# THERMAL RADIATION FROM THE SUN AT 8.6 MILLIMETERS WAVELENGTH

by

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# CHAPTER I

# THERMAL RADIATION FROM THE SUN

1.1 Models of the sun. The sun is a spherical ball of very hot, highly ionized gas. A great quantity of energy is radiated from the sun into space, this energy having its origin at the dense center of the sun. The outward process of radiation is one of continued absorption an re-emission, with some radiation from each level escaping into space. Most of the radiation which escapes comes from within a restricted range having a thickness of only a few hundred kilometers. The fraction escaping tends toward zero with increasing depth. It also falls off at greater heights because the gas density, and with it the emissivity, decreases. The region which is the origin of visible light is called the photosphere, and has a radius of 696,100 km. Physical conditions in this region differ very much from those in the dense center of the sun. The temperature at the center is about $10^7$ $^oK$, while the temperature of the surrounding photosphere is about 5800 $^oK$.

Another region, called the chromosphere, surrounds the visible disk of the sun and extends to a height of about 10,000 km above the photosphere. Above the chromosphere is the relatively rarefied region known as the corona which extends to a height of several times the solar radius. Its temperature is about $10^6$ °K.

Less is known about the chromosphere than about the photosphere or the corona. Opinion is divided as to the temperature of the low chromosphere (below 5000 km above its base), with some authors assuming temperatures near 30,000 °K and others near 5000 °K, while others have made these assumptions alternately. However, most of the recent observations are in favor of the lower value.

The height above the base of the chromosphere at which radiation originates is a function of the wavelength of the radiation. Observations at wavelengths from 1 to 30 cm give information about the upper chromosphere (above about 5000 km).[1] At wavelengths less than about 2 cm the total radiation, excluding occasional bursts, may be regarded as thermal radiation from the undisturbed sun since it is nearly constant.[2] Several models of the distributions of temperature and electron density as functions of height in the chromosphere have been proposed. This paper will describe four of these models of the lower chromosphere. Results of observations made at 8.6 mm in this laboratory will then be compared to these models.

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[1] H. C. van de Hulst, The Sun, edited by G. P. Kuiper (Univ. of Chicago Press, 1953), Vol. 1: The Solar System, p. 242.

[2] J. L. Pawsey and R. N. Bracewell, Radio Astronomy (Oxford, 1955), p. 149.

Several measurements of the temperature of the sun at wavelengths up to 1.25 cm are shown in Fig. 1. The observers are also listed.

1.2 Model of Woolley and Allen.[3] This model (Fig. 2) was proposed with the idea of a quiet chromosphere with spherical symmetry intended to represent minimum (zero sunspot) activity. The model uses a mean temperature for each height. Woolley and Allen find that all the conditions which must be satisfied cannot be met by a spherically symmetric model with a definite temperature at each height. However, to assume otherwise would introduce too much freedom into the model.

For the base of the chromosphere the assumption of equilibrium conditions at the temperature of the sun's surface is made. Also, a hydrogen to metal atom ratio of 6000 to 1 is assumed. From this an electron density for the base of the chromosphere is obtained. The other values for the lower chromosphere are calculated from Saha's equation.[4]

The choice of a low temperature of 5040 °K for the lower chromosphere was mainly influenced by their condition that the far ultraviolet emission, which comes from the upper chromosphere, should equal the amount required to produce the minimum (zero sunspot) ionosphere. If the low chromosphere were at 30,000 °K, its H-atoms would be almost

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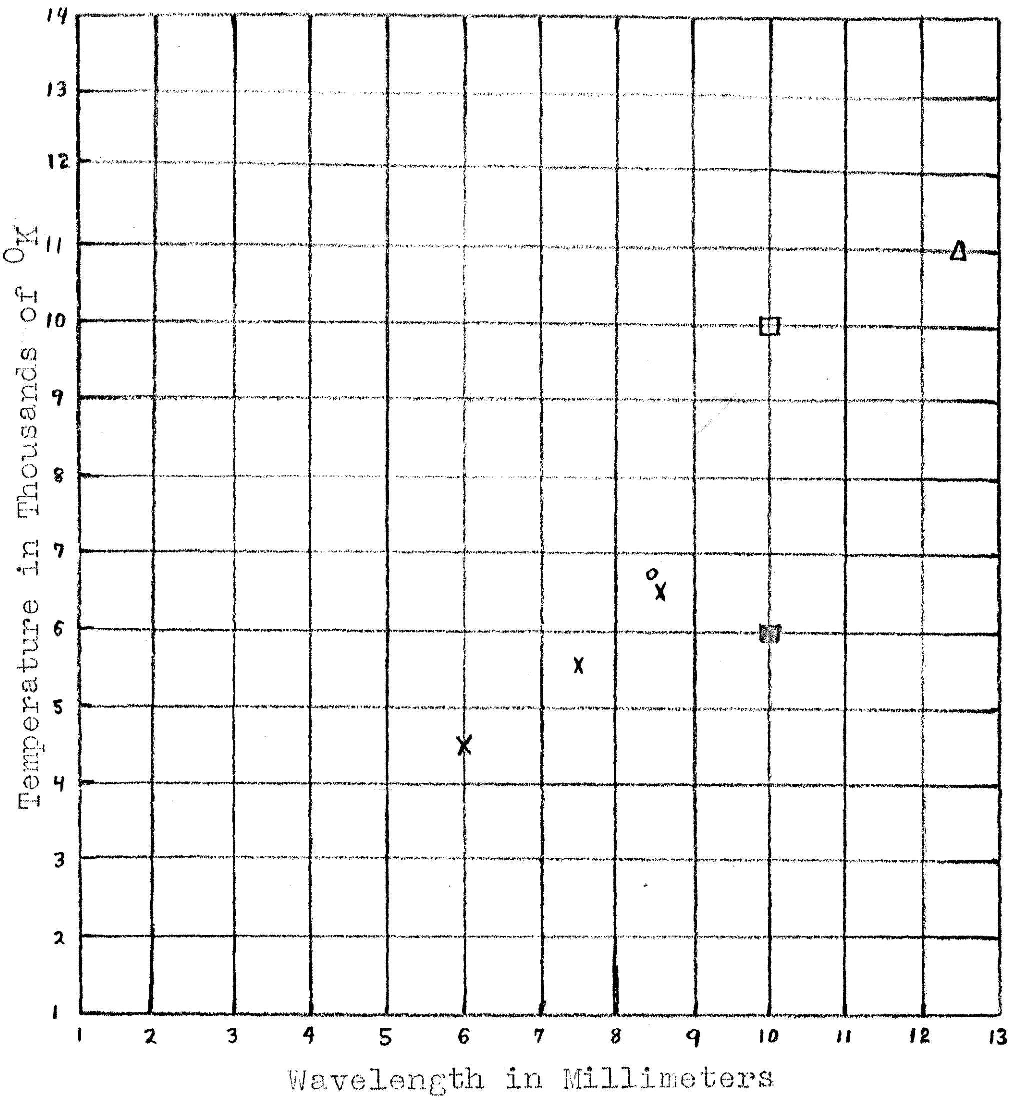
[3] R. v. d. R. Woolley and C. W. Allen, Mon. Not. R. Astr. Soc. 110, 358 (1950).

