551.521.1 : 523.74

Solar radiation

By C. W. ALLEN
University of London Observatory, Mill Hill Park, London, N.W.7

Symons Memorial Lecture, delivered 2 April 1958

1. Introduction

In order to appreciate fully the significance of your invitation to me this evening, I have made a point of listing the Symons Memorial lecturers and their subjects for the past twenty years. I am indeed pleased to add my lecture to the impressive list. I notice the names of some astronomers and hence it is evident that you are willing to listen to those whose main interest in the earth's atmosphere is to do away with it. Many astronomers study the earth's atmosphere with great care to the end that they shall be able to present their observational results exactly as they would have been had there been no atmosphere at all. I hold to this attitude to some extent myself. If you are willing to make due allowance for this I think you could find my subject of ' solar radiation ' well suited to the Symons Memorial series.

As all know, solar radiation is the sun's most generous gift to the earth. It provides energy to make the atmosphere work – thus it gives us our meteorology. Most of our physical knowledge of the sun is obtained from detailed studies of its radiations and therefore my subject could embrace the whole of solar physics. However, the interests of the present audience suggest that I restrict my subject matter in the following two ways; (a) by neglecting all the detailed surface phenomena of the sun and considering only the totality of radiation covering the whole of the sun's visible disk and (b) by neglecting all the detail of the Fraunhofer spectrum lines and considering only a spectrum that is very much smoothed in wavelength. Another restriction you might expect of me is that I should consider only total radiation integrated over the whole spectrum, but the influences of the solar radiation on the earth's atmosphere are so dependent on general wave length (although not on the detailed spectrum lines) that the distribution of energy in wavelength could not be omitted.

These introductory remarks guide my discussion into three main questions. How much radiation comes from the sun ? How does it vary ? How much gets lost in the atmosphere ? You will have noticed that another important question is deliberately omitted. I do not attempt to explain how the solar radiation affects the atmosphere – a question which might well be left to meteorologists.

In order to express results quantitatively we might denote by f_λ the flux of radiant energy from the sun per wavelength unit reaching unit area outside the earth atmosphere. Using the unit, erg cm^{-2} $Å^{-1}$ sec^{-1}, the maximum f_λ is about 216, near $\lambda = 4700$ Å. If we should wish to represent the flux of the continuum *between* the spectrum lines this will be denoted f_λ'.

It will be necessary to consider f_λ over a very wide range of wavelength (10^{-7} to 10^3 cm), and to do this in a single diagram (as in Fig. 3) logarithmic wavelengths must be adopted. However if f_λ be plotted against $\log \lambda$ the area under the curve so produced does not represent total energy over the wavelength range. As total energy is so often our main concern, and as $\log \lambda$ is a very useful abscissa (even for ranges in λ as small as 1 : 100) I have introduced the symbol $f_{\%}$ to represent the flux in ergs per cm^2 per sec and per 1 per cent change in wavelength or frequency. $f_{\%}$ is a more useful quantity than f_λ for expressing the spectral flux when a wide wavelength range has to be considered. We have

$$f_{\%} = \lambda f_\lambda / 100$$

and the total energy flux over a wavelength range can be written

$$f = \int f_\lambda \, d\lambda = 230 \int f_{\%} \, d\,(\log \lambda)$$

where the numerical factor 230 is 100/modulus, and logarithms are to the base 10.

2. The permanent spectrum

It will be convenient to consider the whole spectrum in three parts : (a) the visible spectrum which is to include also the near infra-red and ultra-violet, (b) the radio spectrum and (c) the x-ray and far ultra-violet spectrum.

The visible spectrum together with the near infra-red and ultra-violet (0·2 μ to 10 μ) contains virtually all the solar energy. Much of it reaches the earth's surface and there it can be measured by various types of thermal radiometer. The evaluation of f_λ in this region is dependent on the absolute calibration of radiation instruments and on appropriate allowance for absorption in the earth's atmosphere. Rocket observations are required

