THE STRUCTURE AND DYNAMICS
OF THE SOLAR CHROMOSPHERE

Rawi Bhavilai

1964

A Thesis submitted for the degree
of Doctor of Philosophy in the
Australian National University,
Canberra.
The original work reported in this thesis is entirely that of the candidate, with the exception that the photometric tracings in Chapter 4 were made by Mr J.E. Shaw of the Division of Physics, C.S.I.R.O., Sydney. All subsequent reductions based on these tracings were, however, carried out by the candidate.

Ranu Bhattacharya

24 November 1964
ACKNOWLEDGEMENTS

I have great pleasure in expressing my gratitude to Dr R.G. Giovanelli for his constant interest and guidance. My sincere thanks and appreciation are due to Professor B.J. Bok for his kind advice and encouragement. Professor S.C.B. Gascoigne has kindly given his time generously for consultation and advice. I would also like to thank Dr H. Gollnow and Dr L. Searle for valuable discussions.

This work was carried out largely during the tenure of a Colombo Plan Fellowship, and subsequently an Australian National University Scholarship, while on leave from Chulalongkorn University, Bangkok, Thailand.
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SUMMARY

This thesis presents an observational study of the solar chromosphere in the light of the line $\lambda\,6562.8\,\text{Å}$ of hydrogen. Previous studies of the fine structures of the solar chromosphere and previous identifications of the spicules on the solar disk are reviewed. Various types of motions in the solar atmosphere are then described. The first part of Chapter 2 deals with the development of a two-beam birefringent filter from a $3/4\,\text{Å}$ bandwidth Lyot filter, giving theoretical, constructional and testing details. The 5-inch chromospheric telescope used in the investigation is then described. The observing techniques are given in the last section.

In Chapter 3, spicules have been studied (a) with an $1/8\,\text{Å}$ tunable filter and (b) with a $3/4\,\text{Å}$ filter equipped with a beam splitter yielding simultaneous photographs in opposite wings. These have enabled me to identify specific spicules with bright features observed on the disk and have led to a 3-dimensional model of various chromospheric structures.

The main disk features are (a) mottles which appear dark when observed in the light from one or both wings of the H$\alpha$
line profile, and also in the light from the line centre. These mottles merge to form the general chromosphere near the solar limb; (b) mottles which appear bright on the disk at all positions on the line profile. Features of type (a) have Doppler motions which shows the existence of loops of chromospheric matter usually flowing into the central areas of the clusters of dark mottles. Features of type (b) are found in clusters emerging from the central areas of the network chains or from the clusters of the dark mottles.

Spicules have been followed from outside the solar limb on to the chromospheric disk just inside the limb, where they appear as bright emission features identical with (b) above. The dark mottles, although converging to form the general chromosphere at the limb, do not extend from the chromospheric limb as spicules. There is however a close association between the dark and bright mottles.

A photometric study of 1/8 Å bandwidth filtergrams taken at seven positions on the H line profile is described in Chapter 4, which leads to two types of charts describing the Hα disk chromosphere. Typical profiles in the chromosphere are classified, from which Doppler velocities of representative features in the Hα disk chromosphere are derived.

Chapter 5 reports observations of time changes in the Hα chromosphere. There are two types of bright mottles:
(i) those with short lives around 80 seconds and (ii) bright mottles, usually occurring in clusters which last for long periods, in terms of hours. However, their appearances change and their brightnesses fluctuate indicating recurrent spicular activities. The Doppler velocity fields on the disk at Hα ±0.285 Å are found to be short lived and non-oscillatory.

The relations between local solar magnetic fields and chromospheric features are discussed in Chapter 6. Suggestions for future observations, as suggested by the results of the present investigation, are made, with particular emphasis on the structures in active regions. The significances of spectral purity and resolution, as well as spatial and temporal resolutions are stressed for future observations.

A paper on "The Double Limb in Hα" is included as Appendix 1 because the results described in that paper have a direct bearing on the results presented in this thesis. The paper will appear in the Ap. J., but may still be in press at the time of completion of this thesis.
CHAPTER 1

HISTORY AND GENERAL SURVEY

1. Introduction

The observed radiance of the sun in the visual continuum decreases rapidly as the extreme limb is approached, so that the solar limb in white light appears sharp. This would be predicted by a model atmosphere in hydrostatic equilibrium. The photospheric boundary is defined as that level at which the tangential optical depth in the continuum is unity. This corresponds to a radial optical depth of 0.004 at 5000 Å. The solar boundary in the light of some strong line radiations such as $H\alpha$, H and K, however, extends beyond the photospheric limb. In the $H\alpha$ line centre, for instance, the solar limb is, on average, some 5000 km higher and with a jagged upper boundary in contrast to the smooth photospheric limb. The sun is therefore considered as having a thin envelope: the chromosphere, which is opaque, and hence emitting strongly, in those spectral lines.

Spicules are short-living spike-like, thin, bright, elongated structures observed locally at the extreme
chromospheric limb, where they extend, in general, radially into the corona. In this thesis, Dunn's (1960) definition is accepted, namely: their mean lifetime is less than 30 minutes and the height above the photospheric level does not exceed 30,000 km. Spicules have been observed against the outer part of the unresolved chromospheric 'band' above the superimposed photospheric limb, and it has been generally believed that the chromospheric band consists entirely of unresolved spicules. The existence of spicules demonstrates the inhomogenous and non-static nature of the thin solar envelope.

The solar chromosphere was first noticed early in the nineteenth century, in total solar eclipses, as a thin dark reddish atmospheric envelope of the photosphere. With high magnification, Airy first observed the chromosphere's irregular outline. Its fine structure was not then apparent, probably due to seeing conditions, instrumental resolution, and other factors encountered in eclipse observations. In 1868 Jannsen and Lockyer independently used the spectroscope for the observation of the chromosphere and prominences outside of eclipses. C.A. Young observed the flash-spectrum for the first time in 1871. Secchi (1877) made visual observations of the chromosphere through a spectroscope whose slit was widened just enough to enclose the entire height of the chromosphere and set parallel to the solar limb. He
studied in detail the chromospheric fine structure and described it as comprised of numerous fine 'spikes' or 'vertical flames', for the faintest of which he estimated a width of 0'2-0'4. Secchi's drawing of the chromosphere (1877, Vol. 2, Pl. A) has been studied and referred to by a number of recent investigators who found close similarity between the various features of the drawings and the fine structures which appears in the photographs of the limb chromosphere obtained by various methods. All these recent observations referred to the upper part of the chromosphere.

Photographs taken in white light during the total phase of an eclipse in excellent seeing conditions also show the chromosphere with these short-lived 'chromospheric spikes', as they are called by Menzel (1931). His reproductions (Pl. IX) of the eclipse photographs of the year 1898, 1900, 1905 and 1918 show these chromospheric features clearly, most of them appearing straight and tilted at an angle to the solar radial direction. The usually straight appearance of these spikes, subsequently confirmed by various observers, is in contrast to the mostly curved features shown in Secchi's drawings.

An excellent series of white light photographs was obtained by Marriot of Swarthmore College in an eclipse expedition to Niafoo Island, 1930 October 21. Mohler (1951),
who studied the small chromospheric structures from three of
the Swarthmore photographs, called them 'jets'. He found
them to be uniformly distributed around the solar limb with
an average value of 3.0 jets per degree. He has given
histograms based on one of the photographs, showing eleven
spicules with height 2" and one spicule 1", among other long
spicules. De Jager's (1959) correction of 3000 km and Hiei's
(1963) correction of 2000 km, which have been applied to
Mohler's data are probably not justified, as Mohler himself
stated that the error arising from any lack of coincidence of
the limb of the sun and of the moon is much less than 180 km.
Spicules indeed occur at these low heights on such eclipse
photographs. Mohler obtained an average width of 1/8 from
measured jets.

Spicule images appearing on eclipse spectrograms, such
as obtained with the grazing incidence method by Suemoto and
Hiei (1962), are produced under even more different circum-
stances. The chromospheric arc breaks into spicular
structures with the same appearance for the lines correspond-
ing to the same height. Spicules of average size 3" are
found down to the 1500 km level in the weak lines, and lower
than that in the wings of strong lines. These spicules in
the wings of the strong lines were therefore interpreted by
Suemoto and Hiei as foreground spicules which are at a higher
level than their projected and observed heights. In a more recent paper, Suemoto (1963) concluded that spicules indeed extend down to the photospheric level.

In this connection, it is recalled that Lyot (1944) had noted that more structures appeared in the part of the limb chromosphere near the photospheric limb, when he tuned his filter to the positions in the wings of the Hα line. An examination of Secchi's (1877) drawings of the chromosphere indicates that Secchi probably observed the spicules extending down to the photospheric level. His use of a widened slit spectroscope in connection with a 15-inch refracting telescope for visual observations around H-alpha probably provided the circumstances for obtaining such observational data. It would be very interesting to repeat the observations of Secchi to find out what he actually saw and recorded.

Bugoslavskaya (1946, 1950) measured the height, number and orientation of the spicules of the 1945 eclipse. She found that the spicules at a given solar latitude were usually parallel to the coronal streamers at that latitude.

In 1943, Roberts (1945) found that these fine chromospheric structures of very short life-times could be observed using a Lyot type coronagraph. He observed the 'spicules',
as he called them, by taking 35-mm motion picture sequences of the limb chromosphere using the coronagraph combined with a quartz polaroid filter centered on the line 6563 Å of hydrogen. He found an average life-time of 4 to 5 minutes.

Roberts was the first to study the development of individual spicules, and found that a typical spicule first appears as a minute lump which rapidly enlarges and brightens and then elongates to its maximum height in a minute or two with an average apparent velocity of 30 km/sec. After that it gradually fades out without apparent motion. He estimated the average width to be 3"-4" and height of 10" at maximum extension.

Since Roberts' discovery, many investigators have studied the obvious characteristics of spicules. Dizer (1952) studied the height, velocities and life-times of spicules from Lyot's moving picture films taken through a birefringent filter. Rush and Roberts (1954) measured life-times, velocities and sizes of spicules from Roberts' series of moving picture films. Woltjer (1954) made photometric studies of the spicules from Lyot's photographs, and derived a model of the chromosphere in which the spicules are hot elements in a comparatively cold interspicular medium. Lippincott (1957) made extensive studies of the frequency distribution, heights, life-times and orientations from
Dunn's (1960) excellent photographs in $H\alpha$, taken with the 15-inch chromospheric telescope at the Sacramento Peak Observatory. Athay (1959) analyzed Dunn's observations and computed the number of spicules in the middle chromosphere. He arrived at a number of $9.3 \times 10^4$ spicules on the whole sun at the height of 3000 km, covering about 0.6 percent of the solar surface. Dunn (1960) made photometric measurements of intensity gradients of the chromosphere both in the spicules and in the interspicular regions, and measured the halfwidths of 42 spicules, arriving at an average value of 815 km.

The chromosphere can also be observed as a projection on the solar disk, where its inhomogeneity can be made apparent by filtergrams and spectroheliograms in various chromospheric lines. Detailed studies of the disk chromosphere are possible mainly only with sufficiently narrow spectral bandwidth and in exceptionally good seeing conditions. The chromospheric structures on the solar disk change significantly with lines of different elements, different lines of the same elements, and also with positions on the profile of the same line. The mean chromospheric height of emission of a number of strong lines is given by De Jager (1959). It is generally believed that at least some observed features on the solar disk may be identified as spicules seen in projection. Most of the proposed chromospheric models take spicular structure into
Table 1-1

Comparison of Spicule Characteristics as measured by various investigators

<table>
<thead>
<tr>
<th>Investigator</th>
<th>Diam.</th>
<th>Height</th>
<th>Life-time</th>
<th>Vel.</th>
<th>No./rad.</th>
<th>Total Number on Sun</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>sec. of arc</td>
<td>sec. of arc</td>
<td>min.</td>
<td>km/sec.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Secchi (1877)</td>
<td>0.2-0.4 min.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roberts (1945)</td>
<td>3-4 max.</td>
<td>10 max.</td>
<td>4-5 av.</td>
<td>30</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>Bugoslavskaya (1946,1950)</td>
<td>11 av.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mohler (1951)</td>
<td>1.8</td>
<td>6-7</td>
<td></td>
<td></td>
<td>171</td>
<td></td>
</tr>
<tr>
<td>Dizer (1952)</td>
<td>8-14 av.</td>
<td></td>
<td>2-2.5 20( active area)</td>
<td>40(non- ac.)</td>
<td>143</td>
<td>3x10^4</td>
</tr>
<tr>
<td>Van de Hulst (1953)</td>
<td>1-2 av.</td>
<td>10 av.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rush &amp; Roberts (1954)</td>
<td>2.8</td>
<td>7-20</td>
<td>3.3</td>
<td>31</td>
<td>42</td>
<td></td>
</tr>
<tr>
<td>Woltjer (1954)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>126</td>
<td>3x10^4</td>
</tr>
<tr>
<td>Lippincott (1957)</td>
<td>1.4</td>
<td>12(pole)</td>
<td>5.1</td>
<td>19(ascending)</td>
<td>11x10^3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10(eq.)</td>
<td>mean 24(descending)</td>
<td>26(max.)</td>
<td>1 min. (+4)*</td>
<td></td>
</tr>
<tr>
<td>Athay (1959)</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9.3x10^4 at 3000km</td>
</tr>
<tr>
<td>Dunn (1960)</td>
<td>1.1</td>
<td>26-28(max.)</td>
<td>5-15</td>
<td>120- av.</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>Suemoto &amp; Hiei (1962)</td>
<td>3.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Lippincott adds 4 min. to account for the first 5000 km in which spicules cover, if they start from the photospheric level.
account, yet curiously enough, no attempt has so far been made to include the different types of disk chromospheric structures in a chromospheric model.

For a long time since the first application of the spectroscope to eclipse observations, the main problem in chromospheric research has consisted in observing and interpreting the flash spectra. These exhibit anomalies (1) with regards to large emission scale height, this scale height itself increasing with height, (2) helium line emissions, and (3) enhanced emission from ionized atoms. Recently, more information about the properties of the chromosphere has been obtained from observations in the infrared, radio, and extreme ultra-violet part of the electromagnetic spectrum. It is therefore necessary for a model of the chromosphere to utilize the structures observed and attempt to explain these observed emissions.

2. Previous Identifications of Spicules on the Solar Disk

The first attempt at identifying spicules on the solar disk was probably that by Hale and Ellerman (1916). They identified the dark mottles appearing on spectroheliograms in H$_\alpha$ as the upper parts of hot gas columns which appear as spicules at the solar limb and which also appear as bright calcium flocculi in the disk K spectroheliograms. Spicules
have often been regarded as belonging to a class of prominences. Menzel (1931), for example, examining eclipse photographs of the limb chromosphere, commented that the difference between the chromosphere and prominences is merely one of degree. Kiepenheuer (1953) commented that the transition from prominences to the chromospheric 'structure' is continuous and subsequently (1957) identified as spicules small dark features occurring in the network observed in the wings of H. Following Unsold (1955), who proposed that spicules are 'Kleine Protuberanzen', De Jager (1957) identified them with the fine dark mottles appearing in spectroheliograms at the centre of H, which he photographed at Meudon with a slit width of 0.20 Å. De Jager (1959) described these fine mottles as roundish in form with diameters ranging from 1" to 2"; clusters of fine mottles producing the coarse mottles of sizes 2" to 11". The coarse mottles in turn are often arranged in a coarse network of sizes 34" to 70". He did not find any distinction between long spicules and short eruptive prominences.

Macris (1957), using the Arcetri spectroheliograph set at the centre of Hα, identified spicules with dark features of mean size 545 and mean life-time of 5.5 minutes. Brzez (1959), from filtergrams made in the centre of Hα, found that the dark roundish mottles show elongations to 11"-17" when
they are near the sun's limb. From considerations of their mean life-time, size and Doppler shifts, he identified the mottles with spicules observed at the sun's limb.

On a Mount Wilson spectroheliogram made in the centre of Hα, Cragg, Howard and Zirin (1963) drew attention to the dark bush-like vertical structures which they identified with clumps or groups of spicules. They have not observed that the small dark roundish features which were identified by De Jager and Bruzek have vertical structures.

Using high resolution filtergrams obtained with the O.C.S.I.R.O. 1/8 A tunable filter and a 5-inch chromospheric telescope, Beckers (1963) identified as spicules the dark fine mottles which are visible in clusters on the disk at ±0.5 A from the centre of Hα. He showed that the mottles, whose average length is 475 and width between 077 and 148 have vertical structures, and that they have first upward and then downward motions, with average life-times of 15.5 minutes.

It has generally been held that spicules cannot be followed from the limb down into low chromospheric levels, so that direct identification of spicules with disk structures would be impossible. In consequence, the above identifications of spicules on the disk have all taken the form of a comparison of the physical properties of the suspected disk
features with those of the spicules. This indirect method, although a very useful check can lead to ambiguous results.

