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ON THE TEMPERATURE OF THE SOLAR REVERSING LAYER

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ABSTRACT. The Fraunhofer CN band λ 3883 was photographed with the high dispersion solar spectrograph, at the centre of the disc and at the limb of the sun. Points slightly within the limb are chosen for obtaining limb spectra. The methods of identifying the CN lines and measuring their intensities are described. By means of formulæ deduced from the theory of band line intensities, temperatures of 5000° K and 4500° K are computed for the disc and limb respectively.

The proximity of the sun and its great brightness compared with other stars offer a unique opportunity for studying the physical state of the solar atmosphere. One can bring into operation the most powerful high dispersion spectrographs available without fear of inordinate exposure times. During the past two decades, on account of the large improvements in the observational technique, many interesting results regarding the solar atmosphere were brought to light. It is known for a long time that molecules exist in the reversing layer of the sun and that they give rise to band spectra. Determinations of the the relative intensities of the lines in these bands furnish valuable information regarding the physical conditions in the reversing layer. In recent years, there have been several investigations in this direction. The relations that exist between the temperature of a diatomic gas in thermal equilibrium, the molecular constants and the relative intensities of the rotational lines have been applied for determining the temperature of the reversing layer.

TABLE I

Author	Method	Effective temperature for the integrated solar disc (in degrees absolute)
Milne	Stefan-Boltzmann law	5740
Bernheimer	Wien's law	6079
Fabry and Buisson	Planck's law 2932-3940A	5830-6000
Lindbland	Planck's law	5950
Brill	Planck's law	5775-6075
Plaskett	Planck's law 4800-6700A	6300-6600
Woolley	Ionisation of calcium	6310

Before applying the theory of band spectra to the molecular Fraunhofer lines, it is interesting to just review some of the results obtained by utilising other methods. The most often quoted result is that given by Abbot (1922) who, by the use of radiation laws, arrived at a value of 5740°K for the effective temperature of the sun. Milne(1921), Bernheimer, Fabry and Buisson(1922), Lindbland (1923), Brill, Plaskett(1923) and Woolley (1932) were among others who determined the effective temperature for sunlight integrated over the disc. The results obtained by them are summarised in Table I. In Table II are given the values of the excitation temperatures obtained by different authors from atomic line intensities and molecular band intensities. It will be seen that in general the excitation temperatures deduced from line intensities are lower than the effective temperatures.

TABLE II

Author	Lines used	Excitation temperature in degrees absolute
Atomic determinations :		
King (1938)	Ti I	4400
Menzel, Baker and Goldberg (1938)	Fe I Ti I	4150 4350
Molecular determinations :		
Birge (1922)	CN band at λ 3883	4000
Richardson (1931)	C_2 band at λ 5165	5670 (Mean value)
Adam M.G. (1937-38)	C_2 band at λ 5165	4550 (at the centre) 4790 (at the limb)
Roach (1939)	CN band at λ 3883	5630
Leon Blitzer (1940)	CN band at λ 3883	4490

