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The Solar Extreme Ultraviolet Continuum

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The solar extreme ultraviolet continuum

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[Plate 3]

The most recent results on the e.u.v. continuous emission of the Sun are reviewed, and intercompared. They are discussed in terms of the distribution of temperature in the solar atmosphere particularly in view of determining more precisely the value of the temperature minimum. An attempt will be made to interpret the discrepancies which exist between the observations and the results deduced from theoretical consideration in terms of an unknown source of continuous opacity.

Introduction

In the past decade a great deal of work has been made to investigate the extreme u.v. continuum of the Sun which can be observed from rocket and satellite borne instruments. In this brief review, I must restrict myself and will deal only with these observations and problems covering the spectral rangeextending from *ca.* 1250 to *ca.* 2100 Å† which is to me of great interest for the following reasons:

(1) It includes radiation from the photosphere, the low chromosphere and from the region of the temperature minimum. The accurate measurement of this minimum has been the aim of many investigations;

(2) It contains several photoionization edges of the most abundant metals like Mg I, Si I, Fe I, Al I and the empirical continuous opacities determined in this region show considerable departures from those computed taking into account the known sources of continuous absorption;

(3) Accurate measurements of the e.u.v. solar flux are very important to aeronomists in their investigations of the photo-electrical and chemical equilibrium of the upper terrestrial atmosphere.

I will first review the most recent measurements of the e.u.v. continuum of the Sun and then compare them with the results of computations. In this process, I will deal with the so-called unknown continuous opacity, the solar model and departures from local thermodynamic equilibrium (l.t.e.). I will, for the sake of enlarging our view of the problem, compare the results on the Sun with those obtained on stars in the same spectral region.

1. Review of recent observations

1.1. *The brightness temperature*

Figure 1, plate 3, represents one of the numerous exposures obtained by D. Samain (Samain, Bonnet, Gayet & Lizambert 1974) with a rocket experiment launched on 17 April 1973. The spectrum extends from 1200 to 2100 Å and shows quite well the transition from the photosphere spectrum on the right to the chromosphere spectrum on the left, the region of the minimum lying somewhere in between. The spectrum is obtained through a stigmatic optical set-up and the slit

† 1 Å = 10^{-1} nm.

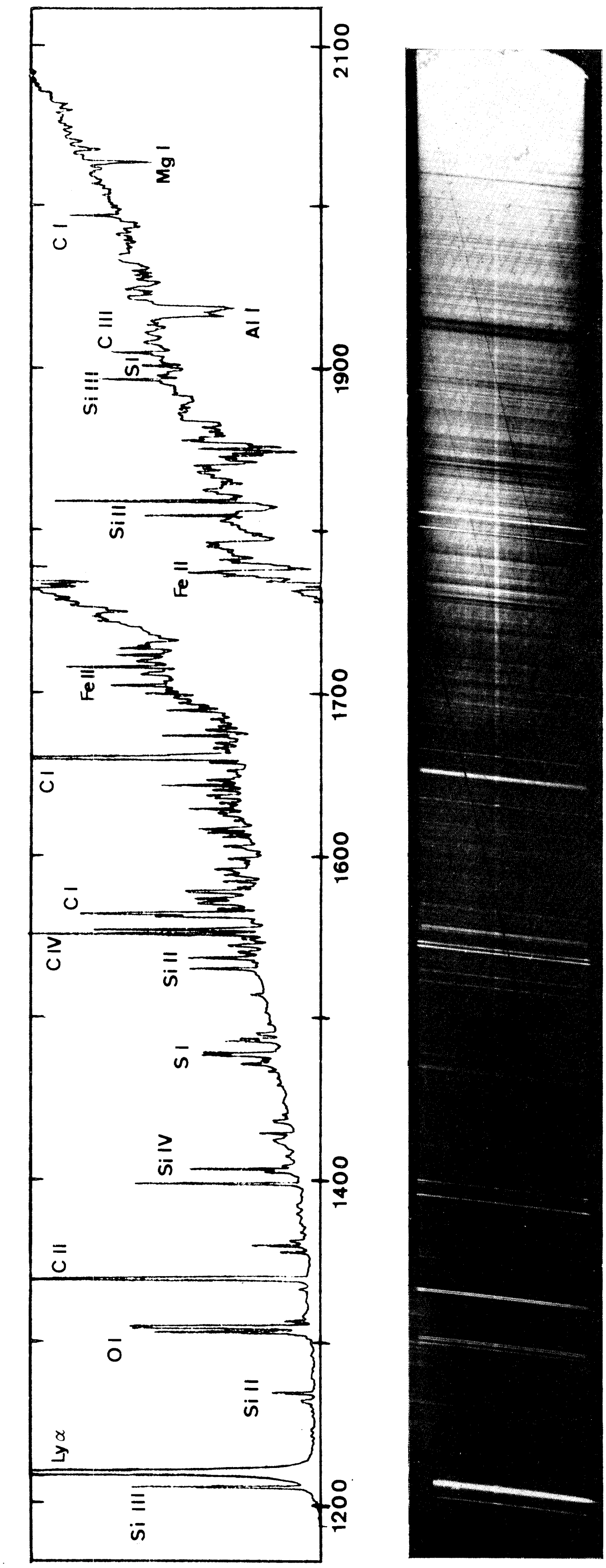

FIGURE 1. A 14 s exposure of the solar spectrum obtained by Samain *et al.* (1974) during the Veronique flight of 17 April 1973.

of the spectrograph cuts across the Sun centre. Hence, the limb of the Sun is delimited at the top and bottom edges of the spectrum while the disk centre corresponds to the middle. Centre-to-limb measurements can be made through the densitometry of lines and continuum perpendicular to the direction of dispersion. Each dark or bright feature of the disk appears as a dark or bright streak on the film, parallel to the dispersion. The dark features inclined with respect to the dispersion correspond to irregularities in the width of the spectrograph's slit. The appearance of limb brightening below 1600 Å is evidenced on this photograph. The spatial resolution is 7″ and the spectral resolution 0.4 Å. This last number is good but might not be large enough to reach the continuum between absorption or emission lines. High spectral resolution is mandatory in the investigation of the e.u.v. continuum.