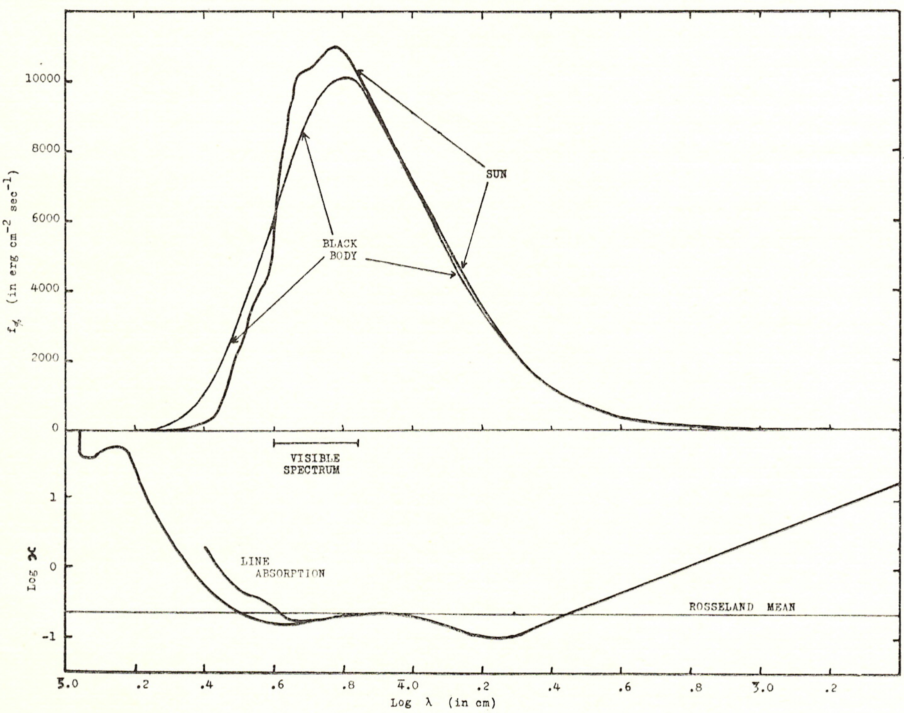

Figure 1. Energy distribution in sun and black body. Absorption coefficient κ of the solar atmosphere.

in the range $0{\cdot}2\,\mu$ to $0{\cdot}3\,\mu$. In Table 1 I have reconsidered earlier data (Allen 1955) with the help of discussions by Deirmendjian and Sekera (1956), Johnson, Purcell, Tousey and Wilson (1954), and Johnson (1954). Some account has also been taken of measurements of the intensity of the centre of the sun's disk in the continuum between Fraunhofer lines by Makarova (1957), Peytureau (1952) and Labs (1957). Such measurements can be converted to f_λ by a knowledge of solar limb darkening and the total absorption of Fraunhofer lines, and available estimates of these have been used (extrapolated to some extent) for compiling Table 1. In this table the wavelengths are chosen to show the variation in as much detail as seems necessary. I have used λ, f_λ and log $f_{\%}$ in the table, but in graphical work I use log λ and $f_{\%}$. The derived energy distribution is shown in Fig. 1 and compared with a black-body distribution for the sun's effective temperature T_e which is 5800°K. The area under the $f_{\%}$ curve is proportional to total energy, and by definition of T_e the areas under the solar and black-body curves are the same. Integration of the f_λ data of Table 1 gives $1{\cdot}380 \times 10^6$ erg cm^{-2} sec^{-1} $\equiv 1{\cdot}978$ cal cm^{-2} min^{-1}.

The departure of the solar distribution from a black-body curve, though small, is significant and interesting. The lower part of Fig. 1 shows the value of κ the opacity of the sun's atmosphere per (g/cm^2). Where κ is less than the mean value (represented in the diagram as the Rosseland mean) we have a ' window ' which enables us to look more deeply than average into the sun's atmosphere. As the sun's temperature rises steeply with depth, the emission in such a window is represented by a black body with temperature higher than T_e. Two windows are shown : one in the visible and one in the infra-red beyond $\lambda = 1\,\mu$. In both cases the emission is greater than the black body, but the effect is much less sensitive in the infra-red than in the visible. Since our f_λ and $f_{\%}$ refer to the spectral flux smoothed through spectral lines the lines themselves must be considered to add to the opacity of the sun's atmosphere. The extra curve in Fig. 1 is intended to represent this extra line absorption. Because of it we see that in the near ultra-violet the absorption is greater than the mean. In this region we are therefore looking at a cooler solar level (nearer the surface) where the radiation intensity is less than black body at T_e.

It is evident that the form of f_λ is dependent on the shape of the κ curve which, as we see in Fig. 1, rises steeply towards either longer or shorter wavelengths. How this will affect f_λ will depend on the distribution of temperature with height in the sun's atmosphere. This is illustrated in Fig. 2. The critical part of the curve near the photosphere is well determined and the temperature in the corona is known to be close to 10^6 °K as shown. However the shape of the temperature curve between the photosphere and corona has been subject to very considerable controversy and there are strong reasons for thinking that in this region there are pockets of high and low temperature material