Investigations on the determination of the temperature of the reversing layer from band line intensities are seriously hampered by the general faintness of the molecular lines and their blending with strong atomic lines. Perhaps due to this fact many of the investigations given above are only of a qualitative nature. As can be seen from Table II, the CN band at λ 3883 has been studied more than any other. The earliest determination of Birge was only from a visual comparison of the intensity distribution in the Fraunhofer CN lines with those in the arc and furnace spectra obtained in the laboratory. From a knowledge of the temperatures of these terrestrial sources of comparison he estimated the temperature of the reversing layer. Roach used Rowland intensities in his investigation. Blitzer made a quantitative study of the intensity distribution of the lines in the CN band from microphotometer tracings. He photographed the solar spectrum with the 75-foot tower telescope of Mt. Wilson having a linear dispersion of 3 mm per Angstrom. But his exposures for the solar spectrum were unusually long, ranging from 40 minutes to 4 hours. During such long intervals the sky conditions can never be constant and it is very necessary that plates, intended for photometric work, should be taken under constant sky conditions particularly to avoid the uncertain influence of the varying sky conditions. Since investigations of this nature provide valuable observational material for an analysis of the physical state of the solar atmosphere, spectrograms covering the region of the CN band at 3883 were secured by the author at the Kodaikanal Observatory during the past ten months. From the large number of plates available, only those of the finest quality were finally selected for photometry. The spectra were taken with a Glass Littrow spectrograph having a linear dispersion of 2.5 mm per Angstrom in the 3883 region. The instrument was particularly designed to minimise the systematic errors due to the scattered light in the spectrograph. A 12-inch Aluminised mirror, run by a siderostat, was used for reflecting the sun's image on to a lens which in turn gave a focussed image of about 6 inches in diameter on the slit of the spectrograph. Pictures at the centre of sun's disc were taken on days when the sky was very clear. Care was taken to see that photographs were obtained only when the centre of the sun's disc was undisturbed. Exposures of 1 to 2 minutes were found to be sufficient to give good pictures. Using a low dispersion spectrograph, standards were impressed on each plate by a step slit which was illuminated by diffuse reflection (by a paper) of the light from a 500-Watt lamp run on 110 volts D.C. The duration of exposure for these calibration spectra was just the same as that given for the solar spectrum. The spectrograms thus obtained were measured with a comparator estimating the intensity of each of the lines in the spectrum. These measurements were compared with the catalogue given in the Revised Rowland Table. The observed wavelength and strength of the lines gave a clue for identifying the lines due to the different elements. The intensities of the CN lines of the 3883 band identified in this manner were measured from microphotometer tracings using for this purpose the Cambridge Photo-electric Microphotometer. Only those lines of the above band which are free from blends and which have got well defined peaks in the microphotometer tracing were utilised for the evaluation of the temperature.

THEORY

The theory involved in these calculations is briefly discussed below:

It is known that the temperature of a diatomic gas in thermal equilibrium can be determined from a knowledge of the molecular constants and the relative intensities of the rotational lines in the band.

Intensity 'I' of the absorption line in the band is given by

$$I = Cie^{-E''/\kappa T} \qquad \ldots \quad (1)$$

where 'C' is a constant for the band, 'i' the relative intensity factor for the rotational line, E″ the rotational energy in the lower molecular state, 'κ' the Boltzmann constant and 'T' the temperature of the gas...

$$E'' = \frac{h^2 J''(J''+1)}{8\pi^2 I''} \quad \text{or} \quad = \frac{h^2 J''^2}{8\pi^2 I''} \quad \text{approximately}$$

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$$E'' = \frac{h^2 J''(J''+1)}{8\pi^2 I''} \quad \text{or} \quad = \frac{h^2 J''^2}{8\pi^2 I''} \quad \text{approximately}$$

where $\frac{J''(J''+1)h}{2\pi}$ is the resultant angular momentum of the molecule in the lower energy state and I'' the moment of inertia of the molecule in the same state.

For the CN band (say for the R branch)

$$i = 2J'' \text{ (Jevon 1932).}$$

Therefore equation (1) becomes

$$I = 2CJ'' \exp.\frac{-h^2 J''^2}{8\pi^2 I'' \kappa T}$$

$$= C'J'' \exp.\frac{-h^2 J''^2}{8\pi^2 I'' \kappa T} \qquad \dots \quad (2)$$

where C' is another constant.

We see from this equation that there will be a particular J'' for which the intensity is a maximum. By differentiating equation (2) with respect to J'' equating to zero and solving for T, we get

$$T = \frac{J''^2_{max} h^2}{4\pi^2 I'' \kappa}$$

Further it can be easily shown that $h/4\pi^2 I''$ is the spacing between the consecutive lines at $J = +1$. Representing this by $\Delta\nu$ we get

$$T = \frac{h.\Delta\nu.J''^2_{max}}{\kappa}$$

For the CN band $\Delta\nu/C = 3.704$

Hence $$J''_{max} = 0.434\sqrt{T} \qquad \dots \quad (3)$$

This is one method of utilising equation (1). There is an alternative method of evaluating T. Taking logarithms of both sides of equation (1) and substituting for the known constants, we get

$$\log_{10} I/i = \log c - \frac{0.628 B''_v J''(J''+1)}{T} \qquad \dots \quad (4)$$

$$\text{since } E'' = J''(J''+1)$$

Plotting $\log_{10} I/i$ against $J''(J''+1)$ we should get a straight line the gradient of which gives $\frac{0.628 B''_v}{T}$ and hence 'T'. This was the method adopted by Roach and Blitzer.