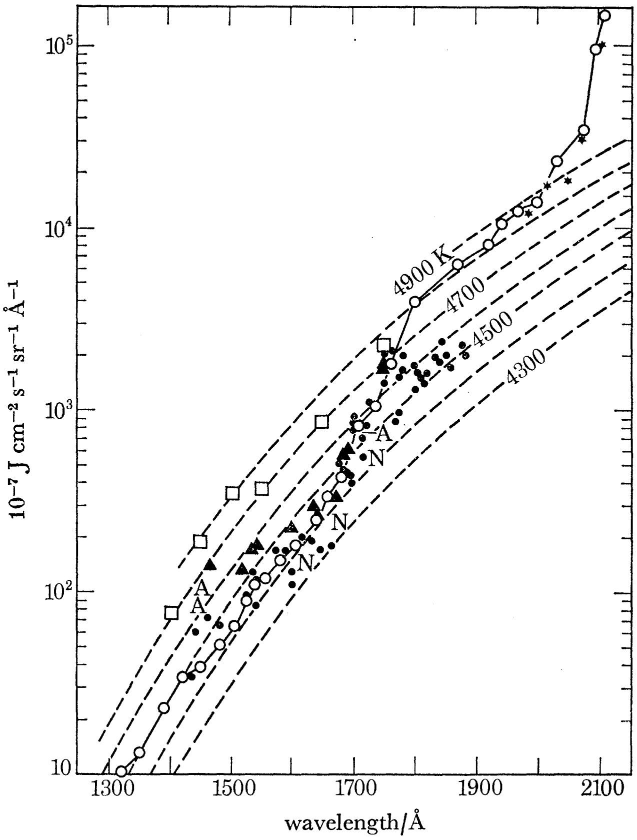

FIGURE 2. The absolute solar intensity at disk centre as measured by Samain. N, Nishi (1973); A, Ackerman & Simon (1973); ▲, Brueckner & Nicolas (1972); □, Brueckner & Moe (1972); ●, Parkinson & Reeves (1969); ★, Bonnet (1968); ○, Samain *et al.* (1974).

The photometry of Samain's results has been very carefully studied. For example, its instrument allowed for film calibration during the flight. Hence, Samain's measurements of the disk intensity seem to be as reliable as photographic photometry can permit. Figure 2 shows the absolute value of the intensity at disk centre. In the region where the solar continuum can best be observed, Samain's results agree fairly well with those of Parkinson & Reeves (1969) and Brueckner & Nicolas (1972). The brightness temperature goes through a minimum between 1500 and 1700 Å. Samain fixes the value of this minimum at 4430 K ± 50 K.

Figure 3 is a compilation made by Vernazza, Avrett & Loeser (1974) as it appears in the most

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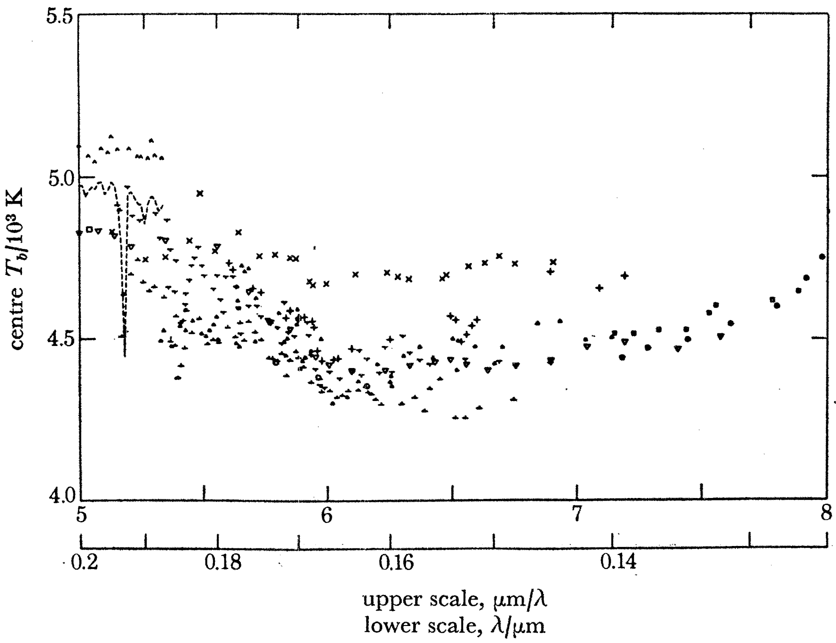

FIGURE 3. Central intensity observations between 1250 and 2000 Å and the corresponding brightness temperature values (from Vernazza *et al.* 1974).