[4] Ibid., p. 362.




o Hagen, J. P., Astrophys. J. 113, p. 547 (1951).

■ Southworth, G. C., J. Franklin Inst. 239, p. 285 (1945).

Δ Dicke, R. H., and Beringer, R., Astrophys. J. 103, p. 375 (1946).

□ Pawsey, J. L., and Yabsley, D. E., Aust. J. Sci. Res. A, 2, p.541 (1949).

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Fig. 1. Apparent Temperatures of the Sun

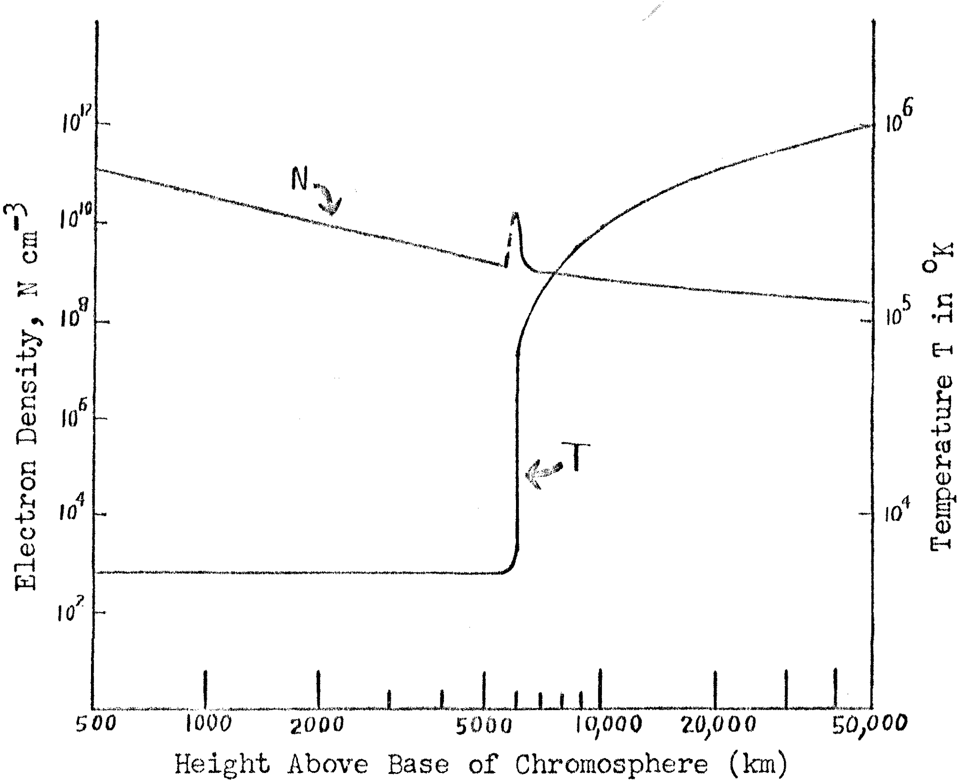


Fig. 2. Temperature and electron distributions in the chromosphere and corona according to a model proposed by Woolley and Allen.

completely ionized instead of neutral, and the total ultraviolet emission would be higher by many factors of ten.[5]

1.3 Model of H. C. Van de Hulst. Van de Hulst obtains the temperatures from Saha's equation,[6] which relates the ionization ratio (ionized atoms to neutral atoms) to the temperature.

The ionization ratio was deduced by comparing two sets of data[7] giving relative ion density as a function of height in the chromosphere. From this comparison a reasonable table of corrected values was obtained. These relative density values were converted to absolute values by taking one value of absolute density given by Stromgren,[8] corresponding to zero height. A table of absolute densities as a function of height was extrapolated from this value by use of the gradient obtained from the relative values. These absolute values, in turn, give the corresponding temperatures from Saha's equation. The temperature and electron distributions are shown in Fig. 3.

A minimum number of theoretical assumptions is used in this model. However, observational determinations of absolute densities in the chromosphere have been entirely omitted, the only such value used being that for the "limb

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[5]van de Hulst, The Sun, p. 226.

[6]M. Minnaert, The Sun, p. 115.

[7]van de Hulst, The Sun, p. 234.

[8]Ibid., p. 238.

