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Fred L. Whipple, Director,
Astrophysical Observatory,
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Cambridge, Mass.
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The observations

The observational material used in the following discussion was obtained by Richard B. Dunn with the 15-inch chromosphere camera at Sacramento Peak. The effective focal length is 957 inches, giving a scale of 1 mm = 8.48, or a solar radius of 4.4 inches; only 12° of arc along the limb are portrayed on a single frame of 35-mm movie film. The light beam traversing the objective is split into two sets of two components each, resulting in four images at the ultimate focal plane. One set gives an image centered at H-alpha with a pass band of 3.5 Å and another image at about 3 Å from the center of H-alpha. The second set of images is the same as the first, except for a reduction of approximately 10 in intensity on the film and a difference in occulting. The reproductions in plates 1, 2, and 4 show the first and third images in the continuum near H-alpha and the second and fourth images centered on H-alpha. The 15-inch chromosphere camera and the photometric measures of the four images taken simultaneously will be discussed in a future paper by Mr. Dunn.

The sun's limb is allowed to fall just above the occulting disk on the less dense image in H-alpha, which permits the use of the limb (shown on the accompanying reproductions) as a reference for all measured heights in the chromosphere. Two types of film sequences are used in this study. First, surveys consisting of three successive exposures for each 12° arc around the limb. The exposure times are all 1/17 of a second, so that a complete survey of 29 times 3 frames can be obtained in less than 5 minutes. The other type of sequence is a movie taken at the rate of 16 frames per minute. For most quantitative studies of the limb fine structure, superior seeing must be maintained throughout the observations, and therefore limits are imposed on the lengths of the films. Although the exposures are short and the survey frames are taken in rapid succession, it is frequently noted that the three exposures of the same 12° arc vary in quality due to changes in seeing.

All the measurements of spicules were made from projected images enlarged 15.2 times.

General aspects of limb chromospheric fine structure

Various names have been given to the fine structure which protrudes above the general chromospheric level, such as brushes, jets, flaming prairies, spicules, etc. The term “spicules” as used...
by Roberts (1945) is employed here. This structure has been observed in white light during eclipses and in H-alpha outside of eclipse. The apparent heights of the spicules above the photosphere measured on the dense H-alpha images range from 5000 to 18,000 km. On the less dense images in H-alpha the foreground spicules sometimes appear superimposed on the general continuous lower chromosphere, and can be traced down to the photosphere; they are so short in projection that some do not rise above the general chromosphere level and are not seen on the dense images. Unless otherwise noted, the dense images have been used for measurements in the following discussion.

There appear to be three main types of spicule group formation. One is characterized by parallel spicules with approximately the same heights and intensities over an arc equal to an average length of 140,000 km (200 sec of arc). An example of this "wheat field" pattern is shown in plate 1. Twenty-one examples with lengths greater than 50,000 km (70 sec of arc) were found on eight surveys from different days, but these were observed only within 30° of the poles. The total duration of this pattern is estimated to be of the order of five minutes, the spicules growing and disappearing as a unit, which may be replaced by any of the spicule formations.

The second type of spicule group formation involves a dome-like rise in the general chromosphere level, averaging 18,000 km across, from which spicules protrude in approximately radial fashion, as in a porcupine (see plates 2, 4). From the symmetry seen in projection, the expected shape on the disk is circular or elliptical. The concentration of spicules over a "porcupine" appears slightly greater per unit area than the number found per unit area for the general polar regions. If one extends the spicules inward, their zone of intersection ranges from 7,000 to 30,000 km below the limb for 27 "porcupine" patterns measured; however, it is not obvious whether the conditions above or those below produce this structure. This type probably has a lifetime similar to that of the "wheat field" structure. It may be found in groups of two or three, or singly. Fifty examples were seen in eight surveys on different days. These were found almost exclusively within 30° of the pole.

The third type of spicule group formation is a mixed arrangement of spicules having random distributions of heights, intensities, and inclinations. This type of spicule manifestation may appear at any latitude (an example is given in plate 3). Besides showing any of the three above aspects, the edge of the chromosphere over a small arc may have for several minutes a rather billowy appearance devoid of prominent spicules, showing only rudimentary mounds or incipient spicules. This appearance is somewhat similar to that seen all over the limb at times of inferior seeing, so that one must check carefully to establish the reality of these quiet regions.