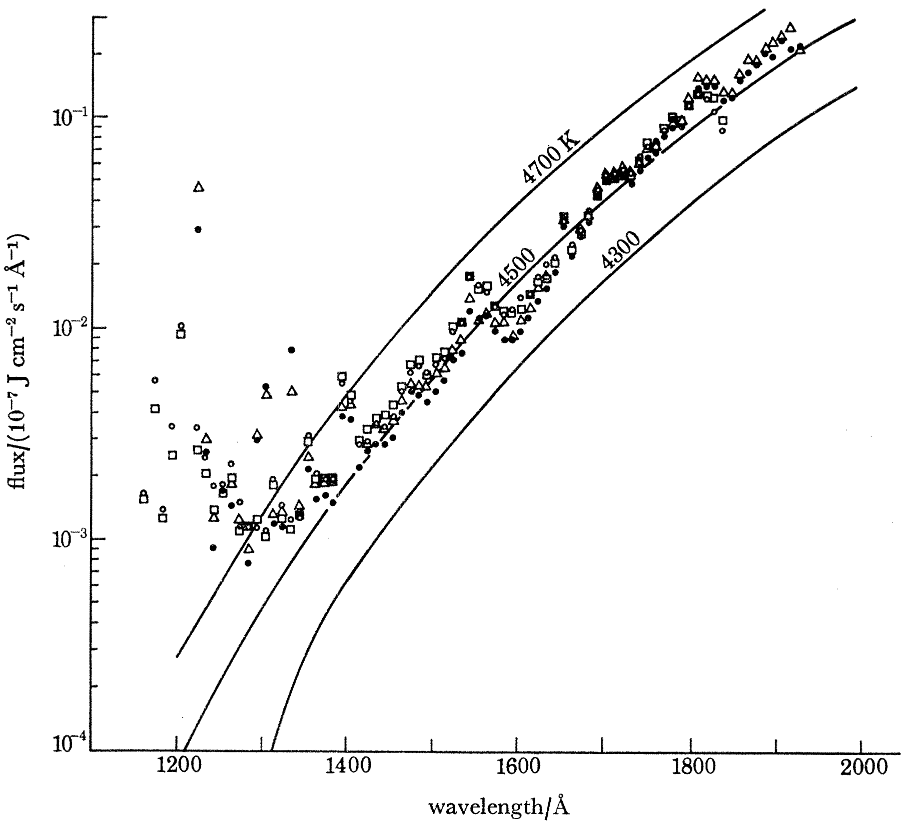

FIGURE 4. Comparison of two independent sets of measurements of the e.u.v. flux from the whole disk. Values are top of the atmosphere measurements. ○, Rottman (1972); □, Rottman (1973); △, Heroux (1973); ●, Heroux (1974).

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complete review written to date on the structure of the temperature minimum region. This figure illustrates the amount of effort spent in the past years on the problem of determining the absolute value of the solar intensity in the region of the minimum. Despite the fairly large spread in the results which shows how difficult is the u.v. photometry of the Sun, the most recent measurements seem to agree fairly well with each others.

Not included in Vernazza, Avrett & Loeser's review are two series of measurements of the whole Sun fluxes conducted independently by L. Heroux from A.F.C.R.L. (L. Heroux 1974, personal communication) and G. Rottmann from the University of Colorado (Rottmann 1974). The measurements are averaged over 10 Å and, in the region of the spectrum free of emission lines the agreement between both is unbelievably good as indicated on figure 4. All measurements are top-of-the-atmosphere values. They were performed in approximately the same conditions of solar activity although somewhat lower for Heroux's measurements which might explain that his values are systematically slightly lower than those of Rottmann. The brightness temperature deduced from these measurements is also very close to 4400 K.

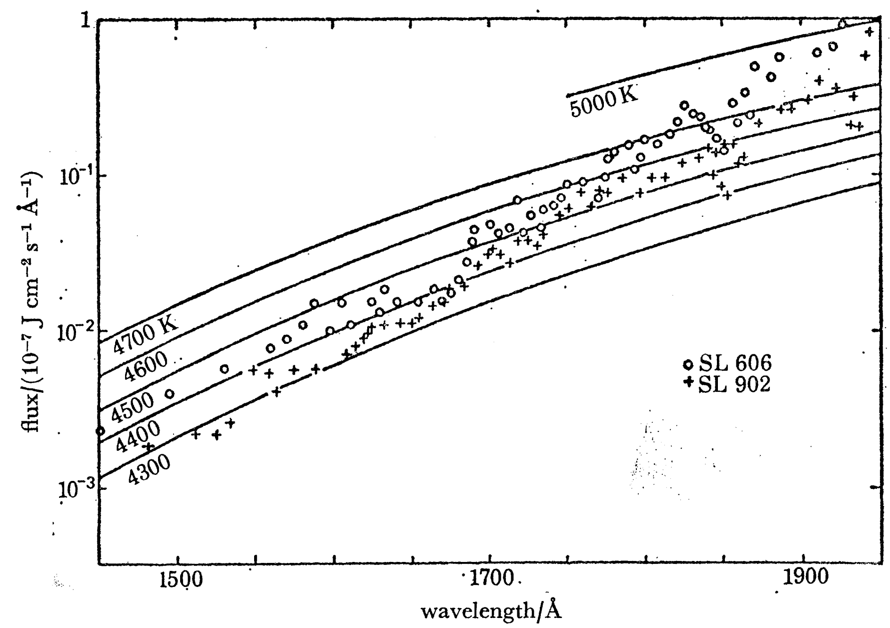

FIGURE 5. Flux observed by Jordan & Ridgeley (1974) from the solar disk on two Skylark rockets nos. 606 and 902.

Figure 5 represents the two sets of measurements made by Jordan & Ridgeley (1974) during two different flights of a Skylark rocket. The fact that the SL 902 values are systematically lower than the SL 606 values is due to a deterioration of the SL 902 optics. For the region of lowest temperature, the SL 606 data give a brightness temperature of 4450 K, very close to that measured by Rottmann, Heroux and Samain. Nishi's wide band measurements which are awaiting publication in *Solar Physics* (Nishi 1974) lead to a value of Tb at the minimum also slightly higher than 4400 K.

Hence, after several years of hard work in this region of the solar spectrum a consensus seems to have been reached as to the value of the minimum brightness temperature very close or slightly larger than 4400 K. It is worth pointing out here that far infrared measurements in the region around 100 μm where the brightness temperature goes also to a minimum lead to a value close to 4200 K. This difference which apparently cannot be explained by experimental errors will be discussed later.