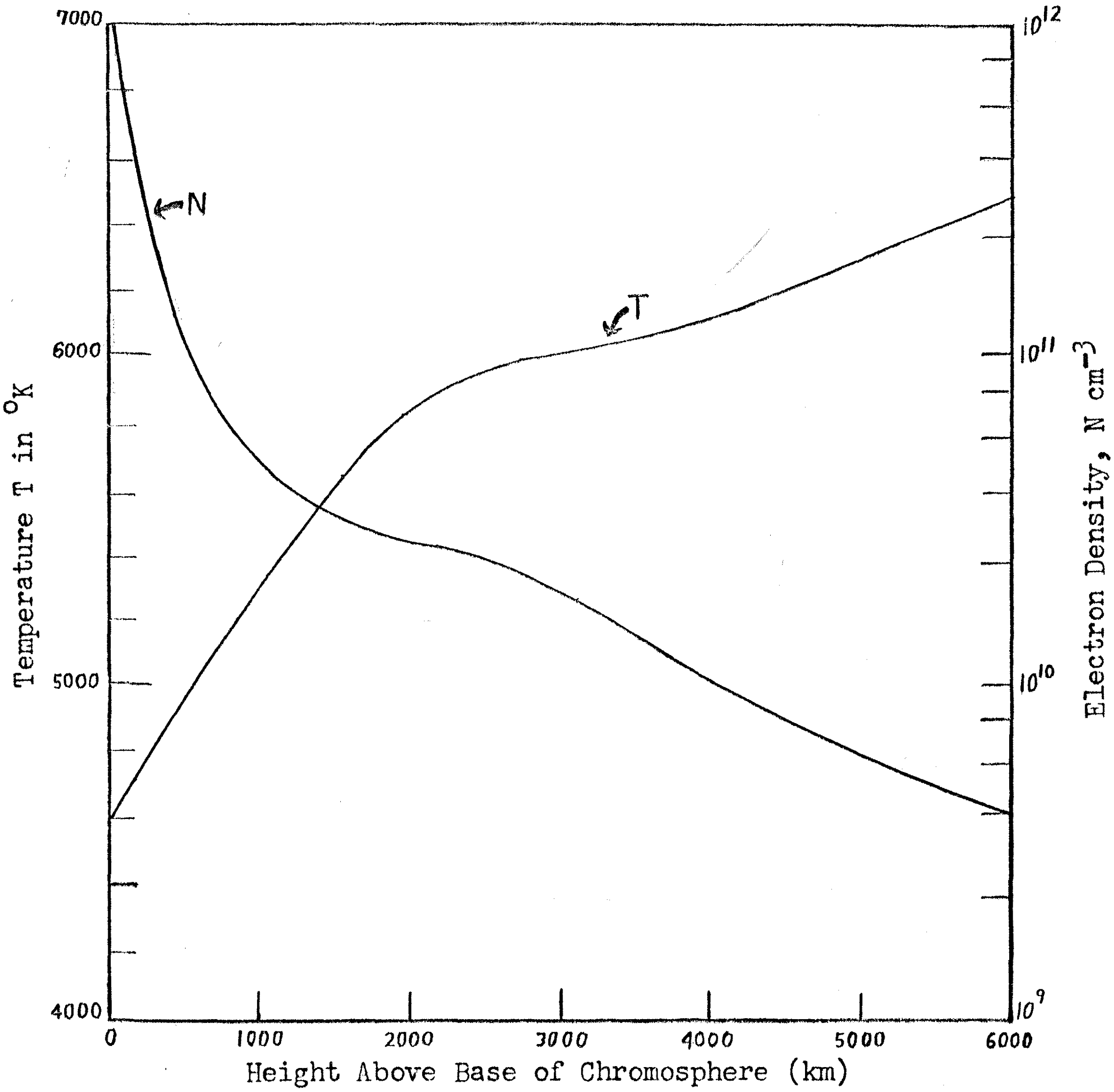


Fig. 3. Temperature and electron distributions in the lower chromosphere, according to a model proposed by van de Hulst.

of the sun" taken from a model of the photosphere.

1.4 Model of Piddington. This is a partial theoretical solution to the problem of determining the mean electron density and temperature in the chromosphere. A relation involving $\frac{N^2}{T^{3/2}}$, where N is electron density and T is temperature in $^{\circ}$K, was obtained from observed apparent temperatures at wavelengths less than 60 cm.[9] It was assumed that in this region ray bending could be neglected (refractive index equals unity), and that the region of origin of this radiation is thin.[10] This region is in the lower corona and the chromosphere, and Piddington estimated the coronal contribution and subtracted it from the total observed radiation.

A second relation containing $\frac{N^2}{T^{3/2}}$ was derived from optical eclipse data,[11] and combining these equations leads to an explicit solution for N and T (Fig. 4).

The numerical results so obtained are subject to considerable uncertainty. The assumptions of an index of refraction equal to unity and a thin emission region may not be true at the longer wavelengths considered. Also, the estimates of the coronal contributions to the temperature are quite uncertain.

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[9] Pawsey and Bracewell, Radio Astronomy, p. 165.

[10] Pawsey and Bracewell, The Sun, p. 487.

[11] Pawsey and Bracewell, Radio Astronomy, p. 167.

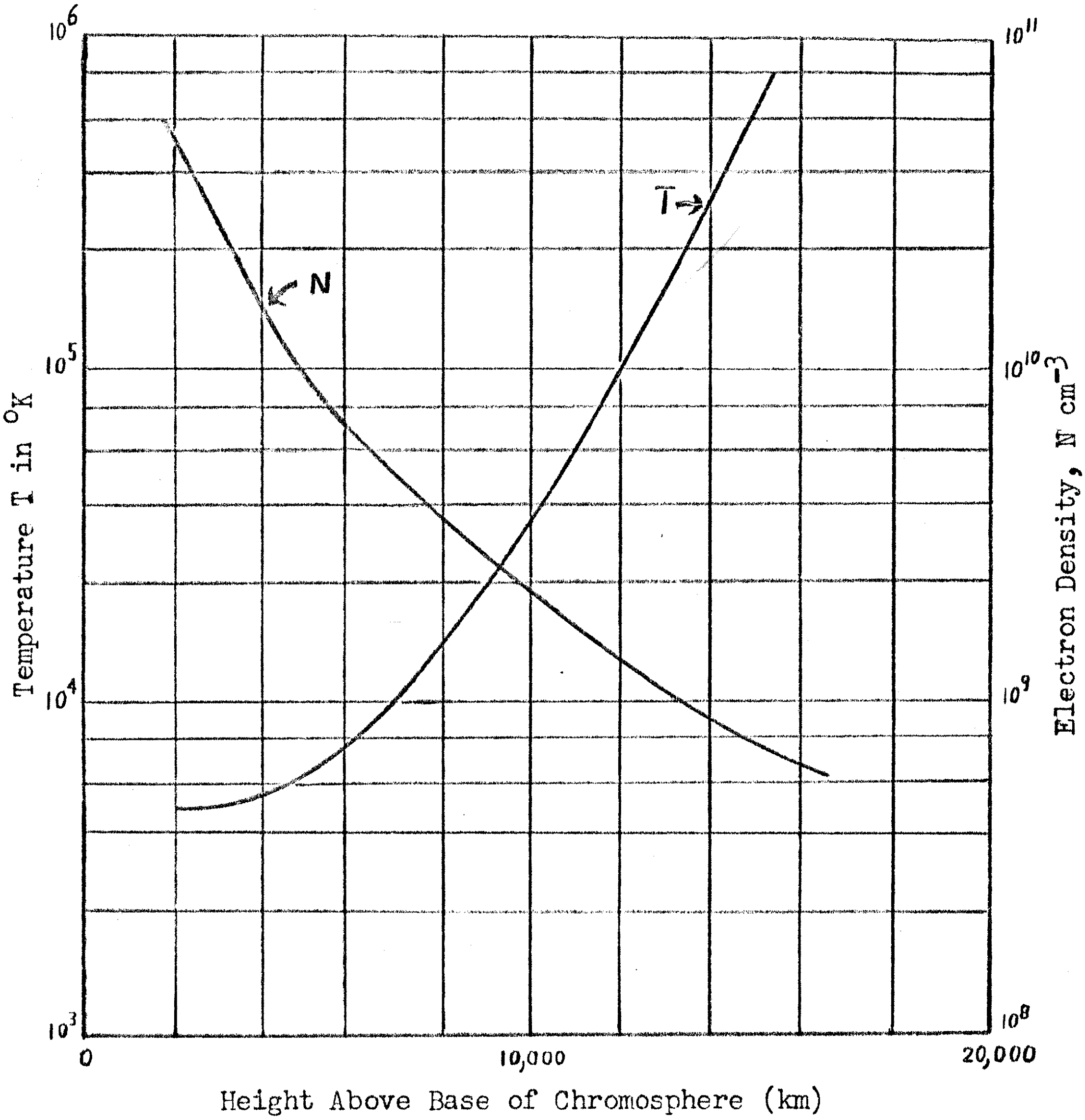


Fig. 4. Electron densities and temperatures in the chromosphere as derived by Piddington.

1.5 <u>Model of J. P. Hagen</u>. This model (Fig. 5) is an empirical solution for the temperature distribution. In obtaining the electron density distribution in the lower chromosphere, the assumption of Wildt concerning the electron pressure gradient is used,[12] even though the resulting distribution is admitted by Wildt to be "somewhat hypothetical." In this model the assumption is also made that the electron distribution is known more accurately than the temperature distribution. Other assumptions are that the sun's atmosphere is spherically symmetric and that it is composed of completely ionized hydrogen at heights above 5000 km.

The equivalent temperature is calculated at several wavelengths using boundary temperatures of 4830 °K at the base of the chromosphere and $10^6$ °K at 50,000 km, and an arbitrary temperature distribution which rises exponentially. This gives a first approximation which is then modified to fit the observed temperature at several wavelengths.

