THE SPECTRA OF NEAR-VERTICAL STRUCTURES
ON THE SOLAR DISK

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Abstract. Bright emission arches in the spectra of Hα and the Ca ii (H and K lines) are identified as the spectroscopic picture of the chromospheric network as it appears near the solar limb. Analysis of the geometrical properties of these spectroscopic arches indicates that the average network is a diverging sheet with a divergence angle of \( \sim 50^\circ \). This sheet extends to 2600 km and 2000 km as an opaque emission feature in Hα and the Ca ii (H and K) lines, respectively.

1. Introduction

Spectroscopy near the Sun's limb is important because the solar fine structure – the network, faculae, spicules – is seen at large angles to the line of sight so that height and projection effects should be observed. Good wiggly-line spectra made with the slit lying radially across the solar limb exhibit such systematic effects because the fine disk structures in the cores of Hα and the H and K lines of ionized Ca are arched toward the limb. McMath et al. (1956) and Prokofyeva (1957) describe this general behavior but do not correlate the arches with individual features seen in filtergrams: whereas, Severny and Bumba (1958), Mattig (1959, 1962), and White and Wilson (1966) study the dark arches produced by sunspots near the solar limb. Evans (1964) describes a similar phenomenon on the disk proper where one occasionally sees a bright thread in the continuum bow along the slit at wavelengths in the cores of strong Fe i lines and the Mg b lines. The arches in sunspots and Evans' curved threads are reasonably interpreted as the spectroscopic picture of solar structures that project upward through an obscuring layer, which is opaque at the line centers. Here I wish to discuss another example of these spectroscopic arches, a type which appears to be closely connected with the chromospheric network near the limb.

2. The Spectroscopic Definition of the Bright Spectroscopic Arches

Beginning in 1962 and continuing up to the present time, I studied the solar chromosphere by means of radial-slit spectra made at Sacramento Peak Observatory. Since the slit always extended some distance onto the disk, these observations confirm the earlier work in strong lines; but a class of bright emission arch stands out in limb spectra of the H and K lines. These bands of emission begin in \( K_1 \) as fine linear threads along the direction of dispersion, but near \( K_2 \) they terminate in bright emission on

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both sides of the line. As the threads cross the K₃ core, they move toward the limb, thus, producing an emission arch that appears to be the continuation of the thread observed in the line wings. Figure 1 shows examples of such arches in the H and K lines. These bright arches can also be seen in Hα, but their identification is more difficult in

![Chromospheric Emission](image)

Fig. 1. Radial-slit limb spectra made in the H and K lines at Sacramento Peak Observatory on 4 September, 1964. Bright spectroscopic arches are marked as a, b, and c on each spectrogram.

this line because the line profile is so steep and lacks a ‘K₂’ peak (see Figure 2). The infra-red triplet of Ca II, the Mg b lines, and the Na D lines also show arches, but in these weaker lines the degree of bowing is much less due to the lower height of formation. Consequently, the analysis here will be restricted to the strong line (Hα, H, and K) where the geometrical properties can be determined more accurately. These bright arches and their properties are mentioned by Evans (1963), Simon and White (1966), White and Wilson (1966), and White (1969).

Although some new spectra have been obtained with the vacuum tower telescope, the results to be given here were obtained from spectra made with a 12-in. coelostat and a horizontal Littrow spectrograph of 12 m focal length. This system produced a solar image 25 cm in diameter on the slit. Two gratings, 1200 line mm⁻¹ Bausch and Lamb and a 600 line mm⁻¹ Babcock grating, allowed me to use a range of dispersions from 3 to 5 mm⁻¹, but the combinations of overlapping orders also permitted simultaneous observations in several lines.

As a means of reducing image motions along the slit, unidirectional limb guider was used directly in front of the slit. This system removed the coherent image motion in one direction and held the limb much more steady than was possible without such a local guider. Such image stabilization was important for good spectra in the K line where the exposure time was 15 s as compared to 3.5 s for Hα.

In order to establish the correlation between spectral features and the familiar
chromospheric structure seen in filtergrams, Hα and K filtergrams were made of the region where the spectrograph slit fell. The primary system was an Hα monitor that photographed the polished slit jaws through an OPL birefringent filter of 0.75 Å bandpass. In addition, Dr J. M. Beckers had built a dual camera system capable of making simultaneous filtergrams in both Hα and the K line with bandpasses of 0.5 Å and 0.3 Å, respectively. Using the programmable light feed system to switch the solar beam from one instrument to another, it was possible to photograph both the spectrum and the slit jaw simultaneously and immediately transfer the image to the dual camera to make better narrowband filtergrams in both lines within 30 s.