1.2. *Centre-to-limb intensity measurements*

Relative centre-to-limb intensity measurements are by far less important in quantity than absolute measurements of the central intensity or of the integrated flux. The most complete set of measurements is that of Samain which he deduced from his 'stigmatic spectra'. Samain made his measurements in the continuum at 25 λ points. They are represented on figure 6 as a function of wavelength and position on the disk. The photoionization limits of Al I, Ca I, and Si I are evidenced on this graph as discontinuities in the curves. We see that limb-brightening definitely

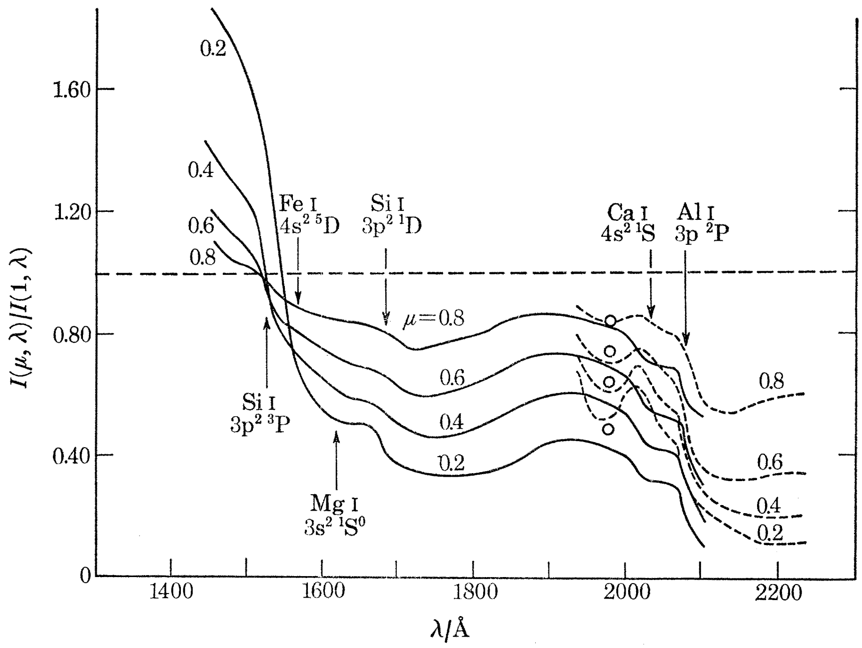

FIGURE 6. Centre-to-limb intensity measurements deduced by Samain from stigmatic spectra of the Sun, between 1460 and 2100 Å, for four different positions on the disk. - - - -, Bonnet (1968); O, Samain (1971); ——, Samain *et al.* (1974).

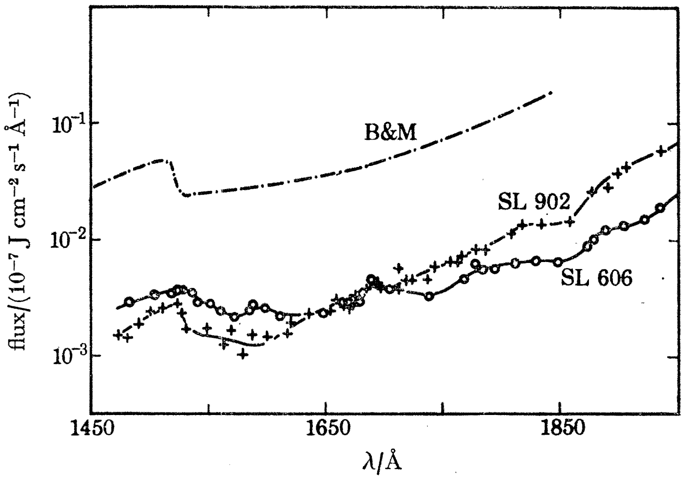

FIGURE 7. A comparison between flux observed at the solar limb by Jordan & Ridgeley and by Brueckner & Moe, 7″ inside the limb. (From Jordan & Ridgeley 1974.)

occurs below 1600 Å and that for wavelengths shorter than the photoionization limit of Si I, the intensity at disk-centre is lower than the intensity emitted from any other region of the solar disk. This agrees well with the conclusion of Brueckner & Moe (1972) who find limb-brightening at $\lambda = 1550$ Å and below. As shown in figure 7 on which their results are represented, the Si I ^{3}P photoionization limit is enhanced at the limb, compared with the centre. The spatial resolution of 7″ achieved in Samain's experiment might not be good enough to show limb brightening at wavelengths longer than 1525 Å. Hence, they might not necessarily contradict Jordan & Ridgeley conclusions that limb brightening exists between 1525 and 1700 Å and that the limb emission in this spectral region originates from layers of higher temperatures than the minimum.

Owing to their very strong dependence upon the solar model and the continuous opacity, absolute intensity and centre-to-limb measurements are very interesting to compare with predictions made from models.

2. The average model of the photosphere and the temperature minimum region

Most observations have been usually compared with the predictions derived from two important models in the past: the BCA (Gingerich & de Jager 1968) and the HSRA (Gingerich, Noyes, Kalkofen & Cuny 1971). These two models are fairly distinct: for example, the temperature minimum is 4650 K for the BCA and approximately 4200 K for the HSRA. None of them in fact does represent correctly the absolute intensity and the centre to limb variation of this intensity particularly in the e.u.v. However, the uncertainty in the opacity in the u.v. precludes the derivation of any firm conclusion as to the validity of the model. Figure 8 compares the HSRA predictions for limb darkening at 1800 and 1950 Å with Samain's measurements. The difference is very striking and shows that a new source of continuous opacity must be looked for. This is why,

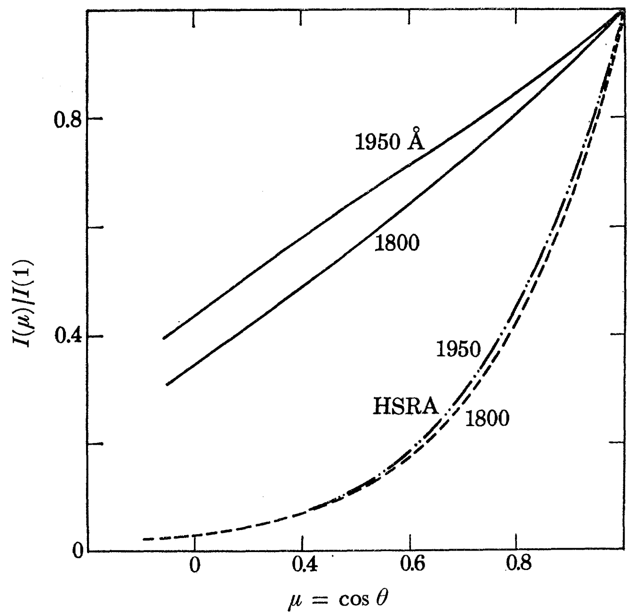

Figure 8. Centre-to-limb intensity variations computed from the HSRA and compared with Samain's observations.

