was qualitatively explained by assuming (see Figure 4):

– that the sample at greater depths contains a large number of spicules situated towards the observer, the spicules rooted beyond the limb being masked by the inter-spicular medium;

– that these more easily visible spicules are predominantly tilted towards the observer, and ascending, according to the remark above.

Observations by Pasachoff *et al.* (1968), which refer to two levels, 5000 and 7000 km, do not confirm this curious result, although there is no real contradiction because of the different ranges of heights best covered by the two sets of data.

We should finally mention a result of great physical significance obtained by Pasachoff *et al.* (1968) from their simultaneous time sequences of Hα spectrograms at two heights, separated by 1800 km; the time variations of the Doppler shift occur nearly simultaneously at the two heights, the average time delay being only 2.5 ± 2 s.

2.3. Spicules in other lines than Hα

Spicules have been observed in practically all strong chromospheric lines of H, He and Ca^+. Here I shall summarize some results relevant to spicule morphology and perhaps in relation with the interspicule medium. Later in this symposium Dr Jefferies will review the physical conditions in spicules as derived from their radiative properties, and Dr Frazier will talk about the mysterious internal motions inferred from peculiarities in the profiles of spectral lines.

Profiles in Hβ and Hγ and also in the H and K lines are qualitatively similar to those of Hα. However in Hγ and Hβ the characteristic self-reversals that we have attributed to the interspicular medium occur only at lower apparent heights.

Mouradian (1965) measured simultaneous height sequences of spectrograms in Hα and Hγ. At great heights a number of faint Hα spicules cannot be detected in Hγ due to reduced emissivity. At low heights, however, the number of spicules seen at the center of Hγ is larger by 30% than can be distinguished in Hα, although the resolution of the Hγ spectra is less good. This is attributed to the reduced opacity of the interspicular medium in Hγ.

Incidentally, the broadening parameters in Hα and Hγ for a given spicule, assumed to be purely a Doppler broadening, are in the ratio of the wavelength of the two lines, as expected.

The He lines are of special interest; simultaneous observations in the D_3 line and Hβ were examined by Giovanelli *et al.* (1965). There is a one-to-one correspondence between the features seen in both lines and they coincide in position within the accuracy of the comparison, i.e. better than 1″. On the other hand, the shape of the D_3 line is gaussian, showing that both the spicules and the interspicular medium are optically thin in this line.

These results were confirmed, refined and extended to the comparison of other lines, by Pasachoff *et al.* (1968). These authors conclude

> that a given spicule emits simultaneously in lines of hydrogen, helium and calcium. This does not mean that the emission comes from the same volume within that spicule; for instance sheathed models are not ruled out. We have found further that although the ratios of intensities in the lines of these elements are often constant, there are certainly features that are relatively brighter in one or another of these lines.

3. Chromospheric Fine Structures on the Disk

The description of the chromospheric fine structure on the disk has been rather a controversial subject, notwithstanding the good observations obtained by several observers. In such lines as Hα or K the chromospheric structure appears on the disk with rather complex changes of morphology depending on wavelength inside the line, the considered line, and position on the disk, Also the question of whether a given observed pattern should be described in terms of 'dark features' or 'bright features' or a convenient mixture of both dark and bright things, has always been a troublesome one with solar observers.

3.1. Summary description

Let us first look at the image in Hα somewhere towards the limb, and rather far off the center of the line, say 0.75 Å, for instance from the beautiful observations by Dunn shown in Figure 3.

One see rows (or 'bushes') of elongated *dark fine mottles* of lengths 5–10000 km. The center-limb variations of the appearance of the dark mottles indicates that they are moderately inclined to the vertical. Nearer the disk center the grouping of dark mottles takes the appearances described by Cragg *et al.* (1963), Beckers (1963) and

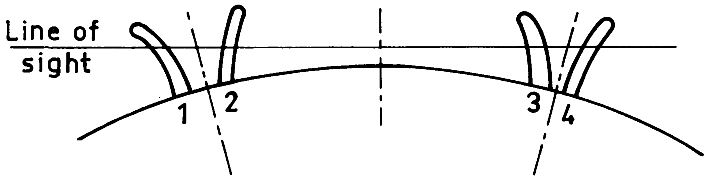

Fig. 6. Tentative explanation of Figure 5 results by a bias favoring the visibility of spicules tilted towards the observer and generally ascending.

others, under the names of 'rosettes' and 'chains' (or more accurately 'double chains').