3. **Motions in the Solar Atmosphere**

The observational study of local velocities on the solar disk was pioneered by the work of Richardson and Schwarzschild (1950), and followed the theory describing mechanisms for heating the solar chromosphere by acoustic waves generated by motions of the photospheric granules, proposed independently by Biermann (1948) and Schwarzscbild (1948). A group of three neutral iron lines at \( \lambda 6500 \) was used in the measurements of Doppler shifts, yielding a r.m.s. velocity of 0.37 km/sec. which was less than expected. The discrepancy was ascribed to the resolution limit of the instrument in comparison with the cell size ( \( \sim 150 \) km) of the turbulent elements. With the successful development of the vacuum spectrograph at the McMath-Hulbert Observatory, McMath et al. (1956) commenced the study of local Doppler shifts in the line-forming levels of the solar atmosphere by measurements on line displacements. The H\( \alpha \) line was found to vary greatly in width from point to point on the solar surface and frequently the line profiles were found to be asymmetrical. The K line was found to exhibit the well known double reversal at its centre. In both lines, the smallest line
elements were about 3"-5" arc in thickness. The r.m.s. velocities measured near the centre of the disk are 0.45 km/sec. for the Ba $^+ \lambda 5383$ line and 0.71 km/sec. for the Cr $\lambda 4626$ line.

Adapting a spectroheliographic technique previously used for the observation of the solar magnetic field to the study of velocity fields, Leighton (1960, 1961) discovered two types of motions in the solar atmosphere. The observations and results were described by Leighton et al. (1962). This method involves the photographic cancellation of two images obtained simultaneously at positions in the two wings of a Fraunhofer line symmetrically displaced from the line centre. The various lines used were of photospheric and chromospheric origin; e.g. Fe $\lambda 6102$, Ca $\lambda 6103$, Na D1, Ca $^+ \lambda 8542$, and H$\delta$. The first kind of motion is a large scale long-lived cellular pattern of horizontal currents in which material flows from an internal source towards the boundaries of each cell with a r.m.s. velocity 0.5 km/sec. The cells have typical diameters of 1.6x10 km and are rather uniformly distributed over the entire solar surface. The boundaries of the cells were found by Simon (Leighton, 1963) to coincide with the well known bright K chromospheric network. Simon (Symposium on Magnetic Field, Rome, Sept. 1964) also reported that photospheric magnetic
fields coincide with K bright mottles down to the limits of spatial resolution.

Secondly, there are the vertical quasi-oscillatory motions in the photospheric and low chromospheric levels. Elements of sizes larger than $2 \times 10^5$ km undergo oscillations with a period of $296 \pm 3$ sec., a velocity amplitude of about 0.4 km/sec., and a mean life of about 0.4 km/sec. No oscillatory motions were observed, however, in the core of $H_\alpha$ ($\Delta \lambda \sim 0.3$ A), but the velocity field with linear scale $3 \times 10^3$ km at that wavelength changes its appearance significantly and very rapidly with a typical life-time of 30 sec. In the far wings of $H_\alpha$, at $\Delta \lambda \sim 0.7-0.8$ A, the velocities are confined to a network of narrow 'tunnels' with predominantly downward motions. Simon (Leighton, 1962) observed that this network corresponds to the bright networks of K spectroheliograms, and therefore coincides with the boundaries of the 'super-granulations' cells of horizontal convective motions. There did not appear to be any relation between the horizontal motions and the short lived vertical oscillations.

Noyes and Leighton (1963) found that the average period of vertical oscillations decreased with altitude in the line-forming regions of the upper photosphere. Oscillatory fluctuation of the residual intensity in the cores of the
stronger lines was found with a smaller period, which also decrease with increasing height. They found a definite phase relation, intensity oscillation in the core leading velocity oscillation in the wing by about $163^\circ$, in the case of Na D1 line, indicating physical connections between the two oscillations. The weaker lines and the core of H$\alpha$ exhibited no intensity oscillations. The intensity oscillation was interpreted as being caused by a periodic heating of the atmosphere by quasi-adiabatic compressions induced by the velocity oscillation.

Prompted by the theoretical work of Whitney (1958) and also by Leighton's discovery, Evans and Michard (1961, 1962a, 1962b, 1962c) utilized the wriggly lines method for the observations of velocity and intensity field on the solar disk. A "random turbulent velocity" was defined by

$$ \xi = \sqrt{2} \left\langle \frac{1}{2} \right\rangle^{1/2} $$

in which $V$ is the measured r.m.s. velocity obtained from line displacements. The variations of $\xi$ with line strengths and positions on the solar disk were determined from carefully guided series of spectrograms. It was found that $\xi$ increases with the logarithm of equivalent width, and therefore with height in the solar atmosphere, in agreement with the results of Leighton et al. (1962). Lines of the same element, whose strengths are similar, show identical
velocity displacements, but the coefficients of correlation decrease as the differences in line strength (i.e. height) increase.

From measurements on Fraunhofer lines of Rowland intensities 2 to 20, Evans and Michard (1962c) found that the velocity field at the disk centre consists of short lived vertical oscillations of small elements of the solar atmosphere whose velocity amplitudes are 0.42 km/sec. and 0.81 km/sec. respectively for Ti λ 5174 line and MgI λ 5173 (b ) line. The periods of oscillation which are independent of amplitude appeared to decrease with height; being 249 sec. and 235 sec. respectively for the two lines mentioned above. The observed phase shifts between oscillations at different heights suggest that an oscillation starts as a progressive acoustic wave which gradually changes into a standing wave during its life-time which lasts about 2-3 oscillations. There is an indication of physical relations between continuum granular motions and the oscillations in that the appearance of a bright continuum granule is followed by an oscillation starting with a violet shift which attains maximum velocity amplitude about 40 seconds later than the maximum brightness of the granule.

The increase in turbulent velocity with height disappears towards the limb. Also the vertical oscillations
which dominate the area around the disk centre are undetectable when $\mu$ is less than 0.5. Near the limb, large elements of the solar surface with characteristic sizes 10000-20000 km exhibit non-oscillatory fields of persistence velocities around 0.5 km/sec. These were identified with Leighton's 'supergranulation' described above. The horizontal velocity field and the vertical oscillations, which were thus found to be the main components of motions in the solar atmosphere at the photospheric and low chromospheric level, are probably independent of each other and have a different physical origin.

Evans and Michard (1962b) also showed that the quasi-periodic fluctuations and Doppler shifts are identical in all lines observed from Rowland intensity 3 (FeI 5168.9) to intensity 20 (MgI 5172.7). For a given $\Delta \lambda$ the r.m.s. intensity fluctuation is greater in the violet wing than in the red for the strong lines, whereas the reverse is true for the faint lines. An explanation was given that violet shifts are associated with widening and/or strengthening of the line. About 70% of strong line shifts of + and - signs are associated with dark elements observed in the centre of the line. Most dark elements are associated with Doppler shifts; 55% towards the violet and 30% towards the red. Only half of the bright elements are Doppler shifted, and these more often
towards the red than towards the violet. It was concluded that, although some strong velocity oscillations could be traced up to the level of formations of the wings of Hα (Δλ = ±0.42 Å), the brightness structure of the photospheric line does not extend to the height of origin of the centre of Hα.

Jensen and Orrall (1963) observed fluctuations in vertical velocity and brightness at positions in the profile of the CaII K line, thus extending in height the observations of vertical oscillatory motions. Two FeI lines, 3931.1 and 3937.3 recorded simultaneously with the K line, showed quasi-periodic vertical velocity fluctuations of average period 273 seconds and r.m.s. velocity 0.203 km/sec. These were used in association with the brightness fluctuations in the wings of the K line on the assumption that the FeI lines are most probably formed within the height ranges of formation of the wings of the K line. The brightness in K (Δλ = ±0.55 Å) fluctuates quasi-periodically in time. This same fluctuation continues in to the far wings to Δλ = 2.21 Å, with phase differences less than 30 seconds, if any. The maximum brightness in K occurs about 1/4 period before the maximum upward velocity in the FeI line oscillation. No definite relation was found between the quasi-periodic fluctuations of
brightness and velocity at the K formation levels and at the higher levels which form the line core, although an autocorrelation analysis reveals that intensities in $K_0$, $K_1 (\Delta \lambda = \pm 0.15 \text{ A})$, and $K$ (line centre) are all periodic. The period of fluctuation in $K_0$, about 250 seconds, is equal to the period of fluctuation in $K_1$, while that of $K$ is about 170 seconds, is much shorter.

The study of vertical velocities in the height ranges of formation of the $H_{\alpha}$ line was made by Giovanelli and Jefferies (1961) on Doppler pictures obtained from pairs of $1/8$ A bandwidth disk filtergrams of limited resolution ($\geq 5^\circ$ arc) by a process of photographic subtraction. Each pair consisted of filtergrams taken at positions symmetrically placed in the wings of $H_{\alpha}$. Pairs obtained at various wavelength deviations were used. They found a strong correlation between brightness and velocity of the chromospheric mottles at all levels, the bright mottles having upward velocities and the dark mottles downward velocities. The chromosphere was considered as consisting of rising and falling columns which occur in widely spaced arrays. In the lower chromosphere, they are separated by relatively undisturbed region, while in the higher chromosphere the pattern becomes much finer.
Turbulence is considered as a type of chromospheric motion different from the large scale horizontal flow and the vertical quasi-oscillatory motions described above, but occurring in the same regions of the solar atmosphere. This type of motion most likely consists of comparatively high speed randomly moving, macroscopic elements much smaller than the resolution limits of observation. Its component velocity tangential to the solar surface is derivable from observed widths of line profiles in limb chromospheric slit spectra obtained either during eclipse or outside eclipse. The vertical component velocity could be calculated either from the density scale height of the chromosphere or from the profiles of the Fraunhofer lines in spectra of the disk centre. These determinations presume a knowledge of \( T \) at the particular levels which may be subject to uncertainty. De Jager (1959) gives extensive reviews of the work up to 1958. Pagel (1964) tabulates the more recent limb spectra observations outside eclipse from 1956 to 1962. De Jager's summary shows an isotropic turbulent field from the photospheric level up to at least 3000 km, with the mean turbulent velocity component increasing almost linearly from 2.7 km/sec. up to about 14 km/sec. respectively. Later works (Unno, 1959; Goldberg et al., 1959; Suemoto, 1963), however, show strong anisotropy in the solar atmosphere in that the
horizontal component greatly exceeds the vertical component: by about a factor of 3 from analysis of K reversal (Pagel, 1964). Since the observed turbulent velocities in the upper chromosphere have the contributions from mass motions of spicules, this anisotropy seems incompatible with the usual impression that spicules have predominantly vertical motions. To overcome this inconsistency, Suemoto (1963) suggested that the observed CaII K line with its well known K reversal characteristic arises from the algebraic sum of emissions from two distinct regions on the normal solar disk. Spicules which occupy small patches constitute the first region which gives an emission line with a width corresponding to 17 km/sec. The second region which covers more area is the bare top of the photosphere. It emits an absorption line spectrum, in the CaII K line, with a very sharp central core, corresponding to a turbulent velocity of about 6 km/sec. It was also proposed that the spicules extend down to the photospheric level and have a high temperature sheath as proposed by Moriyama (1961).

The content of this chapter covers those topics in chromospheric physics which are relevant to the reports and discussions presented in the following chapters. For reviews of chromospheric researches with extensive bibliographies,
references are made to Van de Hulst (1953), De Jager (1959) and Pagel (1964).
1. The Development of a Two-Beam Birefringent Filter

1a. The Lyot Monochromatic Filter

This is a quartz-calcite-polaroid filter designed to give an effective bandwidth of 3/4 Å around H\(_\alpha\). It was produced according to the original design of Lyot (1944) by the firm O.P.L. The birefringent plates are built into a cylindrical block of aluminium which is maintained at a constant temperature. Heating coils wound over the cylinder are parts of an electronic circuit which maintains the temperature of the elements inside the cylinder to a few hundredths of a degree. This scheme of temperature control is necessary because according to Dollfus (1956), an increase of one degree centigrade in temperature causes a decrease of 0.69 Å in the wavelength of the band transmitted by the quartz plates, while causing a decrease of 0.37 Å for the band transmitted by the calcite plates. The temperature controlled unit is housed in a rectangular box whose
dimension is 28.5 by 13.5 by 14.2 cm, the light beam traversing the longest axis. A description of the characteristics of the filter was given by Dollfus (1956). Griethuysen and Houtgast (1959) have made measurements on the transmission profiles of a similar filter.

1b. Modification of the filter

Giovanelli (1959, unpublished data) has initiated the concept of using the Lyot filter in conjunction with a polarizing beam splitter to obtain simultaneously in two channels, the light in the wings of the Hα line positioned symmetrically from the line centre. He computed the transmission profiles for three sets of arrangements giving passbands centering at ±0.25 Å, ±0.63 Å, and ±0.75 Å from the line centre respectively. All these arrangements involve the use of Lyot's "supplementary plate" which is in effect a birefringent channel filter whose bandwidth is 1.125 Å. This unit is not thermally controlled and is physically separated from the box containing the main section of the filter.

In modifying the equipment to my programme, it was first decided to follow the above arrangements. Obviously the "supplementary plate" needed to be controlled thermally with the same accuracy as the main filter, i.e. to a few hundredths of a degree. A new cell was therefore designed for holding
the supplementary plate which facilitated a temperature control system following the design by Kemhadjian (1961). The complete equipment was tested for wavelength drift by photoelectrically monitoring one of the output channels with the telescope guiding on the centre of the solar disk. It was found that, although the stability in transmitted wavelength was considerably improved by the temperature control on the supplementary plate, there was still a slow drift which was undesirable in a programme of this nature where one requires the maximum temperature stability, and hence wavelength stability throughout an observing period extending in terms of hours without interrupting the observation for monitoring. In this respect the temperature control constructed for the supplementary plate was unsatisfactory, and it appeared that a considerable amount of work and time was needed to improve the performance of the system.

I then considered the possibility of splitting the beam without the use of the supplementary plate and computed the transmission profiles of two configurations. These give passbands centering at $+0.285$ Å and $+0.75$ Å respectively from the $\text{H}_\alpha$ line centre.

lc. Theory of the Split-Beam Birefringent Filter

The transmission profile of a unit of a birefringent
filter consisting of a plane-parallel birefringent element followed by a polarizer is given in the form:

\[
\tau = \cos^2 \frac{2\pi \lambda}{W} ,
\]

with \( \Delta \lambda = \) the deviation from the central maximum transmission wavelength;

\( W = \) the width of the transmission profile measured at the half intensity points, which will be subsequently referred to as bandwidth.

Both \( \Delta \lambda \) and \( W \) have the same unit in wavelength.

For a filter consisting of \( n \) such units, the total transmission will be

\[
\tau = \tau_1 \tau_2 \cdots \tau_n
\]

\[
= \cos^2 \frac{2\pi \lambda}{W} \cos^2 \frac{2\pi \lambda}{W} \cdots \cos^2 \frac{2\pi \lambda}{W} .
\]

A unit can be tuned so that its transmission is zero at a specified wavelength. This can be done by turning the o polarizer 90° from the position giving maximum transmission at that wavelength. The transmission profile in this case will have the form:
\[
\tau_1 = \cos^2 \left( \frac{\pi}{2} \frac{\Delta \lambda}{W} + \frac{\pi}{2} \right) \\
\quad = \sin^2 \left( \frac{\pi}{2} \frac{\Delta \lambda}{W} \right)
\]

(2-3)

If the polarizer is replaced by a polarizing beam splitter, such that two components with polarization 90° apart are separated, the transmission becomes:

\[
\tau_1'' = \cos^2 \left( \frac{\pi}{4} + \frac{\pi}{2} \frac{\Delta \lambda}{W} \right),
\]

(2-4)

the sign + indicating two beams emerging from the beam splitter.

The 3/4 A Lyot filter consists of three components.

