



# Limb-Darkening Observations between 1800 and 2900 Å

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Jacques-Emile Blamont, R. M. Bonnet. Limb-Darkening Observations between 1800 and 2900 Å. Solar Physics, 1968, 3 (1), pp.64-81. 10.1007/BF00154244 . insu-03523754

**HAL Id: insu-03523754**

**<https://insu.hal.science/insu-03523754>**

Submitted on 12 Jan 2022

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# LIMB-DARKENING OBSERVATIONS BETWEEN 1800 AND 2900 Å

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(Received 13 June, 1967)

**Abstract.** We succeeded in several attempts at measuring the solar limb-darkening in the continuous spectrum between 1800 Å and 2900 Å. Good spectroheliograms were obtained during a rocket flight in November 1964 and during a balloon flight in October 1966 at 2190 Å, 2665 Å, 2885 Å, and 1980 Å, 2235 Å respectively. A rocket flown at the beginning of 1967 provided excellent spectra allowing the measurement of center-to-limb variation in the continuum and lines from 1800 Å to 2800 Å.

The first series of pictures yielded absolute values of the central intensity leading to a minimum temperature close to 4700°K. The continuous opacity of the photosphere layers has been deduced from the two first experiments. It seems that a non-metallic source of continuous absorption must be taken into account between 2500 Å and 3000 Å. Moreover, as the source functions for the shortest wavelengths show a very flat variation near the minimum temperature, it seems that the transition zone between the photosphere and the chromosphere must be very gradual.

These results are discussed in the light of the latest results deduced from the new spectra obtained.

## 1. Introduction

In order to measure the ultraviolet solar limb-darkening we have launched a series of four balloon and rocket experiments. All of them make use of photographic film. Three consisted in taking spectroheliograms within narrow bands of the continuum. The other one consisted in recording a stigmatic spectrum of the disk. Table I is a general view of the results obtained in each experiment. The different instrumental specifications are also included. Since two of the experiments have just been launched at the beginning of 1967, the results presented in this paper refer mainly to the two earliest.

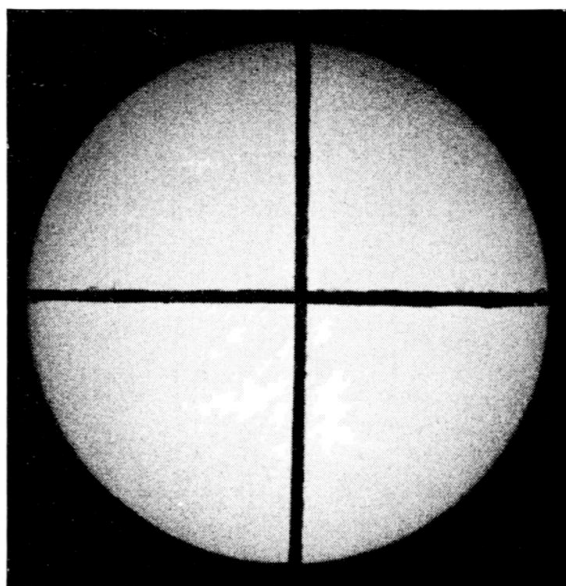
## 2. Observations (Experiments of November 1964 and October 1966)

Several spectroheliograms were obtained in November 1964 with a multiple band-pass filter (BONNET and COURTES, 1962) aimed at the sun by a biaxial pointing system built at the University of Colorado (Boulder, USA). The wavelengths were chosen in the 'windows' of the solar spectrum as free as possible from absorption lines at 2190 Å, 2665 Å, and 2885 Å. The adjustable band-width was taken equal to 43 Å. The resolution achieved on the pictures is always better than 15 seconds of arc (Figure 1). Another experiment of exactly the same type was launched with the biaxial pointing system developed at the Service d'Aéronomie on a 38 000 m<sup>3</sup> balloon in October 1966. The wavelengths were chosen for this second experiment at 1960 Å and 2280 Å in order to frame the silicon discontinuity at 1990 Å. The band-pass was 80 Å.

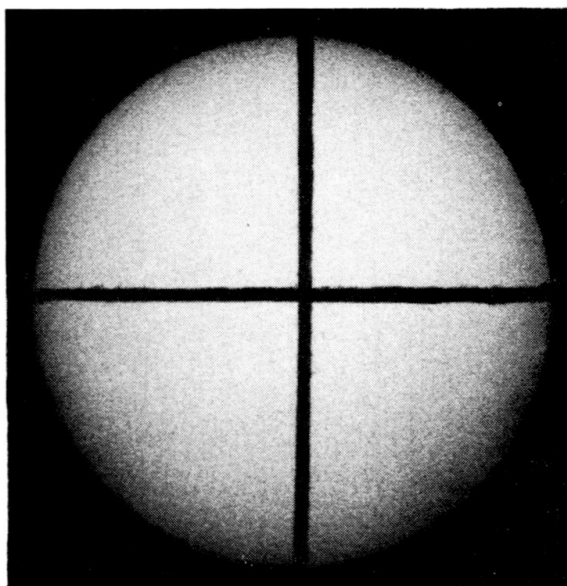
Due to the vicinity of the atmospheric window at 2100 Å, both bands were shifted

TABLE I  
General View of the UV Limb-darkening Results

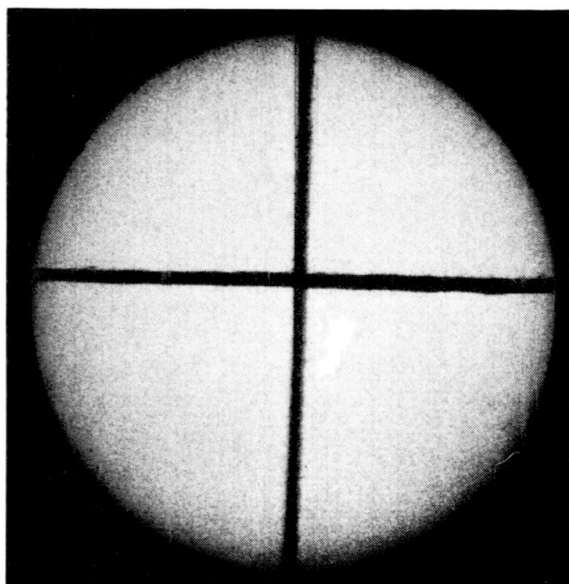
Date of launching	Space Vehicle used	Sun follower	Pointing accuracy during flight	Type of experiment	Spectral resolution	Wavelengths studied	Spatial resolution	Exposure times and photographic emulsion	Main Results
November 8, 1964	Veronique Rocket	University of Colorado	± 1'	spectro-heliograms	43 Å	2190 Å	10"	0.03 sec and 0.06 sec	Continuum limb-darkening curves
						2665 Å	10"	0.03 sec and 0.06 sec	Continuum absolute intensities
						2885 Å	15"	0.03 sec III-0, O, UV (16 mm)	
October 3, 1966	38 000 m <sup>3</sup> Balloon	Service d'Aéronomie	± 1' 30"	spectro-heliograms	80 Å	1980 Å	15" to 20"	0.08 sec and 0.11 sec	Continuum limb-darkening curves and facular structure
						2235 Å	15" to 20"	103a-0, UV 35 mm	
								0.08 sec and 0.11 sec	
								III-0, UV 35 mm	
January 13, 1967	Veronique Rocket	S.P.C. 300 Ball Brothers Research Corporation	± 7"	stigmatic spectra	0.4 Å	Range 1800 Å to 2800 Å	15" to 20"	0.1 sec and 0.5 sec	Continuum and lines
								103a-0, UV 16 mm	limb-darkening curves
									Absolute intensities
March 22, 1967	38 000 m <sup>3</sup> Balloon	Service d'Aéronomie	± 2'	spectro-heliograms	80 Å	2040 Å	1' to 2'	0.08 sec and 0.11 sec	Facular structure
								103a-0, UV 35 mm	
						2215 Å	30"	0.08 sec and 0.11 sec	Limb-darkening curves
								103a-0, UV 35 mm	



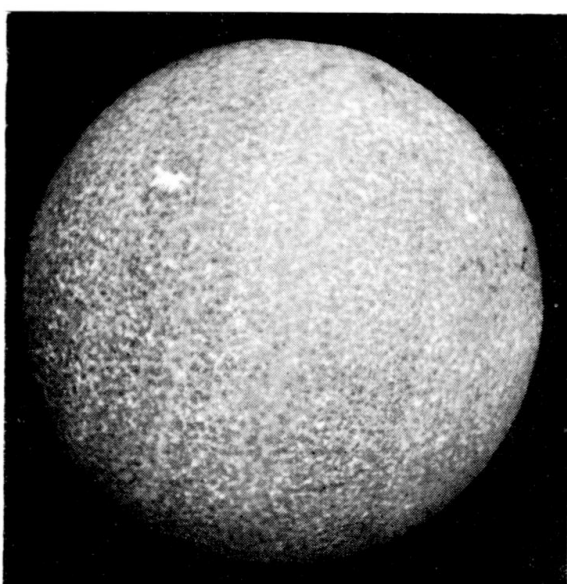
Wavelength = 2885 Å Film: Kodak III-0, UV  
 Band = 43 Å Image diameter = 5 mm  
 Exposure time = 25 m.s.