**Observed frequency of spicules**

Counts per 12° along the limb were made for nine surveys on five different mornings between Aug. 8 and Aug. 29, 1955. Table 1 gives the dates of the observations and the total number of spicules observed. The greatest uncertain-

<table>
<thead>
<tr>
<th>Date</th>
<th>Spicules observed</th>
<th>Total number</th>
<th>Mean heights</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>U. T. h m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aug. 8</td>
<td>13 30</td>
<td>1154</td>
<td>8770</td>
</tr>
<tr>
<td>9</td>
<td>13 32</td>
<td>918</td>
<td>8740</td>
</tr>
<tr>
<td>9</td>
<td>13 43</td>
<td>1032</td>
<td>8880</td>
</tr>
<tr>
<td>21</td>
<td>13 32</td>
<td>1063</td>
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<tr>
<td>21</td>
<td>13 43</td>
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<td>26</td>
<td>13 49</td>
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<td>13 32</td>
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<td>26</td>
<td>13 20</td>
<td>925</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>14 03</td>
<td>1063</td>
<td>8680</td>
</tr>
<tr>
<td>Mean 1016</td>
<td></td>
<td></td>
<td>8740</td>
</tr>
</tbody>
</table>
Four images taken simultaneously of one 12-degree arc centered around latitude —60°. The light beam is split into two sets so that the first and second rows are the same as the third and fourth rows except for a difference in occulting (the sun's limb shows in the upper set) and a reduction in intensity of approximately 10 on the film for the upper set. The first and third images are formed by light in a 3.5-Å pass band about 3 Å from the center of Hα, while the second and fourth rows show images formed from a 3.5-Å pass band centered on Hα. This frame shows many spicules with the same slope, a structure referred to as the "wheat field" pattern. (Photograph from a survey film taken by R. B. Dunn.)
Four simultaneous images centered at latitude \( \pm 68^\circ \) presented as in plate 1. Note several examples of "porcupine" structure.

(Photograph from a survey film taken by R. B. Dunn.)
Four simultaneous images centered at latitude —50° presented as in plate 1. This frame shows a mixed group of spicules characterized by their random slopes.

(Photograph from a survey film taken by R. B. Dunn.)
Two examples of "porcupine" structure with several spicules of the groups extended inward. Only the images centered on Ha have been printed. (Photographs from survey films taken by R. B. Dunn.)
CHROMOSPHERIC SPICULES

metry, so that east and west limb counts have been averaged together. Further means are taken without regard to north or south latitude and appear in figure 16. The internal agreement of the values averaged to obtain each of

$$a$$

![Graph](image)

**Figure 1.**—Observed spicule frequency: (a) Average number of spicules per 12° of latitude (combining east and west limb) determined from nine surveys between Aug. 8 and Aug. 29, 1955 (regions obviously obscured by prominence activity have been omitted, so the frequency distribution with latitude refers to the quiet sun); (b) spicule counts per 12° of latitude (using the same material as in (a)) averaged without regard to the sign of the latitude. Lower portion of (b) shows a measure of the prominence activity per 12° of latitude for the times of the spicule observations.

the 15 points in figure 1a yields a probable error of the order of 1 for each determination of 12° of latitude. By taking nine surveys it is hoped that the effects of intermittent inferior seeing during any one survey will be minimized, and that the true local deviations in the average number of spicules existing at any one moment will average out so as to give at least a true representation of the relative frequency distribution according to latitude.

The trend toward fewer spicules from ±90° to ±36° latitude and the slight increase from ±35° to 0° latitude is assumed to be real, as shown in figure 1. A preponderance of spicules is also noted at the south polar regions, compared to the number at similar regions in the north; the size of the probable error for these points indicates that this difference is probably real. During the time covered by these observations the south pole is inclined 6° toward the observer; however, it is not obvious that this would affect the observed spicule frequency. There is a striking preference of both the “wheat field” and the “porcupine” formations for the south polar regions; the greater concentration of spicules over “porcupine” structure has already been noted. From a survey of the prominence activity on the limb for these dates a maximum is found near latitude ±36°. This is also the region where the spicules are fewest, even at positions where there are no obvious higher chromosphere disturbances. A measure of the prominence activity is given in the lower part of figure 16. An attempt to reduce the frequency of spicules observed projected above the limb to the true number 90° from the center of the disk is discussed in the last section.