in their extensive review on the subject, Vernazza, Avrett & Loeser were led to elaborate a new empirical solar model which bears on observations made over a broad spectral range extending from 1250 Å up to 500 μm. This model labelled M in the author's denomination is shown on figure 9 together with the BCA and the HSRA. It is characterized by a low temperature minimum of 4150 K occurring at about 500 km and a somewhat larger photosphere temperature gradient than the HSRA. It is by far the most complete and elaborate ever made. The minimum temperature has been fixed by the far infrared measurements. Since the opacity in the far infrared is due

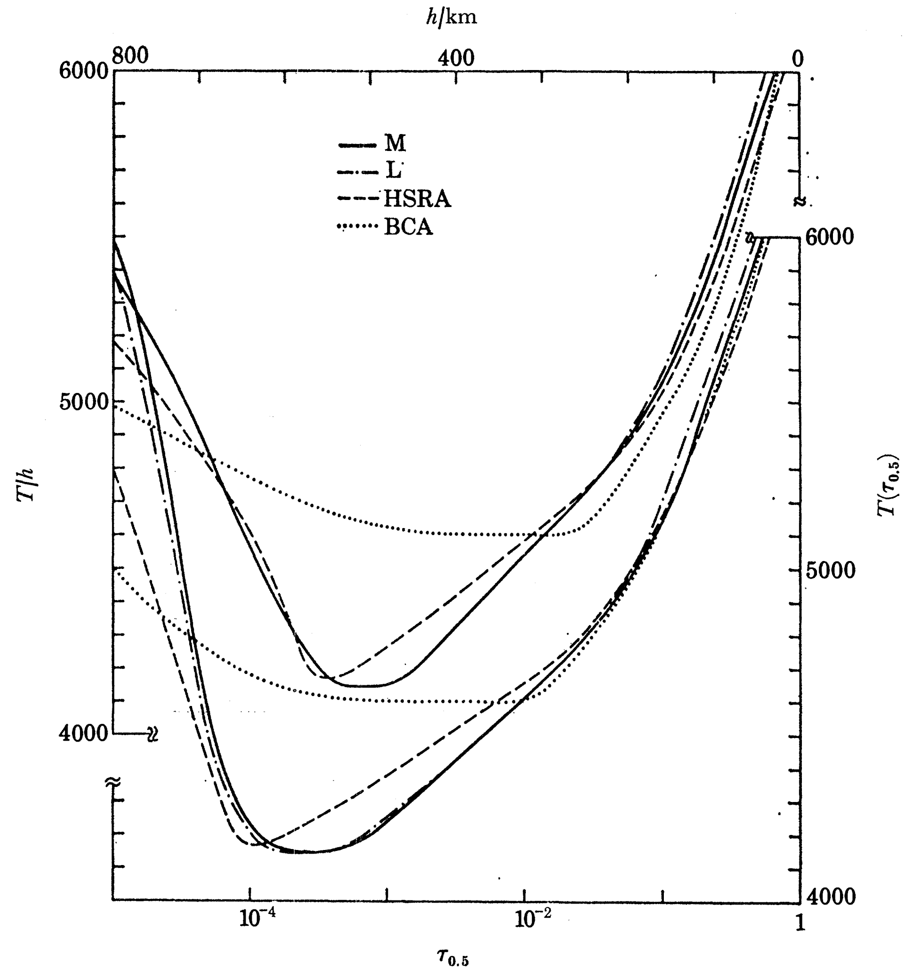

FIGURE 9. Temperature distributions of the BCA, HSRA, Vernazza *et al.* M and L models plotted as functions of h in the region 0–800 km and as functions of $\tau = 5000$ Å in the region $10^{-5}-1$. (From Vernazza *et al.* 1974.)

mainly to H^- and the free–free absorption by H and H^- which have been checked to be formed in l.t.e., the brightness temperature in the far infrared can be equalled to the kinetic temperature of the gas in the region of the minimum and deeper in the atmosphere. Since there is no more direct way for fixing the value of the minimum than measuring the absolute intensity in the region between 25 and 200 μm and since the accuracy of such measurements is quite low, reliable absolute measurements in this spectral range are strongly needed to resolve the problem of the temperature minimum.

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2.1. *Departures from l.t.e. in the e.u.v. continuum*

That the e.u.v. continuum cannot be considered as formed in l.t.e. is immediately evidenced by the value of *ca.* 4400 K derived for the minimum brightness temperature in this spectral region, as compared to the 4100–4200 K measured in the far infrared. In elaborating their model Vernazza, Avrett & Loeser considered H^-, H, C I and Si I without assuming l.t.e. and they computed their contribution to electron density and continuous opacity in the e.u.v. Between 1300 and 1680 Å bound–free transitions from the ground level and the second level of Si I dominate the opacity and the evaluation of departures from l.t.e. for this atom is particularly important.

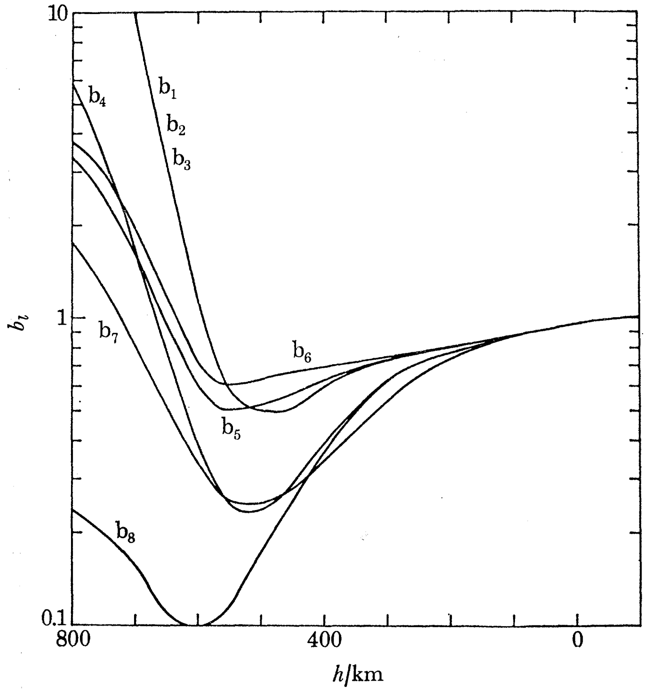

FIGURE 10. Departure coefficients for 8 levels of the Si I atom computed by Vernazza *et al.* (1974).