(i) The central component with a transmission bandwidth \(W = 3\) A, centered on \(H\). It is untunable and has a transmission profile of the form:

\[
\tau_o = \cos^2 \left( \frac{\pi}{2} \frac{\Delta \lambda}{3} \right)
\]

\(3\)A

\[
= \cos^2 \left( \frac{\pi \Delta \lambda}{6} \right) \quad (2-5)
\]

(ii) A unit at one end of the central component with a bandwidth of \(3/2\) A, tunable by the rotation of a polarizer, or of a polarizing beam splitter. The expressions for the transmission profiles corresponding to three main settings are given below.
a. If set to give maximum transmission at a central wavelength, the transmission profile has the form:

\[ T = \cos^2 \left( \frac{\pi}{3} \Delta \lambda \right) \]

b. If set to give minimum transmission at a central wavelength, the transmission profile has the form:

\[ T = \sin^2 \left( \frac{\pi}{3} \Delta \lambda \right) \]

c. If this unit is used in connection with a polarizing beam splitter, the transmission profile becomes:

\[ T = \cos^2 \left( \frac{\pi}{4} + \frac{\pi}{3} \Delta \lambda \right) \]

(iii) Another birefringent filter unit at the opposite end with a bandwidth of 3/4 Å, tunable. Similarly to (ii) the expressions for the transmission profiles are:

a. Central setting:

\[ T = \cos^2 \left( \frac{\pi}{4} \Delta \lambda \right) \]

\[ = \cos^2 \left( \frac{2}{3} \pi \Delta \lambda \right) \]  

(2.6a)
b. Zero set:

\[
\tau_{3A}^{\circ} = \sin^2 \left( \frac{2}{3} \pi \Delta \lambda \right).
\]

(2-6b)

c. With beam splitter:

\[
\tau_{3A}^{\circ} = \cos^2 \left[ \frac{\pi}{4} \pm \frac{2}{3} \pi \Delta \lambda \right].
\]

(2-6c)

Two sets of arrangements of the three filter units are selected:

(I) Combination (i), (ii)a and (iii)c; giving total transmission:

\[
\tau_I = \tau_0 \circ \tau_{3A} \circ \tau_{3A}^{\circ},
\]

or

\[
\tau_I = \cos^2 \left( \frac{\pi \Delta \lambda}{6} \right) \cos^2 \left( \frac{\pi \Delta \lambda}{3} \right) \cos^2 \left[ \frac{\pi}{4} \pm \frac{2}{3} \pi \Delta \lambda \right].
\]

The transmission profile in the two output channels will be:

\[
\tau_{Ia} = \cos^2 \left( \frac{\pi \Delta \lambda}{6} \right) \cos^2 \left( \frac{\pi \Delta \lambda}{3} \right) \cos^2 \left[ \frac{\pi}{4} \pm \frac{2}{3} \pi \Delta \lambda \right],
\]

(2-7a)

and

\[
\tau_{Ib} = \cos^2 \left( \frac{\pi \Delta \lambda}{6} \right) \cos^2 \left( \frac{\pi \Delta \lambda}{3} \right) \cos^2 \left[ \frac{\pi}{4} \mp \frac{2}{3} \pi \Delta \lambda \right].
\]

(2-7b)
(II) Combination (i), (ii)c, and (iii)b; giving total transmission:

\[ \tau_{\text{II}} = \tau_{3A} \cdot \tau_{3A} \cdot \tau_{3A}, \]

or

\[ \tau_{\text{II}} = \cos^2 \left( \frac{\pi \Delta \lambda}{6} \right) \cos^2 \left( \frac{\pi}{4} + \frac{\pi \Delta \lambda}{3} \right) \sin^2 \left( \frac{2 \pi \Delta \lambda}{3} \right). \]

The transmission profile in the two output channels in this case will be:

\[ \tau_{\text{IIa}} = \cos^2 \left( \frac{\pi \Delta \lambda}{6} \right) \cos^2 \left( \frac{\pi}{4} + \frac{\pi \Delta \lambda}{3} \right) \sin^2 \left( \frac{2 \pi \Delta \lambda}{3} \right), \]

and

\[ \tau_{\text{IIb}} = \cos^2 \left( \frac{\pi \Delta \lambda}{6} \right) \cos^2 \left( \frac{\pi}{4} - \frac{\pi \Delta \lambda}{3} \right) \sin^2 \left( \frac{2 \pi \Delta \lambda}{3} \right). \]

The expressions (2-7a) and (2-8a) have been computed for \( \omega \) between \(-3.0\ \text{A}\) and \(+3.0\ \text{A}\). The values of \( \tau_{\text{IIa}} \) and \( \tau_{\text{Ia}} \) are given in Table 2-1, while their transmission curves are given in Fig. 2-1.
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Table 2-1

Computed Transmission Profiles of Lyot Filter + Beam Splitter
10. Laboratory Testing and Calibration

A high dispersion spectroscope was set up at the C.S.I.R.O. Laboratory in Sydney to examine the performance of the Lyot Filter-Polarizing Beam Splitter combination. This spectroscope consisted of a Bausch and Lomb plane grating (No. 188A2) with rulings of 600 lines/mm, two spherical mirrors both having 15 cm. diameter and 300 cm. focal length, and an entrance slit. Light from a hydrogen discharge tube was admitted into the upper part of the entrance slit to facilitate marking the position of the centre of the Hα line. This was done by means of a small right angle prism. A tungsten lamp fed by a step-down transformer provided the continuum light source required. The first order spectrum of the grating was used in the experiment.

Since the Lyot filter needed to be rotated around its axis in relation to the polarizing beam splitter, and the beam splitter has an inconvenient shape for rotation, a special mounting was designed and constructed for the Lyot filter. This mounting was used both in testing and on the spar. The Lyot filter could be dismounted and turned around when it was required to change from an arrangement giving transmissions at ±0.285 Å to another arrangement giving transmissions at ±0.75 Å from the line centre.
Figure 2-1

Computed transmission profiles of the $\lambda_{\text{Lyot}} = \frac{3}{4}$ Å Lyot Filter in combination with a polarizing beam splitter. Central wavelengths are: (a) $H\alpha = 0.75$ Å, 
(b) $H\alpha = 0.285$ Å.
Fig. 2-1

$\Delta \lambda$ Angstroms.

Transmission profile of Lyot filter plus beam splitter for $\lambda = \pm 0.75 \AA$.

(Shown only for violet wing, red wing being mirror image)

(a)

$\Delta \lambda$ Angstroms.

Transmission profile of Lyot filter plus beam splitter for $\lambda = \pm 0.885 \AA$.

(Shown only for violet wing, red wing being mirror image)

(b)
Transmission spectra of the 3/4 Å Lyot Filter in combination with a polarizing beam splitter, obtained with a high dispersion spectrograph.

Central wavelengths are: (a) \( \text{H} \alpha +0.285 \, \text{Å} \), (b) \( \text{H} \alpha -0.285 \, \text{Å} \), (c) \( \text{H} \alpha +0.75 \, \text{Å} \) and (d) \( \text{H} \alpha -0.75 \, \text{Å} \). The parasitic transmission bands can also be seen.
Figure 2-3

The 5-inch C.S.I.R.O. chromospheric telescope on an equatorial spar.
The 5-inch Chromospheric Telescope

Equipped with the Lyot Filter - Beam Splitter Arrangement
Figure 2-4

Close up view of the chromospheric telescope showing mechanical mountings of optical components and accessories.
(C.f. § 2a, 2b; Chapter 2.)
The transmission spectra at the gates of the beam splitter were examined with an eyepiece alternately placed at each gate. The computed transmission curves (Fig. 2-1) were used as guides for adjustments. In the final adjustment, for each setting several exposures were made on a plate with the Lyot filter set at positions displaced progressively by $2^\circ$ around the position determined by visual setting. The correct setting position was then marked where, from the examination of the plate, the transmission spectra on both channels were symmetrical and corresponded to the computed curves (see Fig. 2-2).

2. **The Chromospheric Telescope**

2a. General

The chromospheric telescope is mounted on one face of a 10-feet open air "equatorial spar" at the C.S.I.R.O. Division of Physics Solar Observatory, located in flat country about 30 miles south-west of Sydney at an altitude of about 200 feet (see Figs. 2-3 and 2-4). The spar is in the form of a rectangular box made of 1/4-inch steel plates. The sides measure 16.5 by 12.5 inches. On the upper face of this spar is mounted a 5-inch photoheliograph used for high resolution studies of the photosphere. The 5-inch chromospheric
Diagram of the optical system of the 5-inch chromospheric telescope, as used for obtaining simultaneous filtergrams in opposite wings of Hα. (C.f. § 2b, Chapter 2.)
5-inch CHROMOSPHERIC TELESCOPE

with Lyot filter - polarizing beam-splitter combination.

Fig. 2-5
telescope used in my programme occupies the western face of the spar. The spar is moved in hour angle by means of a synchronous motor controlled by a photoelectric guider unit which utilizes a solar image produced by an auxiliary 3½-inch telescope. This photoelectric guider occupies the front left quarter of the upper face of the spar which is located the photoheliograph. The 3½-inch objective produces a solar image on an occulting disk with four slots parallel to the limb 90 degrees apart having a photocell behind each of which. Signals from the photocells are fed into a servo amplifier the output of which drives the spar both in hour angle and in declination to follow the sun by actuating servo motors. The guiding accuracy is about 1"-2" arc under the best conditions. The spar and guider are based on designs supplied by Dr W.O. Roberts of the High Altitude Observatory, Climax, Colorado.

2b. The Optical Systems

Two arrangements of optical systems were used in the observing programme. Fig. 2-5 shows an arrangement which was used in the simultaneous observations in the two wings of Hα. This constituted the first part of the observing programme. In the second part, in which a time-lapse cinematographic technique was used in conjunction with the C.S.I.R.O. 1/8 Å tunable filter, the telescope optics remained the same.
Therefore we shall use Fig. 2-5 to illustrate the telescope optics.

A two-component achromatic objective, 0 of 129.8 mm (5 inches) diameter produces a 16.6 mm solar image on a small diaphragm D at its focal distance, 1776 mm away. The strain-free mounting of this doublet was designed by Coulman and Norton (unpublished data) of the Division of Physics, C.S.I.R.O. The portion of the image corresponding to an aperture in the diaphragm D is then enlarged by a magnifying lens L1. Two right-angle prisms situated in the optical path after the Lens L1, turn the light beam around the end of the spar, thus shortening the physical length of the spar, while permitting high image magnification. The light beam then enters a birefringent filter via a field lens L2 and an auxiliary interference filter F.

Two filter systems were used:

(i) For simultaneous observations in the two wings of $H_\alpha$, the layout is as shown in Fig. 2-5. A Lyot filter with a 3/4 A bandwidth L was used in conjunction with a polarizing beam splitter, P. The Lyot filter was placed next to the interference filter F in the optical train. A polarizer was taken out from the other end of the Lyot filter and the polarizing beam splitter was joined to this end. A special mechanical mounting was designed and constructed to
carry the Lyot filter so that it could be rotated around its axis (see Fig. 2-4). This facilitates the fine adjustment to obtain light at the right positions on the $H_\alpha$ profile. The adjustments were done in the laboratory with the aid of a high resolution grating spectroscope. The light beam was split into two to form the images at the circular gates A and B on the upper face of the beam splitter. The plate holder fits this upper face so that records are made simultaneously in the two wings of the $H_\alpha$ line.

In this arrangement, the system gives an enlargement of 5.73 times, producing a solar image of diameter 95.1 mm at the photographic plate with a scale of 1 mm to $20^\prime\prime265$ arc on the sun. However, the total disk of the sun was not recorded. The size of the aperture in the diaphragm D at the first image plane is such that only a circular area with a diameter approximately $1/4$ of the solar disk is observed at a setting. This area on the sun could be selected by lateral motions in two axes of both the aperture and the enlarging lens L1. The circular gates of the beam splitter P have a diameter of 25 mm. This is the final factor which determined the size of the area photographed.

(ii) For observations with a $1/8$ A bandwidth, the Lyot filter and polarizing filter combination was replaced by the C.S.I.R.O. $1/8$ A tunable birefringent filter (Steele,
Smartt and Giovanelli, 1961) in conjunction with a 35 mm cinecamera. The magnification of the enlarging system was such that 1 mm corresponds to 20\(^\circ\)0 arc on the sun.

At one stage in the observations with this combination, a slight change was made in the filter and magnification characteristics which resulted in the system becoming a 0 filter with 1/4 A bandwidth, and the magnification became 1 mm corresponding to 13\(^\circ\)3 arc. This was achieved by removing a polarizer from the filter and also the field lens L2, and readjusting the focus. The removal of the field lens had the effect of increasing the magnification by 1\(\frac{1}{2}\) times. It also produced a slight variation in wavelength transmission across the field. The experiment was discontinued. Two sets of filtergrams of the solar limb at +0.75 A from the line centre are shown in this thesis (Chapter 3, Figs. 3-10,11). They clearly demonstrate the extension of spicules down in to the disk where they terminate on the bright disk features.

2c. Air Suction Devices

Sunlight falling on parts of the chromospheric telescope, both out of and in the optical path, producing differential heating, can cause deterioration of images. Arrangements had therefore been included to minimize this effect by shields combined with air suction devices which remove heated air
from surfaces exposed to the sun by drawing it through numerous tiny holes in the surfaces. These surfaces include: (i) the front surface of a hollow aluminium diaphragm A, shielding the front of the equatorial spar and the chromospheric telescope, (ii) the shutter S1 which excludes light from the telescope except during operation, (iii) a diaphragm D at the focal plane, and (iv) the focal plan blade shutter S2 which is solenoid operated. Heat generated in the electrical devices, such as the solenoid operating the shutter S2 is also removed by the same operation. A 1/2 H.p. electric forge-blower, situated about 15 feet from the spar maintains the reduced pressure in the suction system through an underground pipe and flexible couplings. For detailed descriptions and experiments illustrating the efficiency of the air suction system in preserving image-quality, see Loughhead and Burgess (1958).

2d. Exposure Control

The changes in sky transparency and solar zenith distance produce negatives of varying densities during an extended period of observation. This can become very pronounced when a high contrast process is used in development. The exposure (i.e. exposure time x light flux) is therefore maintained constant within 1 percent by an amplified signal
from a photocell unit actuated by a small auxiliary telescope. The Exposure Control unit with its stabilized electronic equipment is situated on the front part of the lower surface of the spar (see Fig. 2-3). The triggering of the shutter is done either by manual switching, or automatically at moments of determined level of good seeing, by a solar seeing monitor developed by Bray, Loughhead and Norton (1959).

3. The Observing Procedures

3a. Simultaneous observations in the two wings of $H_\alpha$

The Polarizing beam splitter was designed for use in conjunction with spectrographic plates of size 4 by 10 inches. The emulsion used was Kodak IV-E or Ilford R-40. Six pairs of exposures could be made on one plate. An auxiliary optical system projected an image of a clock on the plate simultaneously with an exposure pair, providing time recording.

During an observation, a plate was loaded into a magazine in a dark room at the observing site, wrapped in black cloth, and carried to the spar where it was slid on to the beam splitter unit. The whole unit was then covered with a large piece of black cloth to prevent scatter light leaks. After each exposure, the plate magazine was slid along the groove provided on the beam splitter unit by a predetermined amount.
so that new areas on the plate were ready for the subsequent exposure. The minimum time required for this operation was around ten seconds, and this set the lower limit on the interval between two consecutive exposures of the same plate. There were three plate magazines available therefore it was possible with the aid of an assistant to obtain time sequences of filtergrams of the chromosphere. The operation of unloading an exposed magazine and reloading a fresh magazine, however, took about one minute, thus determining the shortest interval between two consecutive exposures between two plates.

A solar seeing monitor (Bray, Loughhead and Norton, 1959) was used in determining the best moments for making exposures. Since, in most of my observation with the beam splitter, I was interested in sequences of filtergrams more or less equally spaced in time, exposures were not triggered directly by the seeing monitor signal. Instead, I observed a volt-meter which gave a quantitative measure of the seeing, and made a compromise between the interval between exposures required and the seeing available. The manual operation of the exposure switch was done at the control panel, which was situated inside a hut at the observing site, some 20 feet from the spar.
After each exposure, an assistant at the spar slid the plate magazine along the grooves on the beam splitter, providing new areas for the next exposure.

The plates were brought back to the C.S.I.R.O. Laboratory for processing after each period of observation. Before processing, two 15-step sensitometric patterns were printed with exposure times of 0.8 sec. on each plate, on areas at two diametrically opposing corners. A sharp cut-off filter ensured that the calibration was made by a band about 400 Å wide roughly centred on H\textalpha{}.

Ilford R-40 plates were developed 5 minutes in full strength developer, while Kodak IV-E plates were developed 5 minutes in full strength D 19 developer.

3b. Observations with 1/8 Å bandwidth

The C.S.I.R.O. 1/8 Å tunable filter has optical components mounted in a cell containing suitable gearing which rotate the various $\frac{1}{2} \lambda$ plates and so vary the wavelength. This cell is temperature controlled to $40 \pm 0.01 \, ^\circ \text{C}$. According to Beckers (1964), the filter has a transmission half-width of 0.124 Å. The temperature within the cell is monitored by a mercury glass thermometer, from which it was found that the filter temperature varied appreciably during an extended period of observation lasting more than an hour. Since it
Figure 2-6

Calibration curve showing the variation in zero setting of the 1/8 A tunable birefringent filter with the filter temperature.
CALIBRATION CURVE
FOR 1/8 Å FILTER SETTING

Fig. 2-6
was considered undesirable to interrupt a time-lapse cinematographic observation to recalibrate the wavelength position, a calibration curve (Fig. 2-6) was prepared so that thermometer readings could readily be translated into wavelength positions. When it was felt that the wavelength drift (indicated by temperature drift) was going to be more than could be tolerated, a slight adjustment in the electronic thermal controller was made to counter the drift. With some experience it was possible to keep the temperature drift within 0.1 C throughout an observing period lasting more than three hours. The position of the wavelength centered on could be known by continual monitoring the thermometer.

The procedure in setting the exact wavelength position was as follows. First the filter temperature was checked to make sure that it was within the range 40±0.05 C, the tuning dial of the filter being initially set at zero. The coarse tuning dial was then tuned to set at 6.4 A on the longer wavelength side, and fine tuning used to tune to a Fe line which is known to be 6.433 A on the red side of the H line centre. Light from the centre of the solar disk was used in this calibration while the output from the filter was monitored by a simple photocell with associated amplifier circuit feeding into an oscilloscope. The position of the Fe line was located accurately by the sharp dip in the photocell
output. The readings on the tuning dials were then noted. The exact position of the setting for the \( H_\alpha \) line centre would then be at -6.433 Å from this position.

The calibration curve was obtained by determining the tuning dial readings for the positions of the \( H_\alpha \) line centre at different filter temperatures. It should be noted that, at 40.0 C the dial settings for the \( H_\alpha \) line centre was 0.0.

The 35 mm Debrie cinecamera uses magazines carrying 100 feet length of film per full loading. An optical system projects a clock image on to one corner of each frame simultaneously with an exposure to provide a record of time. The position of the area on the solar disk observed, the wavelength deviations from the \( H_\alpha \) line centre (\( \Delta \lambda \)), and the emulsion sensitivity determined the exposure time which in turn, determined the maximum number of frames exposed per minute. Many observing programmes were employed with this instrumental set up.