**Observed heights of spicules**

Heights as well as frequency counts were made on six surveys listed in table 1. The heights were measured above the photosphere in units of 520 km (appearing as 3/4 inch on the enlarged projected images). All measurements were made radially, and no compensation was made for those spicules inclined from this direction. Averages for each 12° of latitude for all the surveys were taken and appear in figure 2a. There appears a pronounced trend toward lower heights from pole to equator. On the assumption of north-south symmetry, the points in figure 2b show the height distribution. Each point contains an average of 800 height determinations. The average height for 12° centered around latitude ±36° is 9500 km, whereas at the equator the height is 7300 km, representing a decrease of 23 percent. In the middle latitudes near ±36°, where the prominence activity is greatest, the height appears constant. The aspects of the spicule formation are generally somewhat different in the polar and in the equatorial regions, viz, true “wheat field” and “porcupine” patterns are not a characteristic of latitudes below 60°; but it is not felt that this difference in aspect can give rise to a spurious difference in the heights to which predominantly radial structure can be measured. In order to compare these
heights with those attained by a lower intensity in H-alpha, the less dense images were measured for three of the surveys. The results are shown in figure 2c, where each point represents the mean of some 300 spicule heights. The trend confirms that found with the denser exposures, although somewhat less exaggerated. Figure 3 shows the height frequency distribution for different latitudes from the sum of the six surveys. All eight histograms have similar contours, the drop in frequency on the side of shorter heights being sharper than on the other side of maximum frequency. (The low total frequency for 0° latitude results from combining 30 groups around the limb into 8 groups in one quadrant. The frequency increases fourfold for all the groups except the 0° latitude group, which is doubled.) It must be remembered that these observations are from "frozen" motion. An apparent increase in the mean spicule height with latitude can result if the spicules remain visible at their maximum heights longer near the poles than at the equator.

General chromosphere heights measured over a number of years at Arcetri (Fracastoro, 1948) give an average increase of 2 seconds of arc between the equatorial and the polar regions. This value, however, is by no means constant from year to year; it is greatest near times of minimum sunspot activity. The photometric study being carried out by Mr. Dunn should show any changes that may exist in the general chromosphere level with latitude for a given intensity. It will be of interest to compare these heights with the average spicule heights for different latitudes over the same period of time.
Slopes
Although the spicules project from the limb predominantly radially, certain regions exist on each survey inspected where the majority of the spicules form an angle less than 90° to the tangent at the limb. For every 3° of latitude on 10 surveys, estimates were made of the predominant direction of the spicules. Four categories including three mean directions were considered: (a) toward decreasing position angle, (b) radial, (c) toward increasing position angle, and (d) indeterminate. Roughly one-third of the regions proved to be indeterminate, due partly to obscuration by prominences. Near
prominences, the spicules are sometimes inclined toward and sometimes inclined away from the higher chromosphere activity; they are often lined up with the general contours of the higher activity.

Among the 10 surveys dating from July 18 to Aug. 29, 1955, there were regions in which the spicules maintained predominantly the same inclinations; these slopes are schematically shown in the diagram, figure 4.

A number of observers have noted that eclipse photographs show spicules lined up with the general contours of the white light corona, and, indeed, without much imagination one can picture the gross contours of a typical corona at minimum solar activity extending outward from the schematic spicule slopes in figure 4. Bugoslavskaya (1946) has noted that spicules in the polar regions tend to slope toward the equator, and that those in the active zones (±20° to ±41°) tend to slope toward the poles.

**Lifetimes and velocities of spicules**

Spicule heights were measured on two films, the first made over a 30-minute interval on July 14, 1955, and the second during an interval of 18 minutes on Aug. 4, 1955. Both sequences cover 12-degree arcs centered at −84° latitude. The exact time interval between the frames used for measurements depends on the seeing, but in general it is less than 30 seconds. The lifetimes, heights, and velocities found are in general agreement with those found by Rush and Roberts (1954) and Dizer (1952).

