PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

# The Photo-Electric Measurement of the Diurnal and Seasonal Variations in Daylight and a Globe Integrating Photometer

W. R. G. Atkins and H. H. Poole

*Phil. Trans. R. Soc. Lond. A* 1936 **235**, 245-272
doi: 10.1098/rsta.1936.0003

# VIII—The Photo-electric Measurement of the Diurnal and Seasonal Variations in Daylight and a Globe Integrating Photometer

*By* W. R. G. Atkins, Sc.D., F.R.S., *Head of the Department of General Physiology, Marine Biological Laboratory, Plymouth, and* H. H. Poole, Sc.D., *Registrar, Royal Dublin Society*

(Received April 24—Revised September 26, 1935)

[Plates 23–27]

## Contents



## I—Introduction and Optical Considerations

Photo-electric cells of various types are becoming more widely used every day for the measurement of illumination, both natural and artificial. Their great convenience renders them specially suitable for the measurement and recording of daylight. A word of warning is, however, necessary. What the cells measure is not really "light," *i.e.*, the physiological effect produced on the eye by the radiation, but rather the physical effect produced on the cell by the same radiation. It has been argued with some justice that it is therefore unscientific to use the ordinary units, derived from visual measurements, to measure the effect on the cell. The argument would carry more weight if these units were strictly limited to the measurement of illuminations of definite spectral composition, and so did not attempt to compare effects which are essentially dissimilar. For practical convenience, however, we are driven to measure in "candlepower" illuminants differing widely from the standard candle in spectral composition.

In a similar way we may, again for motives of convenience, use the visual units for measuring illuminations on a photo-electric scale, provided that we remember that the scale differs from the visual one, and take steps to reduce that difference to the utmost by (*a*) using a cell whose spectral response is as near as possible to that of the average eye, and (*b*) standardizing that cell by means of an illuminant whose spectral composition is as close as possible to that of the light which we desire to measure.

The problem is especially difficult with daylight, which differs so widely from common artificial illuminants, but it must be remembered that for very many biological purposes only comparative readings on some definite scale are needed, and the accordance of that scale with the visual may be of no importance.

The most scientific procedure is obviously to measure the energy in the different bands of the spectrum, but, if the accuracy which is claimed by this method of presenting results is to be justified, a set of readings with different colour filters must be made on each occasion. This may not always be practicable, and, with a cell sensitive to a large part of the spectrum, a single reading of an illumination of variable colour is not a reliable basis for a determination in absolute measure of the energy in that wide range of wave-lengths. Moreover, the standardization of the various energy ranges presents certain practical difficulties, which we have not as yet surmounted to our entire satisfaction.

We are accordingly retaining the use of the terms lux (or metre-candle) and kilolux for the presentation of our results, but would like to emphasize that they are used to measure the response of the cell and not the visual effect of the radiation on the eye. Similarly, where the term " luminous efficiency " is used it must be understood to mean the " light " as measured by the cell divided by the energy of the radiation as measured by a sensitive thermopile. With the cells used and the methods of standardization already described* the discrepancies between the scales are unlikely to be comparable to the very large variations that occur—sometimes with great rapidity—in daylight.

Apart from the above considerations we must evidently define what we mean by the illumination at a given point. The problem is complicated by the fact that we have to deal with light travelling in many different directions, the angular distribution varying greatly at different times. Thus with a uniform cloudy sky the light may be approximately uniform over one hemisphere. In addition to this direct skylight there will be some light reflected off the ground, possibly snow covered, or the water.

Several definitions of illumination are possible. Thus we may define it as the vertical illumination in lux (metre-candles) falling on a horizontal surface. This is what is actually measured by photometers, set with opal receiving surface horizontal, when certain small corrections have been applied for reflexion losses at the opal surface, and is denoted throughout by the letter V.

Another definition, which is very useful in photometric measurements in woods, is the illumination on a surface set to catch the maximum amount of light. This may

* 'Phil. Trans.' A, vol. 235, p. 1 (1935).


PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

be termed the maximum illumination and denoted by the letter M. Evidently for pure sunlight the photometer must be set perpendicular to the sun's rays. For actual sunlight, which contains some diffuse skylight, a setting rather nearer to the horizontal would receive more light.

Again, we may consider the horizontal illumination, H, on a plane vertical surface. This is of interest in connexion with the exposure of tubes, such as those containing methylene blue* or uranyl oxalate†. Thus a vertically exposed tube of length L and relatively small diameter D, containing a strongly absorbing liquid, may measure the mean horizontal illumination for all azimuths, the total light flux received being $\pi$ L D ($H_d + H_r$) + $LDH_s$, or $\pi LD\overline{H}$, where $\overline{H} = H_d + H_r + H_s/\pi$ and $H_d$, $H_r$ and $H_s$ denote respectively the horizontal illumination from the sky, as reflected, and from the sun. It is obvious that, when the altitude of the sun is large, direct sunlight does not contribute very much to $\overline{H}$, as $H_s$ is small since $\cos\alpha$ is a factor. Increased reflexion loss at high obliquity will further reduce the effect of high-angle light. This must be remembered when interpreting results obtained in different latitudes. Further, when a tube is standardized against a lamp the effective area of the tube is only LD, whereas when used to measure $\overline{H}$ its effective area is $\pi$LD. Such a tube, therefore, measures $\pi$ ($H_d + H_r$) as far as diffuse skylight and reflected light are concerned, but for pure sunlight it measures $H_s$ (*i.e.*, $I_s \cos\alpha$), or $I_s$, according as it is exposed vertically or normal to the sun's rays. Thus the fact that diffuse skylight has at times been found to produce more action on such tubes than did the direct sunlight does not necessarily mean that the same would be true for a plane surface.

A fourth definition was the one we originally adopted in our work on submarine illumination,‡ namely the total illumination, I, which measures the total quantity of light, regardless of angle, received at a point ; this would appear to be the best for assessing the illumination available for photosynthesis by a unicellular plant in the ocean, or by the aggregate of the leaves of a tree. I may be defined as follows :— let $id\Omega$ be the illumination in lux due to a small pencil of rays of solid angle $d\Omega$ on a small area placed perpendicular to the pencil. Then $I = \int_0^{4\pi} id\Omega$, or if we neglect the reflected light travelling upwards, $I = \int_0^{2\pi} id\Omega$. As for H, we may write $I = I_s + I_d + I_r$, where $I_s$ is the illumination from the small angle comprising the sun's disc, $I_d = \int_0^{2\pi} id\Omega$ is that due to the sky, which for a uniform sky is equal to $2\pi i$, and $I_r$ is the same integral taken over the lower hemisphere, the value of $i$ being now for the reflected light, which may for convenience be taken as uniformly distributed. I may be measured by means of a photometer whose receiving surface

* Hill, 'Proc. Roy. Soc.' B, vol. 102, p. 119 (1927).

† Atkins and Poole, 'Sci. Proc. R. Dublin Soc.,' vol. 19, p. 321 (1929).

‡ Poole, 'Sci. Proc. R. Dublin Soc.,' vol. 18, p. 99 (1925); Poole and Atkins, 'J. Mar. Biol. Ass., U.K.,' vol. 14, p. 177 (1926).

is a complete sphere. This condition is most easily fulfilled by the use of a photo-sensitive solution—such as uranyl oxalate—in a spherical flask. The globe integrating photometer described later on also measures I tolerably well.

It may be shown that the following relations hold between the quantities defined above :—

(1) $I_s = V_s$ cosec $\alpha = H_s$ sec $\alpha$, where $H_s$ refers to a vertical surface set in azimuth normal to the rays of the sun at altitude $\alpha$ ; (2) $I_d = 2\,V_d = 4\,H_d$ ; and (3) $I_r = 2\,V_r = 4\,H_r$, $V_r$ being measured with an inverted photometer.

It was our original practice to calculate I from the readings obtained with photometer (*a*) freely exposed and (*b*) shielded from direct sunlight together with a knowledge of $\alpha$ obtained from the time of observation.