Figure 10 represents the departure coefficients *b* of the Si I levels as a function of the altitude in the solar atmosphere. In the so-called 'visible photosphere', i.e. deeper than altitude zero, all coefficients are equal to unity as should be expected from the high rate of electron collisions. Closer to the surface, the density decreases and the optical depths at the photoionization limits of the upper levels become less than unity. Consequently, these levels become more and more irradiated by the photospheric radiation field whose brightness temperature is larger than the local electronic temperature. Hence, the *b* coefficients are less than unity for these levels. In this same region of the atmosphere, the resonance lines of Si I are optically thick ($\tau > 10^4$) and they contribute to the tight coupling of the ground levels to the higher levels. The three levels of the Si I atoms are strongly collisionally coupled and they are in detailed balance throughout the atmosphere and their departure coefficients are equal.

We then see that the e.u.v. radiation between 1300 and 1680 Å is very weakly coupled to the local electron temperature. One important conclusion which can immediately be drawn is that the e.u.v. emission at least in this spectral region can certainly not be used to determine the temperature minimum. Since the Si I levels are underpopulated as compared to their population in l.t.e., the brightness temperature of the e.u.v. continuum is larger than the kinetic temperature and consequently than the brightness temperature in the far infrared. The only way the far infrared is affected is through the increase in the electron number density, when the electron contributions of H, C I and Si I are properly taken into account, as a consequence of the sensitivity of H^- to Ne. It is only high in the chromosphere that the departure coefficient for H^- differs from unity.

2.2. *Comparison with observations*

On figure 11, we reproduce figure 25 of the Vernazza *et al.* paper. This represents the theoretical intensity curve in the range 1300–2000 Å. At wavelengths shorter than 1682 Å the model predictions are consistent with the observations. In particular, Samain's results which were not used in the elaboration of model M, provide an independent check of its validity, and fall nicely on the theoretical curve. Between 1525 and 1570 Å the theoretical curve shows a drop in intensity which is the result of the assumption of l.t.e. for Fe I in the computation. Since the observations do not show such a drop, there is here an indication that Fe I should be treated the same way as Si I without assuming l.t.e.

Longward of 1680 Å, the predictions of the model are indicated by the upper solid line and it is obvious that a strong disagreement with observations still persists. This is the region where the so-called 'missing opacity' reveals its existence.

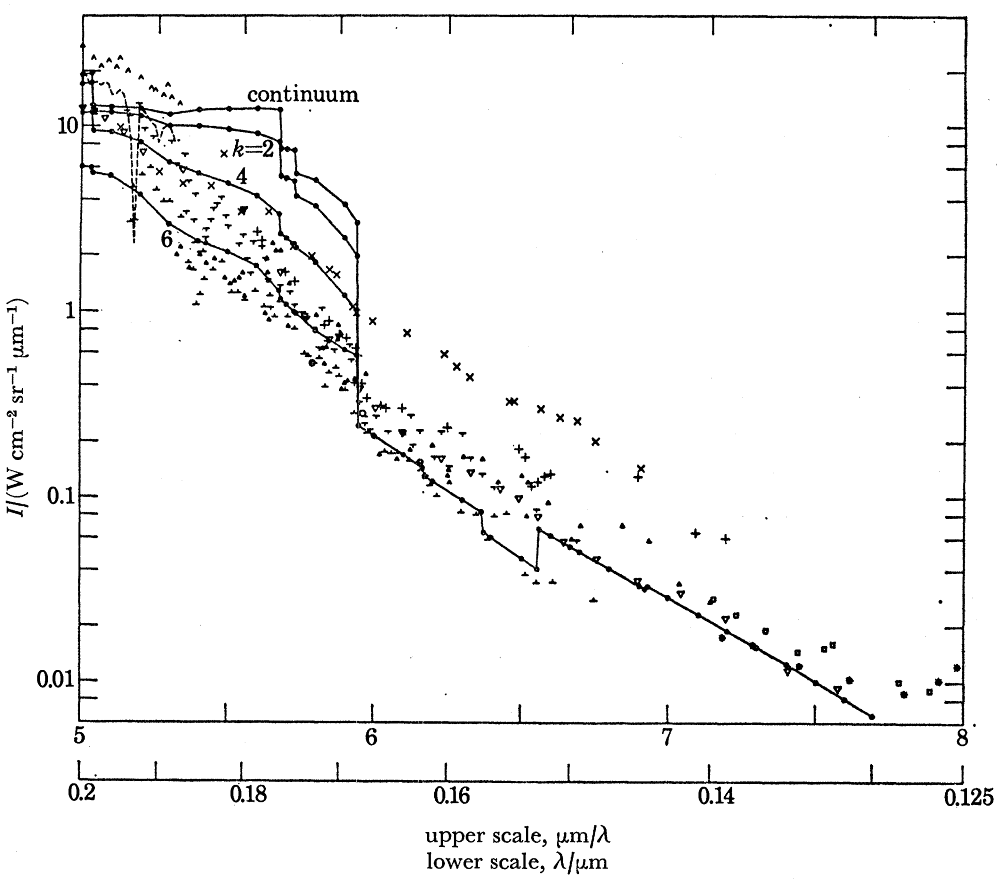

FIGURE 11. Comparison between measurements of the absolute intensity at Sun centre and the computed intensity distributions from model M of Vernazza *et al.* (1974). ▽, Samain *et al.* (1974).