Shifting to the center of the line, one also sees *bright fine mottles* which occur in close association with the dark ones. When looking away from the disk's center, the bright fine mottles are situated farther from the limb than the dark ones, which seem to be rooted in a row of bright features. Banos and Macris (1970) claim that there is a one-to-one correspondence, each bright mottle being the base of a dark elongated one. Other observers, such as Bhavilai (1965) and Bray (1969), do not agree with this simple relationship, and give to bright mottles the full status of independent features. Near the center of the disk, bright mottles are more concentrated towards the center of the rosettes than the dark ones. Both the appearances, at the center of the disk or near the limb, suggest that bright fine mottles do not reach as high in the chromosphere as do the dark ones.

When following individual mottles throughout the Hα line either on spectrograms as done by Grossman-Doerth and von Uexküll (1971, 1973) or on filtergrams by various authors, such as recently Bray (1973) and Loughhead (1973), it is found that most bright fine mottles become dark in the wings, while dark fine mottles remain dark in the whole profile.

The rosettes, chains and bushes of dark and bright fine mottles form under low resolution, the *coarse mottles*; these are either bright or dark depending on the wavelength: bright at the center of Hα or in the strongest lines of Ca^+, dark in Hβ, Hγ, ... and He 10830. The coarse mottles trace (in rather 'dotted lines') the contours of large cells; these were shown by George Simon and Leighton to correspond to the

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cells of the supergranulation and their contours to the regions of locally enhanced magnetic field. It is thus assumed that the occurrence of the fine structures described above are associated with the geometry of the solar fields. These relationships are illustrated, qualitatively, in Figure 7.

It is important to note that the most prominent and most studied fine features of the

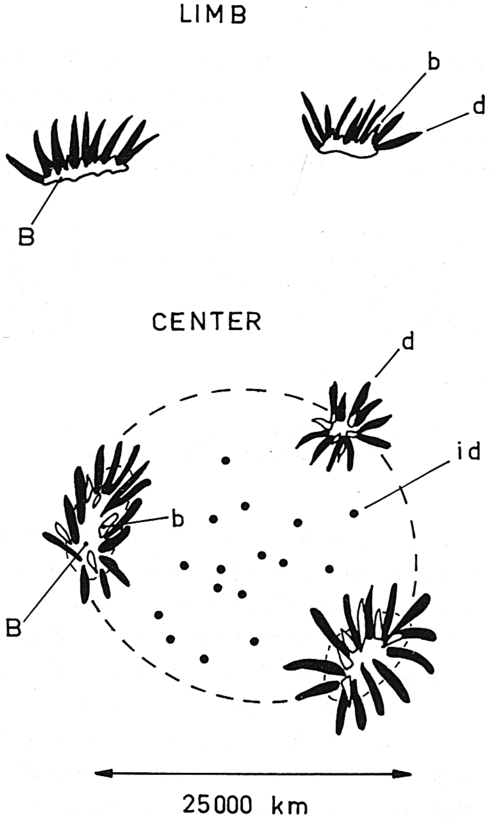

Fig. 7. Scheme of Hα fine structures after Beckers (1968). Bright and dark fine mottles (resp. *b* and *d*) cluster in 'rosettes' or 'double chains' at the center of the disk; near the limb their projected appearance is termed 'bushes'. Bright coarse mottle (*B*) occur in the central area of rosettes. Inner cell dots (*id*) are scattered between chains and rosettes.

chromosphere seem to form a *special class of structures*, associated with the presence of enhanced magnetic field. They are referred by Beckers to BSG structures (for Boundaries of Supergranules).

I am not aware of very systematic attempts to describe the structures inside the cells (or ISG regions for inner supergranules). Near the center of Hα or slightly redwards they look striated by faint contrast threads (bright or dark?) which seem to prolongate the fine elongated mottles of chains and rosettes, and are called fibriles. These disappear in the wings while the photospheric granulation appears. On the

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other hand Beckers emphasizes the presence of numerous dark point-like mottles at Hα − 0.5 Å, in possible correspondence with similar bright grains in the K line.