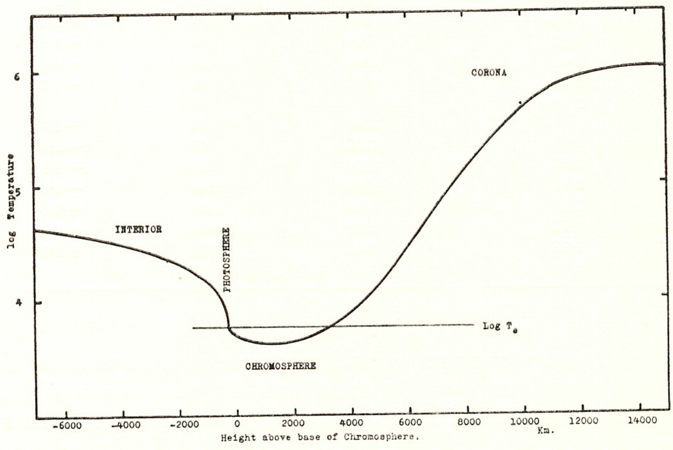

Figure 2. Temperature distribution in the sun's atmosphere.

that create a complex chromospheric structure. The point for us to notice is that there is a level of very high temperature above the chromosphere, and hence if the absorption coefficient of the atmosphere becomes very great the characteristic black-body temperature may be much greater than T_e.

TABLE 1. Solar radiation flux outside the earth's atmosphere

Visible spectrum, etc.

λ μ	f_λ (erg cm^{-2} Å^{-1} sec^{-1})	log $f_{\%}$ (in erg cm^{-2} sec^{-1})
0·20	0·5	1·0
0·22	3·0	1·82
0·24	6	2·16
0·26	12	2·49
0·28	24	2·83
0·30	55	3·22
0·32	75	3·38
0·34	97	3·52
0·35	105	3·57
0·36	109	3·59
0·37	112	3·62
0·38	115	3·64
0·39	123	3·68
0·40	153	3·79
0·41	176	3·86
0·42	186	3·89
0·44	203	3·950
0·46	215	3·995
0·48	214	4·012
0·50	206	4·013
0·55	195	4·030
0·60	183	4·041
0·65	164	4·027
0·70	146	4·009
0·75	128	3·982
0·80	113	3·957
0·9	89	3·90
1·0	72	3·86
1·1	59·5	3·82
1·2	49	3·77
1·4	32·5	3·66
1·6	22·3	3·55
1·8	15·2	3·44
2·0	10·8	3·33
2·5	4·97	3·09
3	2·63	2·90
4	0·93	2·57
5	0·41	2·31
6	0·21	2·10
7	0·12	1·92
10	0·023	1·36

Radio spectrum

λ (cm)	f_λ (erg cm^{-3} sec^{-1})	log $f_{\%}$ (in erg cm^{-2} sec^{-1})
0·6	$2·8 \times 10^{-5}$	− 6·77
1·5	$1·1 \times 10^{-6}$	− 7·78
3	$9·7 \times 10^{-8}$	− 8·54
6	$1·1 \times 10^{-8}$	− 9·18
15	$7·7 \times 10^{-10}$	− 9·94
30	$1·1 \times 10^{-10}$	− 10·48
60	$1·8 \times 10^{-11}$	− 10·97
150	$9·1 \times 10^{-13}$	− 11·87
300	$6·0 \times 10^{-14}$	− 12·74
600	$4·2 \times 10^{-15}$	− 13·60

X-ray spectrum, etc.

λ Å	f_λ (10^{-5} erg cm^{-2} Å^{-1} sec^{-1})	log $f_{\%}$ (in erg cm^{-2} sec^{-1})	log $f'_{\%}$ (in erg cm^{-2} sec^{-1})
10	4	− 5·4	− 5·4
20	23	− 4·3	− 4·5
50	110	− 3·3	− 3·8
70	120	− 3·1	− 3·7
100	70	− 3·2	− 3·8
200	11	− 3·7	− 3·8
300	10	− 3·5	− 4·4
500	8	− 3·4	− 4·4
700	10	− 3·2	− 3·8
800	20	− 2·8	− 3·0
900	60	− 2·3	− 2·3
1000	40	− 2·4	− 2·8
1100	90	− 2·0	− 3·0
1200	280	− 1·5	− 2·8
1400	540	− 1·1	− 1·6
1600	1600	− 0·6	− 0·7
1800	10000	+ 0·2	
2000	50000	+ 1·0	

In Fig. 3 a much more compact logarithmic scale is used to show the distribution of $f_{\%}$ over the whole range from $\lambda = 10^{-7}$ to 10^3 cm. By comparison with the black-body spectrum at T_e there are seen to be superimposed appendages at both the radio and x-ray ends. These are both due to the high temperature corona which is completely transparent to the visible spectrum but is somewhat opaque to certain radio and x-ray wavelengths.

