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THE STRUCTURE OF THE SOLAR CHROMOSPHERE FROM CENTIMETRE-WAVE RADIO OBSERVATIONS

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The atmosphere of the sun is transparent to visible radiation, is nearly transparent to millimetre and centimetre radio radiation, and becomes opaque to the metre and longer wave radiation. Information about the chromosphere can then be given by observing the radiation from the sun at short radio wave-lengths. In its outer part, the atmosphere of the sun is highly ionized. Absorption in any region is directly proportional to the square of the density and the wave-length squared and inversely to the temperature to the three-halves power

$$\kappa \propto \frac{n^2\lambda^2}{T^{\frac{3}{2}}}.$$

This is the familiar equation for the absorption of radio waves in an ionized medium. By consequence of this, the longer wave radiation is absorbed in the outer layers of the sun's atmosphere and can escape only from these outer regions. The shorter wave-length radiation is absorbed very little in the outer part of the solar atmosphere where the density is quite low, and hence radiation from the chromosphere escapes as centimetre and millimetre radio waves. In fact, the principal radiation from the sun in the centimetre and millimetre region comes from the chromosphere.

Since the sun subtends an angle small compared with most radio antenna beam-widths, it is necessary to resort to unusual methods to resolve the sun if the variation in brightness across its surface is to be obtained. At 8 mm. wave-length, this can be done with the N.R.L. 50-ft. antenna which has a beam-width of about 3 minutes of arc at this wave-length. A better way, however, is to observe the sun at the time of a total solar eclipse when the advancing edge of the moon provides the necessary resolution at any wave-length. Eclipses are particularly useful in the centimetre region where the radio diameter of the sun is not too much larger than the visual and where the moon will still effectively eclipse the sun. At metre wave-lengths the radio size of the sun is so large that at totality more than half of the sun is seen around the moon, especially at the longer wave-lengths.

A consideration of early measurements of the radio flux from the sun at many wave-lengths revealed that the radio measurements were an effective means of defining the temperature gradient in the sun's atmosphere. The curve marked (1) in Fig. 1 shows the results of such an analysis.

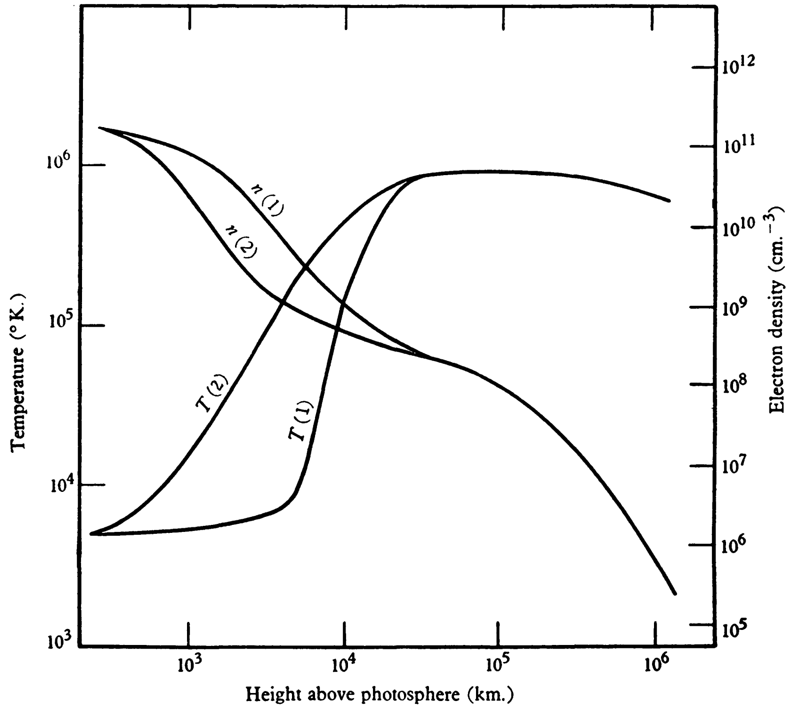

Fig. 1. Temperature and density distributions in the spicules (1) and in the inter-spicule gas (2).

Note that there is a steep temperature rise in the chromosphere. It is one of the consequences of the eclipse measurements that the location of the steep rise in the chromosphere may be better defined. This model of the sun requires limb brightening at all short radio wave-lengths and recent measurements here and abroad have now amply confirmed that limb brightening does exist.