This of course involved the assumption of a uniformly illuminated sky, which is often more nearly true in the absence of direct sunlight. At times also rapid fluctuations in illumination render it difficult to obtain $\beta$, the ratio of the exposed and shaded readings, with certainty. So we adopted a simpler routine and contented ourselves with measuring V, which could be done with accuracy. This is a great simplification in submarine measurements, in which the angular distribution of the light is a matter of some uncertainty.

In the preceding paper* we have dealt with the standardization of a variety of photo-electric cells and measuring instruments for the study of daylight or its components under the conditions encountered in the field and at sea. It is the object of this paper to record some of the variations found in light and in energy radiation in the open under various conditions, as shown by measurements of the vertical illumination, V, and of the total illumination, I. The latter is measured with the globe integrating photometer described in a later section. The radiation for all wave-lengths falling on a horizontal plane was also determined using a Moll solarimeter ; the readings obtained are expressed in milliwatts per square centimetre ($mw.cm^{-2}$) and the radiation thus received is denoted by W.

## II—Photo-electric Cells Used and Measurement of the Currents Generated

The cells and their mountings have been described in the preceding paper on standardization. What position of the spectrum chiefly influences them depends not only on the equal-energy spectrum sensitivity, but also upon the spectral energy distribution curve for the light being measured. Figs. 3†, 2‡ and 4§ show the former curves and fig. 1 the latter, taking the light to be Abbot's natural mean noon sunlight as defined at the Seventh International Congress of Photography, London, 1929. Our choice of cells was governed by the types available from 1924 onwards, but

* ' Phil. Trans.,' A, vol. 235, p. 1 (1935).

† Atkins and Poole, ' Sci. Proc. R. Dublin Soc.,' vol. 20, p. 13 (1931).

‡ Poole and Atkins, ' J. Mar. Biol. Assoc., U.K.,' vol. 15, p. 455 (1928).

§ Iden, ' Sci. Proc. R. Dublin Soc.,' vol. 20, p. 537 (1933).

even to-day we know of no cells superior in constancy to these sodium and potassium cells, though the newer cells are more sensitive and have a greater spectral range. It may be seen from fig. 1 that the response to mean noon sunlight reaches maximum values at 410, 420, and 595 $m\mu$ for the sodium, potassium, and selenium cells, respectively. The international visibility function, calculated for a mean noon sunlight spectrum, and plotted in fig. 1, serves to show that the response of the selenium cell to daylight is far closer to that of the eye than any of the other cells.