3. The 'missing opacity'

3.1. *Line blanketing*

We already saw on figure 8 that limb-darkening measurements around 1900 Å claim for an additional source of opacity. This conclusion was also that of Finn & Jefferies (1974) from their analysis of the centre to limb variation of the Al I autoionization lines at 1932 and 1936 Å who found no other way of reconciling their theoretical non l.t.e. computations of the lines with the observed profiles. I personally invoked some time ago a possible underestimation of the Al I photoionization cross-section which could have explained the low value computed for the discontinuity at 2077 Å and the disagreement also observed at shorter wavelengths. In fact, Kohl & Parkinson (1973) remeasured the photoionization cross-section of Al I from the edge down to 1730 Å and found values three times larger than their previous ones. As a result, Vernazza *et al.* found a good agreement between observations and computations of the Al I edge at 2077 Å but could not substantially improve the agreement at short wavelengths as indicated on figure 11. As of today the problem remains open.

Vernazza *et al.* introduced the effect of line blanketing in their computation. They defined several line opacity distribution functions derived from the extensive calculations of gf values for over 10^6 lines made by Kurucz & Peytremann. The effect of some of these distributions on the e.u.v. emergent continuum is shown on figure 11. The line absorption here is treated in l.t.e. which, based on the computation for Si I should be questioned. $K = 2$, 4 and 6 correspond to the far wings, intermediate wings and near wings of the spectral lines respectively. Broad band measurements should be compared with the $K = 6$ or 4 distribution while higher resolution observations should be compared with the $K = 2$ distribution.

It is worth noting that line blanketing introduced in this manner is a major source of pseudo-continuous opacity and that taking it into account, considerably improves the agreement with observations.

3.2. *What happens in stars other than the Sun?*

Now that u.v. spectra of stars between 1200 and 3000 Å are available from the 0A0-A, 0A0-C and TD1 satellites the problem of the 'missing opacity' can be studied over a fairly large number of stars covering different temperature, gravity and abundance ranges. The most interesting spectral types in this comparison are A, F and G, and it is worth noting that strong depressions in the u.v. fluxes relative to the predictions of models which do not include line blanketing, do exist especially around 2400 Å (C. Jamar & F. Praderie 1975, personal communication). In his analysis of the u.v. spectra of stars, Peytremann (1974) shows that the inclusion of line blanketing by large numbers of lines predominantly from iron leads to a good agreement between theoretical synthetic low resolution spectra and the observations; however, Jamar & Praderie show that even without the inclusion of line blanketing both the u.v. gradients and the u.v. fluxes relative to the visible fluxes are correct for stars of A type. Coming back to the problem of the Al I absorption, despite the low u.v. fluxes, discontinuities similar to the solar one at 2080 Å appear in the spectra of F and G type stars. An interesting case is that of Procyon, an F 5 star very similar to the Sun. As shown on figure 12, kindly provided to us by de Jager and his collaborators at Utrecht, a discontinuity is present on the spectra obtained with the TD 1 satellite. It is less intense than in the Sun however, as could be expected from the higher temperature of Procyon which decreases the number of neutral aluminum atoms. The intriguing feature is the position of the discontinuity *ca.* 30 Å from its theoretical position at 2071 Å. A shift of 9 Å in the case of the Sun does exist between the theoretical and observed positions of the discontinuity. This shift was explained by Boland *et al.* (1971) as due to overlapping of Stark broadened lines from high-lying level and was shown to be very sensitive to the temperature. This explanation could also be valid in the case of Procyon although refined computations must be done before going any further in this direction. If it proved to be true, the position and intensity of the Al I edge could be used as an accurate check for the validity of stellar models in the upper photosphere.

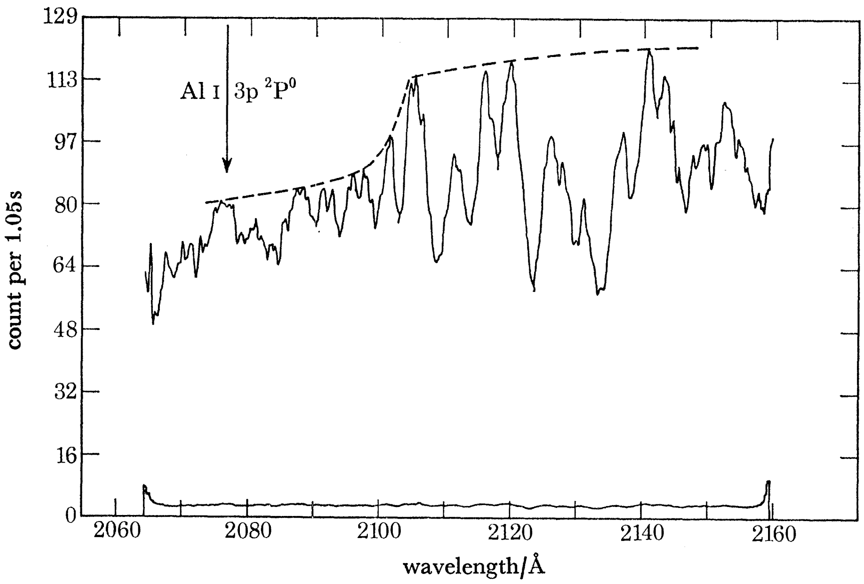

FIGURE 12. The u.v. spectrum of Procyon between 2060 and 2160 Å as observed by Utrecht experiment S 59 on the satellite TD 1.

4. INHOMOGENEITIES

We know from observations (Bonnet 1968; also Samain 1971), that the solar continuum at wavelengths below 2080 Å is not emitted uniformly over the whole disk and there is evidence that the chromospheric network shows up in the continuum in this spectral region. A confirmation of the inhomogeneous structure of the Sun derives from Hersé's high resolution observations (Hersé & Blamont 1971). The recent results of Samain bring some evidence to this also.