There is considerable uncertainty in this model because of the density data upon which it is based. Hagen notes that the temperatures in the low chromosphere might be shown by the dotted portion of the curve in Fig. 5. This would give a smooth curve out of the photosphere through the chromosphere.

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[12] J. P. Hagen, Astrophys. J. <u>113</u>, 555 (1951).

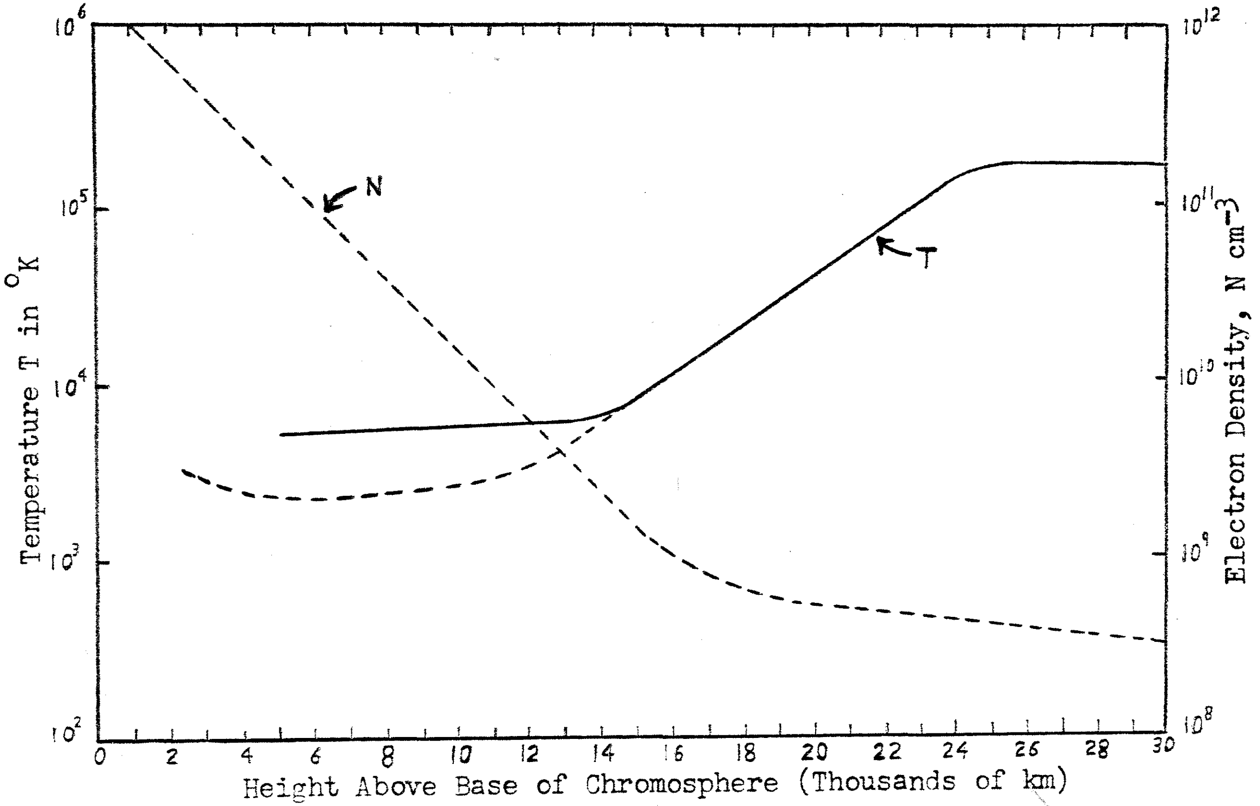


Fig. 5. Temperature and electron distributions in the lower chromosphere, according to a model proposed by Hagen.

1.6 Comparison of models. The models of Van de Hulst and Piddington compare fairly well from heights of 2000 to 6000 km. However, the Van de Hulst model, which seems the more reliable, gives slightly lower electron density values.

The model of Woolley and Allen seems consistent considering both theory and observations. Van de Hulst's model gives a similar picture, although the former gives a constant temperature below 5000 km and the latter indicates a slight rise in this region. The densities are of the same order of magnitude in this region and both models assume a constant hydrogen to metal ratio, with Van de Hulst's being only slightly larger.

Hagen's model gives electron densities which are much higher than those given in the other models. However, the alternate temperature curve (dotted line) in the lower chromosphere is close to the values of Van de Hulst.

A more recent model of the chromosphere has been proposed by R. J. Coates.[13] This model abandons the idea of spherical symmetry of the chromosphere, and considers the effect of randomly distributed cylindrical spicules with their bases at the photosphere and having heights ranging from 3000 km to 18,000 km. The interspicule gas of this model is hot and relatively transparent at millimeter wavelengths, and the spicules are cool (6400 °K) and opaque.

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[13] R. J. Coates, Astrophys. J. 128, 83 (1958).

## CHAPTER II

## DESCRIPTION OF APPARATUS

2.1 Radiometers. The apparatus used for measuring the intensity of radiation is called a radiometer. The basic instrument for measurement of solar radio emission consists of an antenna of narrow beam width connected to a sensitive receiver. The energy collected by the antenna is fed to the receiver, where it is amplified and rectified. This rectified output is usually displayed on a recording milliameter. A calibrating source may be provided which can be connected in place of the antenna.

The angular resolution of a radiometer depends on the width of the antenna aperture measured in wavelengths. Optical telescopes have apertures ranging from about $10^4$ to $10^7$ wavelengths,[14] while the largest radio telescopes have apertures of the order of $10^2$ wavelengths. Therefore, the resolving power of the radio telescope is several orders of magnitude less than that of an optical telescope.

The radiometer output is proportional to the weighted average of the intensities of all the sources within the antenna beam. In order to obtain a "picture" of the sky the antenna must be turned in different directions and a set of

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[14] J. P. Wild, The Sun, p. 677.

readings obtained. A radiometer is essentially monochromatic which is an advantage for most purposes.

2.2 Antenna temperature. Thermal radiation from the sun has the same characteristics as that from a black-body. The distribution of intensity of black-body radiation as a function of wavelength is given by Planck's law. In the microwave region considered in this paper, the Rayleigh-Jeans approximation to Planck's law may be used. In this approximation the relation between intensity of radiation and equivalent temperature is

$$I_f = 2kT\lambda^{-2} \text{ watts/meter}^2\text{/steradian/cps}$$

where k is Boltzman's constant, $1.38 \times 10^{-23}$ watts/$^{\circ}$K, $\lambda$ is the wavelength in meters, and T is equivalent temperature in $^{\circ}$K. It is this equivalent temperature which is used in radio astronomy.

Johnson noise, which is the small fluctuating voltage across the terminals of a resistor due to the random motion of electrical charges in the resistor,[15] is very closely connected to thermal radiation. This fact makes it convenient to assume that the antenna is replaced by a resistive termination at the input to the receiver. If this resistor is raised to a temperature T, the average available power per unit frequency due to Johnson noise is

$$P = kT \text{ watts/cps.}$$

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[15] R. A. Smith, F. E. Jones, and R. P. Chasmer, The Detection and Measurement of Infra-Red Radiation (Oxford, 1957), p. 178.