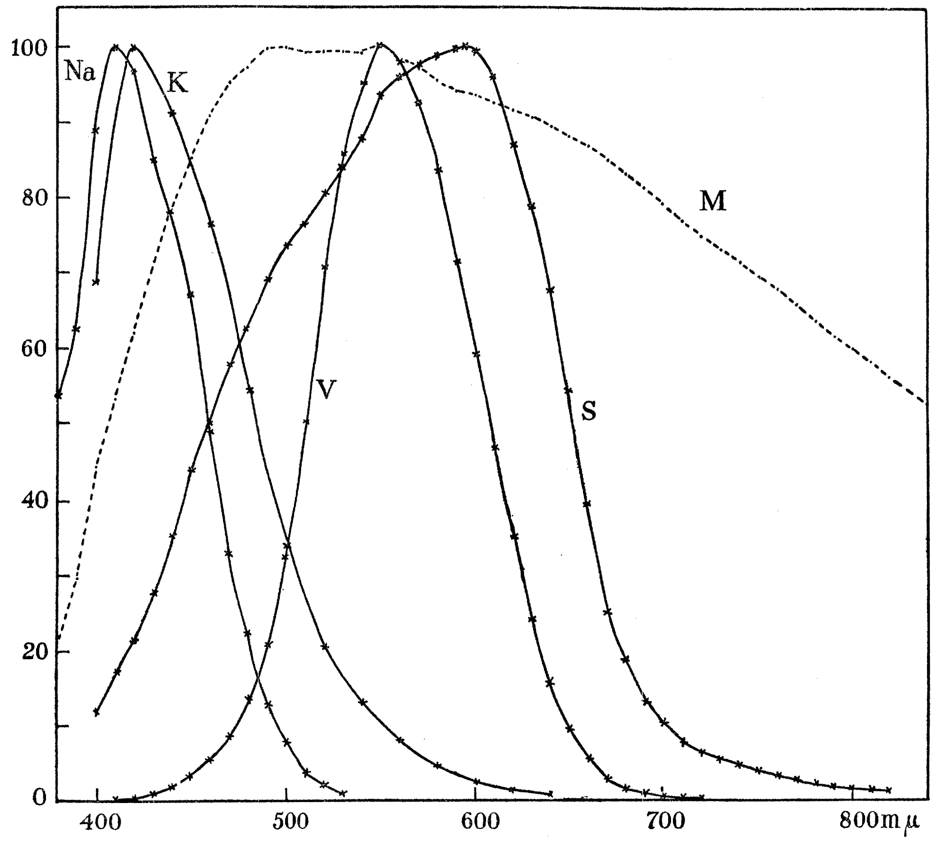



FIG. 1—The ordinates are percentages and the abscissae wave-lengths in millimicrons. Curve M shows the intensity of mean noon sunlight on a percentage basis. Beyond 720 $m\mu$ the curve has been extrapolated with the help of ABBOT's other measurements. Curves Na, K, V, and S were obtained by converting the equal-energy spectral sensitivity curves of our vacuum sodium and potassium cells, of the eye and of our selenium rectifier cell, to their equivalents under a natural mean noon sunlight spectrum.

The new Kodak filters which reduce the response of the selenium cell* to a close approximation to that of the eye were received too late for use in this paper.

The constants of the cells used in this paper may be found in Table III of the standardization paper; those for mean noon sunlight or carbon arc being taken.

* These cells may, however, have appreciable differences in their wave-length sensitivity curves.

When used for diffuse daylight a reflexion loss factor must be introduced,* which on the assumption of a uniformly illuminated sky, equivalent to a beam at an altitude of 30°, amounts to 1·06. For sunlight of known altitude the appropriate factor should be used, and this was done in calculating certain constants and in standardizations.

To make this separate correction for sun and diffuse light we must observe each separately, by taking readings (*a*) with the cell fully exposed and (*b*) with the direct sunlight screened off. The ratio *a*/*b* we have always denoted by the letter β, and used as an index of the proportion of direct sunlight. In this paper we also give the ratio sunlight/skylight in certain cases. Here we have applied the appropriate correction to each reading separately, so that the ratio differs somewhat from the approximate value β — 1. For many purposes it is sufficiently accurate to use the factor 1·06 for total light and this has been our usual procedure.

Since December, 1929, a Burt sodium cell (No. 299) has been exposed on the roof of the Marine Biological Laboratory, Plymouth. Originally standardized in 1929 against a carbon arc, this cell was cross checked against a similar cell in full daylight on May 1, 1934. The latter was then standardized in Dublin on June 8, giving the value 3·53 kl per $\mu a$ for B 299 as against its original direct standardization value 3·55 kl per $\mu a$, for vertical illumination. The slight apparent increase in sensitivity may be attributed to experimental error.

As will appear in a subsequent section the response of the cell is not necessarily the same on different occasions for equal solar altitude, but the figures shown in Table I furnish collateral evidence for the constancy of this cell.

Table I—Current in Micro-Amperes from Burt Sodium Cell No. 299 on Front Parapet of Laboratory Roof, as Measured by Cambridge Instrument Co. "Thread Recorder."

| March | 1930 | 1933 |
|---|---|---|
| 18 | 23·85 | 23·90 |
| 21 | 23·90 | 22·75 |
| 22 | 22·60 | 22·40 |
| 23 | 9·60 | 23·50 |
| 24 | 22·85 | 21·00 |
| 30 | 26·00 | 26·70 |