3. Properties of the Bright Spectroscopic Arches and Their Interpretation

A. CORRELATION WITH THE CHROMOSPHERIC NETWORK

The simultaneous spectra in Hα, H, and K show that a bright arch in the H line also appeared in the other two lines. Furthermore, a study of some of the spectra by C. B.
Kaiser showed that the emission threads associated with arches could be followed out to 3 Å in the wings of Hα, while the author finds extensions to about 2 Å in the Ca II lines. The bright arches then appear to arise from a class of structure that extends from the low chromosphere upward.

Comparison of the spectrograms with the companion filtergrams shows that the bright arches occur at places where the chromospheric network crosses the slit. This correspondence with the network explains the relatively small number of bright arches that appear on each spectrogram. By measuring the distance between successive arches along the slit, one can compute their separation as measured on the solar sphere. These calculations yielded a mean interval of 30,000 km with a range of values from 10,000–52,000 km, values which are in accord with the average and spread for the sizes of supergranulation cells.

In his study Dr Kaiser also determined the Doppler shift in nearby photospheric lines (Fe I λ6569, λ6574) at positions where the arches extend into the wings of the stronger lines, and he found Doppler shifts into the red. Such motion away from the observer is consistent with the outward flow in supergranulation cells.

From these empirical properties of the bright arches I conclude that they are the spectroscopic picture of the chromospheric network near the limb.

B. THE BOW OF EMISSION ARCHES AND THE VERTICAL EXTENT OF THE NETWORK

One of the most useful properties of the arches is the amount of bowing since it will lead to an estimate of the height to which the network extends as an emission structure;

Fig. 3. A schematic illustration that shows the correspondence between positions in a limb spectrogram and different heights in a simple atmosphere. The wavelength $\lambda_0$ refers to the line center while $\lambda_W$ refers to the line wings.
but to make such an interpretation we need some physical picture of how a spectroscopic arch is produced by the solar atmosphere.

First, consider a vertical column or sheet protruding up from the opaque photosphere through the chromosphere as illustrated in Figure 3. The sheet and the chromosphere are taken to be opaque in the center of a strong line such as Hα or Ca II (K), and further, the source function in the sheet is greater than that of the surrounding gas at the same height. However, the opacity does decrease with height as required by the outward decrease of the density.

In such a simple model we can assign a height of formation for each wavelength in the line, i.e., a height where \( \tau_{\lambda} = 1 \) in the surrounding material. At wavelengths in the lines wings and continuum, the height of formation lies in the upper photosphere where the scale height is relatively small, and only the base of the sheet stands out as a bright streak in the spectrum. As we move toward the line center, the chromospheric material becomes progressively more opaque, and thus, obscures the lower parts of the sheet. Therefore, at the line center, the sheet can only be seen at greater heights where the line-of-sight opacity down to the inhomogeneity finally becomes less than unity, i.e., the emission from the sheet appears closer to the limb. At intermediate wavelengths in the line core, the sheet will become visible along a smooth arch that connects the thread in the wings with the emission at the center of the line. The sketch in Figure 3 depicts this correspondence between the spectroscopic arch and the vertical inhomogeneity imbedded in the chromosphere. The arch effect is large in the Doppler core because the absorption coefficient and, hence, the height of formation is changing rapidly with wavelength.

As we took along the slit toward the limb, the initial appearance of the sheet through the intervening foreground material is a contrast problem that involves the relative brightness of the sheet and surrounding gas as well as the rates of change of the sheet emission and chromospheric opacity with height. However, at greater heights the appearance of the arch is controlled principally by the opacity of the sheet itself. The eventual fading with height should follow a sequence where the bright emission structure first displays a maximum in relative brightness and then becomes invisible because of zero contrast with the background radiation field, but it should reappear at greater heights as an absorption feature before disappearing completely. It should be evident that the visibility of an inhomogeneity in a spectrum is governed by a complicated interplay of the wavelength dependence of the absorption coefficient, the height dependence of the opacity in the sheet and foreground material, and the brightness of the sheet relative to the background radiation field.