If the temperature, T, is such that the output from the receiver is equal to that obtained when the antenna is pointed at the source to be observed, T is referred to as the "antenna temperature." This term describes the radiation received by the antenna which, when directed toward surroundings at a temperature T, behaves as a resistor at the same temperature.

In order to justify the assumption that the resistive termination is the equivalent of a black-body, consider an antenna connected to a lossless transmission line which is terminated in a matched load (a resistor whose impedance equals the characteristic impedance of the line). The antenna is also matched to the line. Let the antenna be surrounded by a completely absorbing enclosure (black-body walls) maintained at a temperature T, and also let the resistor be at temperature T. Johnson noise radiated by the resistor is transmitted down the line to the antenna. Here it is radiated by the antenna and completely absorbed by the walls of the enclosure. At the same time, thermal radiation from the walls is being received by the antenna and transmitted down the line to be completely absorbed by the resistor. The Johnson noise from the resistor and the noise power absorbed by the antenna from the walls must be equal, because if this were not true energy would either be gained or lost by the resistor, and its temperature would be changed from the original equilibrium value, T.

If the antenna receives radiation from several bodies which are at different temperatures, the antenna temperature is the average of these temperatures weighted according to the fraction of the total radiation received by the antenna that each body contributes.

2.3 Antennas. Most radiometers designed for measurement of solar or cosmic radio waves at wavelengths of 10 cm and less have used parabolic antennas.[16] The paraboloid directs the rays from a distant source toward its focus, where a small antenna element collects the energy and feeds it to the receiver through a transmission line. At wavelengths of less than 20 cm, the transmission line is usually a wave guide and the antenna element at the focus of the reflector is an electromagnetic horn.

2.4 Receivers. The sources studied in microwave radio astronomy are extremely weak. Therefore, the conversion of the minute signals fed to the receiver by the antenna into a form which can be displayed on the output meter involves a high degree of amplification. Most receivers use the superheterodyne principle. After passing the frequency conversion stage, the signal is amplified by a factor of the order of $10^{10}$ - $10^{12}$ in power,[17] then rectified and connected to the output meter.

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[16] Pawsey and Bracewell, Radio Astronomy, p. 50.

[17] J. P. Wild, The Sun, p. 683.

The input powers are only a small fraction of the electrical noise generated in the receiver itself. The limit to the sensitivity for the measurement of external noise is set by the receiver noise. If the noise power were constant there would be no theoretical limit to the sensitivity. For instance, the difference between the output voltage and a steady comparison voltage could be greatly amplified. This type of procedure is limited by receiver fluctuations. They may be greatly reduced by using regulated power supplies for both high voltages and filaments. An alternative method is to calibrate the instrument at frequent intervals of time. The development of this method will be given in the discussion of the Dicke radiometer. Calibration methods will also be discussed in Chapter III.

The main features of two systems will be mentioned here, and a more detailed account can be found in a reference.[18]

2.5 D. C. radiometer. The noise power received by the antenna is amplified in either a tuned RF or a superheterodyne receiver. The amplified noise is then detected in a diode detector and this output is amplified in a dc amplifier and recorded on a meter.

Although this system is relatively simple, it requires rigid gain stabilization in the receiver. A small percent

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[18] R. M. Ringoen, "Present Status of Microwave Radiometric Receiver Development," Collins Radio Co. Report No. CTR-102 (April 13, 1954).

change in the receiver gain or the noise figure causes an output change equivalent to many degrees of antenna temperature change. Therefore, voltage regulators for all plate and filament voltages are necessary and temperature stabilization of the complete receiver enclosure must also be achieved. This rigid stabilization leads to a long warmup time for the instrument. Two advantages of this type are a large detector bandwidth and the absence of switching transients.

2.6 Dicke radiometer. R. H. Dicke approached the problem of reducing calibration errors due to fluctuating receiver gain and noise factor by developing a system of calibrating the instrument at frequent intervals.[19] A block diagram of the system is given in Fig. 6.

This type of radiometer has been discussed at length in the literature. A mathematical analysis is included in a technical report from this laboratory.[20] Most measurements in the microwave region below 10 cm have used the Dicke radiometer. Both direct and Dicke systems have been used on wavelengths up to a meter. On longer wavelengths most receivers have used the direct system.

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[19] Dicke, R. H., Rev. Sci. Instr., 17, p. 268 (1946).

[20] J. Copeland, F. H. Mitchell, and R. N. Whitehurst, "Solar Radiation and Atmospheric Attenuation at 6 Millimeters Wavelength," Interim Tech. Reports No. 1, Office of Ordnance Research, U. S. Army (August 1, 1956).