It will be seen from these two methods that measurement of the position of the maximum intensity line in the band is a much better and more reliable method for determining stellar temperatures, as it involves the use of such quantities that are accurately measurable.

RESULTS

The results obtained in this investigation are given below in Table III. The wavelengths given in column 2 are taken from Uhler and Patterson (1915) and Heurlinger's notation is used for the quantum number.

TABLE III

Notation	λ	Relative intensity of the line	Rowland wavelengths in the vicinity of the J = 31 line with their intensities and identifications
R_{12} (15)	3864.300	27	
R_{12} (24)	55.622	40	
R_{12} (28)	51.285	49	
R_{12} (31)	47.839	56	
			3848.196 CN −1
R_1 (34)	44.250	46	.116 CN −1
R_2 (34)	.206		.053 CN −1
			47.967 CN −0
R_1 (41)	35.202	37	3847.873* CN 1
R_2 (41)	.147		.828 1
			47.694 −2
R_1 (50)	22.322	31	.521 −2
R_2 (50)	.259		.434 −1
R_1 (52)	19.278	28	* Probably one line
R_2 (52)	213		

It can be seen from the above table that the CN line with $J''=31$ has got the maximum intensity. Solar lines near this line are also given in the table for use in the following discussion. No doubt, it cannot be definitely ascertained that J''_{max} falls at 31 as the CN line of wavelength 3847.967 which belongs to the singlet series from the second head is broad and diffuse and shades into the $J''=31$ line. But it can be seen from the graph (Fig. 1) drawn between J'' and intensity that with reasonable accuracy J''_{max} can be fixed in the vicinity of 31.

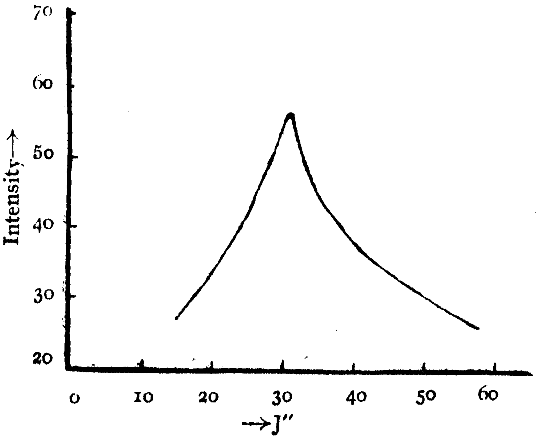

FIG. 1

To confirm this by an alternative method Rowland intensities close to the $J''=31$ line are plotted against wavelengths and it is found that the resulting contour corresponds to that obtained on the microphotometer record at $J''=31$. In both these the contours are asymmetrical the intense portion lying on the short wavelength side. The wavelength of this intense portion, as obtained from laboratory measurements, coincides with the $J''=31$ line. The temperature corresponding to this J''_{max} is, from equation (3), equal to 5100°K.

The other method of plotting $\log I/i$ against $J''(J''+1)$ was also utilised for evaluating 'T'. In Fg. 2 are plotted the values of $\log_{10} I/i$ against $J''(J''+1)$ and it will be seen that the points define a straight line with fair precision, showing that there is a thermal distribution of intensity along the band. A least squares solution was made to determine the line given by the points and a value of $T=4960 \pm 100$°K was obtained from the slope of the curve. The value given in Jevon's Band spectra of diatomic molecules p. 284 was taken for B''_v. Taking the mean of the two results obtained above, the excitation temperature of the solar reversing layer can be fixed at about 5000°K.

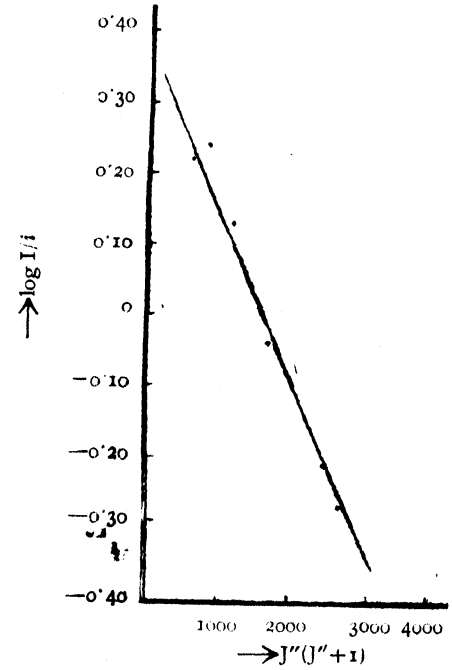

FIG. 2

It is interesting to note that this value also, like all those obtained from a study of the intensities in the molecular Fraunhofer lines, is comparatively low. This is probably due to the fact that intensity methods give a value of the excitation temperature while the others the kinetic temperature.