3.2. Some properties of fine mottles in BSG regions

The most easily observed and best studied features are the *dark fine mottles* in Hα.

- Their average size, about 800×6000 km;
- Their total number on the Sun, about 300000;
- Their average duration, 10 min or somewhat smaller;
- Their average inclination to the vertical, 21°, according to Beckers (1963).

As regards *bright fine mottles*, the situation is less satisfactory because there are discrepancies between the results reported by different observers. It seems, however, that their properties are practically the same as for dark mottles, except that they are shorter and perhaps less numerous. The morphological properties listed so far, show that both types of fine mottles are good candidates for indentification with spicules. The case is most clear for the *dark* fine mottles in view of the divergence remaining between observers in the description of the bright mottles. We consider as quite certain that the *dark fine mottles as observed in the wings of Hα* form a large proportion and perhaps the bulk of the spicule population (according to our Definition 2).

There occurred a controversial point in this problem because Bhavilai (1965) and Mouradian (1965), when trying to connect elongated structures across the solar limb, found correspondence between spicules and *bright* features *just inside* the limb. Accordingly, Bhavilai (1965) and Giovanelli (1967) favored the identification of spicules with bright fine mottles only.

This argument is not however decisive, because the same feature in the outer solar atmosphere may very well look dark at the center of the disk and bright at 1000 km or 2000 km inside the limb, due to the change of the effective depth of origin of the radiation in both the feature and the 'background'.

Beckers (1968) carefully discussed the problem of identification of spicules with disk details. He suggested going further than the simple alternative of always dark against always bright: spicules might be dark or bright on the disk depending on wavelength in Hα, position on the disk, position within the spicule (root or top) and, eventually, phase in the evolution of the feature. From a physical model of spicules (diameter, Te, Ne as a function of height) he derived the emergent radiation of the feature seen on the disk as a function of μ and λ in a few lines, thus predicting the visibility and contrast.

In the most recent calculations of Beckers, theoretical spicules should be dark throughout Hα at the disk center (except that their root below 2000 km could easily be bright!); towards the limb the spicules are bright for the low part of their length and dark for the upper part at the center of Hα; they are dark in the wings.

In the K_3 line their lower part only is bright at the disk center: they are bright all along near the limb. In the He 10830 line spicules should be dark everywhere.

The matter is still complicated because spicules have a *genuine dispersion* in physical properties, probably in correlation with phase in their evolution. We must therefore conclude that *both* dark and bright elongated fine mottles of the disk Hα picture appear as spicules in the low chromosphere and contribute to the various aspects of the limb image. It is very likely that there exist 'connecting' bright and dark features that are part of the same spicule, as observed by Banos and Macris.

3.3. Velocity field of the disk chromospheric fine structure

The disk observations of Doppler effects are potentially suitable to extend our present incomplete information on the velocities of spicules. However, the problem is difficult and the present situation rather confused, with discrepancies reported by different observers. This is not surprising in view of the intrinsic difficulties of the observations themselves, and of the problems outlined above in associating with spicules some easily identified class of disk structures.

One should not also underestimate the difficulty of recovering information on the actual velocities, from the casual observation of the profiles, when one has to deal with moving material embedded in an absorbing medium at rest. This was pointed out by Beckers (1968) and others.

Indications on the velocities have been deduced by Beckers (1963) and Bhavilai (1965) from the differences of appearance of dark fine mottles in both wings of Hα. Title (1966, 1967) made velocity records by photographic subtraction of the blue and red images. These authors agree in the fact that downflow occurs predominantly towards the centers of rosettes. Beckers finds dark mottles reversing their velocities during their lives, but Title does not.

Recently Bray and Grossman-Doerth *et al.* derived the Doppler effects of fine mottles near the disk center from spectrophotometry of the profiles: these were represented by the so-called 'cloud model', that is with the Equation (1) given above (but for the factor representing absorption by the interspicular medium). The results fall in the range ± 9 km s^{-1} and the rms value is much smaller than found from limb spicules, indeed by a factor of 2 or 3.

It is the opinion of the reviewer that this discrepancy does not cast doubt on the identity of spicules and the fine structures of the BSG regions. Its explanation must be sought in systematic effects arising from the fact that the structures are observed under very different conditions: in one case (limb), at great heights and along an horizontal line of sight; in the other case (disk center), at low heights and along the vertical.