Lifetimes were observed for 77 spicules (figure 5); 32 fade at maximum, and out of the 45 which appear to descend, 21 remain at maximum height for 1 minute or more. The mean value found for the visible lifetime is 5.1 minutes; Rush and Roberts find a mean of 3.3 minutes for 400 spicules. Of the 77 spicules used in this study none have lifetimes less than 1 minute. Those with such short lifetimes are extremely faint, alternately appearing and disappearing from frame to frame. It may be that these are visible tops of tall spicules stemming from some degrees off the limb. One must keep in mind that approximately only one-quarter of all the spicules seen are on the limb, i.e., we observe the true total lifetimes above the general continuous chromosphere of not much more than one-quarter of the total number observed. If we consider the spicules in the upper 25 percentile according to their maximum heights, and average their corresponding lifetimes, we find that the mean lifetime has increased to 6.3 minutes. It has been noticed that after a spicule has apparently descended, or the visibility has been reduced to a mound on the edge of the continuous chromosphere, a spicule may appear to rise again from the same source, which suggests that a spicule source may have several times the lifetime of one spicule observed above the mean chromosphere limb. This increases the difficulty in identifying the equivalent of spicule structure appearing on the disk from correlations with lifetimes. If the photosphere is the birthplace of spicules, then their lifetimes should be counted from the photosphere. If we assume that the linear rate of growth during the first 5000 km is the same as that observed above this average height, the total average lifetime is increased by 4 minutes if the spicule fades at maximum; if it drops to the photosphere at the same rate the increase is doubled.
This extrapolation gives total lifetimes of the order of 10 to 15 minutes.

One speaks of the velocities of spicules. An actual rise and fall of material may occur but one should not exclude the possibility that this is only an apparent motion of material; one may really observe the rate at which the material becomes visible in H-alpha. The fade-outs at maximum height suggest the latter notion. Therefore it must be understood that "velocities" determined in this connection do not necessarily imply the rate of displacement of matter.

No certain deviations from linear motion were found. The ascending velocities average 19 km/sec weighted according to the time over which each spicule ascended at a given rate. An unweighted mean of the velocities gives 24 km/sec, which implies that the higher velocities favor relatively short time intervals. A histogram of the velocity frequencies is given in figure 5. Frequently the spicules rise in jerks, but each succeeding upward velocity is approximately the same. Changes in seeing and fluctuations in the brightness of the spicules
account for some of the unevenness of the upward motions.

Previous observers have noted that some spicules fade over their entire lengths at maximum and others descend or fade gradually, starting at the top. Forty-five out of the 77 appear to descend or fade from the top; their average velocity weighted in the same fashion as were the ascending velocities equals 24 km/sec, while the unweighted value is 28 km/sec. Figure 5 shows the frequency distribution of the descending velocities.

A histogram of the maximum heights is also given in figure 5. The average maximum height is 11,600 km. Not many more than a quarter of these are on the limb, as found from calculations in the following section. If we assume that all spicules have the same maximum height (which is probably not true) the upper quarter, 13,000 to 18,000 km, represents the true maximum height to which spicules are generally visible above the limb near the poles at this time.

**True height and frequency distribution**

The observed height and frequency distributions include not only those spicules situated on the limb, but also a fraction of those on either side of the sun extending 8° from the limb. Therefore the total number of spicules observed is a maximum and only the frequency ratios between different latitudes are truly valid. In order to reduce the number of observations to a known small area surrounding the limb, the method suggested by Rush and Roberts (1954) has been applied to the observed frequency-height distribution from the sum of six surveys for all latitudes averaged together, shown as the solid line histogram in figure 6. By this method the material was divided into 8 equal-interval height groups. The 13,500 to 14,500 km group was taken as representing the highest attained in any abundance by the spicules, so that all these spicules may be considered as extending from the limb. Values for arcs measured in the line of sight from the limb were computed so that each succeeding arc contributes an additional height group to all the spicules projected on the limb. The ratio of each succeeding arc to the 2° arc adjacent to the limb represents the proportion of spicules on that arc compared to the total number found on the 2° arc next to the limb for each height group. By this means all spicules from 2° to 8° were successively eliminated on either side of the limb in the line of sight, which resulted in a new frequency distribution. The dashed histogram in figure 6 represents the distribution of spicules within 2° of the limb both in front and away from the observer. Note that the general shape of the curve remains. The distribution of the height frequency is not sensitive to the choice of group denoting maximum height on the limb. It is quite certain that the sharp decline in the frequency of short spicules is spurious, but only a few of the shorter spicules have a chance of being hidden behind the long ones. The true number of spicules within 2° of the limb on both sides is 37 percent of the total number observed. The total number of spicules on the solar surface is then reduced from a maximum of \(34 \times 10^4\) to \(11 \times 10^6\). Making use of the reduced value we find a mean separation of 23,000 km between the centers of the spicules. All estimates of the total number of photospheric grains are substantially larger than the frequency of spicules found for the entire sun. Attention has been called to dark areas seen on the photosphere (Miller, 1955).
These dark areas have a diameter of the order of 15,000 km, or a total of $4 \times 10^4$ on the entire surface, and they have an average lifetime of 3 to 4 minutes.