Wavelength = 2665 Å Film: Kodak III-0, UV  
 Band = 43 Å Image diameter = 5 mm  
 Exposure time = 60 m.s.



Wavelength = 2190 Å Film: Kodak III-0, UV  
 Band = 43 Å Image diameter = 5 mm  
 Exposure time = 60 m.s.

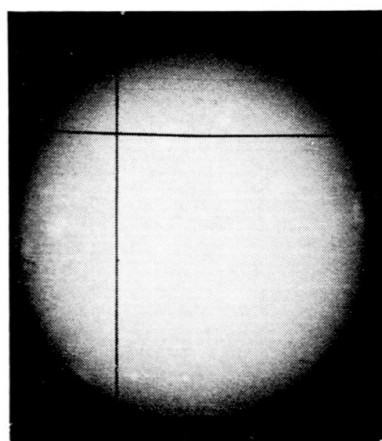


Spectroheliogram in the Calcium K line  
 Picture of November 8, 1964  
 (Observatoire de Meudon)

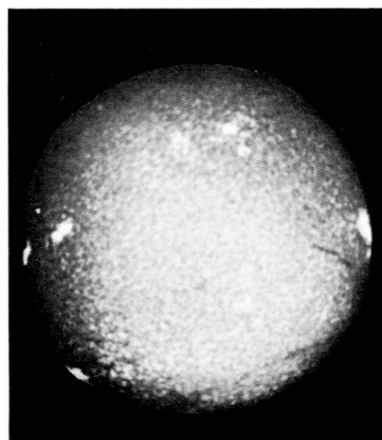
Fig.1. Rocket spectroheliograms of November 8, 1964.

toward this wavelength and the pictures actually correspond to  $1975 \pm 5 \text{ Å}$ , and  $2235 \pm 5 \text{ Å}$ . On these pictures too, the resolution is of the order of  $15''$  (Figure 2).

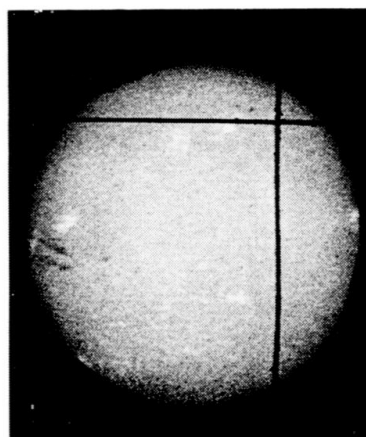
Absolute photometric calibration allowed us to measure the central intensity averaged over the band-pass of the filter in the rocket experiment. The results are reported in column 2 of Table II. In the balloon experiment, absolute measurements



Wavelength = 2235 Å  
 Band = 80 Å  
 Exposure time = 110 m.s.  
 Film = Kodak III-0, UV  
 Image diameter = 14 mm



Spectroheliogram in the Calcium  
 K line  
 Picture of October 3, 1966  
 (Observatoire de Meudon)



Wavelength = 1980 Å  
 Band = 76 Å  
 Exposure time = 80 m.s.  
 Film = Kodak 103a-0, UV  
 Image diameter = 8 mm

Fig. 2. Balloon spectroheliograms of October 3, 1966.

are impossible because we do not know the actual ozone thickness above the balloon. The results obtained at 2190 Å, 2665 Å, 2885 Å have already been published (BLAMONT and BONNET, 1966). A strong difference was noticed between the 2190 Å and 2235 Å data, obtained during the rocket and the balloon flights respectively (BLAMONT and BONNET, 1967). After a careful analysis, it was found that the photometric calibration used to process the results of the 2190 Å pictures was not reliable. New calibrations were undertaken, which led to the final result shown in Figure 3. It can be seen that



the curves are very similar. Thus, for further computations we have taken only one curve, since the differences between them lie within the experimental errors, estimated at 5%.

TABLE II

Different Determinations of the Central Intensity at 2190 Å, 2665 Å, 2885 Å, averaged over 40 Å given in ergs cm<sup>-3</sup> sec<sup>-1</sup> steradian<sup>-1</sup>

Wavelength	Our rocket measurements	Computed from Tousey's measurements of the flux	Computed for		
			<i>T</i> = 4500	<i>T</i> = 4600	<i>T</i> = 4700
2190 Å	9.9 × 10 <sup>12</sup>	1.4 × 10 <sup>13</sup>	5.0 × 10 <sup>12</sup>	6.95 × 10 <sup>12</sup>	9.4 × 10 <sup>12</sup>
2665 Å	7.2 × 10 <sup>13</sup>	6.0 × 10 <sup>13</sup>	3.75 × 10 <sup>13</sup>	4.86 × 10 <sup>13</sup>	6.25 × 10 <sup>13</sup>
2885 Å	1.8 × 10 <sup>14</sup>	1.2 × 10 <sup>14</sup>	7.3 × 10 <sup>13</sup>	9.3 × 10 <sup>13</sup>	1.2 × 10 <sup>14</sup>

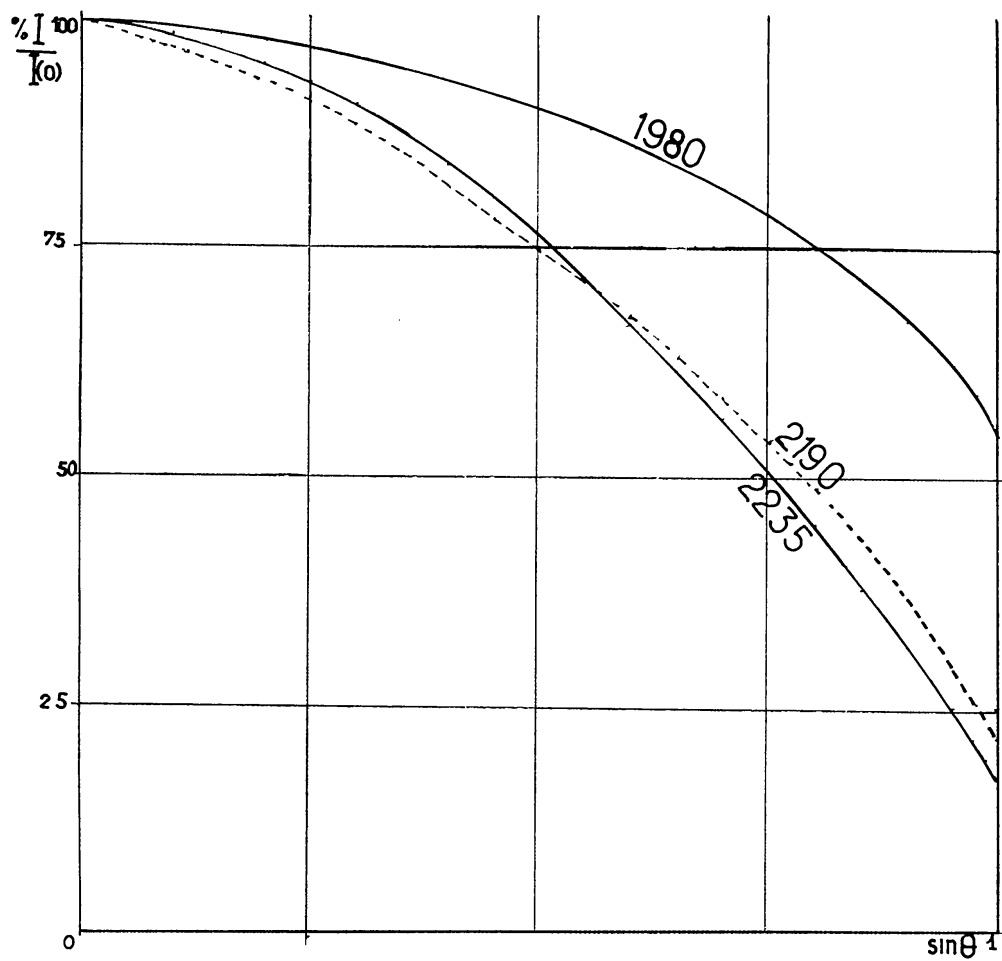


Fig. 3. Comparison of the solar limb-darkening at 2190 Å and 2235 Å plotted versus sin  $\theta$ .