The systematic effects will include the genuine properties of the velocity field in spicules, various selection effects arising from different visibilities of the features in the two geometrical situations, and also eventual bias in the data arising from the methods of analysis.

In attempting to explain the discrepancy between line-of-sight velocities at the disk center and apparent velocities on the plane of the sky, or line-of-sight velocities at the limb, one should first consider as likely, systematic changes of the bulk velocities with height.

In several sets of observations there is evidence for an increse of velocities with height. This increase is large and evident for some spicules with large Doppler effects

(Michard, 1959). Beckers in his 1968 review suggested that perhaps these form a special class; they may also be cases where a general phenomenon is most readily seen.

One should also consider the probable distribution of spicule inclinations to the vertical which is far from being definitely known. For instance one could perhaps assume that most spicules are far from vertical, with a distribution of inclinations θ peaked at say 60° but extending towards small values.

Then above 5000 km at the limb only the tail of the distribution with small θ would show up, and provide for the large apparent velocities; near the center, the bulk of the population with large θ would provide most of the elongated mottles in rosettes, with velocities reduced by $\cos\theta$.

A situation with a wide variety of spicules inclinations, and therefore different visibilities near the disk center and at the limb, is in line with the ideas of Bhavilai and Giovanelli. However, there is presently no very strong argument to assume that the high standing, near vertical objects, and the very inclined ones, are of a different physical nature.

In summary I would say that careful and extended studies of the velocities of the fine structure of the chromosphere all across the disk and at the limb are still needed.

4. Summary

(1) The most conspicuous fine structures of the solar chromosphere under various appearances can be brought under the general name of spicules because they share the fundamental properties of size and forms, enhanced opacity (i.e. density), lifetimes and numbers.

(2) They show an intrinsic dispersion in all parameters that can be individually measured, notably in the source functions for Balmer lines emission. These fluctuations are related to height in the chromosphere, and most likely also to phase in the evolution of these features.

(3) In the spicules there is a predominant bulk motion along the axis, which is ascending during the first phase in the life of each feature, then stops and eventually reverses.

Important aspects in the kinematics of spicules are still controversial or unknown, although there are indications of changes with height, which need not be of the same sense for ascending and descending motions.

(4) Spicules are denser *than their immediate surroundings* at all heights. They are also most likely colder at heights greater than some unknown level, and possibly hotter below this level. However the height where the spicules start is uncertain between 0 and 2000 km. Models in which spicules start where the chromosphere ceases to be roughly isothermal are not excluded.

(This point 4 is a personal remark from data not reviewed above!).

(5) Spicules cluster in 'coarse mottles' forming a 'coarse network', delineating the boundaries of supergranules (BSG regions). The surroundings of spicules are thus somewhat special regions of the chromosphere with enhanced emission in many lines

such as center of Hα K line, Ly-α, and XUV lines characteristics of transition to coronal temperatures, as shown by OSO-4 and -6 data.

This shows enhanced density and perhaps also enhanced temperature; it is not clear how much of these emissions come from spicules, transition sheats around spicules or the general coarse mottle areas.

The coarse mottles are coincident with enhanced magnetic fields and there is a nearly continuous sequence of situations between the quiet sun coarse mottles, and the plages of active regions.