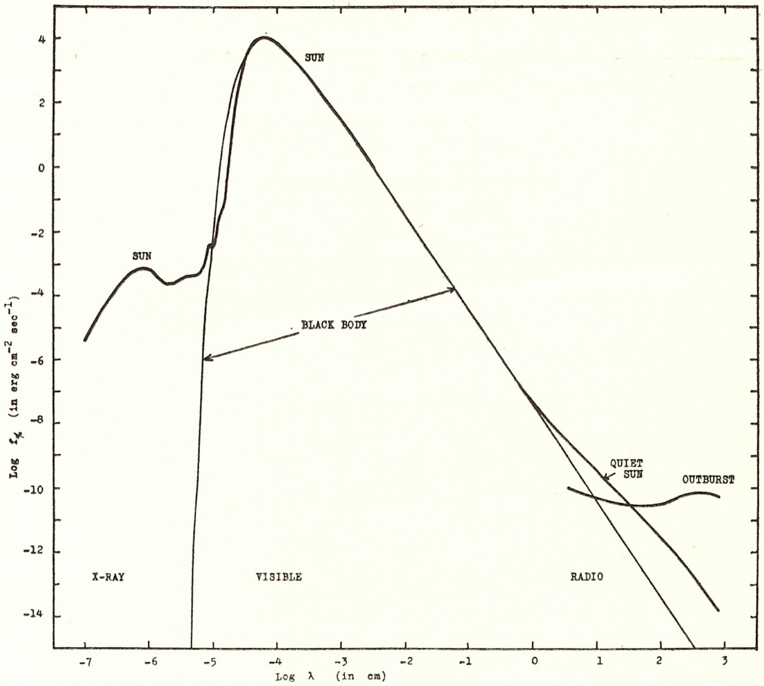

Figure 3. Energy distribution of sun and black body at T_e.

In the radio wavelengths the most intense radiations, such as those from outbursts, are neither thermal nor permanent. The permanent thermal (quiet sun) radiations can be measured by radio techniques with considerable absolute accuracy but these too vary with solar activity. The values quoted in Table 1 represent the permanent (but not precisely constant) component after the radiation from active areas has been subtracted (Allen 1957a, 1957b). The energies involved are vanishingly small. We see, for example, that the energy received from wavelengths greater than 10 cm is of the order 10^{-8} erg cm^{-2} sec^{-1}, as compared with $1{\cdot}39 \times 10^6$ erg cm^{-2} sec^{-1} for the total radiation.

The x-ray and far ultra-violet regions cannot penetrate the earth's atmosphere and therefore these radiations cannot be measured at the earth's surface. Their importance is due to their ability to ionize the upper atmosphere and produce the ionospheric layers. There are three ways by which we estimate the flux; (i) by measurements from rockets, (ii) from solar coronal and chromospheric theories and (iii) from interpretation of ionospheric observations. None of these is particularly reliable but fortunately they show some measure of agreement. In order to evaluate the radiation we start with the coronal calculations of Elwert (1954). Values for both emission lines and the continuum are available and are shown on the left of Fig. 4. In this diagram the individual line fluxes are represented in erg cm^{-2} sec^{-1}, and therefore in order to compare them quantitatively with the continuum they should be regarded as having a width of 1 per cent in λ, i.e., (1/230) $\times$ logarithmic unit. It is found that the emission lines provide a more significant contribution than the continuum. The spectrum lines further to the right in the diagram have been either observed, (Lα) (Byram, Chubb, Friedman and Kupperian 1956a), or calculated (Woolley and Allen 1948, 1950) from models of the corona (Mg x) or the chromosphere (other lines). The calculations have been reduced by a factor 6 to allow for over-estimation mentioned by Elwert (1954). The totality of emission lines when represented as a smooth curve show approximate agreement with x-ray flux measurements made from rockets (Byram *et al.* 1956a, 1956b, Friedman 1957) but no measurements are available in the interesting region from 100 Å to 1000 Å. The curve of $f_{\%}$ in Fig. 4 and represented in Table 1 is a compromise between calculations and measurements.