The four curves used in our computation are plotted in Figure 4 versus cos  $\theta$ . We have included the curve obtained from photoelectric ground-based observations by PEYTURAUX (1955). It will be noticed that there is a huge discontinuity between 2190 Å

and 1980 Å in the solar limb-darkening. This is also observed in Figure 2, where the sun looks very different from one wavelength to the other. The similarity between the 1980 Å picture and the Ca K spectroheliogram is especially striking.

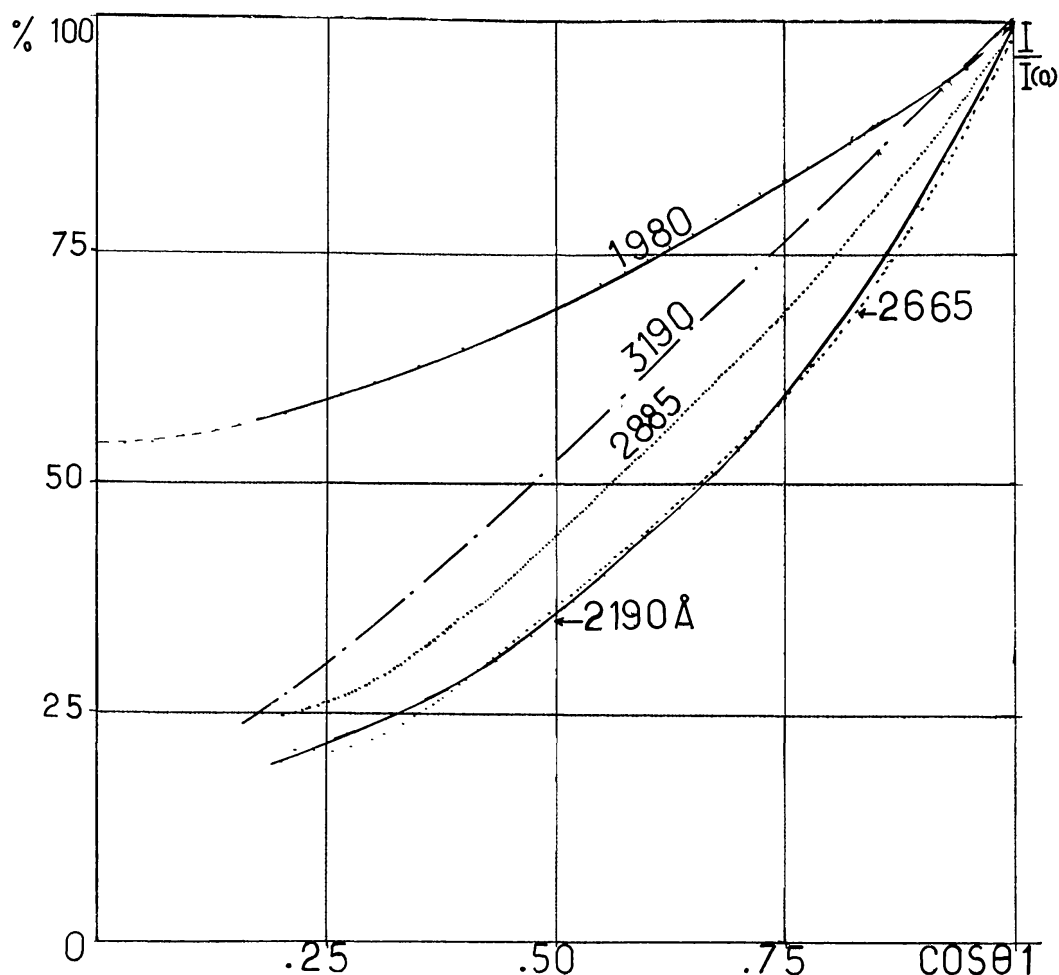


Fig. 4. Solar limb-darkening at 1980 Å, 2190 Å, 2665 Å and 2885 Å, plotted versus  $\cos \theta$ . The curve corresponding to 3190 Å is taken from PEYTURAUX (1955).

### 3. The Source-Function

We have used an analytical method to invert the Laplace Integral:

$$\frac{I_{\lambda}(\mu)}{I_{\lambda}(\mu=1)} = \int_0^{\infty} \frac{S_{\lambda}(\tau_{\lambda})}{I_{\lambda}(\mu=1)} e^{-\frac{\tau_{\lambda}}{\mu}} \frac{d\tau_{\lambda}}{\mu} \quad (1)$$

where  $\mu$  is  $\cos \theta$ ,  $\tau_{\lambda}$  the optical depth, and  $S_{\lambda}(\tau_{\lambda})$  the source-function, these last two quantities referring to the single wavelength  $\lambda$ .

The information one can get on  $S_{\lambda}(\tau_{\lambda})$  is entirely concentrated in the  $(I_{\lambda}(\mu))/I_{\lambda}(\mu=1)$  curve. It is clear that it decreases exponentially with increasing optical depths. Therefore, instead of integrating Equation (1) over  $\tau_{\lambda}$  one can assume to

integrate it over intervals containing the same amount of information, i.e. to take  $x_\lambda = e^{-\tau_\lambda}$ .

Hence, Equation (1) becomes:

$$\frac{I_\lambda(\mu)}{I_\lambda(\mu=1)} = \int_0^1 S'_\lambda(x_\lambda) x_\lambda^{\frac{1}{\mu}-1} \frac{dx_\lambda}{\mu}. \quad (2)$$

The inversion of Equation (2) is then made by means of a least-squares method in expanding  $S'_\lambda(x_\lambda)$  in a power series in  $x_\lambda$ .

Applied to several test problems, this method gave good results (BONNET and LAGO, 1966). For experimental problems, the agreement between the observed and computed values of  $(I_\lambda(\mu))/(I_\lambda(1))$  is very good and of the order of a few percents. Nevertheless, since we must introduce negative powers of  $x_\lambda$  in the expansion of  $S'_\lambda(x_\lambda)$  the values of  $S_\lambda(\tau_\lambda)$  for large values of  $\tau_\lambda$  are certainly overestimated. The variation of  $S_\lambda(\tau_\lambda)$  with  $\tau_\lambda$  is reported in Figure 5 for the wavelengths we are dealing with.

Using the expansion of  $S_\lambda(\tau_\lambda)$  one can compute the monochromatic flux as a