The exposed Kodak IV-E films which were used throughout the observations were calibrated with the same sensitometric wedge used in the 3/4 A data, with the same filtered light. Each 100 feet film was given three to four patterns to ensure against failure. Each roll was then developed 5
minutes in full strength D-19 in tank at \(20^\circ C\), giving a gamma around 3.2 to 3.6.

Spicules have been studied in the \(\text{H}_\alpha\) line with (a) a 1/3 \(\text{A}\) tunable filter, and (b) a 1/4 \(\text{A}\) filter equipped with a 3% or 7% glower yielding simultaneous photographs in opposite wings. Spicules have been traced from outside the solar limb onto the chromospheric disk just inside the limb, where they appear as bright emission features. On the disk, they appear in sections which are bright at all positions across the limb profile. The well-known dark sections, although not extending into the general chromosphere at the limb, do not extend beyond as spicules. However, there is a close association between spicules and filaments.

This chapter, in the form of a paper, has been accepted for publication in the Monthly Notices of the Royal Astronomical Society. It is presented here unaltered.
CHAPtER 3

IDENTIFICATION OF SPICULES ON THE DISK*

THE STRUCTURE OF THE SOLAR CHROMOSPHERE

I. IDENTIFICATION OF SPICULES ON THE DISK

Rawi Bhavilai

SUMMARY

Spicules have been studied in the Hα line with (a) a 1/8 A tunable filter, and (b) a 3/4 A filter equipped with a beam splitter yielding simultaneous photographs in opposite wings. Spicules have been traced from outside the solar limb onto the chromospheric disk just inside the limb, where they appear as bright emission features. On the disk, they appear as mottles which are bright at all positions across the line profile. The well-known dark mottles, although merging to form the general chromosphere at the limb, do not extend beyond as spicules. However, there is a close association

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between the dark and bright mottles, the latter being found in the central parts of the well-known chains of the chromospheric network or of clusters of dark mottles.

A three-dimensional model of some of these structures is described.

1. Introduction

Spectroheliograms and filtergrams of the solar disk in $\text{H}_\alpha$ taken at moments of good seeing are rich in chromospheric detail, and numerous attempts have been made to ascertain which of the features are spicules. The latter, which are short lived projections of the chromosphere beyond the solar limb, have often been regarded as belonging to a class of prominences (Menzel 1931, Kiepenheuer 1953, Unsold 1955). In recent years, many authors have concluded that spicules are identical with the dark mottles which may be seen on the disk at various parts of the $\text{H}_\alpha$ line (de Jager 1957, 1959, Macris 1957, Kiepenheuer 1957, Bruzek 1959, Beckers 1963). As a variant of this, Cragg, Howard and Zirin (1963) identified the spicules with dark bush-like vertical structures seen just within the limb.

While it has generally been considered that spicules cannot be traced from the limb down to the disk, so that direct identification of spicules with disk structures is
impossible, the agreement between these authors is strong indeed. Nevertheless the work described below shows that the spicules do not originate in the dark mottles, but rather in bright structures which often occur in close association with dark mottles.

The following sections describe these observations and lead to a discussion of the typical three-dimensional forms of chromospheric structures.

2. **Instrumentation**

The observations of the solar quiet regions described below were obtained with the 5-inch chromospheric telescope of the C.S.I.R.O. Division of Physics at Fleurs. The telescope has an achromatic objective of diameter 130 mm and focal length 1776 mm. An enlarging system produces a solar image of about 100 mm diameter at the final image plane.

Two groups of observations have been obtained.

(i) Between April and September 1963, a Lyot filter having a 3/4 Å bandwidth was used either at the line centre or in conjunction with a polarizing beam splitter (Steel, Smartt and Giovanelli 1961) to produce two simultaneous images at H$_\alpha$ ±0.75 Å (the latter observations reveal Doppler velocities). Records were made on Kodak IV-E or Ilford R-40 plates.

(ii) The second series of observations was made between
Figure 3-1

a, b, and c, i: Hα filtergrams of a quiet central region of solar disk, at different positions on the line profile, 9 May 1964, obtained with a \(1/8\) \(\text{Å}\) filter. \(\Delta \lambda = (a) 0.0 \text{Å}, (b) +0.75 \text{Å}, (c) -0.75 \text{Å}\).

ii: Identification maps of the right halves of (i); dark mottles are outlined, while crosses indicate position of bright mottles.

iii: Maps superimposing selected pair of wavelengths.

a.iii: \(\Delta \lambda = 0.0 \text{Å}\), shaded contours
\(\Delta \lambda = +0.50 \text{Å}\), filled contours

b.iii: \(\Delta \lambda = +0.75 \text{Å}\), filled contours
\(\Delta \lambda = -0.75 \text{Å}\), shaded contours

c.iii: \(\Delta \lambda = -0.75 \text{Å}\), filled contours
\(\Delta \lambda = -0.50 \text{Å}\), shaded contours.
Fig. 3-1
February and June 1964 with a 1/8 Å tunable birefringent filter (Steel, Smartt and Giovanelli 1961). A 35 mm cine-camera was used in conjunction with this filter to obtain photographs of the sun in rapid succession in the light from different positions on the profile of the $H\alpha$ line, thus revealing structures at different optical depths. Kodak 35 mm spectroscopic film type IV-E was used for this series.

3. **The $H\alpha$ Disk Chromosphere**

We consider first the appearance of the chromosphere on the disk, particularly because some of the important features have not been described adequately in the literature.

Fig. 3-1(a) shows a filtergram of a central region of the solar disk obtained with a 1/8 Å filter centred on $H\alpha$. The most obvious features are the dark and bright mottles, some of which are indicated on the accompanying map. Many of the dark mottles are connected together by faint bridges to form single (or sometimes complex) elongated features, while some of the dark mottles are themselves elongated. We shall call both types of dark elongated mottles "fibrils", to distinguish them from the roundish mottles (the name "fibril" will also be used to describe elongated bright mottles, to be discussed later). Some of the dark mottles occur in groups or clusters though, as we shall see presently, the latter are
Figure 3-2

a, b, c, and d, i: Hα filtergrams of a quiet central region of solar disk, at different positions on the line profile, 9 May 1964, obtained with a 1/8 Å filter. \( \Delta \lambda = (a) +0.5 \, \text{Å}, \) (b) \(-0.5 \, \text{Å}, \) (c) \(+0.25 \, \text{Å}, \) (d) \(-0.25 \, \text{Å}. \)

ii and iii: Same as in Fig. 3-1 with additions:

3-2(c.iii): crosses and circles indicate positions of bright mottles at \( \Delta \lambda = +0.25 \, \text{Å} \) and \( \Delta \lambda = -0.25 \, \text{Å} \) respectively.

3-2(a.i) and 3-2(b.i): areas marked by lines on the sides of the frames are discussed in 6.

a.iii: \( \Delta \lambda = +0.50 \, \text{Å}, \) filled contours

\( \Delta \lambda = -0.50 \, \text{Å}, \) shaded contours

b.iii: \( \Delta \lambda = -0.50 \, \text{Å}, \) shaded contours

\( \Delta \lambda = -0.25 \, \text{Å}, \) unfilled contours

c.iii: \( \Delta \lambda = +0.25 \, \text{Å}, \) filled contours

\( \Delta \lambda = -0.25 \, \text{Å}, \) shaded contours

d.iii: \( \Delta \lambda = -0.25 \, \text{Å}, \) filled contours

\( \Delta \lambda = 0.0 \, \text{Å}, \) shaded contours
more readily identifiable on filtergrams obtained in the wings of Hα. Some of the bright mottles are also elongated while some (no doubt below the limits of resolution) are roundish.

The dark mottles exhibit many grades of darkness. Their general appearance is reminiscent of that of photospheric granules observed with a small (e.g. 3-inch) telescope, suggesting that these features too are not yet fully resolved.

Filtergrams at Hα $+$0.75 Å, illustrated in Figs. 3-1(b) and 3-1(c), show the chromosphere more sparsely populated by dark mottles of differing intensities. Most are elongated, usually in the form of an extension from one end which gradually fades out. The mean width is 2"-3"; the length may be 5"-15" or even more. There are more very dark mottles in the red wing than in the blue, so that a filtergram in the red wing appears to show the greater contrast.

The mottles which are dark at Hα $+$0.75 Å become darker and increase somewhat in size at Hα $+$0.5 Å, and their general arrangement is now much more obvious (Figs. 3-2(a) and 3-2(b)). The dark mottles are more elongated at Hα $+$0.5 Å, and in some cases these elongations become fibrils linking two or more mottles together. Mottles barely visible at Hα $+$0.75 Å attain clear visibility at Hα $+$0.5 Å.
At both intervals from the line centre, the dark mottles in general appear to be more contrasty in the red than in the blue wing. However the chromosphere gives the appearance of being more densely populated at $H\alpha -0.5\,\text{A}$ than at $H\alpha +0.5\,\text{A}$. Particularly in the red wing, many of the mottles are quite clearly arranged in tight clusters or in chains, the latter forming part of the well-known chromospheric network. In the blue wing, fine dark roundish mottles of diameters of the order of 2" or less fill the spaces between the network chains in great numbers.

At $H\alpha \pm 0.25\,\text{A}$ (Figs. 3-2(c) and 3-2(d)), the mottles which were dark at $H\alpha \pm 0.5\,\text{A}$ lose contrast, and at the same time pairs or groups of them join to form fibrils. On the whole, the appearance of dark mottles at $H\alpha \pm 0.25\,\text{A}$ is more like that at the line centre, small roundish mottles and fibrils being about equally conspicuous. At the line centre itself, the fibrils invariably overlie the mottles which were conspicuously dark at $H\alpha \pm 0.5\,\text{A}$, though the latter have now lost contrast and intensity to such an extent, and have become so blurred and joined together, as to form the fibrils. Underlying any fibril we can almost always find a chain or at least a pair of dark mottles at $H\alpha \pm 0.5\,\text{A}$. The small, dark, roundish mottles observed clearly only at $H\alpha -0.5\,\text{A}$ have expanded and merged together to form patches which are more or
less an homogeneous grey at the line centre. They are identifiable only because the outlines of these patches still follow the pattern of the underlying network.

Both at \( H_\alpha \pm 0.75 \, \text{Å} \) and \( H_\alpha \pm 0.5 \, \text{Å} \), a comparison of the two wings shows that, while the dark mottles are not invariably at the same locations, numbers of them can be paired in the sense that a mottle in the red wing occupies a position adjacent to a mottle in the blue wing (e.g. see map in Fig. 3-1(b.iii)). In some of the pairs at \( H_\alpha \pm 0.75 \, \text{Å} \), the mottles are connected by faint fibrils, the combined length of a pair being 8"-15" arc. Interpreted in terms of a Doppler shift, there is a flow of matter outwards where a mottle is darker in the blue wing, and inwards where a mottle is darker in the red wing. Consequently in a pair of this type we are observing motion in a loop, matter flowing outwards at one mottle and inwards at another (c.f. § 6).

At both 0.75 and 0.5 Å from the line centre, we may note that where the dark mottles form clusters, these appear fairly tight, or compact, in the red wing, whereas the mottles are further apart in the corresponding clusters in the blue wing; there is always a vacant central area in the blue wing corresponding to the central regions occupied by the mottles in the red wing. This description is therefore one of a set of roughly radial loops, equal in number to pairs of mottles,
the flows being directed in towards the centre of the cluster.

In some cases the chromospheric network is formed of double chains (e.g., just to the right of centre near the bottom of Fig. 3-2(a, b)), and in these too the individual chains are closer together in the red wing than in the blue. These double chains are also formed of loops in which the matter rises in the outer regions and flows inwards and then downwards into the central parts.

The bright mottles are visible in the wings of Hα, and both at Hα ±0.75 A and Hα ±0.5 A some can be identified in both red and blue wings. At Hα ±0.75 A they are detectable on the negatives and transparent prints, while at Hα ±0.5 A they also reproduce on paper prints. They are frequently associated with clusters or chains of dark mottles. At Hα ±0.75 A, however, some mottles which are bright in the blue wing appear as very dark in the red wing; some which are dark or very dark in the red wing appear only very faintly or may be even invisible in the blue wing. Occasionally there are bright streaks starting from bright mottles, usually associated with clusters of dark mottles, and the streaks may extend as far as 160" across the disk. The same streaks are identifiable at Hα ±0.5 A. However, they do not reproduce well on paper prints, but can be identified on transparent
prints. The majority of mottles which are bright at $-0.5\,\text{Å}$ are bright at $+0.5\,\text{Å}$ (e.g. see crosses on the maps accompanying Fig. 3-2 (a, b)), though a few of them are invisible in the red wing.

The bright mottles visible in the wings become more conspicuous towards the line centre. They occur between dark mottles and fibrils in the clusters and in the network chains, as well as individually away from the network chains. At the line centre, in particular, they become very bright in the central parts of the clusters. Their positions are indicated by crosses on the various maps in Fig. 3-1 and 3-2.

The core of the line behaves in the reverse way from the far wings, in that filtergrams at $\text{H} \alpha -0.25\,\text{Å}$ have greater contrast than those at $\text{H} \alpha +0.25\,\text{Å}$. Bright mottles are more distinct at the former wavelength than at the latter. Greater numbers of bright mottles are present per unit area on the blue side than on the red. Although the bright mottles appear bigger at $\text{H} \alpha +0.25\,\text{Å}$, the effect is not due to the merging of bright mottles in the blue wing to form one mottle in the red wing, as can be seen on inspecting the map superimposing the two wavelengths (Fig. 3-2 (c.iii)). Moreover, inspection of a number of filtergrams at both wavelengths shows that these conclusions do not result from differences in seeing conditions.
4. The Solar Limb in H

4a. General.

The chromosphere has been described by van der Hulst (1953) as a more or less homogeneous layer about 6"-7" arc wide lying between the sharp photospheric "inner" limb and an outer rugged boundary, from which the spicules emerge as fine streaks.

Most previous filtergram studies of spicules have involved birefringent filters of comparatively wide passbands, and wavelength scans around the $H\alpha$ line profile have been impracticable. Rush and Roberts (1954) used a 4 A filter, Woltjer's (1954) results were derived from Lyot's $1\frac{1}{2}$ A filtergrams, while the best photographs so far - those by Dunn (1960), also analysed by Lippincott (1957) - were obtained with a 3.5 A filter. Rush and Roberts found on their photographs that the chromosphere beyond the photospheric limb was over-exposed and appeared as a luminous band with a rather irregular upper edge. Woltjer described the mean level of the chromosphere as extending to some 7" arc above the photospheric limb beyond which the spicules protruded. Dunn (1963, private communication) commented that spicules do not appear in his photographs below about 2000 km; but they may be traced down to this level by examining the photometric
contours in his thesis (1960). Lippincott (1957) reported that some spicules could be traced down to the photospheric limb on Dunn's less dense photographs, but these have usually been interpreted as foreground spicules.

Photographs of spicules obtained during total solar eclipses differ greatly from those through birefringent filters. White light eclipse photographs (Menzel 1931, Mohler 1951) show spicule images produced by all the chromospheric emission lines in the relevant visual spectrum. Whether or not all the emission lines come from the same spicules, as suggested by Suemoto and Hiei (1962) is a problem still to be resolved.

There has been a good deal of confusion from the use of monochromators and filters of inadequate spectral purity, for it is with these that the well-known double limb phenomenon has been observed. As shown by Rawi Bhavilai, Norton and Gionvanelli (1964), the sharp inner limb is a superimposed image of the photosphere in light from outside the core of \( \text{H}_\alpha \); it disappears with purely monochromatic light in the range \( \text{H}_\alpha \pm 0.75 \, \text{Å} \). Filtergrams which show a sharp inner limb are generally under-exposed in the chromospheric band between the inner and outer limbs. If the exposure is increased so as to record fully the spicules projecting beyond the outer boundary, for example in the photographs of Dunn
Figure 3-3

Hα filtergrams of the sun near the north pole obtained with a Lyot 3/4 Å filter (c.f. 4.b.i).

a and b: $\Delta \lambda = 0.0$ Å on 3 March 1963, short and long exposures. Prints of different densities are given for each.

c, d; e, f; and g, h: pairs of simultaneous photographs of the same position on the north limb, at (c, e, and g) $\Delta \lambda = +0.75$ Å, and (d, f, and h) $\Delta \lambda = -0.75$ Å, on 31 May 1963, showing Doppler velocities in the chromosphere. An occulting disk is placed just below the superimposed photospheric limb.

e and f each comprises: top - the upper portions of c and d respectively; middle - short exposures 7 seconds earlier than c and d; below - sketches of above.

Figure 3-4

a and b: simultaneous filtergrams of the solar disk near the north polar limb on 28 May 1963 at 01 14 UT. (a) $\Delta \lambda = +0.75$ Å, (b) $\Delta \lambda = -0.75$ Å.
(1960), the inner regions are so over-exposed that no details are visible. It is not surprising, therefore, that there has been no recorded observation of spicules crossing the photospheric sharp "inner" limb.

As described below, the use of sufficiently pure filters makes this possible, and spicules can indeed be followed down into the chromospheric disk. Nevertheless, with a less pure spectrum the presence of a superimposed image of the photosphere in the light from the neighbouring continuum makes it possible to compare precisely the locations of features observed at different intervals from the line centre.

4b. Present Observations

(i) Simultaneous Observations in opposite wings with 3/4 A bandwidth.