The most effective means in the centimetre region for measuring the radio brightness distribution has been to measure the changing flux through the course of the total eclipse. Our most recent measurement was at

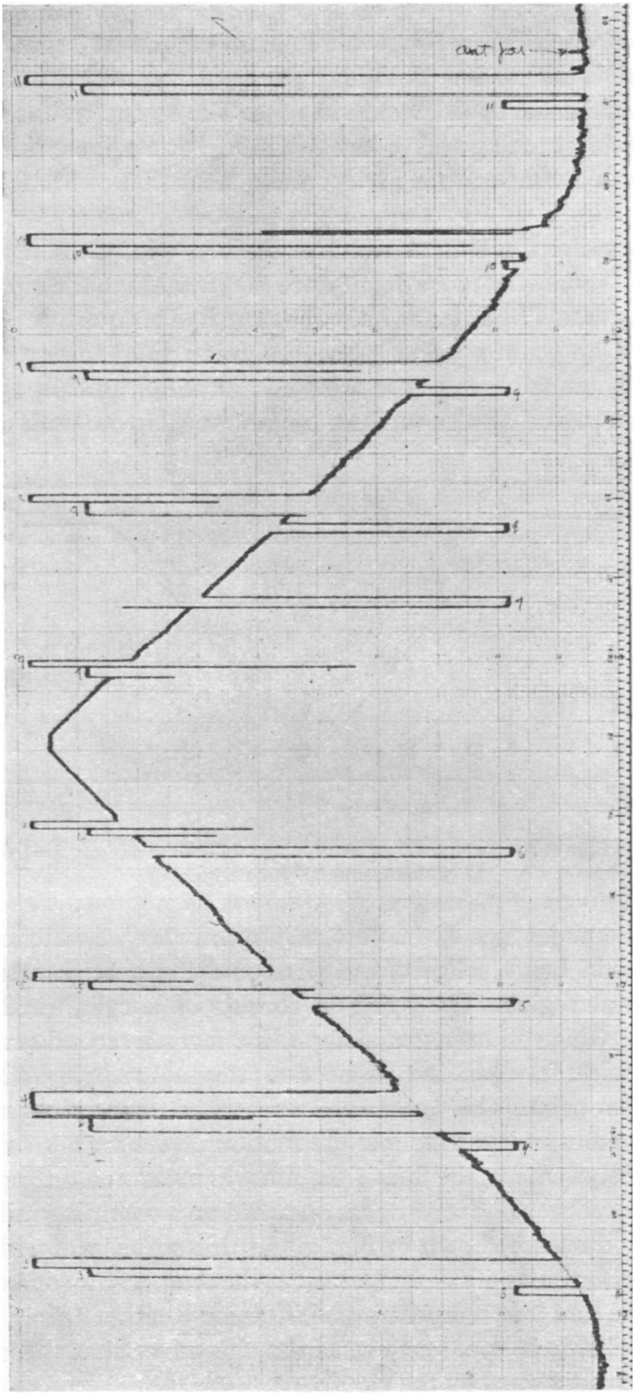

Fig. 2. Record of the solar eclipse obtained at Oskarshamn at $\lambda = 8{\cdot}65$ mm.

Oskarshamn, Sweden, in 1954 where measurements at 8 mm. and 10 cm. wave-length were made. Both measurements improved and confirmed measurements made in Khartoum in 1952. The 10 cm. results show a clear case of limb brightening and reduce to a model atmosphere similar to those of Fig. 1 with a temperature rise occurring near that of Model (1) of that figure.

I will describe the 8 mm. results, obtained with Gibson, Coates and McEwan, in somewhat more detail since they pertain to the most important aspect of my talk. The antenna used at 8 mm. had an aperture of 16 ft. × 2 ft. producing a fan beam 1° wide in one dimension and 8 minutes wide in the other. The antenna beam was so oriented that the elliptically shaped cross-section was centred on the sun and aligned so that the path of the moon was along the major axis of the pattern. In this way we watched a central slice of the sun being eclipsed and derived a radio brightness curve for the equatorial region. The antenna consists of a cylindrical parabola, 16 ft. × 2 ft., which illuminates along a line focus a second smaller cylindrical parabola 2 ft. × $\frac{1}{4}$ in. in cross-section; this in turn brings the radiation to a focus at a point. This antenna was mounted equatorially and driven by a synchronous motor to follow the motion of the sun.

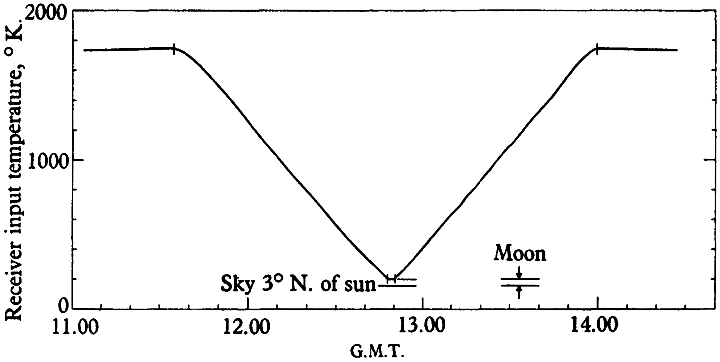

Fig. 3. Eclipse curve corrected for gain and atmospheric variations, $\lambda = 8{\cdot}65$ mm., Oskarshamn, 30 June 1954.