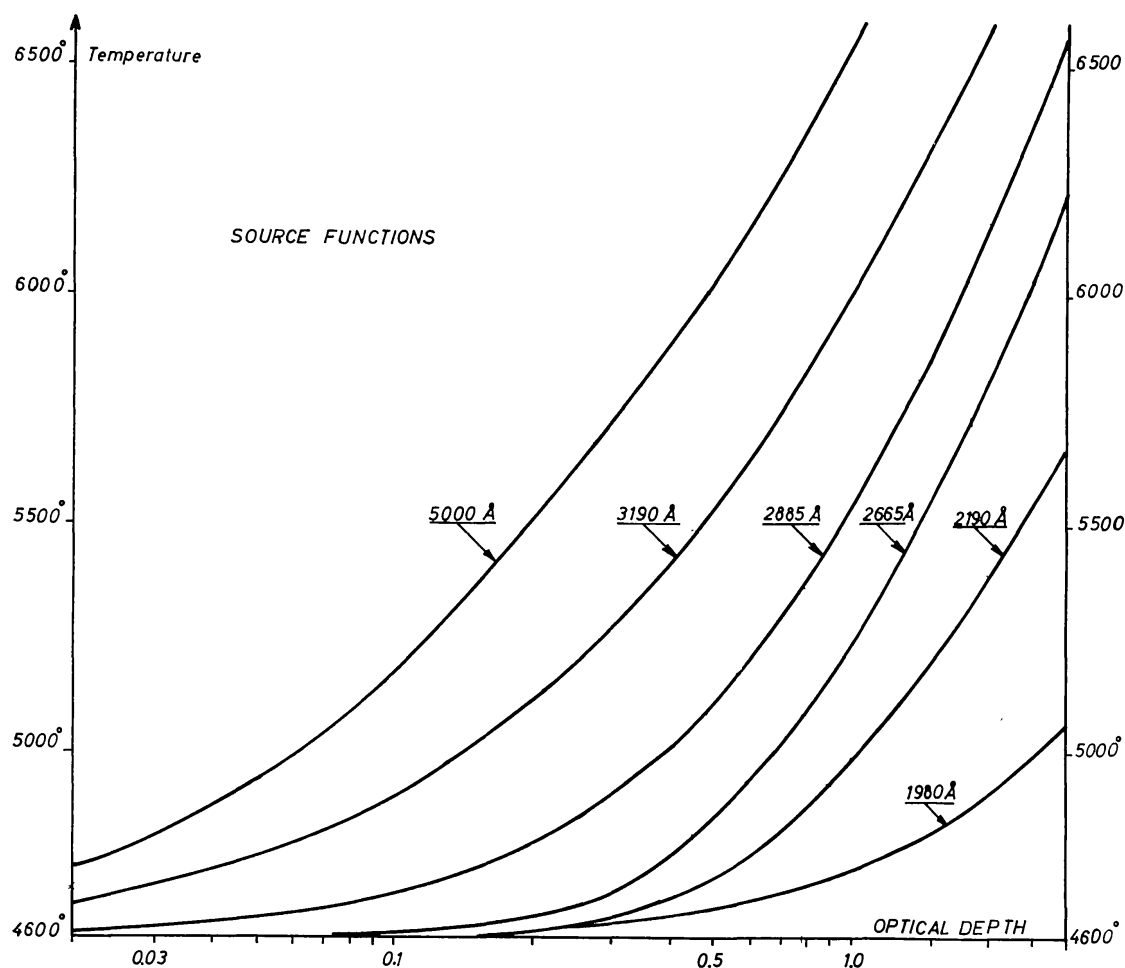


Fig. 5. The empirical source functions deduced from limb-darkening measurements assuming a unique surface temperature of 4600°K.



function of  $\tau_\lambda$  from:

$$\frac{F_\lambda(\tau_\lambda)}{I_\lambda(\mu=1)} = 2 \int_{\tau_\lambda}^{\infty} \frac{S_\lambda(t_\lambda)}{I_\lambda(\mu=1)} E_2(t_\lambda - \tau_\lambda) dt_\lambda - 2 \int_0^{\tau_\lambda} \frac{S_\lambda(t_\lambda)}{I_\lambda(\mu=1)} E_2(\tau_\lambda - t_\lambda) dt_\lambda.$$

From this, one can get the flux at  $\tau_\lambda=0$ . If we set  $F_\lambda(\tau_\lambda)$  to be equal to the U.V. flux values given by TOUSEY (1963), we are able to determine the central intensity  $I(\mu=1)$ . The result of this computation is reported in column 3 of Table II.

#### 4. The Minimum Temperature (assuming LTE)

Assuming local thermodynamic equilibrium, we can set  $S_\lambda(\tau_\lambda)$  to be equal to the blackbody radiation function at the wavelength  $\lambda$ , and thus get a relation between  $\tau_\lambda$  and  $T$ . In particular we obtain the temperature corresponding to  $\tau_\lambda=0$ , the so-called boundary temperature  $T_0$  or minimum temperature as far as a minimum can be revealed in the variation of  $S_\lambda(\tau_\lambda)$  with  $\tau_\lambda$ .

In columns 4, 5, and 6 of Table II, we report the values of the central intensity which give a surface temperature  $T_0$  successively equal to 4500°, 4600°, 4700°. Our measurements, together with the determinations from the U.V. fluxes, lead to a surface temperature higher than 4700°.

As far as LTE is assumed, this result is in good agreement with the determinations of Matsushima, who found from visible limb-darkening observations a surface temperature close to 4650° for wavelengths longer than the Balmer discontinuity of hydrogen and a temperature greater than 4700° below this discontinuity (MATSUSHIMA and TERASHITA, 1967).

Nevertheless, experimental errors are important and lead to a rather broad uncertainty for  $T_0$ . Let us put

$$X = \frac{I(\mu=0)}{I(\mu=1)} \quad \text{and} \quad Y = I(\mu=1).$$

We have:

$$X \cdot Y = \frac{C_1}{\lambda^5} \frac{1}{e^{\frac{c_2}{\lambda T_0}} - 1} \cong \frac{C_1}{\lambda^5} e^{-\frac{c_2}{\lambda T_0}}.$$

Through logarithmic derivation we obtain:

$$\Delta T_0 \cong \frac{T_0^2 \lambda}{C_2} \left( \frac{\Delta X}{X} + \frac{\Delta Y}{Y} \right).$$

If we assume that  $T_0=4700^\circ$ , and for  $\lambda=3000 \text{ Å}$ , we can write:

$$\Delta T_0 \cong 450^\circ \left( \frac{\Delta X}{X} + \frac{\Delta Y}{Y} \right).$$

We include in  $X$  and  $Y$  the experimental errors and the uncertainty due to the averaging over the band of the filter. Experimental errors on  $X$  can be estimated to 5% in the best conditions. But the error due to the inversion of the Laplace Integral cannot be estimated with any certainty.

Errors on  $Y$  are certainly more important since absolute photographic photometry is not very accurate; we think that they must lie between 15% and 20% at best.

The fact that the measurements are not made in the true continuum but are averaged over a finite spectral range including a lot of absorption lines, have opposite effects in modifying  $X$  and  $Y$ .  $X$  is certainly overestimated since the center-to-limb contrast is lower in the lines than in the continuum, as we shall see later, and therefore will lead to a value of  $T_0$  too high. Conversely,  $Y$  is underestimated since the absorption by the lines decreases the continuum intensity. Which of these two effects is the most important is difficult to assert! A computation of the limb-darkening and of the blanketing of the lines for all those included in the bands of the filter is the only way to answer the question. This is in progress now, but not entirely finished.

If the experimental errors were only taken into account,  $T_0$  could be determined with an accuracy of  $\pm 100^\circ$ .

## 5. Empirical Opacity

The analytical derivation of  $\tau_\lambda(T)$  leads to  $d\tau_\lambda/dT(T)$  which, with respect to the same quantity at a given reference wavelength  $\lambda_0$ , gives the ratio  $x_\lambda/x_0$  of the corresponding absorption coefficients. As usual, we have taken  $\lambda_0 = 5000 \text{ \AA}$ . The  $\tau_0(T)$  relation for this wavelength has been deduced from Pierce and Waddell's limb-darkening observations (PIERCE and WADDELL, 1961). We note that the model atmosphere given by these authors is in better agreement with the observations at  $5000 \text{ \AA}$  than the Utrecht Reference Model Atmosphere or U.R.M.A. (HEINTZE, HUBENET, and DE JAGER, 1964). In the same way the empirical model of MÜLLER and MUTSCHLECHNER (1964) agrees very well with the observations at  $5000 \text{ \AA}$ . Consequently, assuming that there must be a unique surface temperature we have chosen  $4600^\circ$ , which is the boundary of the Müller and Mutschlechner model. It leads to central intensities at  $1980 \text{ \AA}$  and  $3190 \text{ \AA}$  respectively equal to:

$$\left. \begin{array}{l} 1.015 \times 10^{12} \\ 2.020 \times 10^{14} \end{array} \right\} \text{ergs/cm}^3/\text{steradian/sec.}$$

As shown by BARBIER (1946) the fact that  $T_0$  is not accurately defined is not of great importance for the determination of the empirical opacity.

In Figures 6, 7, and 8 we have reported the results obtained for  $4800^\circ$ ,  $5200^\circ$ ,  $7000^\circ$ , and  $8000^\circ$ . They are compared to a theoretical computation made at Meudon following Gingerich's evaluation of the continuous absorption by various hydrogenic sources and by metals such as magnesium, silicon, carbon, and aluminium (GINGERICH, 1965).