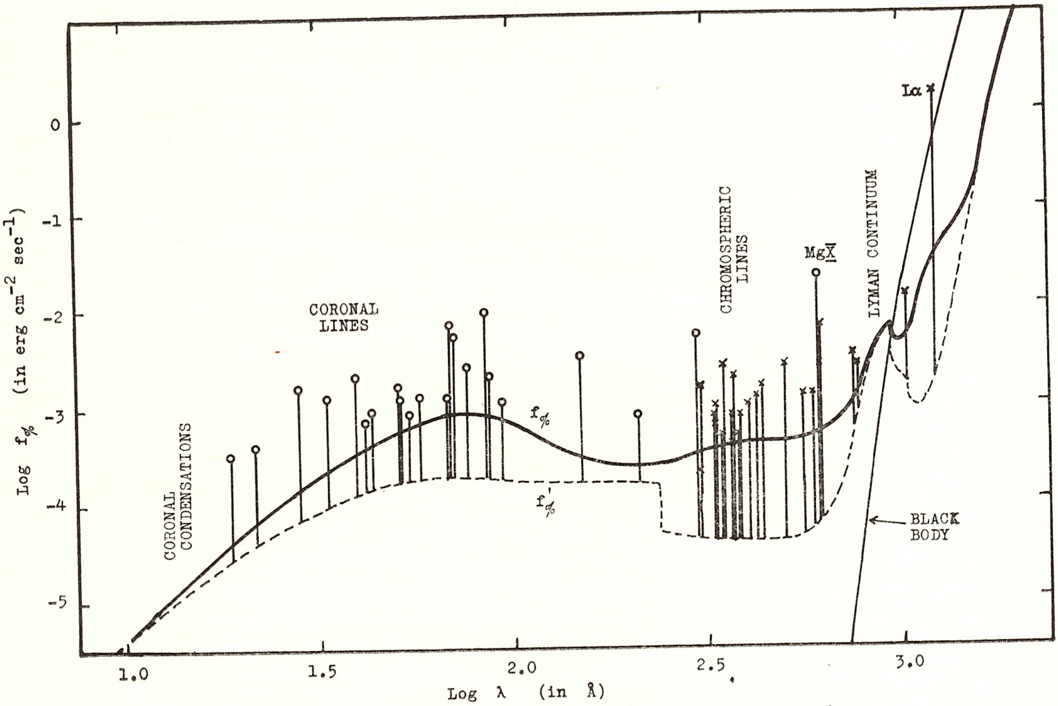

Figure 4. Emission lines and continua in the X-ray and far u-v regions.

The $f_{\%}'$ curve for the continuum is mainly from Elwert's calculations and has not been observed. The continuum peak in the neighbourhood of the Lyman limit (912 Å) is suggested by chromospheric theory (de Jager 1955) but also has not been observed. The shortest wavelength to which the continuum has been observed is 1550 Å (Johnson, Mallitson, Purcell and Tousey 1958).

A point of considerable interest, noted by Elwert, is that the smoothed distribution representing the totality of coronal emission lines has a maximum at a wavelength close to the coronal temperature black-body maximum. In coronal condensations, where temperatures are thought to reach 6×10^6 °K, emission lines of shorter wavelength become prominent (Elwert 1956). Thus a change of emission wavelength with change of solar activity is to be expected. Fig. 4 is intended to represent quiet conditions, i.e., the sun without coronal condensations.

We might now compare energies in various parts of our spectrum with those required to form the ionospheric layers. The energies in various parts of Fig. 4 might be summarized as follows :

Spectroscopic range	x-ray	200-800 Å	Lyman Cont.	Lα
Energy (in erg cm^{-2} sec^{-1})	0·10	0·05	0·16	1·6

Comparable data for the ionosphere (Allen 1955 p. 124, 1956) are :

Ionospheric region	D	E	F
Ionization (ion pairs cm^{-2} sec^{-1})	10^5	6×10^8	25×10^8
Energy (in erg cm^{-2} sec^{-1})	10^{-5}	0·013	0·06

For these data each ionizing photon is considered to have 1 Rydberg of energy and the D region recombination coefficient is taken as 10^{-6} cm^3 sec^{-1} (Waynick 1955). There are two factors which may increase the calculated energy required to form the ionospheric regions : (i) the ionospheric effective recombination coefficients may be greater than assumed and (ii) x-radiation has more than 1 Rydberg of energy per photon (which however might produce more than one ion pair). We find a great discrepancy between the energy required for the D region and the Lα emission that is thought to produce it (Friedman 1957). For the other regions and ranges there is reasonable agreement between spectroscopic and ionospheric energies. None are known accurately enough to help with the recognition of the spectral ranges responsible for the E and F regions. However, arguing from the absorption coefficients of the Earth's atmosphere (Allen 1956) it is plausible to ascribe the E region to x-rays and the F region to the line radiations in the 200-800 Å range.

3. The variations of solar radiation

There are certainly considerable variations in the radiation from small regions of the sun's surface as shown by the existence of sunspots, and analogous variations can be detected within certain narrow spectrum lines. But these phenomena do not necessarily affect the total radiation to any appreciable extent. Our first problem then – the problem of prime interest for meteorological purposes – is to decide whether the total radiation varies effectively or measurably.

We can see from Fig. 1 that for total radiation we need consider only the wavelength range 0·2 μ to 10 μ, and we have already seen that this radiation is almost entirely thermal in origin. Our interest relates to possible variations of the order 0·1 per cent. The observed dispersion of the variation is not much greater than this and variations that are much smaller could not be detected nor would they have any meteorological significance. Possible variations in the solar radius need not concern us since they are not much greater than 0·01 per cent (Gething 1955, Giannuzzi 1957) and have negligible effect on radiation output. A variation of 0·1 per cent in the solar constant represents a change of only 0·025 per cent or 1·5 °K in T_e.