We may now compare the present frequency determination of spicules with those obtained by others. A summary is given in table 2. Due to different observing conditions and different instrumental properties, the wide frequency range is not unexpected.

Table 2.—Summary of observed spicule counts

<table>
<thead>
<tr>
<th>No. spicules per radian (uncorrected)</th>
<th>Position on limb latitude</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>86</td>
<td>0° to ±30°</td>
<td>7-inch refractor, 1 mm=69&quot;, (Bugoslavskaya, 1946.)</td>
</tr>
<tr>
<td>76</td>
<td>±30° to ±60°</td>
<td>5-inch High Altitude Observatory coronagraph, 1 mm=6&quot;, (Rush and Roberts, 1954.)</td>
</tr>
<tr>
<td>30</td>
<td>±60° to ±90°</td>
<td>6-inch Ross lens, 1 mm=135&quot;, Ha spectrum 1952 eclipse. (Rush and Roberts, 1954; Athay and Roberts, 1955.)</td>
</tr>
<tr>
<td>42</td>
<td>±90° to ±120°</td>
<td>9-inch aperture, 1 mm=26&quot;, white light, 1930 eclipse. (Mohler, 1951.)</td>
</tr>
<tr>
<td>45</td>
<td>±120° to ±150°</td>
<td>15-inch chromosphere camera, Sacramento Peak, 1 mm=8&quot;, (Present Investigation.)</td>
</tr>
<tr>
<td>171</td>
<td>30° to 33°</td>
<td>38 cm aperture Pic du Midi, Aug. 22, 1942, 1 mm=11&quot; (approximate). (Woltjer, 1954.)</td>
</tr>
<tr>
<td>126</td>
<td>East limb</td>
<td>15-inch chromosphere camera, Sacramento Peak, 1 mm=8&quot;, (Present Investigation.)</td>
</tr>
<tr>
<td>135-200</td>
<td>0° to ±30°</td>
<td>15-inch chromosphere camera, Sacramento Peak, 1 mm=8&quot;, (Present Investigation.)</td>
</tr>
</tbody>
</table>

Rush and Roberts have reduced their counts to the entire solar surface and find a provisional value of 5000. Woltjer (1954) has used a different method of reduction, taking into account those spicules hidden by taller ones, and has arrived at 30,000 for the total number on the entire surface.

The author has not noticed, nor has he seen any account of, any differences in the scale of the fine structure of the quiet chromosphere on the disk between the polar and the equatorial regions. Undoubtedly this would be difficult to observe because the polar regions are never seen in true perspective. However, if the number per unit area at ±30° latitude is only 70 percent of the number in the same area at the poles, as found in this investigation, one should expect to see some indication of this difference from observations on the disk. This discrepancy could be accounted for by assuming a great number of small spicules unobserved in the lower latitudes; however, an inspection of the height frequency distribution (figure 3) for different latitudes does not suggest this.

In conclusion, these observations represent the conditions of certain chromospheric phenomena for isolated moments within a 6-week period. One wonders what changes with the solar cycle will take place. Certainly observational analyses of this nature should be made at least every two years for the entire solar activity cycle. Correlations with disk phenomena with a similar latitude frequency distribution should be looked for at this time in the solar cycle.

I am very happy to thank Mr. R. B. Dunn for the use of his excellent films for this study, and for his help and suggestions throughout the investigation. Also, I express my appreciation to Dr. John W. Evans for the very warm hospitality shown me during my stay at the Upper Air Research Observatory of the Geophysics Research Directorate, Air Force Cambridge Research Center, and for his interest in making this project possible.

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Miller, W.
1955. Private communication.
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Roberts, W. O.
Rush, J. H., and Roberts, W. O.
Woltjer, L.

Abstract

Spicule structure is studied from the films in H-alpha taken with the 15-inch chromosphere camera at Sacramento Peak. Frequency distributions of spicules around the limb show a systematic decrease from the poles to about 35° latitude and a slight increase from 35° to the equator. The number of spicules observed on the limb leads to a value of 11,000 for the entire sun. The average height of the spicules above the photosphere at the poles is 9500 km; the height steadily decreases, reaching a low of 7300 km at the equator. Spicules have an average observed minimum lifetime of 5 minutes. The average apparent rates of growth and recession in H-alpha are 19 km/sec and 24 km/sec, respectively. No certain deviations from linear motion are found.