It can be noticed that:

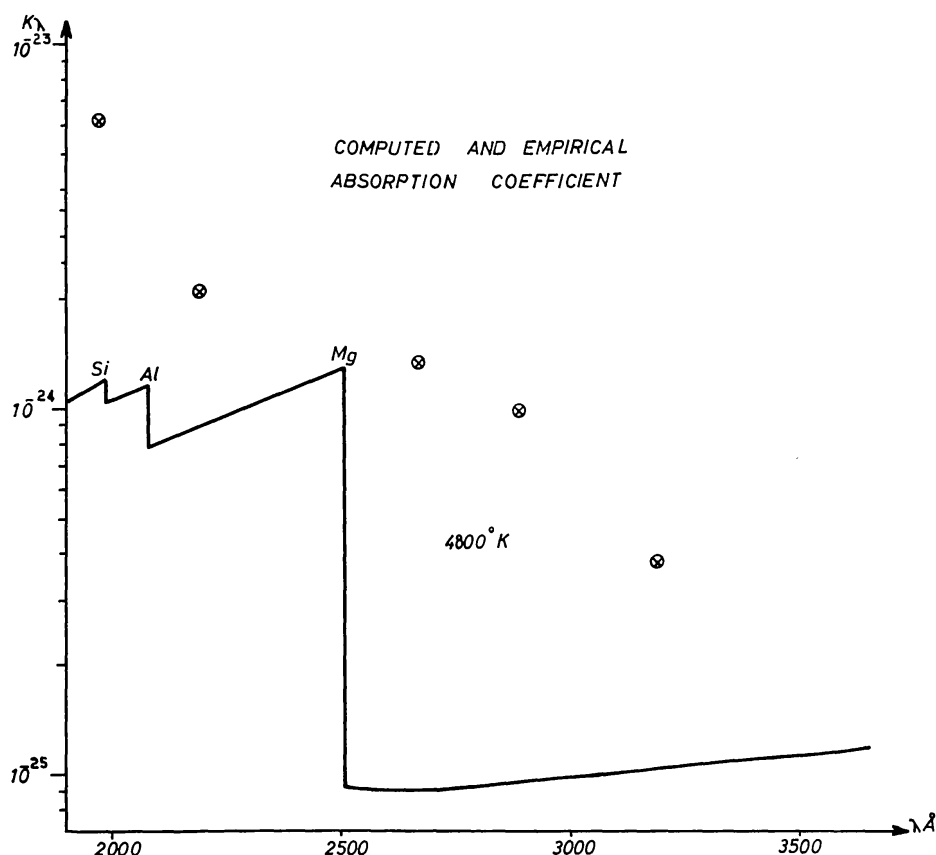


Fig. 6. Comparison between the empirical opacity deduced from limb-darkening observations and the computation made at Meudon following GINGERICH (1965) for an electron temperature of 4800°K. The full line refers to the computation, the circles with crosses represent our determinations.

(1) In the transition zone, i.e.  $T \simeq 4800^\circ$ , the empirical opacity is always higher than the computed one, especially between 3190 Å and 2500 Å where its variation with  $\lambda$  is entirely different.

(2) The discontinuity due to magnesium does not appear so strong in the empirical determination as it does in the theoretical one.

(3) There is a large increase in the opacity between our two measurements at 2190 Å and 1980 Å as could be deduced from the aspect of the limb-darkening curves.

(4) At higher temperatures, the agreement between measurements and computations including metals is considerably better in the range 2500 Å, 3190 Å, but the measured opacity at 1980 Å is in excess by a factor of 3 to 5 with respect to the computed one.

#### DISCUSSION

That the disagreement is greater for low temperatures is not surprising. Given the profile of our source-functions in the corresponding layers, a slight variation in the temperature induces a large variation in the optical depth. More curious is the variation of the empirical opacity compared to that of the computed one. Several factors can be taken into account to explain the discrepancy.

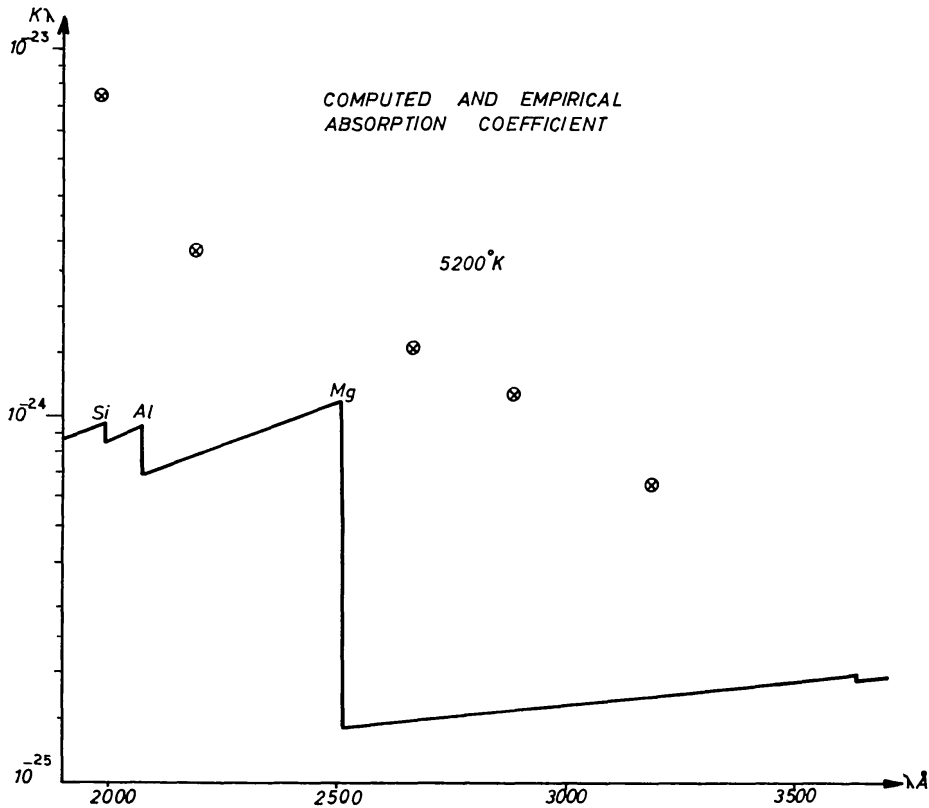


Fig. 7. Comparison between the empirical opacity deduced from limb-darkening observations and the computation made at Meudon following GINGERICH (1965) for an electron temperature of  $5200^{\circ}\text{K}$ . The full line refers to the computation, the circles with crosses represent our determinations.

### 1. Effect of the Lines

As seen earlier, lines intercepted by the filter have the effect of decreasing the center-to-limb contrast. The result is an apparent increased continuous opacity, and the more numerous the lines, the greater this effect. We think that this effect is very important and our values of the continuous opacity are certainly an upper limit of what can be found in the solar atmosphere.

### 2. Effect of Inhomogeneities

That the sun, even with a resolution of some  $15''$ , cannot be considered as homogeneous is shown in Figure 2: the  $1980\text{ \AA}$  picture looks very much like the CaK spectroheliogram and, at least for this wavelength, smoothing the limb-darkening curve certainly leads to a poor approximation of the source-function. But as we shall see in Section 6 and as it can be observed on the other pictures of Figures 1 and 2, the inhomogeneities of dimensions greater than  $15''$  are very diffuse for wavelengths higher than  $2190\text{ \AA}$ . Hence, the disagreement appears in a region where this effect must not play the prime role.

Although these two effects must modify the final result once they have been taken into account, we suggest that a non-metallic source of continuous opacity contributes to the solar absorption coefficient in the range  $2500\text{--}3000\text{ \AA}$ . This result confirms that

of MATSUSHIMA and TERASHITA (1967), deduced from observations in the visible. The variation of this opacity with temperature and wavelength suggests that it could be the quasi-molecule  $H_2$  (ERKOVITCH, 1960). As pointed out by Dalgarno (PAGEL, 1959), the rate coefficient for the association detachment reaction  $H + H^- \rightarrow H_2 + e^-$  is of the order of  $10^{-10} \text{ cm}^3 \text{ sec}^{-1}$ .

It is possible that the  $H_2$  molecule thus produced might be a quasi-molecule contributing to the UV opacity (BELY, 1967).