These Burt sodium cells gave consistent results when cross checked against each other and both potassium and thin film caesium (type C.M.V. 6 of the General Electric Co.) vacuum cells under similar conditions of daylight differing in intensity. We also checked a potassium cell against an arc, and its response was rectilinear up to 140 kl, beyond which we could not go. Burt's own figure for his sodium cell shows a rectilinear response as far as he went, namely up to over 10 kl ; this held both for 10 and 240 volts anode potential, though naturally the higher voltage

* *See* Poole and Atkins, 'J. Mar. Biol. Ass.,' vol. 14, p. 177, Table I (1926).

gave a somewhat greater sensitivity. Though not completely saturated till over 120 volts, we adopted 60 volts for the working potential as a convenient figure ; at this, tests in bright daylight showed that the sensitivity changed only by about 0·2% per volt. This renders of no importance small changes in the anode potential, such as arise through deterioration of the dry cells or accumulators.

For the Bergmann selenium rectifier cell, Weston type, the current-illumination characteristic is curved. We have already discussed the measurement of this curvature and its variation with the resistance of the measuring instrument. Since the cell may give as much as 6 milliamperes in bright daylight we designed a shunt* to reduce the current to 0·2, 0·1, or 0·02, while maintaining the total effective resistance of the shunt and 10 ohms galvanometer circuit at 10 ohms.

## III—The Recording of Vertical Illumination

Alterations in illumination have an obvious bearing on plant growth in air and in water, also upon the phototropic movements of the zooplankton, so we had been for long desirous of a systematic study of the subject. The photographic recording of our galvanometer deflexions was ruled out as too tedious, and the cells available to us in 1927 were too insensitive to permit of a direct recording apparatus such as the Cambridge Instrument Company's "thread recorder," which gives a full scale deflexion for 5 micro-amperes for a resistance of 2000 ohms. The advent of the relatively large and inexpensive Burt sodium cell of high sensitivity in daylight solved the problem for us†. Photographic records were however obtained by Aurén‡ and by Harrison§, while Dorno|| had made prolonged studies of the ultra-violet by means of a cadmium cell and also by photographic records of the spectrum.

Our cell as mounted in a gun-metal case for submarine measurements¶ was placed in position on the front parapet of a flat roof at Plymouth in December, 1929, where it has a free exposure to the sky save for some chimneys to the north-east and north-west, which appear to be quite unimportant. The rubber cables were brought down to the laboratory, where was situated the thread recorder, and the high tension storage batteries to supply 60 volts anode potential. Since then daily records have been obtained with but few intermissions. New lead alloy sheathed cables were provided in November, 1933.

* Poole and Atkins, 'Sci. Proc. R. Dublin Soc.,' vol. 20, p. 537, fig. 1 (1933).

† 'Nature,' vol. 125, p. 305 (1930).

‡ 'Medd. met.-hydr. Anst. Uppsala,' vol. 5, No. 4, 1930 ; and Ark. Mat. Astr., Fys., vol. 24 A, No. 4 (1933).

§ 'Nature,' vol. 125, p. 704 (1930).

|| 'Physik der Sonnen- und Himmelsstrahlung.' Braunschweig, 1911, and Conf. int. Lumière, Lausanne-Leysin, 1928, Paris.

¶ 'J. Mar. Biol. Ass., U.K.,' vol. 17, p. 617, fig. 1 (1931).



PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

This photometer, set with opal surface accurately level, measures V. The opal is cleaned daily and any water which may have got under it, wiped off the plate glass window. Only in mid-winter can our cell be used without a shunt; × 2, × 5, and × 10 shunts are introduced as the intensity increases. One micro-ampere is the current given by 3·8 kilolux mixed daylight on the carbon arc potassium* cell scale, and from the dimensions of the chart it follows that one square centimetre is equivalent to 1·48 kilolux for one hour. The clockwork was altered to give one revolution in exactly 24 hours. This enables one to compare successive days on one chart.

The full scale, unshunted deflexion, is 5 $\mu a$, and is subdivided to 0·1 $\mu a$; each division can be read to 0·1, which is equivalent to 0·01 $\mu a$. The zero is checked from time to time by covering the photometer.

Proofs of the stability of the cell and of the rectilinear relation between its current and the light intensity have already been adduced.