The existence of the sunspot cycle and its superficial similarity to certain variable stars might be thought to indicate a considerable variation in solar radiation. The importance of the question led the Smithsonian Institution to embark on an extensive programme of daily measurements of the 'solar constant,' which is the term used to represent total radiation from the sun outside the earth's atmosphere expressed in calories per cm^2 per min at mean solar distance. Early observations in and around 1922 (Abbot, Aldrich and Hoover 1942) showed some variations as large as 1·5 per cent but such variations were not repeated in later years and were apparently not real. In the following years a careful search was made for any systematic relation between the solar constant and the sunspot cycle but up to 1940 no such relation could be detected. There was indeed very little evidence that any of the apparent variations were real.

The two analyses most likely to give indications of real variability are (a) a study of the covariance of measures of the solar constant made at independent stations and (b) a further study of solar constant variations with the sunspot cycle. In either case extensive and independent estimates of solar constant variations are the main requirement.

As there has been a discontinuity in the Smithsonian observing programme at the end of 1955 it would appear that it will be very many years before there are any more data available that can help with this problem and therefore the appropriate time to make a decision on this matter is *now*.

Three different estimates of the standard deviation of the solar constant by covariance methods gave the results in Table 2. The only correlation of entirely independent data (S, C) gave no evidence of covariance. The data for the two (T, M) correlations were reduced by the same institution, and there is a danger of a spurious covariance resulting from : (a) adjustment or selection of one value to improve agreement with the other, (b) meteorological correlation between the stations and (c) similarity in the residual annual term at the two stations. With regard to (c) it has been noticed that all four stations annual term and a linear secular variation have been extracted. An ultra-violet intensity variation of perhaps 10 per cent in phase with the sunspot cycle would appear to be possible but the linear secular correction I have adopted gives a rather optimistic idea of the true correlation. We have seen that the radiation concerned is from thermal causes. A 10 per cent ultra-violet variation would represent a 200°K temperature change and a consequent 15 per cent solar-constant change which is certainly not observed. This leads to the conclusion, already generally agreed, that the measured variations are associated with atmospheric transmission rather than solar variation.

While the variation of total radiation is very small and uncertain the variations in radio emissions from the sun are large and show well-defined solar activity effects. The variable part can be sub-divided into slowly varying thermal emissions and three types of erratic bursts. All of these change significantly with wavelength. All come from localized regions of activity and are additional to the general thermal radio radiation of Table 1. All of them change with the sunspot cycle but only the thermal emissions from active areas (in the decimetre wave band) show the rather smooth daily and monthly variations characteristic of sunspot numbers (Allen 1957b). The bursts are more erratic. These variable radiations penetrate the atmosphere to reach the earth's surface and could possibly produce some geophysical effects. However the extreme smallness of the available energy makes this unlikely and they are probably swamped by man-made radio noise.

It was shown earlier that both the radio and the x-ray emissions were due to the hot corona. Since these may be considered as being due to the same cause one might expect that the variations would show striking similarities. This is indeed the case. The variations in the ultra-violet or x-ray emissions giving rise to the E and F layers may be estimated from ionospheric critical frequency measurements. The detailed comparison of the data (yearly, monthly and daily) of the ionospheric regions, the decimetre wave radio emission, and various solar activity indices agree with such precision (Allen 1946, 1948, 1957b; Denisse and Kundu 1957) that the association of causes is no longer in doubt. Small differences in the form and timing of these variations are now being studied for solar information on various phenomena associated with a centre of solar activity. For geophysical consideration the results can be expressed by empirical relations between the radiation and the activity indices (Minnis and Bazzard 1958).

4. Loss of solar radiation in the earth's atmosphere and the solar constant

The quantitative problem of radiation loss in the earth's atmosphere is one that is of vital interest to both astronomers and meteorologists. The main atmospheric absorbing agents that operate in the parts of the solar spectrum containing appreciable energy are listed below. For each agent one requires an absorption coefficient as a function of wavelength λ. If the absorption is continuous the radiation loss may be determined simply

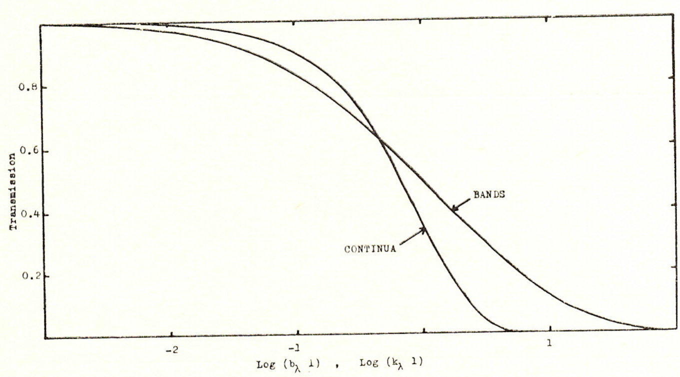

Figure 8. Comparison of transmission through bands with transmission associated with the exponential absorption of continua.