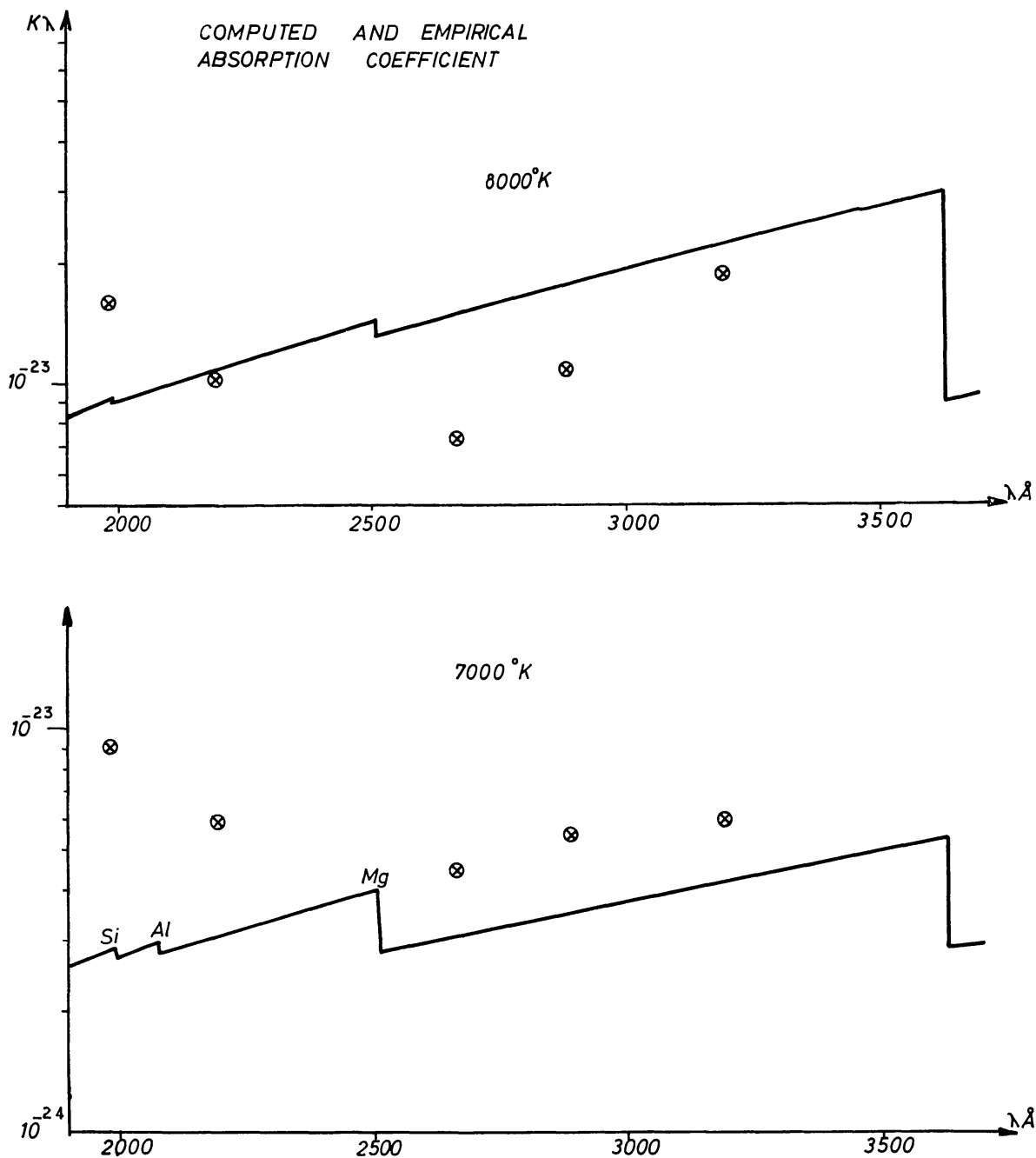


Fig. 8. Comparison between the empirical opacity deduced from limb-darkening observations and the computations made at Meudon following GINGERICH (1965) for an electron temperature of  $7000^\circ K$  and  $8000^\circ K$ . The full lines refer to the computation, the circles with crosses represent our determinations.

### 3. Departures from Local Thermodynamic Equilibrium

Let us assume that local thermodynamic equilibrium cannot hold in the photospheric layers studied, and that the source functions cannot be identified exactly to the Planck function  $B_\lambda(T)$  but to (PAGEL, 1963):

$$\frac{B_\lambda(T)}{\bar{b}} = B_\lambda(T_{\text{ex}}) \quad \text{with} \quad \bar{b} < 1.$$

Hence we have  $T < T_{\text{ex}}$ . We have introduced in our computation  $b$  factors  $\simeq \frac{1}{2}$  in order to lower the surface temperature close to the minimum of  $4500^\circ$  of the Utrecht Model 1964. The source functions thus obtained have been compared to the  $\tau_{5000}(T)$  relation given by the average column of this model. The result is a general slight increase of the empirical opacity. We have not evaluated what the effect would be of introducing departures from LTE in the computation of metallic absorption but if  $Ni^*$  is the number density of any metallic atoms involved, computed in LTE,  $\alpha_{\lambda i}$  the corresponding absorption cross-section, and  $bi$  the coefficient of departure from LTE. The actual number density of the absorbing atom  $i$  is  $Ni = biNi^*$ , and we have:

$$\frac{x_\lambda}{x_{5000}} \simeq \frac{\sum_i biNi^* \alpha_{\lambda i}}{N_H^* - \alpha H_{5000}^-} = \bar{b} \cdot \frac{\sum_i Ni^* \alpha_{\lambda i}}{N_H^* - \alpha H_{5000}^-} = \bar{b} \frac{x_\lambda^*}{x_{5000}}.$$

The asterisk refers to computation in LTE. Since  $\bar{b}$  is lower than unity, we see that the computed opacity in the case of LTE departure is lowered.

Consequently the effect of introducing LTE departures is to increase the discrepancy existing between computed and measured opacity.

### 6. Latest Observations (Experiments of January 1967 and March 1967)

In order to study in more detail the observed discontinuity in the balloon experiment of October 3, 1966 between  $1980 \text{ \AA}$  and  $2235 \text{ \AA}$ , we launched on January 13, 1967, a Veronique rocket equipped with a stigmatic double dispersion spectrograph and a biaxial SPC 300 sun follower built by Ball Brothers Research Corporation. The spectral range covered was  $1800 \text{ \AA}$ ,  $2800 \text{ \AA}$ , with a spectral resolution varying from  $0.37 \text{ \AA}$  near  $2300 \text{ \AA}$  to  $0.7 \text{ \AA}$  at the extremities.

Excellent spectra were obtained corresponding to exposures of 0.1 sec, and 0.5 sec. Given the very good pointing accuracy, details of angular dimensions lower than  $20''$  could be resolved in the direction of the slit, which cut across the disk at a distance less than  $1'$  from its center. Figure 9 represents two such exposures corresponding to approximately the same solar diameter. It can be seen that the facular plages appear strongly in the regions where the absorption is important and in the chromospheric emission lines.

Numerous data were obtained on center-to-limb variations both in the continuum and absorption lines. Figures 10 and 11 represent two low-resolution densitometer





Fig. 9. Solar disk stigmatic spectrum 1800 Å–2800 Å. Veronique flight of 13th January 1967. Mean spectral resolution 0.5 Å, angular resolution 20 seconds of arc.

tracing referring to the center and limb of the disk. Although the corrections due to instrumental transmission and film sensitivity are not yet finished, the most striking features of the solar spectrum can be revealed in terms of central intensity and limb-darkening.

The most conspicuous one occurs at 2076 Å which corresponds to the ionization limit of Al I. The central intensity varies by a factor of 5 to 7 from one part to the other of this wavelength. Apart from the discontinuity of Ca I at 2028 Å and that of Si I at 1990 Å which is hardly seen on our spectra, it is the only feature which can explain the very different structures observed on our 1980 Å and 2235 Å spectroheliograms.