Fig. 3-3(a) shows the solar limb photographed through the 3/4 A Lyot filter tuned to the centre of Hα. The exposure is such that the emulsion density inside the disk falls within the linear part of the characteristic curve. However, the parasitic continuum light which produces the superimposed photospheric image contributes appreciably to the illumination within the sharp limb, beyond which the chromosphere is under-exposed. When the exposure is increased so that the spicules emerging from the rugged
chromospheric limb are recorded fully, as in Fig. 3-3(b), the area inside the photospheric disk is now over-exposed.

Figs. 3-3(c) and 3-3(d) show simultaneous photographs taken when the filter, combined with the polarizing beam splitter, is tuned to transmit the light at +0.75 Å and -0.75 Å from the line centre. There are spicules which are bright on one wing and do not appear or appear much fainter on the other. This phenomenon indicates mass motions in spicules, some of which must have line-of-sight (i.e. tangential) velocities higher than 20 km/sec. Figs. 3-3(g) and 3-3(h) show striking examples. During the life-time of an individual spicule, the mean value of which is about 5 minutes, its Doppler velocity is observed to keep the same sign throughout. By inference, the direction of motion is always outwards or always inwards (we have as yet no evidence as to which!) during the life-time of an individual spicule.

The pairs of photographs shown in Fig. 3-3(e) and 3-3(f) are also at Hα ±0.75 Å. They were taken at a short time interval from the above pair, but with a shorter exposure. Just above them we print the upper chromosphere from the longer exposure photographs, for the purposes of comparison and identification, to be discussed below. The sharp photospheric limb is now seen, the fainter band of chromosphere projecting just above this level consisting of discrete
"emission" regions, the large scale structures of which have life-times in excess of 1½ hours, the maximum period of observation. They have size ranges of 15"-75" arc, and project outwards only about as far as the rugged outer limb, i.e. they form part of the ordinary chromosphere.

At such wavelengths, of course, the upper chromosphere is much more transparent than at the line centre, enabling us to see further into the chromosphere.

When a pair of long and short exposure photographs of the same wing are superimposed and compared, the spicules of the upper chromosphere can be traced down to the photospheric limb level, where they join the bright features of the emission regions described above. This may be seen from Figs. 3-3(e) and 3-3(f) which show long exposure frames printed above the shorter exposure frames. Careful examination reveals that, in the less dense exposures, spicules can be seen faintly emerging from the emission regions and can be identified with the spicules which appear at higher levels in the denser pictures.

Examinations of the negatives at Hα ±0.75 Å show that some of the parts of the emission regions, having widths of 3"-4" arc and lying just outside the photospheric sharp limb, extend inside, there they appear as bright emission features against the general limb-darkened extreme disk. Some can be
traced to about 3" inside the sharp limb.

As in the case of the spicules, large scale bright emission features on the less-dense limb photographs do not have precisely the same appearance in the two wings of $H\alpha$ at $\pm 0.75$ Å, indicating line-of-sight velocities in these features also.

There are places on the limb, on the less-dense photographs, which are free from discrete bright emission features. As shown by arrows in the photographs of Fig. 3-3(e) and 3-3(f), the upper chromosphere above these positions is somewhat depressed.

Simultaneous photographs of the disk near the north polar limb at $H\alpha \pm 0.75$ Å are shown in Figs. 3-4(a) and 3-4(b). The chromosphere beyond the sharp (photospheric) limb is under-exposed and invisible. The dark mottles, which are obvious features, are arranged in chains whose general outlines in both wings coincide. The chains are of similar sizes to the large-scale emission features at the limb.) The mottles in general show elongations in the radial direction, indicating that they are probably mainly vertical structures.

However, the mottles in opposite wings do not all coincide. A large number of dark mottles in the red wing appear only very faintly, or not at all, in the blue wing. The reverse is true to a much lesser extent. In consequence,
Diagram showing the predominance of recessive velocities as due to a predominantly downwards motion in the mottles (§ 4.b.i). It is clear that, for a considerable range of distances of mottles from the solar limb, $V_1$ is greater than $V_2$. 
pictures in the red wing have greater contrast than in the blue wing. Interpreted in terms of a Doppler effect, since the dark motions in the red wing have, curiously enough, somewhat lower velocities near the observer. It seems likely, this is a purely geometrical effect due to a predominantly eccentric motion in the nebula (e.g., see Giovannelli and Jeffries 1981); there are inclined at fairly large angles to the surface, and so have predominantly escocentric velocities (Fig. 3-5).

Fig. 3-5
pictures in the red wing have greater contrast than in the blue wing. Interpreted in terms of a Doppler effect, most of the dark mottles in the red wing have, curiously enough, radial velocities away from the observer. At least in part, this is a purely geometrical effect due to a predominantly downwards motion in the mottles (e.g. see Giovanelli and Jefferies 1961); these are inclined at fairly large angles to the surface, and so have predominantly recessive velocities (Fig. 3-5).

(ii) Observations with a 1/8 Å bandwidth filter.

The 1/8 Å tunable birefringent filter (Steel, Smartt and Giovanelli 1961) has been used in conjunction with a cinecamera to obtain photographs in rapid succession of the solar limb in the light from different positions on the profile of the Hα line. At each wavelength a range of exposure times has been used so that features of differing intensities are recorded adequately on at least one exposure. In a full set of observations, the filter was tuned to positions from Hα +1.0 Å to Hα -1.0 Å. However, the limb chromosphere does not show significantly different types of features at equal intervals on either side of the line centre, and it is sufficient for the present to describe one wing only.

The appearance of the Hα limb chromosphere varies greatly with wavelength. This may be seen from Fig. 3-6,
Figure 3-6

a, b, c, d, and e: The solar limb chromosphere at the north pole obtained with a 1/8 Å filter on 6 April 1964 at different positions on the Hα line profile, with different exposure times (c.f. § 4(b.ii)).

UT at exposure:

a. $\Delta \lambda = 0.0$ Å
   i. 23h31m43s
   ii. 23h31m15s
   iii. 23h30m13s

b. $\Delta \lambda = +0.25$ Å
   i. 23h29m01s
   ii. 23h27m44s
   iii. 23h26m20s

c. $\Delta \lambda = +0.50$ Å
   i. 23h24m40s
   ii. 23h23m59s
   iii. 23h23m35s

d. $\Delta \lambda = +0.75$ Å
   i. 23h22m37s
   ii. 23h21m38s
   iii. 23h20m58s

f. $\Delta \lambda = +1.0$ Å
   i. 23h19m21s
   ii. 23h18m41s
   iii. 23h18m22s
   iv. 23h17m52s

e. $\Delta \lambda = +1.0$ Å

f: Map superimposing features at the line centre (Fig. 3-6 (a.iii)), and features at Hα +0.75 Å (Fig. 3-6(d.iii)).

Dotted line and unfilled solid line represent dark features and bright mottles respectively at the line centre. Filled contours represent dark mottles at Hα +0.75 Å (c.f. § 4.c).
which contains a series of photographs of the north limb of the sun taken with the 1/8 Å filter centered at $\text{H}\alpha +0.0$, $+0.25$, $+0.5$, $+0.75$ and $+1.0$ Å.

At the line centre, spicules protrude from the rugged chromospheric limb, the mean height of which measures 8" arc or 5800 km from the level of the superimposed photospheric limb. The chromosphere between the two levels is far from homogeneous, and appears quite similar to the chromosphere further inside the disk (this may also be seen from Fig. 3-6 (a). Many spicules extend down to brighter-than-average areas of the chromosphere inside the limb. Just inside the disk, the chromosphere shows bright and dark mottles although the contrast of the latter is low. Many of the bright mottles are in chainlike formations and some give the impression of being vertical structures. The dark mottles seem to do so to a lesser extent.

The contrasts of the chromospheric features are rather more enhanced at 0.25 Å from the line centre, as shown in Fig. 3-6(b). The chromospheric limb is more rugged and the disk slightly more inhomogeneous. The bright and dark mottles at the line centre can be identified with corresponding bright and dark mottles appearing at $\text{H}\alpha +0.25$ Å.

At 0.5 Å from the line centre, the chromosphere at the extreme limb resolves at many places into elongated radial
bright structures (the spicules) some of which extend inside to the photospheric limb level. Some of them can be traced further inside, where they still appear bright on the disk, as can be seen in Fig. 3-6(c), near the left corner. The chromospheric limb, which becomes progressively more rugged, now has a mean height of about 6" arc or 4300 km from the photospheric limb level. Dark mottles extend across the photospheric limb outwards, where they continue on as the dark portion of the chromosphere at the limb and not as the spicules. Tracing many spicules back from outside the rugged chromospheric limb, we find that they extend downwards to appear as the brighter features of the disk chromosphere.

The bright and dark mottles now become more distinct, and exhibit elongations in the general direction of the limb. A comparison of photographs at this wavelength with those nearer the line centre shows that the earlier rather unresolved patches are now resolved into chains and clusters of mottles. The dark mottles seem to be more obvious at this wavelength, yet the bright mottles are still identifiable in close association with the dark ones in the clusters and chains. Some of the bright mottles are greatly elongated, their extensions appearing as faint bright streaks emerging from the clusters of mottles (see arrows marked B on Fig. 3-6(c.iii)). Many dark mottles appear curved.
The limb chromosphere at \( H\alpha \pm 0.75 \) Å is diminishing rapidly in height at positions which correspond to the spaces between the bright spicules. As shown in Fig. 3-6 (d), it is not convenient now to talk of the mean height of the chromosphere above the projected photospheric level, because contours of equal brightness at the limb fluctuate greatly with position along the limb. Once again, the dark mottles do not appear at the limb as spicules; as before, the bright spicules of the upper chromosphere can be traced down to terminate on bright mottles which occur in close association with the dark mottles (see arrows marked S on Fig. 3-6(d)). On close inspection, it becomes clear that where dark mottles occur very near to and extending towards the limb, they appear as darker-than-average chromosphere between the spicules, and certainly not as the spicules. With long exposure, these dark mottles combine to form the more-or-less unresolved chromosphere, while the bright elongated mottles extend outwards as the spicules.

Although filtergrams of the limb at \( H\alpha \pm 0.75 \) Å appear to be less populated than those at \( H\alpha \pm 0.5 \) Å, dark and bright mottles in the former wavelength can be identified with corresponding dark and bright mottles in the latter.

Clusters of both dark and bright elongated mottles may be observed on the disk inside the limb, out to at least
$\theta = 80^\circ$. These elongations generally have fan-shaped forms, with the axis of symmetry radially towards the limb. The elongated bright mottles extend outside the limb where they appear as clusters of spicules with the elements radiating as if from common origins. These are the 'porcupine spicules' of Lippincott (1957). We have definite evidences here that the clusters of bright mottles on the disk are the sources or seats of these 'porcupine' spicules.

At +1.0 A from the line centre, as shown in Fig. 3-6(e), the chromospheric limb has fallen to a level very near the photospheric limb. However, spicules appear in clusters, and individually, in the long exposure pictures and can be traced down to the photospheric limb. It is difficult to trace any of them across the limb, because the disk is already over-exposed, but correct exposures nevertheless show dark and bright features crossing the photospheric limb, supporting observations at the other wavelengths. Dark and bright mottles can be traced over the main part of the disk, though the bright mottles are very faint.

(iii) Observations free of stray photospheric light.

We now supplement the above observations by referring to filtergrams taken in sufficiently pure, monochromatic light with a 1/8 A bandwidth as described by Rawi Bhavilai, Norton...
**Figure 3-7**

Hα chromosphere photographed in sufficiently pure monochromatic light, 1/8 Å wide at different intervals Δλ from the line centre, 2 June 1964. Δλ = (a) 0.0 Å, (b) -0.25 Å, (c) -0.5 Å, (d) -0.75 Å. The white markings indicate identical positions on the sun corresponding to the limb in the centre of Hα. The photographs were spaced over about 14 minutes.

**Figure 3-8**

(C.f. § 5). Hα filtergrams of a quiet central region of the solar disk, Δλ = (a) 0.0 Å, (b) +0.5 Å, spaced ½ minute apart. Some of the bright mottles, identified as spicules, are identified by pairs of positions of lines drawn at the sides. Many mottles in both pictures show curved structures.
and Giovanelli (1964), stray photospheric light being eliminated with auxiliary filters. At the extreme edge of the sun and at the line centre, as shown in Fig. 3-7(a), we note that spicules extend down from outside the disk on to chains of bright mottles, many of which are as much as 4"-5" arc inside the chromospheric limb. A picture at H\(\alpha\) -0.25 Å, shown in Fig. 3-7(b), demonstrates this a little more clearly because of the greater contrast at this wavelength. Further inside the disk, at both wavelengths, similar bright mottles can be seen in chain-like formations. These bright mottles can be identified as bright features on the H\(\alpha\) disk as we scan in wavelength from the line centre to \(\Delta\lambda = 0.75\) Å, as illustrated in Fig. 3-7(a-d).

At 0.5 Å from the line centre, as in Fig. 3-7(c), the chromospheric limb becomes rather darker within a band about 5" arc wide, though regions where the spicules extend downwards remain bright. The indications are that the dark mottles of the chromospheric networks which converge at the solar limb contribute to the main portion of this darkening. At \(\Delta\lambda = 0.75\) Å, shown in Fig. 3-7(d), the darkening has progressed further. The mean level of the chromospheric limb at this wavelength is about 4"-5", some 2500 km lower than at the line centre. However, the limb is far from smooth. Bright elongated features cross it and appear as spicules at
the higher levels. Dark mottles also cross it at places, the extrapolated positions remaining dark.

One of the main consequences of the observations in sufficiently pure monochromatic light is to indicate that there is no significant difference between the chromosphere on the disk and at the extreme limb, apart from purely perspective effects. The inner smooth limb has been proved spurious; although it is convenient for use as a reference level, physical features on the sun should not change their radiation characteristics while crossing it. Spicules, which are bright features outside the limb and extend down as bright mottles at and inside the limb, should therefore appear as brighter-than-average features on the disk, as indeed we find.

4c. The associations between bright and dark mottles near the limb

The obviously vertical structure of dark mottles near the limb about Hα $\pm 0.75$ Å shows that at these wavelengths we can see features extending through a considerable height range. The elongated dark mottles near the limb in Fig. 3-6 (d) have an average vertical height of about 5", corresponding to the average height of the limb chromosphere at this wavelength. Using the sharp inner (i.e. photospheric) limb as a datum position, we may superimpose filtergrams for
various wavelengths, and it is then found that the bright mottles near the limb in the line centre lie just further from the limb than the corresponding rows of elongated dark o mottles at Hα ±0.75 Å (see Fig. 3-6(f)). Yet at the extreme limb and the line centre, the bright mottles extend upwards as spicules! At Hα ±0.5 Å also, bright mottles appear at the roots of clusters and rows of dark mottles. Thus the bright mottles which give rise to spicules in the upper chromosphere extend down to quite a low level in the solar atmosphere.

Although the general opacity at the line centre is such that we cannot see the photospheric limb, the above results show that there are great fluctuations in opacity from point to point, so that the bases of the bright mottles can be seen relatively unobscured deep in the chromosphere. In the wings of the line, say from Hα = 0.5 Å to 0.75 Å, the opacities of the dark mottles are considerable, but this is not so between them, since we can observe their extensions in height through about 5" through the surrounding medium.

Fig. 3-6(f) also shows in dotted lines the outlines of the dark patches appearing at the line centre. These rather unresolved dark chromospheric features clearly extend to higher levels than the elongated dark mottles at Δλ = ±0.75 Å. The former features are probably extensions of or loops
from the latter, as already discussed in Section 3.

The bright mottles at the line centre do not coincide with the dark elongated mottles at $\Delta \lambda = \pm 0.75$ Å. They appear to lie at the roots of the dark mottles ($\Delta \lambda = \pm 0.75$ Å), at some positions extending upwards between the dark mottles but rarely overlapping them (or at least not to within the limits of the present observational uncertainties). Many elongated bright mottles at H$\alpha$ $\pm 0.75$ Å and H$\alpha$ $\pm 0.5$ Å appear to be transparent in their upper parts, and only a few are dense enough to obscure the dark mottles in the background (see arrow marked A in Fig. 3-6(d)). Therefore, although the bright mottles are optically dense at their roots, their extensions in the higher levels are not very opaque. Moreover, the bright mottles are to be seen only on the sides of their associated dark mottles away from the limb, though observations of higher resolution are needed to establish an unambiguous interpretation of this.

5. The Number of Bright Mottles in the H$\alpha$ Chromosphere

On disk filtergrams at the H$\alpha$ line centre, the bright mottles sometimes appear in clusters, generally overlying the central parts of clusters and of chains of dark mottles which appear prominent at 0.5 Å from the line centre (see Fig. 3-8(b) in comparison with Fig. 3-8(a)). Individual bright
mottles are also observed in the Hα line centre. These are usually roundish, but some are accompanied by elongations to one side. The bright mottles associated with clusters of dark mottles or mottle chains include both roundish and elongated forms. The shorter dimension of the mottles lies in the range 2″-6″, and the longer 4″-12″.

Although the dark mottles are the more obvious features of the solar chromosphere in the Hα wings at Δλ = ±0.5 Å and beyond, the bright mottles become prominent features at the line centre and the inner wings (Δλ = 0.25 Å), as can be seen in the illustrations. Counts of the bright mottles are therefore best made at the line centre, and of dark mottles at Δλ = 0.5 Å.