Since the relevant scales are beyond the limits of resolution in the observations, I shall not attempt to construct a model to describe these fine points about the visibility of vertical structures. However, I can reliably measure the bow of many arches to give a direct estimate of the height to which the network extends as an opaque emission feature. The change of an emission arch to a distinct absorption feature at greater heights is not seen clearly; but on positive copies of a few good frames a dark, but diffuse, band is seen on the limbward side of the emission arch.
From microphotometer tracings, the positions and widths of the emission maxima were determined for many arches on three films. As Table I shows, the thickness of the emission band at the centers of Hα and the Ca II lines is 1900 km and 3000 km, respectively, but this thickness varies from 1000–4000 km. The width of the arches themselves range from 0.7–1.4 Å in Hα and 0.2–0.8 Å in H and K, values which reflect the Doppler width of the foreground material.

**TABLE I**

Properties of spectroscopic arches

<table>
<thead>
<tr>
<th>Line</th>
<th>No. of arches measured</th>
<th>Separation (units of 10³ km)</th>
<th>Minimum angle</th>
<th>Thickness (units of 10³ km)</th>
<th>Width FWHM (Å)</th>
<th>Height of emission (units of 10³ km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>Range</td>
<td>Mean</td>
<td>Range</td>
<td>Mean</td>
</tr>
<tr>
<td>Hα</td>
<td>57</td>
<td></td>
<td></td>
<td>64°</td>
<td>1.9</td>
<td>1 → 4</td>
</tr>
<tr>
<td>Ca II K</td>
<td>12</td>
<td>30</td>
<td>10 → 52</td>
<td></td>
<td>68°</td>
<td>2 → 4</td>
</tr>
<tr>
<td>Ca II H</td>
<td>52</td>
<td></td>
<td></td>
<td></td>
<td>1.8</td>
<td>1 → 3</td>
</tr>
</tbody>
</table>

Once an arch is identified as it extends into the line wings, the sagittae at line center can be immediately measured from the tracings. Column 7 of Table I shows the average heights of emission corrected for foreshortening. On the average, then, the network appears as a vertical, opaque structure in emission up to 2600 km in Hα and up to 2000 km in both H and K. Although there is considerable variation in height from arch to arch, the height difference between Hα and the Ca lines is systematic and significant.

C. RESTRICTION OF THE BRIGHT ARCHES TO THE LIMB REGION AND THE DIVERGENCE ANGLE OF THE NETWORK

The emission arches associated with the network are visible only at position angles between 64 and 84° from the center of the disk. There is no reason to believe that they do not occur at the extreme limb where the foot of the arch is lost among other fine structures but where the arch itself appears in the chromospheric emission bulge. The existence of the lower limit of 64° suggests that the network is a diverging structure with a divergence angle no greater than about 50°. Such a ridge-like structure with its top wider than its base would display its apparent height when viewed at angles greater than one half of the total divergence angle; but at viewing angles less than this limit, no projection of the object would be visible because the top would obscure the base. Although such a simple geometrical model of the network does not account for the known inhomogeneities in the network itself, it is supported by the observation of the limiting angle of visibility of 64° in all of the spectra. Furthermore, the divergence angle of 50° is close to the 40° value for the average divergence for spicules at the limb (Beckers, 1964, p. 57).
4. Conclusions

This interpretation of the arches as vertical inhomogeneities imbedded in an obscuring medium indicates that the average network is a upward-projecting, divergent sheet, which is visible as an emission feature up to 2600 km in H\alpha and 2000 km in the H and K lines. The angle of divergence of the sheet is about 50°. The existence of the arches also means that the foreground material inside the supergranulation cells is not opaque above these heights, when observed at the centers of the lines and near the limb. Therefore, these empirical heights set upper limits to the heights of formation for the three lines at the center of the disk. The systematic difference in the heights of arches between H\alpha and the Ca II (H and K) lines demonstrates that the hydrogen line is formed above the Ca lines. The arched structures described here do not appear to be spicules on the disk because the arches are not tall enough; therefore, the bright spectroscopic arches should be identified with the emission features at the bases of spicule bushes.

In a companion paper, Beebe and Johnson (1972) present some results from non-LTE calculations of line profiles produced by sheetlike inhomogeneities.

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References

Beebe, H. A. and Johnson, H. R.: 1972, this issue, p. 34.