In order to be sure of this, we have taken spectroheliograms with wavelengths peaked at 2040 Å and 2215 Å, during a balloon flight in March 1967. Despite the fact

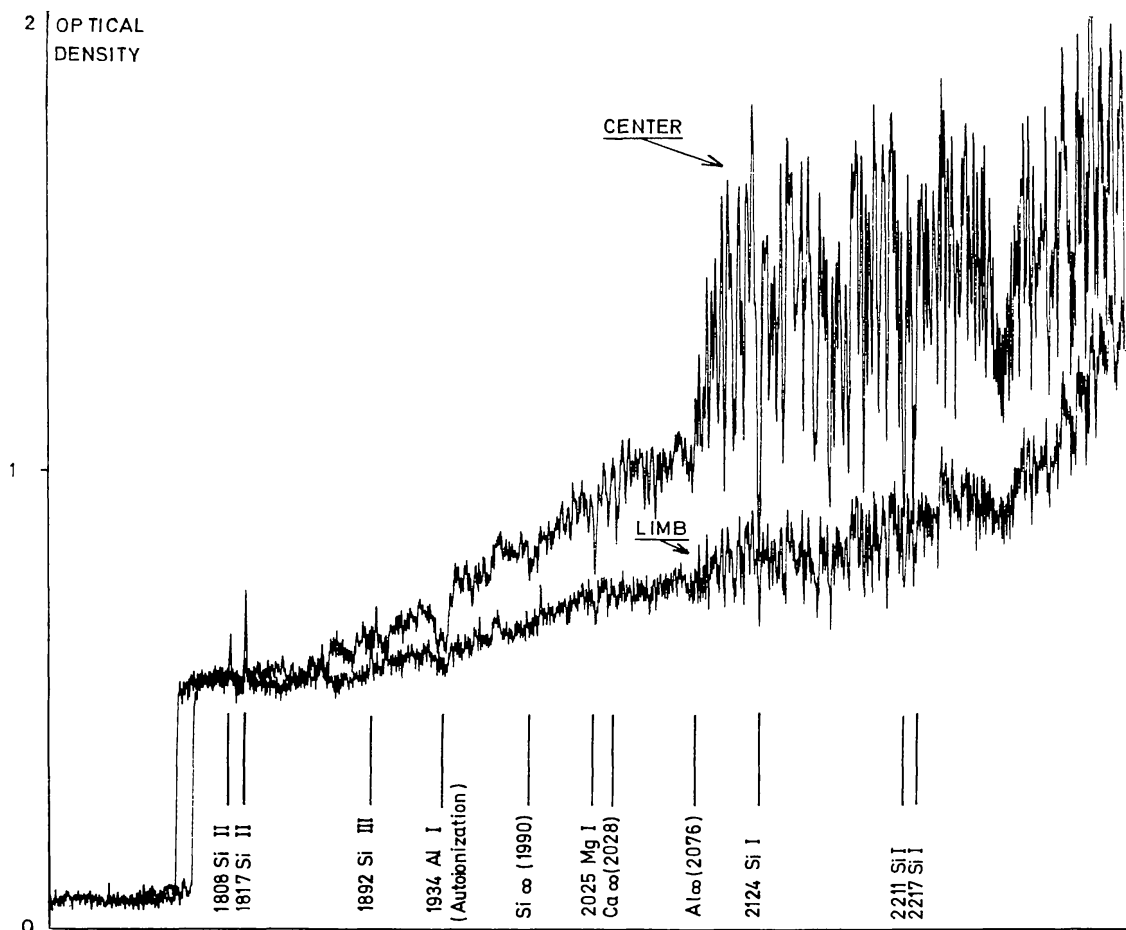


Fig. 10. Low-resolution densitometer tracing for the center and limb of the solar disk. The ordinates represent the optical density of a 0.5 sec exposure.

that the angular resolution was very poor (of the order of 1 min of arc), the sudden change in the solar structure from one picture to the other is well shown.

Anyhow, theoretical computations of metallic absorption must inevitably include a new source to explain the variation of the central intensity at 2076 Å. As already shown by KODAIRA (1965), Aluminium could be that source.

The discontinuity due to the photo-ionization of MgI which theoretically occurs at 2510 Å is less easily observed, owing to the presence of a strong blend of Fe lines. Nevertheless, the variation of the central intensity by a factor of 2 to 3 at 2650 Å and 2500 Å can be more likely attributed to magnesium than to any other absorber.

The discontinuity observed at 2412 Å corresponds to a change in the film sensitivity.

Another important feature of the spectra is the AlI auto-ionization doublet at 1934 Å. As shown by WITHBROE (1966), the center-to-limb variation of this line brings information on the solar model. Withbroe computed this variation using two different models, the Utrecht Reference Model and the Model of Müller and Mutschlechner. The first predicts a strong limb brightening while the latter leads to the exactly opposite conclusion. The difference is due to the presence of a chromosphere in the first Model, while in the second one the electron temperature decreases monotonically with de-

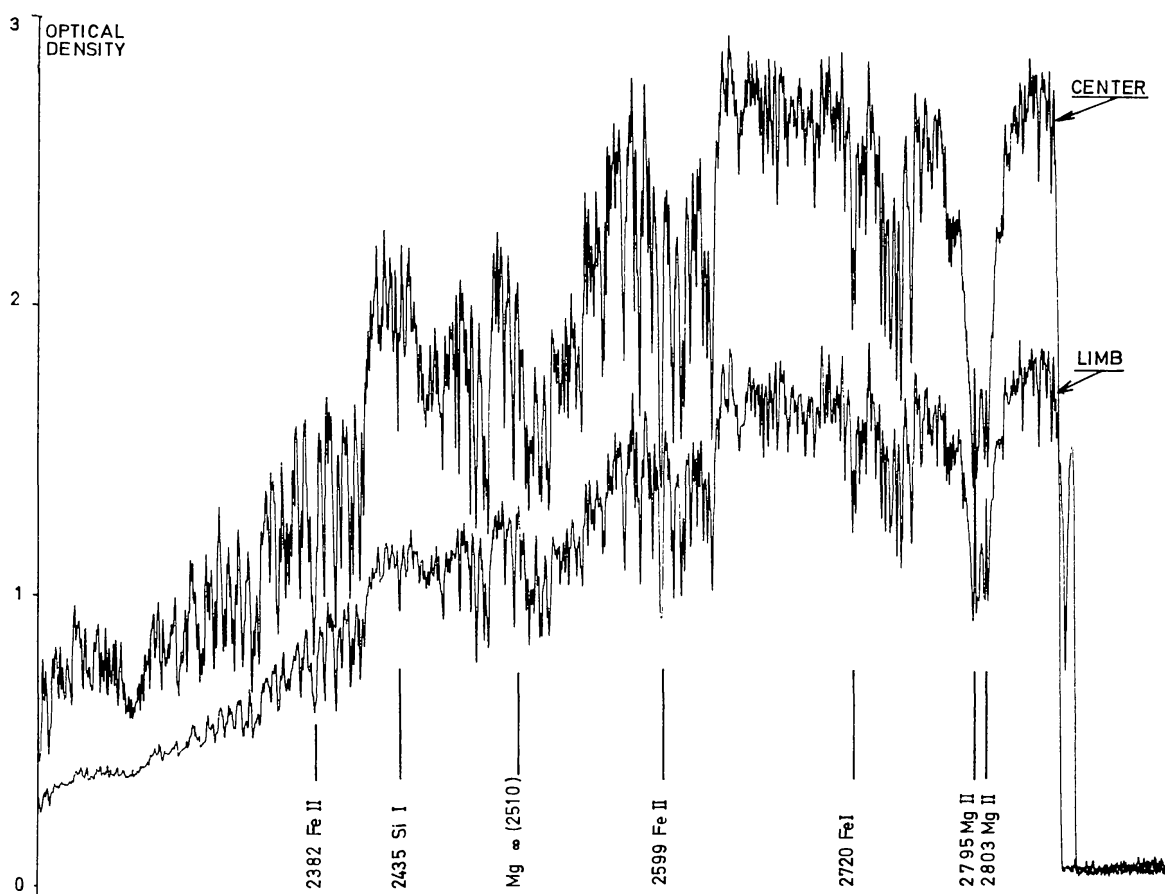


Fig. 11. Low-resolution densitometer tracings for the center and limb of the solar disk. The ordinates represent the optical density of a 0.1 sec exposure.

creasing optical depths. We have made several tracings of the center-to-limb variation of the line: no limb brightening can be revealed, but the observation corresponds fairly well to the variation predicted by the computation using Müller and Mutschlecner's model.