The total number of bright mottles N on the solar surface in the line centre of Hα has been estimated from counts in three areas, each 100″ x 120″, on 9.5.64. If n is the number in such an area, then

N = 9.75 x 10^2 n.

Results are shown in Table 3-1.

<table>
<thead>
<tr>
<th>Area</th>
<th>Time</th>
<th>n</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0416UT23s</td>
<td>62</td>
<td>6.0 x 10^4</td>
</tr>
<tr>
<td>II</td>
<td>0440UT36s</td>
<td>103</td>
<td>1.0 x 10^5</td>
</tr>
<tr>
<td>III</td>
<td>0447UT07s</td>
<td>74</td>
<td>7.2 x 10^4</td>
</tr>
</tbody>
</table>
Figure 3-9

(§6). A three-dimensional model of the solar chromospheric structures.
The average value for $N$ is $7.7 \times 10^4$, in satisfactory agreement with Athey's (1959) estimate of $9.3 \times 10^4$ for the number of spicules on the sun at 3000 km height.

6. **A Structural Model of the $\text{H}_\alpha$ Chromosphere**

We can now construct a provisional simple model of chromospheric structures. The Doppler velocities of the features observed on the disk, described in § 3, indicate the existence of matter flowing in loops from the peripheries into the central areas of clusters of dark mottles and of double chains in the chromospheric networks. Confirmatory evidence is also obtained from observations of curved structures both on the disk and near the solar limb (see Fig. 3-6(c), 3-8(a), 3-8(b)).

Fig. 3-9 shows a simple diagrammatic sketch of the chromospheric structure on a plane perpendicular to the solar surface and passing perpendicularly through the centre of a cluster of dark mottles or through a chromospheric chain. $A$ is the centre of the cluster or chain. Material flows in loops into $B_1$ and $B_2$, close to $A$. The lower depths, such as $B_1$ and $B_2$, will be observable best in the red wing of $\text{H}_\alpha$, e.g. on filtergrams at $\Delta \lambda = +0.75$ $\AA$. Some of the material flowing into $B_1$ and $B_2$ comes from $C_1$ and $C_2$, which makes $C_1$ and $C_2$ appear as dark mottles on the filtergrams at
\[ \Delta \lambda = -0.75 \text{ Å}; \text{ obviously C1 and C2 are paired to B1 and B2.} \]

At higher levels, there are small isolated areas where matter appears to flow upwards with fairly high velocities (D1 and D2), and probably downwards more slowly around them; the evidence is the set of small roundish dark mottles in the areas between the chromospheric networks at \( \Delta \lambda = -0.5 \) Å, and by contrast, the much fainter and more diffuse blurs at the same position at \( \Delta \lambda = +0.5 \) Å (for instance, compare the areas marked on Figs. 3-2(a) and 3-2(b)). It is not clear at present whether the resultant upward flow in these fine mottles contributes to the material flowing into the central part of the clusters and network chains or not.

Spicules, which are bright throughout the line profile, originate in the central parts of clusters of mottles or network chains. They are observable at greater heights than the dark mottles, and seldom, if ever, show observable loop structures. Doppler velocities observed at the limb indicate that the spicules have one-way motions during their observed life-times, but there is no evidence to decide between inward and outward directions. We do not at present know whether matter flows solely outwards or solely inwards, or whether there are two types of spicules, some with outward and some with inward motions.
Acknowledgments

I am greatly indebted to Dr R.G. Giovanelli, who suggested the project, for his continual interest and guidance. My thanks are also due to Mr D.G. Norton, who assisted materially in overcoming instrumental problems and in securing the observations, and to Messrs R.N. Smartt, Prayoon Rompo and H. Gillett who all rendered considerable assistance at various stages.

This work was carried out largely during the tenure of a Colombo Plan Fellowship, and subsequently an Australian National University Scholarship, while on leave from Chulalongkorn University, Bangkok, Thailand.

C.S.I.R.O. Division of Physics,
Sydney, Australia.
1964 August.
SUPPLEMENTS TO CHAPTER 3

The filtergrams on the following pages illustrate in some more detail the appearances of the solar limb at Hα +0.75 Å, as described in § 4b.(ii) Chapter 3. Spicules can be followed from outside the solar limb on to the chromospheric disk just inside the limb, where they appear as bright mottles. The dark mottles, which show vertical structures on the disk near the limb, although they converge at the limb to form the general chromosphere there, do not extend outward as spicules. Filtergrams of Fig. 3-10 and 3-11 are of 1/4 Å band width, while Figs. 3-12 and 3-13 are different density prints of a filtergram of 1/8 Å bandwidth.
The pictures a, b, c, d and e are prints of increasing densities of the same negative showing limb features of different ranges of brightness. The original negative was exposed just enough to record the lower part of the limb chromosphere at Hα +0.75 Å, but not enough for the upper chromosphere. In a, b and c, bright mottles at the extreme limb can be seen to extend outwards as spicules, while the dark mottles extend outward as the darker-than-average chromosphere. In c, d and e, dark mottles show vertical structure and cluster to form the chromospheric networks. Elongated bright mottles, which have transparent appearances, occur between them at places.
CHROMOSPHERE AT NORTH LIMB, FEB. 13, '64  2350 U.T.

$\frac{1}{4}$ Å FILTER AT $\text{H}\alpha + 0.75$ Å

Fig. 3-10
The three original negatives of the prints (a,b), (c) and (d,e) were given different exposures so that features differing greatly in their brightnesses can be studied and related. In (a) spicules occur at heights above the general chromospheric level. A number of them can be traced through the pictures (b), (c), (d) and (e) to extend downward and terminate on the bright mottles on the solar disk just inside the limb. Comparing (b), (c) and (d), it can be seen that, at positions where the dark mottles cross the limb outward, the chromosphere appears darker than average.

The solar arc shown is 356" in length, subtending an angle of 21° at the solar centre. Forty spicules are counted from the negative of (a,b), giving 110 spicules/radian. [Lippincott (1957) counted 138-200 spicules/radian on Dunn's limb filtergrams of bandwidth 3.5 Å centred on Hα.]

**Figure 3-11**
CHROMOSPHERE AT NORTH LIMB, FEB. 1. '64

$\frac{1}{4}$ Å FILTER AT Hα + 0.75 Å

Fig. 3 - 11
This is a print of an original negative. It is a filtergram of the north polar limb of the sun at $H\alpha +0.75$ Å with a $1/8$ Å bandwidth. It was obtained at a moment of particularly good seeing and the exposure was suitable for recording the features at the extreme disk near the limb. It can be seen that the bright and dark mottles occur in close associations, yet the bright mottles extend outward as spicules. This serves to illustrate the descriptions in § 4b(ii) of Chapter 3.

The scale of the print is $1$ mm = $1\frac{4}{3}$, and the filtergram was obtained on 3 April 1964.
A print from the same negative as Fig. 3-12, but with greater density to show the appearances of the features on the disk near the north polar limb. This serves to illustrate the descriptions in § 4b. (ii) of Chapter 3.

The scale of the print is 1 mm = 1′3, and the filtergram was obtained on 3 April 1964.
CHAPTER 4

PHOTOMETRY OF THE Hα DISK CHROMOSPHERE

1. Introduction

Observations of the mean solar Hα line profile have been described by many authors: e.g. de Jager (1952), White (1962, 1963), etc. However, the profile changes significantly from point to point on the solar disk. This chapter describes results from a photometric study of 1/8 A bandwidth filtergrams taken at seven positions on the Hα line profile, giving line profiles for different fine chromospheric features. Although the results are semi-quantitative, the good spatial resolution of the filtergrams used allows study to be made of the variations in profiles of individual fine features, which have a bearing on the structure of and motions in the chromosphere. The relations between chromospheric features appearing at different Δλs have been described in Chapter 3.

On many occasions, confusion has arisen by describing the brightness of chromospheric features loosely as "bright" or "dark". It is well known that many features or
chromospheric mottles which appear "bright" at one position on the line profile may appear "dark" at another position, and in consequence the relative brightnesses of mottles vary according to the bandwidth of the monochromatic light used in producing the image. Furthermore the absolute intensity of a bright feature at the line centre is much less than that of a dark feature in the far wings. Because the term "bright" and "dark" are only relative, and are not consistent under different observing conditions, I have adopted below a form of presentation in which a chromospheric feature or a position on the solar chromospheric disk is represented by a set of seven figures which give variations in brightness around the mean profile at seven wavelength positions. Their spatial arrangement in rows and columns constitutes a numerical chart of the solar H\(\alpha\) chromosphere which contains a considerable amount of information about its properties. A graphical chart of the chromosphere is also shown which exhibits some of its characteristics at a glance.

2. The Observational Data

The filtergrams used in this investigation are selections from a series of wavelength scans in H\(\alpha\) at the centre of the solar disk made on the afternoon of 9 May 1964 with a 1/8 Å tunable birefringent filter (Steel, Smartt and Giovanelli,
**Figure 4-1**

H$\alpha$ filtergrams of an area near the centre of the solar disk, 9 May 1964. The area chosen for photometry has the size 44"x30" and is indicated as shown.

(a) H$\alpha$ \(-0.75\) Å  \(\circ\)  
(b) H$\alpha$ \(+0.75\) Å  \(\circ\)

(c) H$\alpha$ \(-0.50\) Å  \(\circ\)  
(d) H$\alpha$ \(+0.50\) Å  \(\circ\)

(e) H$\alpha$ \(-0.25\) Å  \(\circ\)  
(f) H$\alpha$ \(+0.25\) Å  \(\circ\)

(g) H$\alpha$ \(+0.0\) Å  \(\circ\)
The field photographed covers an oblong area of size 480''x360''. An area of size 44''x30'' was chosen for photometry near the middle of this field, with the intention of obtaining a representative quiet chromosphere. The pictures of the area at seven wavelengths are shown in Fig. 4-1. The area is also partially shown in Fig. 3-8 of Chapter 3, near the index numbers 1, 5 and 2 on the right edges of the filtergrams.

The times at exposure for the filtergrams are given in Table 4-1.

### Table 4-1

<table>
<thead>
<tr>
<th>Wavelength Deviation</th>
<th>Time at Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>o A</td>
<td>UT</td>
</tr>
<tr>
<td>+0.75</td>
<td>15h15m05s</td>
</tr>
<tr>
<td>+0.50</td>
<td>15h15m23s</td>
</tr>
<tr>
<td>+0.25</td>
<td>15h15m40s</td>
</tr>
<tr>
<td>0.0</td>
<td>15h15m54s</td>
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<tr>
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<td>15h15m59s</td>
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<tr>
<td>-0.50</td>
<td>15h16m27s</td>
</tr>
<tr>
<td>-0.75</td>
<td>15h17m01s</td>
</tr>
</tbody>
</table>

Kodak 35mm spectroscopic film type IV-E was used for recording. Calibration was made with a 15-step sensitometric
wedge with an exposure time of 0.8 sec. The sharp cut-off red filter used in calibration combined with the IV-E emulsion characteristics gives a calibrating waveband about 400 Å wide roughly centred on Hα. Development was 5 min. in full strength Kodak D 19 at 20°C, giving a gamma of 3.3.

Positive prints were made with 15x enlargement on Ilford N-30 plates. The printed plates, together with a print of the sensitometric wedge, were developed together in the same tank, with full strength Kodak D-76 at 17.5°C for 7.5 min., giving a gamma of 0.7. Positions on the sun's disk in different wavelengths were identified with the aid of a comparator, to ensure identical photometric registrations.

3. Photometry

Tracings giving records of percentage transmission were made on each plate with a Hardy General Electric Recording Spectrophotometer (Michaelson, 1938; Gibson and Keegan, 1938). The scanning beam used was 0.5mm circular, corresponding to an angular resolution of 0.67 arc. To provide enough light for the photometer the monochromator was bypassed and white light from a tungsten filament lamp was introduced instead of monochromatic light. The plate was driven across the beam, emulsion facing the integrating sphere, at the rate of 6.35 mm/min.; most of the light scattered from the emulsion was
Tracings of the filtergram at Hα +0.5 Å.

Percentage transmission of the positive print can be read by referring to the respective zero level of each tracing, as indicated on the right edge of the diagram. The total length of each tracing (22 divisions on the horizontal scale) corresponds to 43" on the sun.
Calibration curve for transferring the measured transmittance into relative brightness on the sun.
received by the integrating sphere. The length of a tracing was 32.2 mm, corresponding to 43" on the sun. On each plate, 13 tracings were made with 1.905 mm spacings (2\textsuperscript{25/54}) so that the tracings cover an area of size 43"x30"5 on the solar disk. The original sensitometric wedge, its print on the negative, and the transferred print on the positive plate were measured in the same way. All 13 tracings of each plate were recorded on the same sheet of paper, the abscissa for each successive tracing being moved by 5 percent along the transmission scale. A sheet of 13 tracings from one plate is shown in Fig. 4-2. The length of 110 scale divisions on the tracing corresponds to 43" on the solar disk.

4. Reduction

The transmittances of the original wedge (to be called A), the wedge on the negative (to be called B), and its transfer on the positive print (to be called C) were plotted on log-log graph paper as A vs. B and B vs. C. From these two curves, a graph representing the relation between A and C was plotted on a linear scale, as shown in Fig. 4-3. This has been used as a calibration curve for transferring the measured transmittance into relative brightness on the sun for each plate.
On each tracing, readings were taken from 21 points spaced five scale divisions apart, corresponding to 1"96, so that 273 readings were made on a plate, covering an area of size 39⅔5 x30⅔5 on the sun.

The mean intensity or transmittance of each plate was computed by averaging the values for 273 points. This value was transformed into mean intensity (relative) at the particular wavelength by the calibration curve A vs. C. The mean values of intensities at the various wavelengths cannot be directly compared because they are not normalized (though they no doubt correspond fairly closely to the mean solar Hα profile). However, this is of no great consequence, because only deviations from the mean profile are considered.

The appropriate mean intensities have been subtracted from the photometric readings of the 273 positions on each plate. The resulting values divided by the appropriate mean intensities are deviations of intensities from the mean profile \( \Delta I_\nu / \bar{I}_\nu \), which is usually expressed in percent. To obtain the deviations in terms of continuum brightness \( \Delta I_\nu / I_c \), it is necessary to know the mean profile of Hα in continuum unit, \( \bar{I}_\nu / I_c \). In this paper, de Jager's (1952) H profile measured at Meudon is adopted, although the use of any other profiles would not materially affect the results. Percent \( \Delta I_\nu / I_c \) is calculated from:
Figure 4-4

A numerical chart of the quiet solar chromosphere in Hα, representing an area $39\times30$ at the centre of the solar disk, obtained from photometric data. The spacing between adjacent rows is 270, and that between adjacent columns is 2754. The seven numbers give relative values of $\Delta I/\bar{I}$ for $\Delta \lambda = -0.75, -0.50, -0.25, 0.0, +0.25, +0.50$ and +0.75 Å respectively from left to right. Negative values have bars on top.
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Figure 4-4
A graphical chart of the quiet solar chromosphere in Hα, representing an area 3975×3075 at the centre of the solar disk, obtained from photometric data. The profiles show variations of $\Delta I_\nu / \bar{I}_\nu$ with $\Delta \lambda$ for 273 positions evenly spaced to scale.
The graphical chart of Fig. 4-5 is shown here superimposed on the appropriate filtergram at $\lambda \approx +0.50 \ \text{Å}$ so that the profiles $\Delta I_\nu / I_\nu$ can be studied in connection with the features they represent.
4-7

Percent $\Delta I_\nu /I_c = (\Delta I_\nu /I_\nu ) \times 100$. 

The values of percent $\Delta I_\nu /I_\nu$ and percent $\Delta I_\nu /I_c$ for a number of representative positions are listed in Table 4-2.

5. **The chromospheric charts**

Intensity fluctuations in the $H\alpha$ chromosphere with wavelength and position are presented in two different forms. The numerical chart, Fig. 4-4, consists of groups of seven numbers arranged in rows and columns. The seven numbers represent intensity fluctuations at $-0.75$, $-0.50$, $-0.25$, $0.0$, $0.25$, $0.50$, and $0.75$ A respectively from left to right. Figures with negative values have bars on top: e.g. 2331235. The graphical chart, Fig. 4-5, gives curves showing relative intensity fluctuations around the mean value through the range of wavelength deviations from $-0.75$ A to $0.75$ A. The curves are drawn to scale so that the central point of each curve coincides with the positions on the solar disk represented.

To facilitate identification of the profiles with positions, the graphical chart is also presented as superimposed on the filtergrams at $+0.50$ A, enlarged to scale (Fig. 4-6).

In preparing the numerical chart, it was realized that only the numbers 1 to 9 were available for representing the
ranges of values of $\Delta I_\nu / \overline{I_\nu}$. It was thus necessary to choose an arbitrary scale in which the intensity fluctuations did not exceed the corresponding values of nine units. Inspection of the data of 273 positions showed that $(\Delta I_\nu / \overline{I_\nu})_{\text{max.}} = 14\%$. The results were therefore presented in an arbitrary scale in which a unit means $\Delta I_\nu / \overline{I_\nu} = 1.5\%$. At a few positions where $\Delta I_\nu / \overline{I_\nu}$ exceeds $13.5\%$, the values are written $9$ or $9^+$ as may be the case.