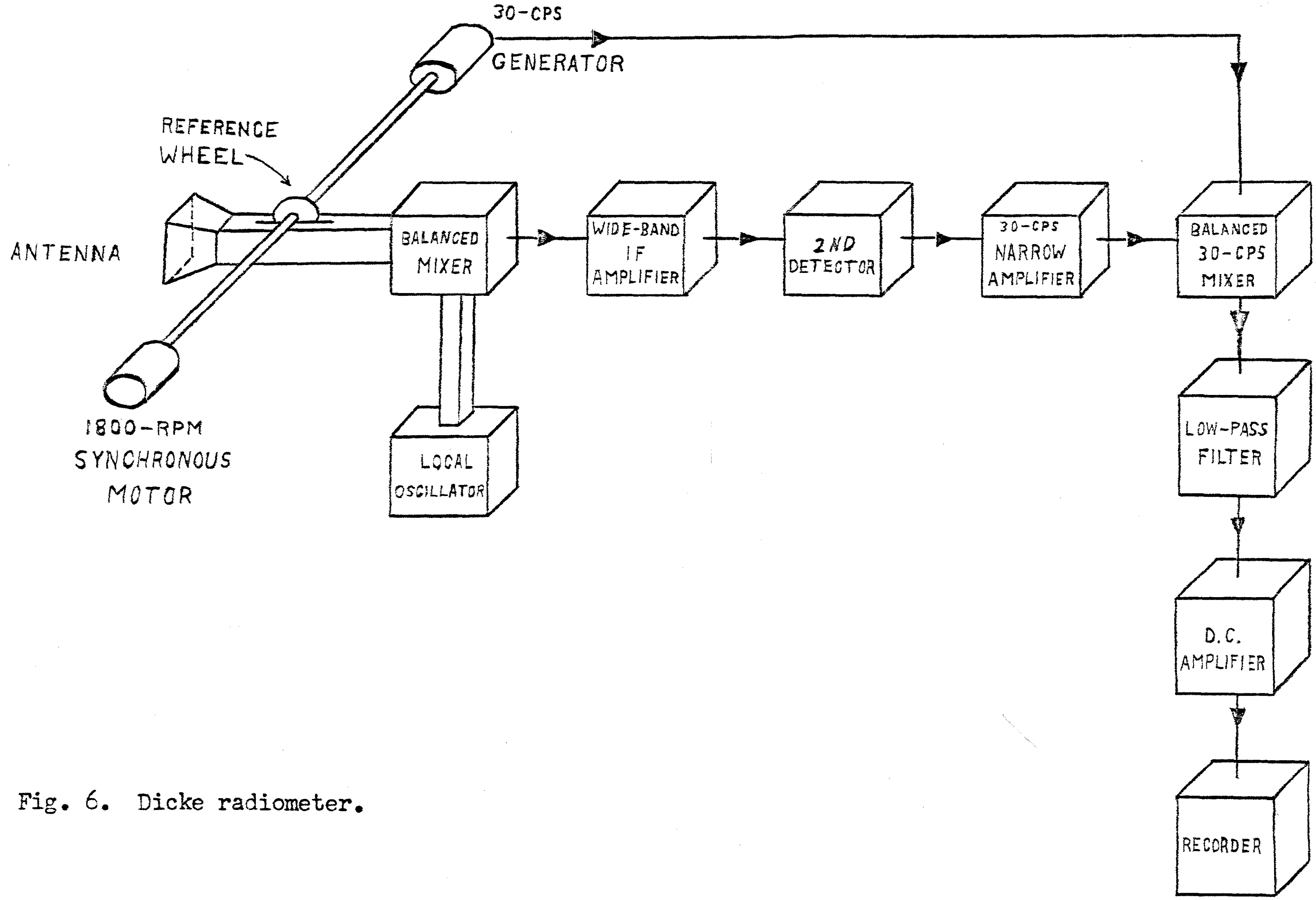


Fig. 6. Dicke radiometer.

There is no marked difference between the sensitivities which have been attained using the different systems.[21] This is probably due to the elaborate stabilization of power supplies which the workers using the direct system have been forced to use. It seems probable that with equal care the Dicke system could give greater sensitivity.

2.7 Dicke microwave radiometer for observations at 6 mm.

A Dicke microwave radiometer was constructed for observations at 6 and 7.5 mm[22] and the same instrument was used, after some modification, for the present observations at 8.6 mm. The original radiometer had an antenna beamwidth to tenth-power points of 2 degrees. The noise bandwidth of the IF amplifier is 12.5 mc and the gain is about 100 db. The center frequency is 45 mc. The narrow-band amplifier is tuned to 30 cps and has a bandwidth of 3 cps. The overall gain of this amplifier is about 2000.

2.8 Modifications of original equipment for use at 8.6 mm.

The same parabolic mirror was used, but the feed horn was replaced by a larger one. It was electroformed of copper with an inside silver plating. The method of finding the antenna pattern was the same as that described by Copeland.[23]

The horn was connected as before to the balanced mixer by a section of RG-97/U waveguide. The beamwidth to tenth-power points was 2.8 degrees. The antenna pattern in the

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[21] Pawsey and Bracewell, Radio Astronomy, p. 43.

[22] Copeland, Mitchell, and Whitehurst, "Solar Radiation," p. 15.

[23] *Ibid.*, p. 26.

E-plane is shown in Fig. 7. The pattern in the H-plane was found to be approximately the same.

The QK-294 klystron was replaced by a QK-291 klystron designed for use in the 8-9 mm wavelength range. The output frequencies were measured by the usual slotted line techniques. Crystal currents above 0.5 ma were easily obtained.

The QK-294 klystron was connected to the balanced mixer by a length of RG-97/U waveguide. To avoid the necessity of replacing this by a larger waveguide when the QK-291 klystron was used, a short length of transition waveguide was inserted between the klystron and the RG-97/U waveguide. This transition guide was electroformed in the same manner as was the microwave horn.

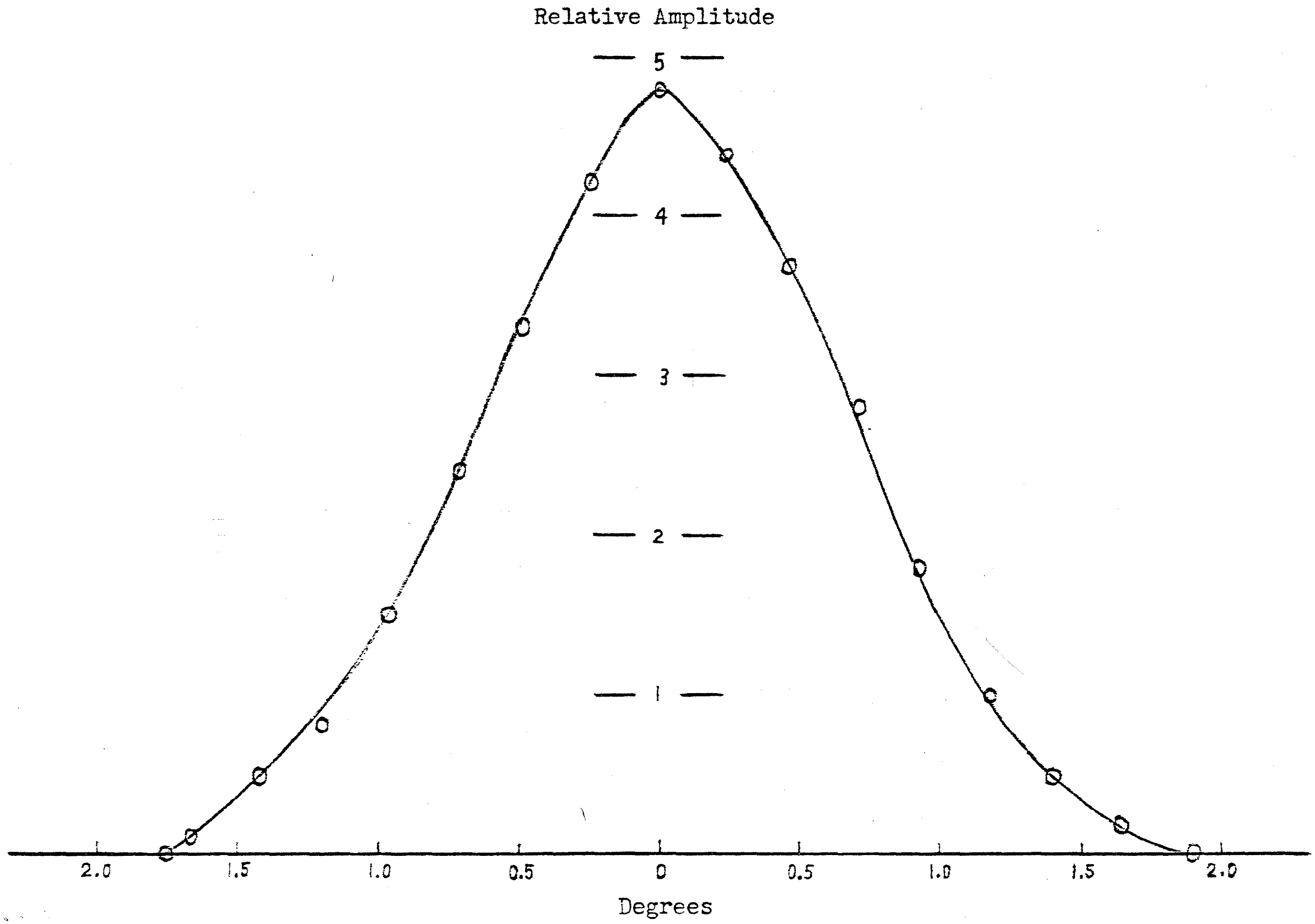


Fig. 7. Antenna pattern.