from the Lambert exponential law. If however the absorption is made up of complex lines or bands other less precise methods must be devised and an effective absorption coefficient must be defined. Let T be the transmission in a spectral region λ which is taken wide enough to include several spectrum lines. T will depend on an effective absorption coefficient b_λ and the amount of the agent which may be denoted l. Fortunately the function $T(b_\lambda l)$ is not too seriously dependent on the distribution of absorbing lines (Cowling 1950, Goody 1952, Howard, Burch and Williams 1956), and useful accuracy may be obtained from a mean curve. The curve adopted here (Allen 1955, p. 118) is compared with a curve representing exponential absorption in Fig. 8. If the value of b_λ is based on measurements near $T(b_\lambda l) \simeq 0{\cdot}5$ the amount of light absorbed will not depend very greatly on the shape of the $T(b_\lambda l)$ curve.

The main absorbing agents (Allen 1955, pp. 116, 118, 120) are as follows :

(a) Molecular (Rayleigh) scattering. This is known with a precision of about ± 2 per cent. It has a continuous spectrum following a λ^{-4} law.

(b) Ozone. Absorbing bands occurring in the ultra-violet and yellow-red regions have virtually a continuous spectrum. Absorption coefficients are known and the ozone world distribution is fairly regular.

(c) Aerosols (dust, droplets, smoke, etc.). The amount of this absorption and its dependence on wavelength may vary and hence they must be determined experimentally for each occasion. The absorption is continuous and usually decreases slowly with wavelength.

(d) Bands of water vapour and other molecules. The estimation of transmission through these complex spectrum line structures may be made by the approximate method mentioned above. Values of b_λ are available but not very precise.

The flux of solar radiation transmitted through the earth's atmosphere computed from data of the type enumerated and from Table 1 is represented in Fig. 9. Using unit air mass of aerosol-free air containing 10 mm of precipitable water I obtain a calculated total solar transmission $T_c = 0{\cdot}758$. If pyrheliometric observations representing these conditions were available the observations could be converted to the solar constant by division by T_c. As an attempt to do this I use the solar-radiation measurements of the Commonwealth Observatory (Rimmer and Allen 1950, p. 40) which are reduced in such a way that the solar radiation at mean distance is given by

$$T_m \times 1{\cdot}940/1{\cdot}024.$$

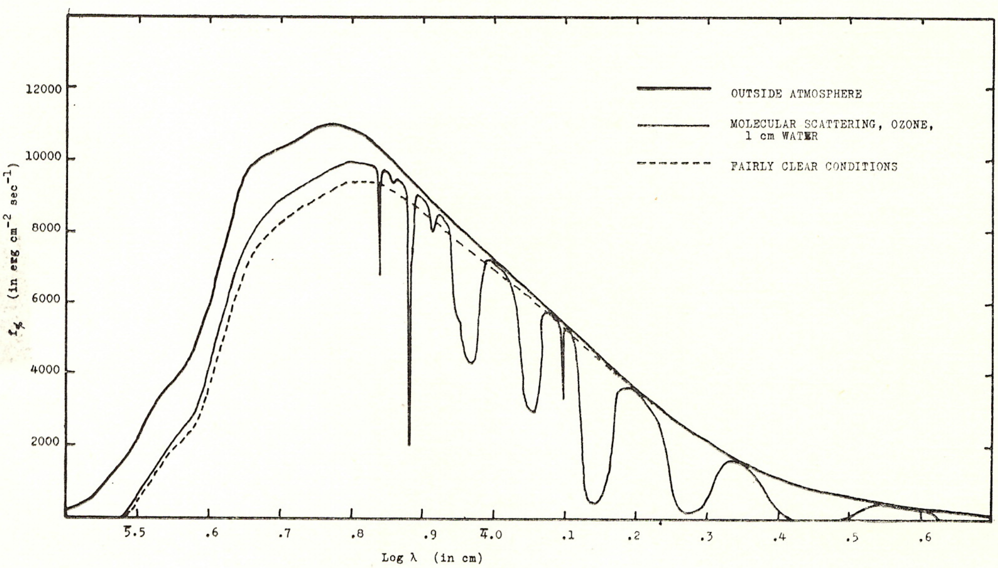

Figure 9. Effect of atmospheric absorption on the flux of solar radiation.