PART II

COMPARISON OF THE LIMB AND DISC SPECTRA

In a recent paper by Miss Adam (*loc. cit.*) it was reported for the first time that her investigations on the intensity distribution in the C_2 band at λ 5165 at the centre and the limb yielded a hitherto unsuspected higher temperature for the layers at the limb than those at the centre. This strengthening of faint lines towards the limb is attributed to an anomalous temperature distribution in the outer layers of the solar atmosphere. The assumption of reduced re-emission in a double layer atmosphere is shown to predict this strengthening. In order to examine this rather novel result of Adam and with a hope of clarifying the situation, it has been decided to study the intensity distribution in the CN band at λ 3883 photographed at the limb of the sun also.

The observational material consisted of spectrograms taken with the high dispersion instrument referred to in the previous section, on the west limb of the sun on all clear days when the seeing was 5-7 on a scale of 1-10 (1 representing the poorest seeing and 10 the best). Standards were impressed on these plates and the intensities of the unblended cyanogen lines of the 3883 band were calculated from microphotometer tracings. The results are summed up in the following table :

Notation ...	$R_{12}(24)$	$R_{12}(28)$	$R_{12}(31)$	$R_1(34)$	$R_2(34)$	$R_1(41)$	$R_2(41)$	$R_1(50)$	$R_2(50)$
Relative intensity of the line ...	32	39	52	36		28		23	

It has been pointed out previously that measurement of the position of the maximum intensity line in the band is the best method for determining stellar temperatures. But an unprejudiced result cannot be obtained by applying this method to the above values of intensities of the lines in the limb spectra, as there is not an appreciable change in temperature for the layers at the limb when compared with that for the disc. The second method is therefore adopted in this case.

A curve is drawn between log I/i and $J''(J''+1)$ and it will be seen from Fig. 3 that the points define a straight line with fair precision. A least squares solution was made to determine the straight line. As already discussed in the previous section, the slope of this straight line gives $0.628\ B''_v/T$ where T is the temperature of the limb. T_{limb} was obtained to be 4500 ± 100°K.

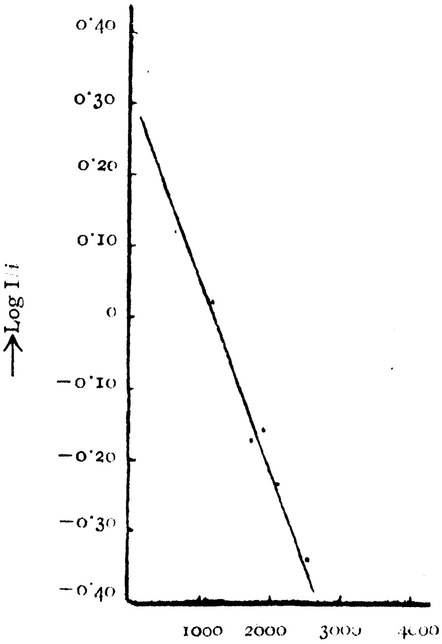

Fig. 3

The intensities of the CN lines were in all cases found to be lower than those at the centre and T_{limb} evaluated from these intensity values less then T_{disc}.

It is interesting in this connection to recall the observation of Hale and Adams (1907) *viz* :

"...... Carbon and cyanogen are particularly interesting (for a comparison of the limb and disc spectra). Many lines in the violet carbon band are of unchanged intensity or slightly strengthened at the limb. The cyanogen fluting, which begins at 3884 is, on the contrary, very decidedly weakened at the limb ...."

It is possible that the strengthening of the C_2 lines, observed by Miss Adam, is not due to the higher limb temperature but to some other cause. From these and other observations made by the author, it seems certain that there is a low excitation at the limb.

With a view to clarifying this point further, investigations are in progress, particularly as regards the intensity distribution in the CH and the C_2 bands in the laboratory and solar spectra.

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