# CHAPTER III

# CALIBRATION PROCEDURE

3.1 <u>Direct Calibration</u>. The most common method of calibrating a radiometer is to provide a standard source which can be connected in place of the antenna. This source may be a standard signal generator or a "noise generator," two types of which will be discussed below. The noise generator has the advantage that the frequency response of the receiver does not affect the relative readings.

3.2 <u>Thermal noise generators</u>. This type of noise generator uses the thermal noise from a variable-temperature resistor and was the type used by Dicke and Hagen. Two methods of producing a source of this kind have been used. In the first a long lossy waveguide termination is heated to a known temperature by a heating coil. At centimeter wavelengths this effect is achieved using a long wedge of absorbing material, such as carbon, lying inside a length of waveguide which can be heated and cooled. For long wavelengths long lengths of flexible feeder are coiled up in a small oven or thermos flask.

The second method requires two separate resistors, the "hot" and "cold" resistor. Each is adjusted to the correct impedance at its working temperature and they are connected in turn to the receiver. A tungsten lamp may be used for the hot resistor so that a temperature of about $2000^{\circ}$ K is attained. The temperature is measured by the change in resistance of the lamp.

The main defect in thermal noise generators is the small amplitude of the output.

3.3 Diode noise generators. This type of noise generator consists of a temperature-saturated diode with directly heated filaments. Such a diode is essentially a source of noise current, not of power. The impedance into which it flows must be known in order to calculate power, and stray reactances must be avoided. At higher frequencies, diodes have been designed which approximate a small section of uniform transmission line.

Diode noise sources have two advantages over the thermal noise type; the output can be made greater and it is conveniently made continuously variable. However, there is greater uncertainty of calibration due to stray reactances.

Diode circuits require great care to avoid these stray reactances at frequencies above 20 mc. The effective temperature is computed from its relation to the diode current.[24]

3.4 Gas-discharge noise generators. A recently developed standard noise source which uses the noise emitted by the ionized gas in the positive column of a discharge tube has

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[24] Pawsey and Bracewell, Radio Astronomy, p. 46.

been developed for use in the microwave range and was used by Coates for observations at 4.3 mm wavelength.[25]

In an arrangement for coupling into a waveguide, the discharge tube runs diagonally through the waveguide making about a 10-degree angle with its axis. This results in a discontinuity which produces little reflection. When the discharge is turned on, the tube behaves like a high-temperature matched termination to the waveguide.

In order to determine the effective temperature of this noise source, it must be calibrated against a primary standard such as a black-body termination at a known elevated temperature. A disadvantage of this method is that gas discharges are likely to produce oscillations and spurious noise and this can be avoided only by finding suitable operating conditions by trial and error.

3.5 Indirect calibration. The main difficulties in the preceding methods of calibration arise in constructing noise generators which deliver an accurately known noise power at their output terminals, in producing an antenna and noise generator with the same terminal impedance, and in determining the effective area of antennas and complete antenna patterns.

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[25] R. J. Coates, "The Measurement of Atmospheric Attenuation at 4.3 mm Wavelength," Naval Research Laboratory Report No. 4898 (April 2, 1957).

The procedure outlined below is a method of calibration developed at the University of Alabama[26] which reduces these problems.

3.6 Experimental procedure. In most calibration procedures the calibrating signal is fed into the radiometer by replacing the entire antenna system with a standard source, the effective temperature of which is known. Therefore, in order to measure an unknown temperature it is necessary to obtain a complete antenna pattern. The procedure to be described eliminates this difficulty and also does not require knowledge of the atmospheric attenuation.

Fig. 8 shows an idealized antenna for which A, B, and C are the fractional energies received by the forward, side, and back lobes respectively. The antenna is pointed at the sky to the west of the source whose temperature is to be measured. In this case the antenna temperature is

$$T_1 = AT_o(1 - e^{-TVA\sec\theta}) + BT_b + CT_c \ .$$

In this equation $T_o$ is the temperature of the atmosphere which is assumed to be isothermal at ambient temperature. TVA is the total vertical attenuation and $\theta$ is the zenith angle. $T_b$ and $T_c$ are the average temperatures "seen" by the side and back lobes respectively.

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[26] R. N. Whitehurst, F. H. Mitchell, and J. Copeland, Proc. IRE 45, 410-11 (1957).

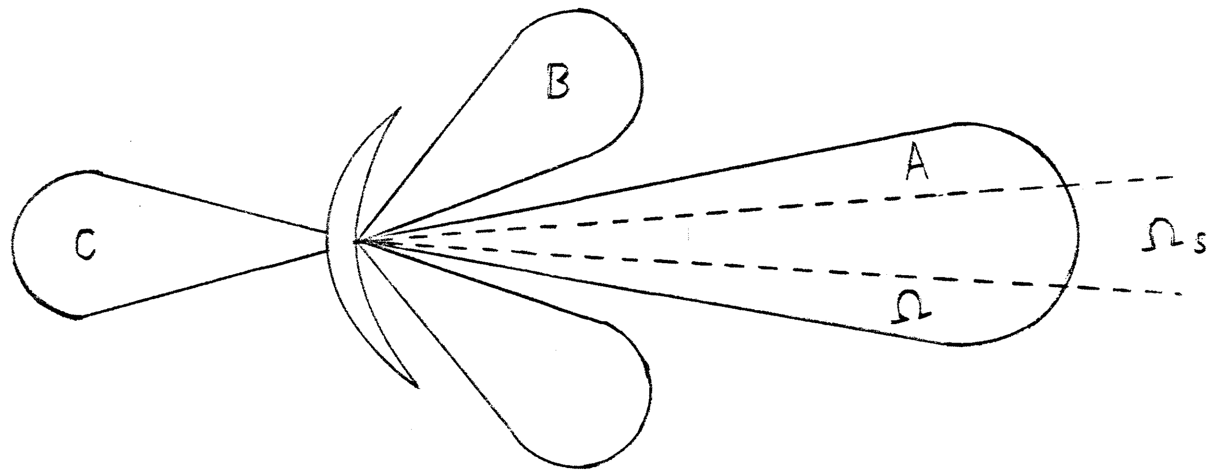


Fig. 8. Idealized antenna pattern.

Due to the rotation of the earth, the source moves into the center of the forward lobe of the antenna and changes the antenna temperature to a value given by

$$T_2 = T_1 + \frac{\Omega_s}{\Omega} A T_s e^{-TVA\sec\theta}.$$

$\Omega$ and $\Omega_s$ are the weighted solid angles subtended by the forward lobe and the source respectively. $T_s$ is the effective temperature of the source.