The value of T_m deduced for the conditions described was $(0{\cdot}793 + 0{\cdot}0005)$ where the small correction represents dust absorption. The solar radiation was therefore $1{\cdot}503$ cal cm^{-2} min^{-1}, and the deduced solar constant $1{\cdot}503/0{\cdot}758$

$$= 1{\cdot}983 \text{ cal cm}^{-2} \text{ min}^{-1}.$$

This simple procedure I have adopted for re-determining the solar constant has the advantage that it is almost independent of the procedures of the Smithsonian Institution. A recent discussion on the solar constant by Johnson (1957) leads to $2{\cdot}00 \pm 0{\cdot}04$ cal cm^{-2} min^{-1}. I would think the probable error not quite so high as this and would be willing to compromise with

$$1{\cdot}99 \pm 0{\cdot}02 \text{ cal cm}^{-2} \text{ min}^{-1}$$

as a suitable modern estimate of the solar constant. The corresponding effective solar temperature is 5,800°K.

References

Abbot, C. G., Aldrich, L. B. and Hoover, W. H. 1942 *Ann. Ap. Ob. Smithson. Inst.*, **6**.
Aldrich, L. B. and Hoover, W. H. 1954 *Ibid.*, **7**, pp. 165-174.
Allen, C. W. 1946 *Terr. Mag.*, **51**, 1.
1948 *Ibid.*, **53**, 433.
1955 *Astrophysical quantities*, Athlone Press, London, 1955.
1956 *Solar eclipses and the ionosphere*, p. 150, London (Pergamon Press).
1957a I.A.U. Symp. No. 4, ' Radio Astronomy,' p. 253.
1957b *Mon. Not. R. Astr. Soc.*, **117**, p. 174.
Byram, E. T., Chubb, T. A., Friedman, H. and Kupperian, J. E. 1956a *Astrophys. J.*, **124**, p. 480.
Byram, E. T., Chubb, T. A. and Friedman, H. 1956b *J. Geoph. Res.*, **61**, p. 251.
Cowling, T. G. 1950 *Phil. Mag.*, **41**, p. 116.
Denisse, J. F. and Kundu, M. R. 1957 *C.R., Acad. Sci.*, **244**, p. 45.
Diermendjian, D. and Sekera, Z. 1956 *J. Opt. Soc. Amer.*, **46**, p. 565.
Elwert, G. 1954 *Z. Naturf.*, **9a**, p. 637.
1956 *Z. Astrophys.*, **41**, p. 67.
Friedman, H. 1957 *9th Rep. Sol. Ter. Rel.*, p. 41.
Gething, P. J. D. 1955 *Mon. Not. R. Astr. Soc.*, **115**, p. 558.
Giannuzzi, M. A. 1957 *Oss. Astron. Roma*, No. 243.
Goody, R. M. 1952 *Quart. J. R. Met. Soc.*, **78**, p. 165.
Howard, J. N., Burch, D. E. and Williams, D. 1956 *J. Opt. Soc. Amer.*, **46**, p. 334.
Jager, C. de 1955 *Ann. Geophys.* **11**, p. 330.
Johnson, F. S. 1954 *J. Met.*, **11**, p. 431.
1957 *9th Rep. Sol. Terr. Rel.*, p. 53.
Johnson, F. S., Purcell, J. D., Tousey, R. and Wilson, N. 1954 *Rocket exploration of the upper atmosphere*, Ed. Boyd and Seaton, London, (Pergamon Press), p. 279.
Johnson, F. S., Malitson, H. H., Purcell, J. D. and Tousey, R. 1958 *Astrophys. J.*, **127**, p. 80.
Labs, D. 1957 *Z. Astrophys.*, **44**, p. 37.
Makarova, E. A. 1957 *Astron. Zhurnal.*, **34**, p. 539.
Minnis, C. M. and Bazzard, G. H. 1958 To be published.
Pettit, E. 1932 *Astrophys. J.*, **75**, p. 185.
1933-38 *Bul. Character. Figs. of Sol. Phenomena.*
Peytureau, R. 1952 *Ann. d'Astrophys.*, **15**, p. 302.
Rimmer, W. B. and Allen, C. W. 1950 *Mem. Com. Obs. Canberra*, No. 11, **3**, p. 1.
Sterne, T. E. 1942 *Astrophys. J.*, **96**, p. 484.
Sterne, T. E. and Dieter, N. 1958 In press.
Waynick, A. H. 1955 ' Physics of the ionosphere,' *Rep. Phys. Soc.*, p. 1.
Woolley, R. v.d.R. and Allen, C. W. 1948 *Mon. Not. R. Astr. Soc.*, **108**, p. 292.
1950 *Ibid.*, **110**, p. 358.