Although not given here, $\Delta I_\nu / I_c$ can also be presented by the two forms of charts. A different scale, however, needs to be chosen such that $\Delta I_\nu / I_c$ utilizes the range 1 to 9 conveniently. The $\Delta I_\nu / \overline{I_\nu}$ charts can be mentally transformed into the $\Delta I_\nu / I_c$ charts by remembering that $\Delta I_\nu / \overline{I_\nu}$ is approximately transformed into $\Delta I_\nu / I_c$ by multiplying with the factors $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{5}$ and $\frac{1}{6}$ for the wavelengths at $\Delta \lambda = \pm 0.75$, $\pm 0.50$, $\pm 0.25$ and 0.0 respectively.

Scattered light is an obvious source of error in these results. At different positions on the line profile, different proportions of parasitic continuum light fall on the negative along with the chromospheric light "on band". Beckers' (1963) values of the continuum light for this $1/8$ Å filter cannot be used to make corrections here, because in the present investigation a different interference filter has been used to reduce further the parasitic continuum light.
Figure 4-7

(a to j): Hα profiles of 16 selected positions near the centre of the solar disk, 9 May 1964, in relation to the mean Hα profile of de Jager (Meudon, 1952).
Fig. A-7 (1,1)
However, Beckers' value of about 15% of scattered light in the optical system is applicable to this observation. It has been estimated, however, that the errors from this cause are second order, and that the uncertainty of brightness estimations amounts to about 1 on the adopted brightness scale.

The series of filtergrams covers a period of a little less than two minutes, which is comparable with the life-times of some types of short-lived chromospheric features. However, the life-times of the dark mottles are 5 to 15 min., e.g. de Jager (1959), Beckers (1963), considerably longer than two minutes.

Poor atmospheric seeing has the effect of lowering the contrast between two closely spaced features. In Chapter 3 it has been shown that the dark and bright mottles are closely related. Therefore the observed profiles at some positions on the solar disk may be the combined effect of two or more types of features which lie close together.

6. Typical profiles in the Hα chromosphere

Figs. 4-7 (a to j) are drawings of profiles selected from 16 out of the 273 positions. A position is given in rectangular coordinate form, together with the graphical representation of $\Delta I/\bar{I}$ so that it can be located in Fig. 4-5 and identified with a feature at $\Delta \lambda = +0.50$ A in Fig. 4-6. The
values of percent $\Delta I_{\nu} / I_{\nu}$ and percent $\Delta I_{\nu} / I_c$ are given in Table 4-2. The main types of profiles are:

i. Bright profiles (i.e. $\Delta I_{\nu}$ is positive at all $\Delta \lambda$'s) with Doppler shifts indicating receding velocities. Examples are shown in Figs. 4-7a, 4-7d and 4-7e for positions (10,20), (7,20) and (11,13) respectively.

ii. Bright profiles with Doppler shifts indicating approaching velocities. Examples are shown in Figs. 4-7b, 4-7c and 4-7f for positions (11,20), (6,15) and (1,19) respectively.

iii. Dark profiles (i.e. $\Delta I_{\nu}$ is negative at all $\Delta \lambda$'s) with Doppler shifts indicating receding velocities. Examples are shown in Figs. 4-7a, 4-7b, 4-7c and 4-7e for positions (9,17), (2,12), (8,13) and (11,4) respectively.

iv. Dark profiles with Doppler shifts indicating approaching velocities. An example is shown in Fig. 4-7f for the position (10,4).

v. Dark-bright profiles (i.e. $\Delta I_{\nu}$ is negative at some $\Delta \lambda$'s and is positive at some $\Delta \lambda$'s) with Doppler shifts indicating receding velocities. Examples are shown in Figs. 4-7g, 4-7h and 4-7j for positions (9,7), (13,6) and (12,12) respectively.

vi. Dark-bright mottles with Doppler shifts indicating approaching velocities. An example is shown in Fig. 4-7i for the position (12,19).
There are a few dark profiles showing no Doppler shifts. An example of this is given in Fig. 4-7d for the position (5,9).

Doppler shifts in wavelength were estimated from the profiles at the ±0.50 Å positions. Estimation of line shifts nearer the core is difficult due to the shallow shapes of the line profiles. The values of wavelength shifts and derived Doppler velocities are listed in the last two columns of Table 4-2. Bright profiles and dark profiles show upward (-) velocities and downward (+) velocities up to a maximum of about 2.4 km/sec. The dark-bright profiles have smaller velocities of both signs. These results are in good agreement with those of Leighton (1962) who found typical velocities of 2 km/sec for the granular Doppler field at Hα ±0.3 Å.
Table 4-2

Typical Profiles in The Hα Chromosphere

| Position Coordinates | Δλ = -0.75Å | Δλ = -0.50Å | Δλ = -0.25Å | Δλ = 0.0 Å | Δλ = +0.25Å | Δλ = +0.50Å | Δλ = +0.75Å | Profile Doppler Velocity on shift V
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<td>Δλ/Δν/Δλ%</td>
<td>Δλ/Δν/Δλ%</td>
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<td>Δλ/Δν/Δλ%</td>
<td>Δλ/Δν/Δλ%</td>
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Note: The data in the table represent typical profiles in the Hα chromosphere. The columns show the Doppler velocity on shift V for different position coordinates. The values indicate the variation in Doppler shift across the profile, with positive values indicating blue shifts and negative values indicating red shifts. The table provides a snapshot of the Doppler velocity distribution across various positions, aiding in the study of the chromospheric dynamics.
1. Time variations of bright mottles

On the afternoon of 9.6.64, the following observations were obtained by time-lapse cinematography of the centre of the solar disk at the centre of Hα with the 1/8 A filter. The period of observation lasted from 0349UT to 0514UT with about 23 exposures per minute. The seeing conditions on this day were particularly good. There was a break in the data from 0401UT to 0412UT due to guiding failure. From 0419UT to 0440UT the record is not continuous, exposures being made with an automatic device triggered only at moments of particularly good seeing. However, 144 frames were obtained during this period at such spacings that the individual events can be followed in detail. At the end of the observing period, a wavelength scan was made around the profile of Hα. The longest period of really continuous film is therefore 34 minutes from 0440UT to 0514UT.

To study the lives of bright mottles, individual mottles have been followed frame by frame, the life-time being
determined by noting the frame on which it first appears distinctively and that on which it merges with its surroundings. During its life-time, it usually changes somewhat in appearance. Most bright mottles occur at positions formerly not occupied by the dark fibrils; they therefore appear out of relatively brighter-than-average fibrils. The life of a mottle is timed from the brightening of a small region at an end of this fibril. The brightening may or may not extend faintly along the fibril during the development period. The life is considered to be over when the brightening subsides, and the area returns to its former appearance.

By this process we have distinguished two types of bright mottles. The more numerous occur individually and are transitory. They occur only once at a position and the maximum brightness attained is not as great as for the second type. The latter occur in clusters and chains. Their appearances on filtergrams with lower spatial and temporal resolutions might give the impression of rather long life-times. Closer inspection shows that although some of the centres of such clusters of bright mottles remain distinctively bright and recognizable throughout the 34 minutes of observation, their appearances change continually, and indicate the frequent changes of component mottles. We interpret such a cluster of bright mottles as a centre of spicular activity
Chosen frames from time-lapse cinematography of a quiet region near the centre of the solar disk, 9 May 1964, with bandwidth 1/8 Å, centre on Hα. The 15 frames presented cover a period lasting from UT 04h12m40s to UT 05h17m33s. For descriptions of changes see text p. 5-3.
Figure 5-2

Same as Fig. 5-1. The area shown is chosen to include fully developed chromospheric networks and clusters of mottles. See text p. 5-3.
from which bunches of spicules are recurrently ejected. They would be seen at the limb as Lippincott's (1957) 'porcupine' spicules.

The development of clusters of bright mottles is shown in the series of photographs, Figs. 5-1 and 5-2. The two bright centres in the pictures of Fig. 5-1 are evidently interrelated clusters of bright mottles associated with dark mottles and fibrils. At 04h21m51s, in frame 3, a loop of dark fibril connected the two. Later in frame 10, at 04h45m55s, they were joined by thin bright fibrils, one of which brightened up rapidly and became a very outstanding arch bridging the bright centres in frame 12 at 04h49m39s. It was still visible at 04h51m50s, in frame 14. During the whole period, the two centres repeatedly emanated short lived fibrils, both dark and bright, in different directions. The bright fibrils, which are thinner than the dark ones, would appear at the limb as spicules. At 05h17m33s, in frame 15, a bright fibril again bridged the two centres. In this series of filtergram we probably have, for the first time, evidence of bright arch- or loop-structures in the chromosphere. Most of the bright roundish mottles which appeared scattered in the field of each frame were short lived.

The filtergrams shown in Fig. 5-2 were actually chosen from the same exposures as those of Fig. 5-1. In this area,
Figure 5-3

Histogram showing distribution of lives of bright mottles type I.
DISTRIBUTION OF LIFETIMES OF 47 BRIGHT MOTTLES ON AN AREA 100"X120" AT THE CENTRE OF SOLAR DISK

NUMBER OF MOTTLES
however, fully developed networks and clusters of mottles were observed in the wings of the Hα line. We may therefore expect stronger magnetic field in this region, in comparison with the area shown in Fig. 5-1. The chains of bright mottle clusters in the filtergrams of Fig. 5-2 delineate the central parts of the chromospheric networks and clusters. It can be seen that rapid changes were occurring in both the bright and dark mottles and fibrils throughout the period. In the chromospheric network at the middle part of the frames close to the right edge, a group of bright and dark fibrils occurring in a row became suddenly straight and elongated to more than 30″ in frame 10, at 04h45m55s. On the same frame, we may notice a loop of dark fibril near the left edge. This loop occurred around 04h34m30s. Its shape changed during its life-time and started breaking into detached units of dark mottles at 04h49m39s, in frame 12. The changes occurring in and around a bright centre observed in such an area lead us to conclude that such bright centres are seats of recurring spicular activities.

On a selected area of 100″x120″ on a selected frame (frame 2 of Fig. 5-1), 62 bright mottles have been counted, of which 47 belong to the first group (short life-time), all with lives less than four minutes. The distribution of their lives is shown in Fig. 5-3. Their mean life is 1m2ls, the
brighter mottles having the longer lives. The median life is found to be 1ml6s. There are also eight centres of recurrent bright mottles. The remaining mottles are faint and cannot be identified with certainty on earlier and later frames.

Lives determined in the above way refer only to the period that the mottle is brighter than usual. In the majority of cases, this brightening is accompanied by a faint extension in the direction of an already existing bright channel or fibril. In identifying these bright mottles with spicules, for which the average life around five minutes, one has to take other factors into consideration such as the level which contributes to the disk emissions at the line centre, also the opacity and the source function of the spicular material. The spicule must presumably exist above the mottle for a period longer than that of the mottle brightening.

2. **Time variation of the velocity field in the Hα chromosphere at the centre of the disk**

The study of the velocity field on the solar disk was made using the method of photographic cancellation of simultaneous filtergrams in the light from the wings of the Hα line. The photographic cancellation method was described by Giovanelli and Jefferies (1961). The filtergrams are at ±0.285 A from the line centre, made with the 3/4 A Lyot
Simultaneous filtergrams at $\Delta \lambda = \pm 0.285$ Å, of the centre of solar disk, 22 June 1963. Two pairs of filtergrams spaced 27 sec. apart are shown with their corresponding Doppler pictures.

Frame No. 7
03h50m58s UT
a. $+0.285$ Å
b. $-0.285$ Å
c. Doppler picture

Frame No. 8
03h51m25s UT
a. $+0.285$ Å
b. $-0.255$ Å
c. Doppler picture
Fig. 5-4
filter in conjunction with a polarizing beam splitter.
Fifteen consecutive pairs of exposures made on 22.6.63 were used in the study. Their times at exposure are given below. The total interval between the first and last frame is 7m26s.

<table>
<thead>
<tr>
<th>Frames No.</th>
<th>Time at exposure UT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>03h47m03s</td>
</tr>
<tr>
<td>2</td>
<td>03h47m17s</td>
</tr>
<tr>
<td>3</td>
<td>03h47m46s</td>
</tr>
<tr>
<td>4</td>
<td>03h48m10s</td>
</tr>
<tr>
<td>5</td>
<td>03h50m07s</td>
</tr>
<tr>
<td>6</td>
<td>03h50m15s</td>
</tr>
<tr>
<td>7</td>
<td>03h50m58s</td>
</tr>
<tr>
<td>8</td>
<td>03h51m08s</td>
</tr>
<tr>
<td>9</td>
<td>03h51m25s</td>
</tr>
<tr>
<td>10</td>
<td>03h51m38s</td>
</tr>
<tr>
<td>11</td>
<td>03h51m47s</td>
</tr>
<tr>
<td>12</td>
<td>03h51m55s</td>
</tr>
<tr>
<td>13</td>
<td>03h52m32s</td>
</tr>
<tr>
<td>14</td>
<td>03h53m46s</td>
</tr>
<tr>
<td>15</td>
<td>03h54m29s</td>
</tr>
</tbody>
</table>

In Fig. 5-4 are shown square areas of size 150"x150" taken from pairs of filtergrams Nos 7 and 9, together with their respective Doppler velocity pictures. Bright areas signify motions upwards while dark areas signify motions downward in the Doppler pictures. Many mottles with motions, both upwards and downwards, can be identified on both frames which are spaced 27 seconds apart in time. Many motions
observed on frame 7, however, had subsided and did not appear on frame 9, while new motions were observed in the latter frame. Total counts of mottles with downward motions (dark on the Doppler pictures shown) and mottles with upward motions (appearing bright on the Doppler picture) were made on frames 7, 8, 9, 10, 11 and 12. Also counts were made of the mottles with downward and upward motions on frames 8, 9, 10, 11 and 12 which could be identified to the respective mottles with downward and upward motions observed on frame 7. Identification could not be extended with certainty to the other frames because of poor resolutions of frames 5 and 6, and also of frame 13, combined with the long interval between the exposures in comparison with the life-times of the Doppler field being studied.

Table 5-2

Counts of mottles with downward and upward motions on six consecutive Doppler pictures. Area counted 150"x150" square.

<table>
<thead>
<tr>
<th>Frames</th>
<th>Time at Exposure UT</th>
<th>Time Elapsed sec.</th>
<th>Total Number of Motions</th>
<th>Number of Motions Identified to Frame 7</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Downward</td>
<td>Upward</td>
</tr>
<tr>
<td>7</td>
<td>03h50m58s</td>
<td>0</td>
<td>170</td>
<td>128</td>
</tr>
<tr>
<td>8</td>
<td>51m08s</td>
<td>10</td>
<td>156</td>
<td>152</td>
</tr>
<tr>
<td>9</td>
<td>51m25s</td>
<td>27</td>
<td>152</td>
<td>121</td>
</tr>
<tr>
<td>10</td>
<td>51m38s</td>
<td>40</td>
<td>105</td>
<td>97</td>
</tr>
<tr>
<td>11</td>
<td>51m47s</td>
<td>49</td>
<td>182</td>
<td>174</td>
</tr>
<tr>
<td>12</td>
<td>51m55s</td>
<td>57</td>
<td>140</td>
<td>59</td>
</tr>
</tbody>
</table>
Figure 5-5

Time changes of velocity fields in the o disk chromosphere at Hα ±0.285 A, Note that the number of identifiable motions reduces to 1/3 in less than 30 seconds.
**Figure 5-5**

- **X** — Downward Motions
- **Δ** — Upward Motions
  - **○** — Total Motions

**Number of Motions in Area 150" x 150"**

**Time Elapsed (Sec.)**

- 0
- 20
- 40
- 60
The fluctuations of the total number of counts are probably partly genuine and partly due to estimates of contrasts in counting. Fig. 5-5 shows graphs in which numbers of mottles showing motions in frames 8 to 12, which can be identified to those in frame 7 are plotted against the time elapsed. It can be seen that the Doppler velocity field at Hα ±0.285 Å changes rapidly with time in such a manner that less than 1/3 of the total number of motions (upward plus downward) remains after 30 seconds. This is in good agreement with the observations of Leighton et al. (1962) according to which the small scale motions in the core of Hα have life-times of only about 30 seconds. This value of Doppler velocity life-time includes contributions from both the bright and dark mottles in the H core, while the mottle life-time of the last section refers only to the short-lived bright mottles.

The mottles at Hα ±0.285 Å for which Doppler velocities are described in this section are somewhat elongated so that their lengths are at least resolved. Their diameters are in the range 275-570. They appear to cluster and some are arranged irregularly while others are in closed chain structures. When a velocity picture is compared to the respective filtergram in the red wing, it is found that most of the darkest mottles show downward velocities, while the
moderately dark ones may or may not have downward velocities. The bright mottles usually have upward velocities, yet with some exceptions. On the other hand, most darkest mottles in the filtergrams of the blue wing have upward velocities.

It can be seen from Fig. 5-4 that many mottles with strong upward and downward velocities lie close together in pairs indicating flows of chromospheric material in loops, in confirmation with the result described in § 3, Chapter 3. Actually, the Doppler pictures can be directly compared to Fig. 3-2 (c.iii), the filled contours in the latter picture corresponding to mottles of upward motions.

Few of the motions studied during the 57 seconds period appeared to change signs, but the effect might be caused partly by poor seeing conditions which shifted and distorted local features. In general, studies of the 15 Doppler pictures indicated no oscillatory motions, although recurrent motions of the same signs occurred at some positions.