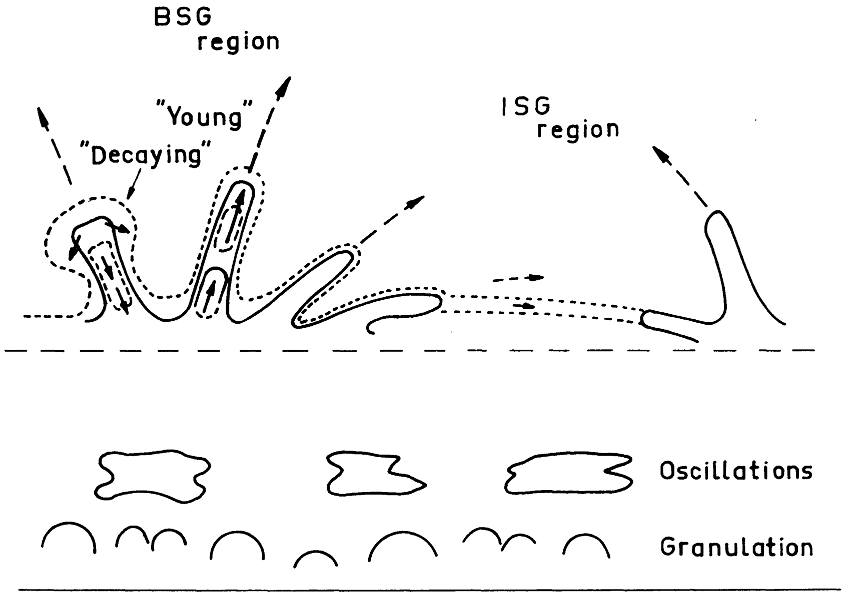

Fig. 8. Tentative summary picture of the chromospheric structure, shown along a vertical cut in the solar atmosphere. A distinction has been made between 'young' and 'decaying' spicules, assuming that the two classes have systematically different velocities and brightnesses.
– – → magnetic field; → velocity; – – – limit of roughly isothermal chromosphere; ------ transition layer $T \simeq 10^5$ K; == Spicular material with $S(\mathrm{H}\alpha) > 0.2$; and ----- spicular material with $S(\mathrm{H}) \simeq 0.1$.

(6) Away from the BSG, the chromosphere still has fine structures of at least two different types near the disk center:

– very elongated 'fibrils' near the Hα center with lower opacities than spicules, which are horizontal formations probably oriented by faint magnetic fields;

– point-like grains, prominent in the K line.

(7) The characteristic structures of the *photosphere* and *low chromosphere* (granulation, oscillations) are essentially unchaged between BSG and ISG, except perhaps for a tendency of oscillations to have a broader spectrum in BSG.

A concluding Figure (8) tentatively summarizes the possible situation as seen by the reviewer.

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DISCUSSION

The discussion was summarized by the chairman J. M. Beckers and divided according to topics:

(i) *Relation of Spicules and Polar Plumes*

Athay questioned the observational support for the association of spicules with polar plumes in the corona. An association could possibly exist (*Athay*) or would almost certainly exist (*Zirin*) but would be hard to establish observationally since coronal observations include many plumes well in front and behind the limb (*Beckers*).

(ii) *Height of Origin of Spicules*

Souffrin raised the question of the height of origin of spicules. It is very hard to answer this question observationally because of the merging of spicules with the background, or with other spicules, at low heights above the limb (*Athay*). In the wing of the Hα line one can see spicules well down because one selects only the few spicules with large Doppler shifts and/or line width. Indeed one sees there that some spicules start near $\sim$1500 km. This may however be explained by a sharp increase with height of the spicule Doppler shift or line width (*Beckers*). *Beckers* suggested to look in optically thinner lines like Hγ or Hδ where one might see spicules extending down even in the line center. Schmidt suggested to study the spicule apparent or Doppler velocity with height and/or time and to extrapolate downward to find the height with zero velocity which could be considered to be the height of origin. This seems however a very difficult and dangerous task (*Beckers*, *Thomas*).

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(iii) *Spectral Tilts of Spicules*

If a correlation exists between spectral tilts of spicules and their Doppler shift, this may have some implications about their kinetics, the magnetic field, for example, both accelerating and twisting motion (*Altschuler*). No such correlation is however clearly established (*Pasachoff*). What causes the spectral tilt (*Giovanelli*)? Two interpretations were offered: blending of two spicules (*Rösch*) and/or rotating spicules (*Pasachoff*).

(iv) *Height and Abundance of Spicules*

The average height and abundance of spicules is derived from spicule count statistics made at the solar limb. *Schatten* pointed out that counts should be made per unit area and not per unit angle at the limb. There is however no way known to us to do this and one will have to rely on limb counts per unit angle and convert these to numbers per unit area (*Athay*, *Beckers*). These counts will depend on the threshold intensity adopted for the spicule visibility (*Beckers*). *Zirin* suggested that threshold effects may be responsible for the differences in height of the spicule bushes as seen on the disk near the limb and at the limb.