In their analysis of the 0S0-4 and 0S0-6 Lyman continuum data, Vernazza & Noyes (1972) show that significant amounts of u.v. radiation are absorbed by spicules, thereby reducing the brightness observed at the limb. Jordan & Ridgeley in their analysis of the limb and disk intensities derive the height of formation of the u.v. continuum and find a height range of 2000–5000 km which has to be compared with the 606–758 km range indicated by the HSRA. They attribute the difference to the effect of inhomogeneities. Although not directly connected to the u.v. but more puzzling is the problem of the low temperatures derived from the observations of the rotation–vibration fundamental band of CO near 4.8 μm (R. N. Thomas 1975, personal communication). CO exists in the Sun and is concentrated in a very narrow layer close to the temperature minimum. The computations show that these lines are formed in l.t.e. (P. J. Lena 1975, personal communication). Nevertheless the centre to limb variation of the line leads to a very cold surface temperature (3400 K is quoted !). Independently of the fact that no physical explanation will be straightforward in accounting for such low temperatures, inhomogeneities and in particular, cold structures which have been observed in some areas of the disk (10 % of the disk could be covered with such structures) might well lead to 'anomalous' centre-to-limb variation of the CO lines.

We must strongly point out as a partial conclusion here that all investigations of the structure of the temperature minimum and low chromosphere regions bearing upon lines or continuum centre to limb studies which do not take into account the influence of inhomogeneities are highly questionable. This assessment is valid for both the e.u.v. and the far i.r. continuum.

5. Conclusion

After many years of work on the absolute photometry of the Sun in the e.u.v. some firm conclusions can be drawn:

(i) The minimum brightness temperature reaches a minimum value of 4400 K.

(ii) The e.u.v. brightness temperature does not represent the kinetic temperature due to the large departures from l.t.e. of the main absorber below 2000 Å and Si I in particular. Thereby, the infrared spectrum around 100 μm although less sensible to the temperature distribution, which is emitted in l.t.e. is more suited to the investigation of the temperature structure of the upper photosphere and temperature minimum region. Since the accuracy of the far i.r. measurements is still low, more refined observations are strongly needed in this region of the spectrum.

(iii) The 'missing opacity' can be, for a large portion, accounted for by line blanketing.

Future efforts in the investigation of the solar spectrum go into the direction of high resolution observations both spectral and spatial in order to study the effect of inhomogeneities. The University of Colorado experiment on OSO-I will certainly represent an important contribution in this matter. Line blanketing should be re-evaluated relaxing the restrictive hypothesis of l.t.e. Although this is not straightforward, it has to be done in order to fully appreciate its contribution to the opacity. If l.t.e. departures lead to mean values for the *b* coefficients less than unity as in the case of Si I, then the emergent intensity will be more intense and more opacity will be needed in order to bring the model predictions into agreement with the observations.

Finally, coupling between different domains of wavelengths particularly the e.u.v. and far i.r. should be made as frequently as possible, in order to check the consistency of successive iterations of the solar model.

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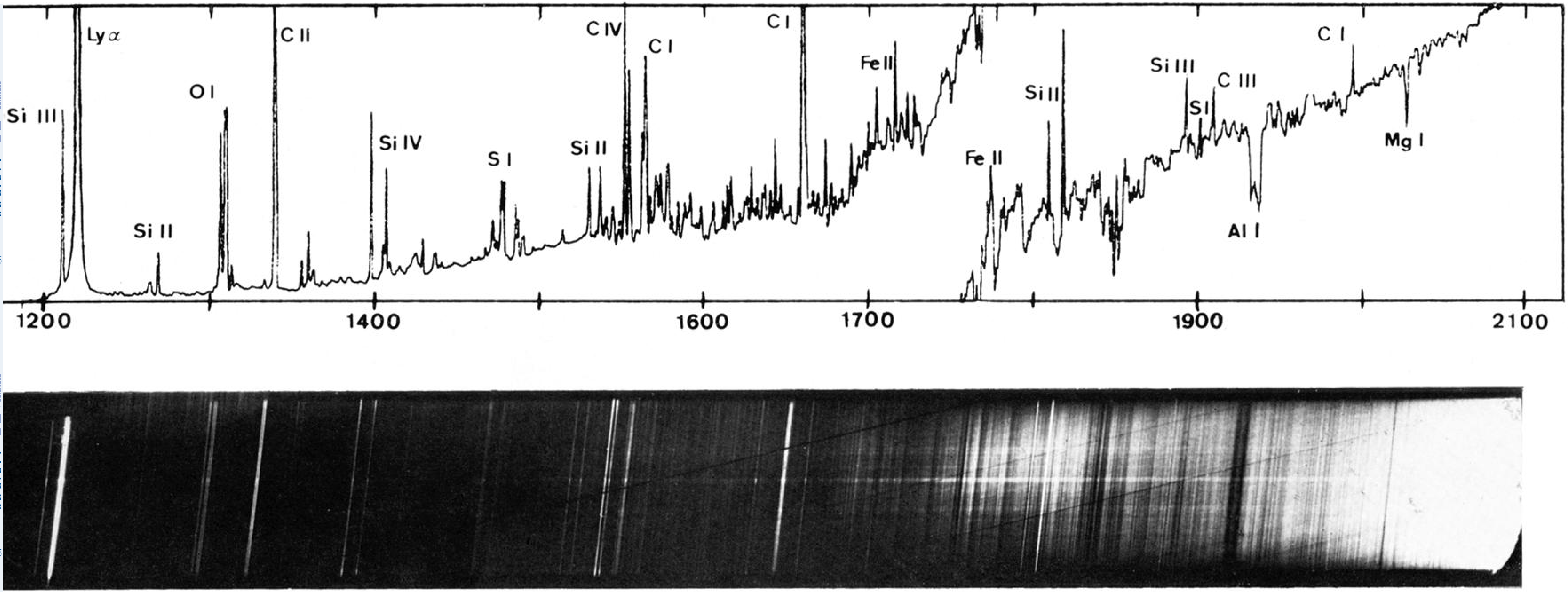

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FIGURE 1. A 14 s exposure of the solar spectrum obtained by Samain *et al.* (1974) during the Veronique flight of 17 April 1973.