In summary, the Doppler field of the central solar region in the light from the core of Hα (±0.3 Å > Δλ > -0.3 Å) at any one instant contains roughly equal numbers of upward and downward motions. There is evidence in support of the concept of loop motions in the chromosphere at this level of line formation. The Doppler field changes rapidly with time such that less than 1/3 of the motions remains after about 30
seconds. This observation refers only to the upper portions of the solar chromosphere in which the core of the Hα line is formed, and the observation is of limited duration. The study of motions in the chromosphere by this method should, in the future, be extended to utilize other positions of the line profile (e.g. at \( \Delta \lambda = +0.63 \) Å and \( +0.75 \) Å; see §1, Chapter 2) so that a comprehensive Doppler picture of the Hα chromosphere can be obtained.
Observation has made it obvious that almost all active sun phenomena are determined by the development of solar magnetic fields. Evidences reported earlier in this thesis, that small scale chromospheric features have loop structures, indicate that magnetic fields are also responsible for the phenomena of the quiet areas of the solar atmosphere. Differences between active and quiet solar regions are thus the result of differences in intensity, extent and configuration of local solar magnetic fields. It is reasonable to visualize magnetic flux as embedded in loops and columns of moving plasma; therefore, changes in chromospheric features and in local solar magnetic fields are closely related. In this respect, the observational study of simultaneous changes in small scale chromospheric features and their associated magnetic field deserve immediate attention.

The bright \( \text{H}_\alpha \) disk features identified as clusters of spicules in this thesis are called 'plagetts' by Howard and Harvey (1964). Approaching active regions, these plagetts
increase in size and brightness and become bright Hα plages. They occupy areas coinciding with the central parts of calcium plages observed in K spectroheliograms. Hα plages are enclosed within the 60G isogauss contours on fine-scan magnetograms of Howard and Harvey. Magnetic observations also indicate that the plagettes of the quiet solar regions have comparable magnetic fields, although higher resolutions are needed in observation.

With a blink comparator, Dr R.G. Giovanelli (private communication) examined simultaneous spectroheliograms in Hα and K obtained by Suemoto at the Sacramento Peak Observatory. He found that bright mottles in the K line coincide with bright mottles in Hα. The K mottles were bigger but otherwise the patterns agreed. Combining this result with Simon's report (Rome Meeting on Solar Magnetic Field, 1964) that photospheric magnetic fields coincide with K bright mottles down to the limits of resolution, we conclude that magnetic fields are strong in Hα bright mottles, and hence in spicules, which occur in the central areas of chromospheric networks and clusters. The dark mottles and dark fibrils in Hα which are parts of arch- or loop-structures in the chromosphere (Chapter 3) occupy the peripheral areas of comparatively weaker magnetic fields.
Leighton (1963) has given a schematic picture of magnetic fields and material flows in the chromospheric and photospheric levels. In his model, systematic convective motions of the supergranulations push the magnetic field lines to concentrate in the boundaries of the cells. These boundaries coincide with the chromospheric networks in $H\alpha$ and $K$ lines. With some modifications, Leighton's picture fits in quite well with the 3-dimensional structural model of the chromosphere presented in Chapter 3 of this thesis (Fig. 3-9). In the present model, we visualize spicular motions along the tubes of force in the central areas of the networks and clusters where the magnetic fields are strongest. Spicules therefore line up with the coronal streamers, as observed by Bugoslavskaya (1946,1950). It will be the task of future eclipse observations to study the transition regions between the tops of spicules and the lower parts of coronal streamers.

In the peripherial areas of the chromospheric clusters and networks corresponding to regions of weaker magnetic fields, chromospheric material flows into the sun in loops (Fig. 3-9). The clusterings of the legs of the loops nearer the central areas constitute the 'tunnels' of downward moving material observed by Leighton et al. (1962). It has been observed that spicular activities are suppressed in active regions, implying that magnetic fields exceeding a certain
limit inhibit spicular motions, although radiations may be enhanced. There are therefore structural differences between the quiet chromosphere and the chromosphere around active regions. In this respect there is a need for extensive studies of the relations between local solar magnetic fields and the types of chromospheric features occurring in the same regions.

Magnetic observations of the quiet solar disk with limited resolution (e.g. 10" as reported by Howard and Harvey, 1964) show no significant changes in the appearances of isogauss lines during observing periods lasting in terms of hours. It is to be expected that when the resolution of magnetic observations is increased to a magnitude comparable with the sizes of chromospheric features, we may observe changes of local magnetic field in accordance with time changes of chromospheric features. Although the problems to be encountered in developing magnetographs to such requirements are great, the project is worth considering in planning for future solar observations.

Although attempts have been made by many observers to correlate the Hα or K chromospheric features with the continuum features, no conclusive result has so far been reported. In the course of my investigation, a few sets of observations were made in which the 1/8 Å filter was tuned quickly from the
Hα line centre to a position 10 Å away, so that photospheric pictures were obtained while the telescope was guiding on the north polar region of the solar disk. Comparison of the Hα filtergrams with the photographs in continuum light show that a few of the groups or clusters of bright mottles at the Hα line centre (identified as spicules in this thesis) coincide with bright photospheric features (faculae) near the limb. This observation, however, needs confirmation by photospheric photographs with higher resolution than ours. It would be possible to make simultaneous observations in Hα and in the photospheric light with separate telescopes mounted on the same spar. Such equipment is readily available at the C.S.I.R.O. Solar Observatory at Fleurs (see § 2 of Chapter 2). This programme therefore should be attended to in the immediate future.

Since the observations of Hale and Ellerman (1916), it has been generally accepted that bright calcium flocculi in K spectroheliograms correspond to dark mottles in Hα. However, as quoted above, the central parts of bright calcium flocculi occurring in chromospheric networks and clusters has been found to correspond to the bright mottles in Hα. There is therefore a need for careful simultaneous observations in Hα and the K line. This should be best done by time-lapse cinematography with the highest spatial and spectral
resolutions available. In identifying chromospheric disk features occurring in different lines or at different positions on the profile of the same line, one should bear in mind that one is looking at a 3-dimensional region. A feature having extension in height and increasing in horizontal cross section at the same time will obscure adjacent features which occur only at lower levels. Combinations of disk-centre and near-limb observations with scans in wavelength, as has been done in this investigation, will most likely yield fruitful results.

The theoretical resolving limit of the objective lens (5-inch aperture) used in the observations described in this thesis is about 0.78 arc for photospheric observation. However, it is exceedingly difficult to approach this limit in chromospheric observation because the narrow bandwidth used requires a long exposure time for such objective aperture. We can therefore expect much improved spatial resolution by increasing the telescopic aperture by a factor of 2 to 3. A combination of a coronagraph-type instrument having a 15-inch aperture such as that used by Dunn (1960) with the 1/8 A tunable filter of the C.S.I.R.O. would be very useful for chromospheric observation. In Australia, a 12-inch chromospheric telescope being planned for the C.S.I.R.O. Solar Physics Observatory at Culgoora in New South Wales will
enable chromospheric observations to be made with a resolution limit approaching 0.75 arc.

The investigations reported in this thesis have demonstrated the significance of spectral resolution, in addition to spatial and temporal resolutions, in chromospheric studies. The planning of future observations should include the above considerations. Also spectral purity is a great asset, as is shown in Appendix 1. Specifically in chromospheric observations of active regions around sun spots, considerable contributions of continuum light will leak through the parasitic pass bands of an imperfect monochromatic filter. This is because of great fluctuations in continuum brightness over the area. In this regard it will be interesting to observe the chromosphere around sun spots in pure spectrum lines uncontaminated by the superimposed photospheric picture. In general, the structural studies of the quiet solar chromosphere by the methods described in this thesis should be extended to cover the more active regions around sun spots. Whenever possible, cinematography should be used as there have been indications that the time scales of changes in active and quiet regions are different.

The reduction of the photometric data of Chapter 4 can be carried further so that the half-width, line strength and Doppler shift are obtained for many points on the solar disk.
The study should also be extended to cover regions containing fully-developed chromospheric networks as observed in the Hα wings, and also into the active areas around sun spots. Correlation studies of the three quantities obtained will be valuable for the computations of a new chromospheric model.

It may be noted that Doppler velocities of the bright mottles as determined from the profiles of Chapter 4, and also as estimated from photographic cancellation Doppler pictures at $\Delta \lambda \sim +0.3$ Å (Leighton et al., 1962), are much less than the observed Doppler velocities of spicules at the limb. Actually no quiet solar disk features examined have Doppler velocities comparable to the values ascribed to the limb spicules (20-40 km/sec.). The explanation of this apparent discrepancy is that the upper portions of the spicules are so transparent that in disk observations we are actually looking through the spicules and observe only their denser roots as bright mottles. A high resolution disk filtergram at $\Delta \lambda \sim 0.50$ Å should illustrate this point well in that it shows faint extensions from bright mottles. These faint extensions have transparent appearances such that they do not obscure the chromospheric disk features underneath them. The limb observations of spiculare velocities, both by the Doppler velocities method and in the cinematographic method, refer to heights more than 5000 km above the
photospheric level. The bright mottles are identified as the roots of these spicules in the much lower levels of the chromosphere.

Photographs of the solar chromosphere in monochromatic light of pass band 1/8 Å centred on Hα show that the well-known double line vanishes on eliminating all traces of the surrounding continuum. The inner line is spurious, and is simply an image of the photosphere in stray light of unwanted wavelengths.

Attention has recently been drawn by Zirin and Zirin (1963) and by Cragg, Howard and Zirin (1963) to the curious "double line" seen in Hα spectroheliograms and filtergrams. Using the Mount Wilson spectroheliograph with a pass band of
APPENDIX 1

THE "DOUBLE LIMB" IN Hα

Rawi Bhavilai

C.S.I.R.O. Division of Physics, Sydney, and Mount Stromlo Observatory, A.N.U., Canberra: on leave from Chulalongkorn University, Bangkok.

D.G. Norton and R.G. Giovanelli

C.S.I.R.O. Division of Physics, Sydney.

ABSTRACT

Photographs of the solar chromosphere in monochromatic light of pass band 1/8 Å centred on Hα show that the well-known double limb vanishes on eliminating all traces of the surrounding continuum. The inner limb is spurious, and is simply an image of the photosphere in stray light of unwanted wavelengths.

Attention has recently been drawn by Zirin and Dietz (1963) and by Cragg, Howard and Zirin (1963) to the curious "double limb" seen in Hα spectroheliograms and filtergrams. Using the Mount Wilson spectroheliograph with a pass band of...
width 0.1 Å centred on Hα, the latter authors obtained photographs showing a sharp inner limb and a coarse outer limb, fainter and irregular, the region in between being unresolved. They referred to objections sometimes advanced against interpreting the outer limb as a real solar phenomenon; for example, it had been alleged to be due to inadequate elimination of stray light. However they pointed out that the irregular nature of the outer limb was sufficient to disprove its origin in stray light, while it also blocked out light from prominences behind the limb. They also commented that "the inner limb is so bright that it likewise could not be scattered light". They concluded that the two limbs are genuinely solar features, the outer limb being identified with the upper chromosphere and being "the confluence, due to foreshortening, of many bushes or clumps of spicules".

This raises an interesting paradox. The visibility of the inner limb implies that, surprisingly enough, the transverse opacity of the chromosphere is not very high immediately above this limb. Perhaps this result might be due to a fine, unresolved fibril structure in the chromosphere, so that we could see to considerable distances via gaps between fibrils. However this appears to be incompatible with the obscuration of prominences by the chromosphere, reported by Lyot (1944) and Roberts (1950).
The chromosphere at the equatorial west limb 29 May 1964, observed at the centre of Hα through different combinations of filters. The levels of the chromospheric limb marked "ch" are identical in all photographs. The positions of the "inner limb" are marked "p". (a) through 1/8 Å birefringent filter; (b) through 1/8 Å and auxiliary 3 Å interference filter; (c) through 1/8 Å + 3 Å filters and additional "supplementary plate".
Fig. 1
To investigate this further, we have used the 1/8 A bi-refringent filter (Steel, Smartt and Giovanelli, 1961) which reveals the two limbs distinctly - Fig. 1a. As described by Cragg, Howard and Zirin, the inner limb is quite smooth. It appears to be in approximately the same position as the limb photographed shortly before or after with the filter tuned off Hα; though our ability to establish this is limited to the reliability of the photoelectric guider and of this we are not certain. The outer limb is ragged and is some 8 seconds of arc higher.

It is well known that monochromators of one sort or another all transmit stray light of unwanted wavelengths. Before the introduction of modern gratings it was necessary, for example, to make large corrections to the central intensities of absorption lines measured with high-dispersion spectrographs. The 1/8 A filter also is quite an impure monochromator, transmitting weak bands near Hα, the first and strongest being ± 3/16 A from the centre of the pass band, together with other subsidiary bands at approximately multiples of 32 A from Hα. Because of the low intensity at the centre of Hα as compared with the continuum, the integrated effect of these weak subsidiary bands may nevertheless be significant, as Beckers (1963) had found. The question arises as to whether the \textit{inner} limb in our photographs may be
partly or wholly due to this stray light which would effectively give a picture of the photosphere superimposed on that of the chromosphere; Lyot (1944) had already given such an explanation for the double limb in photographs obtained with a 1.5 Å filter.

To test this we have used firstly an auxiliary narrow-band interference filter kindly constructed by our colleagues J.V. Ramsay, E.G.V. Mugridge and R.N. Smartt. This has multilayer reflective coatings on either side of a mica plate of such thickness that the transmission bands are about 0.3 Å wide, one being centred some 1 to 2 Å to the violet of $\text{H}_\alpha$ for normally incident plane-polarized light. The line centre is transmitted sufficiently well. Photographs of the sun with this auxiliary filter show the inner limb much diminished in intensity (Fig. 1b), so that a substantial fraction of the light forming the inner limb has been clearly due to wavelengths further than about 3 Å from $\text{H}_\alpha$. But what about the remaining inner limb?

The 3/4 Å birefringent filters produced by the firm 0.P.L. according to Lyot's original design are equipped with a supplementary plate, a calcite birefringent element having transmission maxima spaced at intervals of 2-1/4 Å; the function is to suppress the first side-bands at ± 1-1/8 Å from the line centre. We have used one of these supplementary
Figure 2

The Hα chromosphere photographed in a "pure" spectral line 1/8 Å wide at different intervals Δλ from the line centre.

Δλ = (a) 0 Å, (b) -0.25 Å, (c) -0.5 Å, (d) -0.75 Å. The white markings indicate identical positions on the sun corresponding to the limb in the centre of Hα. The photographs were spaced over about 14 minutes and so do not present identical features.
plates in combination with the 1/8 A filter and the auxiliary interference filter, securing additional limb photographs for which, however, considerably greater exposures (10 secs.) are necessary (Fig. 1c). These show no trace of the inner limb whatsoever (though in Fig. 1c there is a genuine chromospheric feature at about the same position just underneath the chromospheric limb markers; a photograph free of such a feature is shown in Fig. 2a). The inner limb has been due entirely to light from outside the core of Hα and is solely that of the photosphere, which thus appears in stray light of unwanted wavelengths superimposed on the genuine chromosphere.

The long exposure times needed at the line centre inevitably make it more difficult to obtain images unaffected by seeing. However we have used a seeing monitor (Bray, Loughhead and Norton, 1959) to record seeing conditions during the observations (these consisting of a large number of exposures in rapid sequence). Only frames obtained during moments of good seeing have been selected for consideration, though even the worst seeing encountered was insufficient to smear out the smooth inner limb if it had not already been eliminated by the filters.

The disappearance of the inner limb may also be followed visually, since the action of the supplementary plate depends on its orientation. By rotating it about the optic axis, we
can observe the continuous transition from lb to lc, and have seen quite clearly the complete disappearance of the smooth inner limb.

At first sight, it may seem surprising that the amount of stray light present can be so great as to make the inner limb so obvious in Fig. 1a, and yet not have too adverse an effect on the contrast of images such as photographed by Beckers (1963). This is largely a photographic effect. Beckers found that, for an equi-energy spectrum, about 78 percent of the light transmitted by the 1/8 A filter (used alone) lies within the pass band; but that when the filter is centred on the solar Hα line, whose central intensity is about 0.15 of that of the continuum, only about 48 percent of the transmitted light lies within the nominal pass band. The characteristic curve of the emulsion used (Kodak IV-E) has a gamma of approximately 3.5 and varies, under our standard development conditions - 5 minutes in full-strength D-19 developer at 20°C - only from 3.6 to 3.25 as the exposure is changed from 0.8 to 10 seconds, a range exceeding those in our present observations. Moreover, the densities of the features described fall within the linear range of the emulsion. Thus a 2:1 variation in illumination on crossing the inner limb causes about 10:1 change in transparency of the negative! The appearance of the print is, of course, adjustable in
processing, and Fig. 1a has been processed to show the two limbs simultaneously.

Fig. 2 shows the limb in sufficiently pure, monochromatic light at different intervals from the centre of \( H\alpha \). These limb appearances can vary appreciably depending on the exposure and precise photographic processes used, but the general pattern can easily be recognized. At no stage is there an obvious inner-limb visible through a transparent chromosphere; if there be such, it is below the limits of our present resolution. Generally speaking, the height of the \( \alpha \) chromosphere remains constant out to 0.5 Å from the line centre, but is diminishing rapidly at 0.75 Å.

In connection with work of this type, it may be worth drawing attention to the importance of the characteristic curve of the photographic emulsions used. This can play funny tricks with the appearance of contrasts on the negatives (and on prints), and care need be taken in interpreting intensities unless adequate photometric checks are used.
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