## 7. The Photospheric Model

The preceding observations and computations are often in disagreement with some characteristics of the Utrecht Reference Model Atmosphere 1964. On the contrary, the model of Pierce and Waddell and that of Müller and Mutschlecner seem to fit quite well visible and UV observations.

### A. CRITICISM OF THE UTRECHT REFERENCE MODEL 1964

#### 1. Visible Observations

The  $\tau_{5000}(T)$  relation deduced from visible limb-darkening (PIERCE and WADDELL, 1961) is not in agreement with the same relation given in the average column of the U.R.M.A., especially for optical depths lower than 0.1. As a matter of fact, the variation of the temperature with  $\tau_\lambda$  is considerably more gradual for the empirical

$\tau_{5000}(T)$  relation. As pointed out by the authors themselves, the computed radiation intensity is 10% too small near 5000 Å.

The determination of the surface temperature through extrapolations of the  $\tau_\lambda(T)$  relations toward  $\tau_\lambda=0$  yields to a minimum temperature of 4600°–4650° (MATSUSHIMA and TERASHITA, 1967).

## 2. Ultraviolet Observations

Since the solar ultraviolet radiation comes from the upper layers of the photosphere near the transition zone, they give more information on these layers than the visible observations (Figure 12).

The gradual variation of the temperature near the transition is confirmed:

- (1) by the smooth limb-darkening profile below 2076 Å;
- (2) by the center-to-limb variation of the auto-ionization doublet of AlI;
- (3) by the very slow variation of the brightness temperature between 2000 Å and 1500 Å which never falls under 4700°K (TOUSEY, 1963).

The minimum temperature as determined from our measurements would be close to 4700°K. Nevertheless, as seen earlier this determination is not very precise and the extrapolation of  $T$  near  $\tau_\lambda=0$  is certainly affected by inhomogeneities. Therefore, a minimum temperature of 4500°K is not incompatible with our observations. In the

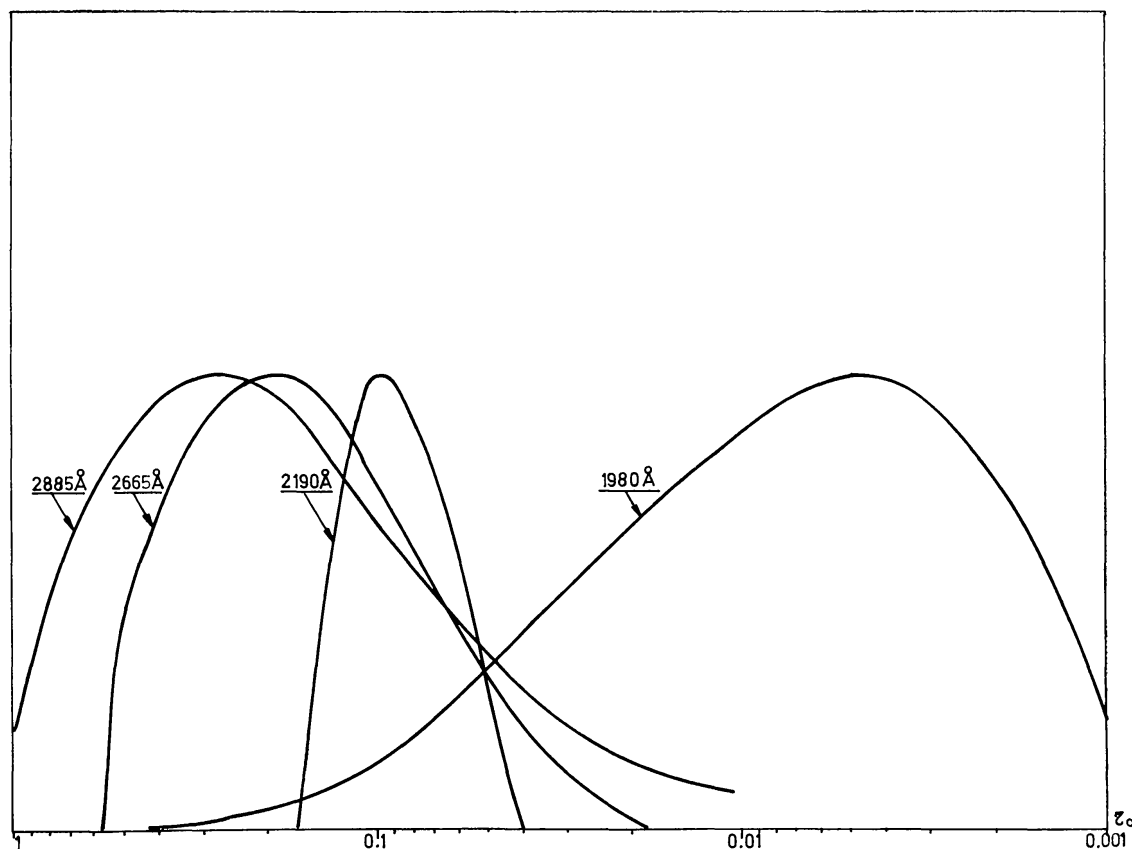


Fig. 12. Contribution functions plotted vs. the optical depth at 5000 Å.

assumption of L.T.E., it seems to be in contradiction with the fact that the transition is gradual or even flat with a brightness temperature always higher than 4700°K.

### 3. Eclipse Observations

The gradient  $dT/d\tau_{5000}$  of the U.R.M.A. has been deduced from eclipse observations of the intensity decrease at the extreme limb. RODDIER and DELACHE (1967) pointed out that eclipse determinations of the  $dT/d\tau_{5000}$  gradient are always overestimated. This could explain the remarkable stressed transition of the U.R.M.A.

### B. REQUIREMENTS FOR A PHOTOSPHERIC MODEL

The major criticism that we address to the U.R.M.A. concerns the transition between the photosphere and the chromosphere. The average empirical models of Pierce and Waddell on the one hand and Müller and Mutschlecner on the other hand, which do not present any chromospheric temperature rising and therefore can be considered as models with very low temperature gradient, are in good agreement with visible and UV observations. The boundary temperature of these models is of some 4600°K, which is a good compromise between the 4500°K of the U.R.M.A. and our overestimated determinations of more than 4700°K.

## References

- BARBIER, D.: 1946, *Ann. Astrophys.* **9**, 173–198.  
 BELY, O.: 1967, Private Communication.  
 BLAMONT, J. E. and BONNET, R. M.: 1966, *C.R. Ac. Sciences* **262B**, 152.  
 BLAMONT, J. E. and BONNET, R. M.: 1967, *C.R. Ac. Sciences* **264B**, 1158.  
 BONNET, R. M. and COURTES, G.: 1962, *Ann. Astrophys.* **25**, 367–373.  
 BONNET, R. M. and LAGO, B.: 1966, *C.R. Ac. Sciences* **262B**, 1636.  
 ERKOVITCH, S. P.: 1960, *Optics and Spectroscopy* **8**, 162.  
 GINGERICH, O.: 1965, Contribution to the 120th meeting of the American Astronomical Society, Berkeley, Calif., December, 1965.  
 HEINTZE, J. R. W., HUBENET, H., and DE JAGER, C.: 1964, *Bull. Astron. Inst. Neth.* **17**, 442.  
 KODAIRA, K.: 1965, *Z. Astrophys.* **60**, 240.  
 MATSUSHIMA, S. and TERASHITA, Y.: 1967, *Ann. Astrophys.* **30**, 183.  
 MÜLLER, E. A. and MUTSCHLECHNER, J. P.: 1964, *Astrophys. J. Suppl.* **9**, 1.  
 PAGEL, B. E. J.: 1959, *Monthly Notices Roy. Astron. Soc.* **119**, 609.  
 PAGEL, B. E. J.: 1963, *Planetary Space Sci.* **2**, 333.  
 PEYTURAUX, R.: 1955, *Ann. Astrophys.* **15**, 302.  
 PIERCE, A. K. and WADDELL, J. H.: 1961, *Mem. Roy. Astron. Soc.* **68**, 89.  
 RODDIER, F. and DELACHE, P.: 1967, Private Communication.  
 TOUSEY, R.: 1963, *Space Sci. Rev.* **2**, 3.  
 WITHBROE, G. L.: 1966, *Astrophys. J.* **146**, 295.