After the source has passed out of the beam, let a piece of microwave absorber which is at ambient temperature $T_o$ be held up to fill the entire forward lobe only. This is the calibrating signal. The antenna temperature is now

$$T_3 = AT_0 + BT_b + CT_c.$$

As the antenna is subjected to each of the above conditions, a different scale deflection is observed on the output meter. Let the deflections for $T_1$, $T_2$, and $T_3$ be $d_1$, $d_2$, and $d_3$. The above equations may be combined to give two equations, each containing the term $e^{-TVA} \sec\theta$. We have

$$d_2 - d_1 = k(T_2 - T_1) = k\frac{\Omega_s}{\Omega} A T_s e^{-TVA\sec\theta}$$

and

$$d_3 - d_1 = k(T_3 - T_1) = kAT_0 e^{-TVA\sec\theta}$$

where k is the sensitivity of the radiometer. Dividing the first equation by the second results in the expression for the average source temperature $T_s$,

$$T_s = \frac{\Omega}{\Omega_s}\frac{d_2 - d_1}{d_3 - d_1} T_0.$$

It is now necessary to measure the three output meter deflections and the shape of only the forward lobes of the antenna pattern. The ration of the solid angles $\frac{\Omega}{\Omega_s}$ is found graphically.[27]

The main advantages of this method are the simplicity of the procedure and the elimination of the difficulties of constructing a noise source and determining the complete antenna pattern.

The assumption of an isothermal atmosphere at ambient temperature is, of course, not actually true. However, the density of the atmosphere decreases rapidly with height and with it the emissivity. Therefore, most of the contribution to the radiation comes from the lower layers which must be near ambient temperature. If this lower region is sufficiently narrow, it may be assumed isothermal. Also, if the assumption were not true the measured temperature of the source would be a function of zenith angle. No variation of this type has been detected.

A possible source of error in this procedure is the assumption that the microwave absorber is at ambient temperature. However, it is unlikely that this assumption is more than $\pm$ 10°K in error. An error of $\pm$ 10°K in the absorber temperature would introduce in error of only $\pm$ 3% in the final result.

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[27] Copeland, Mitchell and Whitehurst, "Solar Radiation," p. 28.

## CHAPTER IV

## EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Effective Solar Temperature at 8.6 mm. Using the indirect calibration procedure described in section 3.2, a single solar transit can be used to obtain the effective temperature of the sun. The ratio of the solid angle subtended by the beam to the solid angle subtended by the sun, $\frac{\Omega}{\Omega_s}$, was found to be 12.3. The average of 15 solar transits made during August of 1957, shows an effective solar temperature of 6500 °K. An 8.6 mm transit is shown in Fig. 9.

This value for the temperature is not in conflict with measurements at this wavelength in other laboratories, in particular the value given by Hagen of 6740 °K ± 10% at 8.5 mm. It is also consistent with an extrapolation of Copeland's[28] previous observations at 6.0 and 7.5 mm, which show temperatures of 4500 °K and 5600 °K respectively.

Attenuation of radiation at 8.6 mm by haze and clouds not containing large amounts of water vapor was negligible.

4.2 Discussion. Upon extending the range of the experiments to 8.6 mm wavelength, the increase in solar temperature in the lower chromosphere reported by Copeland between 6.0 and 7.5 mm has been shown to continue to 8.6 mm. The

[28] Ibid., p. 37.

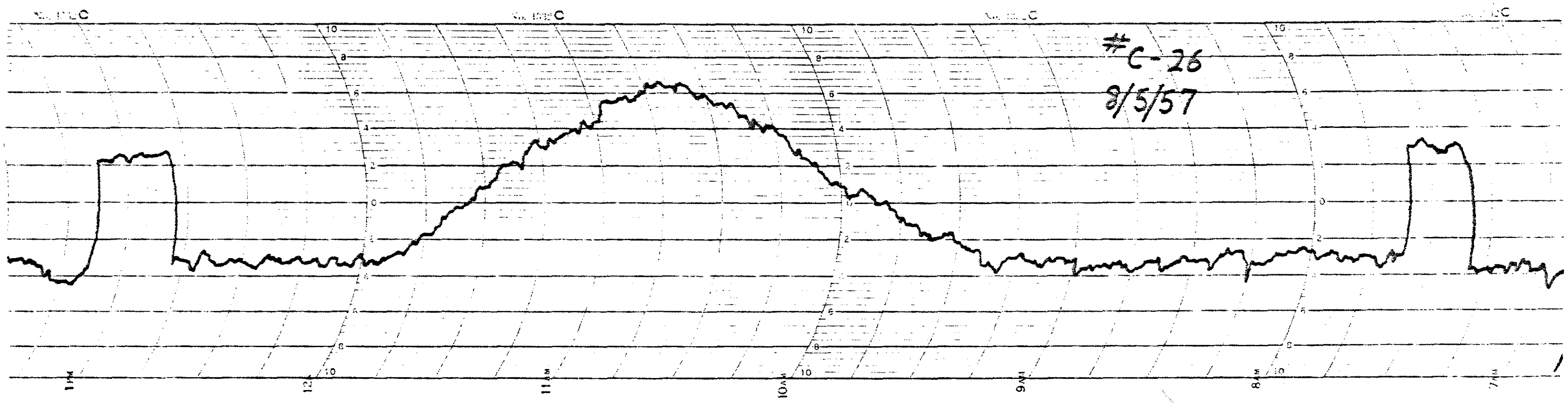


Fig. 9. Transit of the sun at 8.6 mm wavelength

measurements made in this laboratory are represented in Fig. 1 by crosses. This graph suggests that the minimum temperature and the wavelength at which this temperature occurs are still uncertain.

Of the models of the lower chromosphere considered in this paper, the model of Van de Hulst appears to be the most attractive. The temperature increase given for the region from the base of the chromosphere to 6000 km height is from 4600 °K to 6500 °K. This is practically the same as the increase from 4500 °K to 6500 °K found between 6.0 and 8.6 mm wavelength in this laboratory.

In arriving at the final electron density and temperature distribution for this model, Van de Hulst has considered a great deal more observational data than was used in the other models. The arguments for high and for low temperatures in the lower chromosphere which are based on observational data are listed and each is discussed in some detail. The contribution to the final model of each bit of data considered was weighted carefully according to its validity and its bearing on the problem of temperature and electron distributions.

Even though observational determinations of absolute densities were omitted, the two methods available for such determinations are discussed. It is shown that there is no serious discrepancy in the final values of this model and the values given by such observations.

The first method is based on absolute photometry of the Balmer continuum, and was used by Cillie and Menzel. The resulting values of electron density exceed the values of this model by a factor of 5. However, Van de Hulst states that an error of a factor of 5 is not unlikely in this type of observation.

The other method is based on attributing the broadening of Balmer or Paschen lines to intermolecular Stark effect, so that the amount of broadening gives the concentration of electrons and ions. This method was applied by Wildt to the chromosphere and the resulting densities exceed the final values of this model by a factor of 5 to 10. Van de Hulst reasons that there may be other unknown reasons for this broadening so that the computed electron density is too high.

It is seen from the graphs that the other models give a temperature increase quite different from the Van de Hulst model. Since the minimum temperature is uncertain and may be below the value of about 4800 °K for the limb of the sun, the alternate temperature distribution of Hagen's model, showing a minimum temperature and then an increase toward the limb, may be more plausible.

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