With this equipment, the flux of the sun was measured during the entire course of the eclipse. The record was obtained on a recording milliammeter and the raw data are shown in Fig. 2. In this curve, you will see many breaks for calibrations of sky temperature, the temperature of a calibrating hot load, and ambient temperature. While the weather was quite cloudy at Oskarshamn, it is apparent even from this curve that there was little effect on the radio data by the clouds.

This curve has been corrected for variations in receiver gain, for deviations from linearity, for effects due to antenna beam shape and for atmospheric absorption. In its corrected form it appears as Fig. 3. It is to be noted that there is a very small residual radiation at totality, less than half of 1 % of the total flux of the sun, and in addition, that at totality the principal radiation entering the receiver appears to be thermal radiation from the moon. Earlier measurements on the moon have allowed this radiation to be evaluated.

The radio brightness distribution derived from this 8 mm. curve differs markedly from that predicted on the basis of the simpler model. The model shows a relatively flat distribution with a narrow bright ring at the edge of the disk. The derived curve, Fig. 4, shows limb brightening but in addition shows a pronounced amount of brightness at the centre. A model of the chromosphere that could produce this effect has been constructed and this is what I would like to report today.

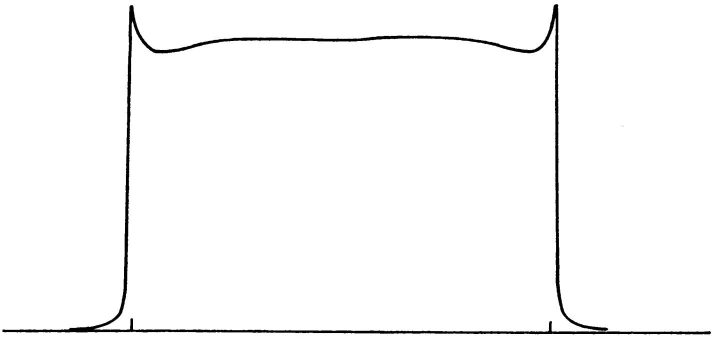

Fig. 4. Radial brightness distribution of the sun at $\lambda = 8{\cdot}5$ mm.

It was earlier suggested by Giovanelli that the chromosphere may not be uniform but may have a grass-like structure. Roberts and others have observed spicules extending through the chromosphere. I have assumed that the chromosphere is made up of spicules blending into a gas which smoothly joins the photosphere with the corona. The spicules would have a random or gaussian distribution about a given size and would also be random in duration and occurrence. For simplicity of analysis, it is assumed that all spicules are pyramidal in shape, have the same base width, 3 seconds of arc, and have the same height, 10,000 km., which is assumed to be the average height of all spicules. These dimensions were arrived at by trial and error to obtain a fit with the radio radial brightness distribution curves. The derived temperatures and pressure gradients in the spicules (1) and in the inter-spicule material (2) are shown in Fig. 1. It is seen that the spicules are cooler, and hence more dense than the ambient gas. Equality of pressure across the face of the spicules was assumed. Schematically the chromosphere will appear as shown in Fig. 5.

Qualitatively, one can see that such a model will fit the radio results. At millimetre waves where the penetration is deep, the central ray will emerge from the region high in the spicule and low in the inter-spicule material. The equivalent temperature will be the average of the two and will be high. For the ray emerging nearer the limb, the spicules will be seen more nearly face-on and since their absorption coefficient is higher than that for the inter-spicule material they will contribute more to the escaping radiation than will the inter-spicule material. Hence, the equivalent temperature of this ray will be lower. In this way centre-brightening is seen. At the extreme limb the escaping ray must pass tangentially through the atmosphere and absorption will occur at greater heights where temperatures are higher and thus limb brightening will be observed. In this way the radial brightness distribution of Fig. 4 can be reconstructed from the spicule model. At the longer centimetre wave-lengths, where absorption and radiation by the corona plays a larger part, the penetration is such that the spicules will play little part and one would expect strong limb brightening with only a mild centre-brightening at 10 cm. wave-length.

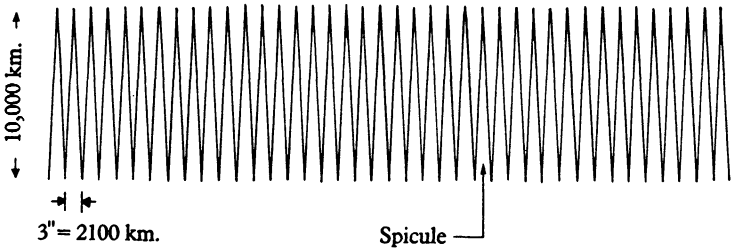

Fig. 5. Schematic shape of the spicules.

It is thus seen that radio measurements predict a two-fluid chromosphere with cooler spicules surrounded by a more tenuous, hotter gas.