(v) *Spicule Velocities and Mass Flux*

The apparent motions of Hα spicules is predominantly upward; 75 to 80% of the spicules show an upward motion (*Athay* quoting Rush and Roberts). Apparent velocities are near 25 km s^{-1}. Doppler shift statistics confirm the magnitude of this velocity provided that the shifts are caused by the motion along the spicule. This results in an upward mass flux sufficient to replace the solar corona in less than an hour (*Pasachoff*) or to give one hundred solar winds (*Beckers*). Since this is clearly not possible the spicule matter has to return in some less visible way (*Beckers*). *Souffrin* asked about the motion of the interspicular medium. Nothing is known about it. At the limb it shows a zero Doppler shift in contrast to the spicular motions (*Pasachoff*). Spicule-like structures seen on the disk show both up and downward motions (*Grossman-Doerth*) although some observers claim that in the wings of Hα (e.g. $\Delta\lambda \gtrsim 0.6$ Å) one sees a predominant downward motion at the supergranule boundaries (*Giovanelli*). Doppler velocities of the disk structures are however small (~ 5 km s^{-1}). *Grossman-Doerth* believes that this small velocity is caused by seeing effects. The real Doppler shifts may well be of the order of the 25 km s^{-1} spicule velocity. It could be that the predominantly dark, downward moving, mottles at the supergranule boundaries represent the returning spicule matter (*Beckers*).

(vi) *Observations in λ 10830 Helium Line*

Giovanelli stresses the importance of observations in the λ10830 line. On the disk some 30–50% of the total absorption in this line comes from the network boundaries. The absorption structures at the boundaries correspond to both Hα bright and dark mottles lending support to the notion that both dark and bright Hα mottles should be identified with spicules. The λ10830 absorption at the centers of the supergranule cells has no pronounced structure.

(vii) *Spicule Temperature*

Beckers raised the question of spicule temperatures. For the last 15 yr our estimates of the temperature has dropped from 50000 K to 15000 K, and according to some estimates, even to 6000 K. These low estimates (6000–8000 K) are the results of observations which do not resolve spicules but which rely on center-limb variation of EUV and radio data. The temperature is a very hard quantity to measure. There is probably not a unique temperature for all spicules and at all heights within a spicule (*Zirin*). *Giovanelli* reports some low spatial resolution observations of the limb chromosphere in λ10830, *Paschen* β and λ8542 (Ca^+). If the emission lines originate in spicules one derives $T \leqslant 7500$ K when one assumes that the lines originate in regions with the same nonthermal motion and temperature.

(viii) *Significance of Spicules for their Surroundings*

If spicules are removed from the Sun ('shaved off') how will the corona and solar wind be affected? There was no agreement on this question. They are probably important in the mass balance and in the energy flux (*Athay*). If spicules are absent in plage regions their absence and the behaviour of the corona and the solar wind above the plage may indicate the effect of spicules (*Wilson*). It is not clear whether spicules are absent in plages (*Beckers*). *Pasachoff* suggested that the solar wind expands mainly from the 'coronal holes'. *Brandt* responded that we really don't know the solar origin of the solar wind. Other things are different in plage regions apart for spicules so that even when differences are found in the corona and solar wind one cannot necessarily derive information on spicules (*Beckers*, *Jordan*). *Zirin* points out that independent of the question if spicules are significant for the solar corona and wind, spicules are important for our interpretation of observations of the chromosphere. *Sturrock* and *Schmidt* consider the existence of spicules quite unessential as far as the solar wind per se is concerned. *Schmidt* believes, however, that the understanding of spicules, and specifically of their mechanical energy flux, is important since it should be related to the as yet poorly known and understood mechanical energy flux which is responsible for the coronal heating.

(ix) *Role of Spicules in the EUV Line Intensities*

The combined area of the spicule surface is only approximately 5% of the total solar surface. At supergranule boundaries spicules contain however ten times the area of the underlying region (*Beckers*). *Pasachoff* suggests even higher values. It is therefore likely that spicules are a significant contributor to the enhanced EUV emission at the supergranule boundary. *Schmidt* pointed out that dT/dx may be very high across a spicule because of the insulation by the magnetic field. This would tend to decrease the spicule EUV emission measure. This topic will be further discussed by *Jordan* at another session.

(x) *Spatial Orientation of Spicules*

Vrabec commented on the appearance of the dark mottle (= spicule?) rosette structure when viewed at the disk center. Very few mottles are visible at the center of the rosette, most mottles seem to make rather large angles with the vertical forming what he calls "a flowering horn of a trumpet."