Since the sodium cell has its region of maximum response in the violet, when exposed to daylight it is obviously not ideal for measuring light as it affects the eye.

The stability and high sensitivity of the sodium cell are, however, essential requirements, and the eye is only one special case of biological response to light. Moreover there are such reliable records of total radiation in existence, of which the red and infra-red constitute 59 to 66% around noon in June and December, respectively, that more information is obtainable from a record near the other end of the spectrum. In this violet region the sunlight is from 0·5 to 2·5 times as intense as the skylight. At the red end, however, the sun–sky ratio may be up to 4·5. The changes in the records when the sun is obscured by a small cloud would therefore be much more abrupt were a red-sensitive cell to be used.

As regards its colour sensitivity the selenium rectifier cell now available is a great advance on other cells for measuring visible daylight. Its maximum sensitivity for an equal energy spectrum at around 595 $m\mu$ is not appreciably shifted when used in light of the spectral composition of sunlight, and so remains close to the region of maximum sensitivity of the eye. Since the cell gives about 6 milliamperes in full mixed daylight it is obvious that it would have to be heavily screened to cut down the current so as to reduce the curvature correction, and would have to be used with a recorder constructed with a low resistance galvanometer. That of the standard "thread recorder" is 2000 ohms, with which curvature would be too pronounced. A 20 ohms coil giving a sensitivity of 200 $\mu a$ full scale deflexion could, however, be obtained. The error due to curvature would only amount to slightly under 4% for the full deflexion, and a neutral filter or other simple arrangement might serve to reduce the intensity. PETTERSSON and LANDBERG† have used a recording galvanometer of 266 ohms resistance with a selenium cell to obtain

* Our determinations show that for mixed daylight this is very close to the corresponding sodium cell scale, which is not surprising in view of the similarity of the curves in fig. 1.

† 'Göteborg Vetensk. Samh. Handl.,' vol. 3, No. 7 (1934).

submarine records from a pier. On the pier the curvature error was lessened by the use of a filter reducing the light intensity to 1/25.

To sum up, it may be said that when we started this work in 1929 the Burt sodium cell was the only suitable cell ; it provides information as to the violet, thus supplementing the data supplied by measurements with a thermopile ; the Burt cell has maintained a high degree of constancy, and we know of no other cell that could equal its performance save a large and far more costly potassium cell. Possibly the selenium rectifier cell could be used with a low resistance galvanometer, but its stability over long periods is unknown, and it is subject to temperature errors which are usually in the same direction as the curvature effects.

As previously mentioned, we determined the curvature of the selenium cell, W 21104–2, with great care on the photometer bench. The cell was compared, on the roof of the Plymouth Laboratory on May 1, 1934, in bright mixed daylight, against the vacuum potassium cell in photometer H. The carbon arc scale was used for H, and the whole light has been taken as diffused in each case. For a comparison this assumption only amounts to taking β to be the same for each cell ; this is not strictly correct, but it only comes to a correction on the relative proportions of the current to be multiplied by 1·015 (reflexion loss proper for sun's altitude) and 1·06 (factor for sky), in each case. Table II shows this comparison and the constancy of the ratio.

Table II—Comparison of Potassium Cell, H, and Selenium Cell, S, on Roof, in Bright Mixed Daylight ; Plymouth, May 1, 1934

| H<br>V, in kl | S<br>current in $\mu a$<br>(corrected by curvature) | | S<br>lux per $\mu a$ |
|---|---|---|---|
| 98·5 | 5640 | | 17·46 |
| 99·1 | 5750 | | 17·22 |
| 81·3 | 4700 | | 17·30 |
| 80·9 | 4680 | | 17·28 |
| 80·9 | 4670 | | 17·32 |
| 78·3 | 4456 | | 17·58 |
| | | Mean | 17·36 |

A similar comparison with a sodium cell was also carried out the same day.*

The "mean noon sunlight" (artificial) standardization of the selenium cell (*loc. cit.*) gave 16·4 lux per $\mu a$ for normal incidence. For diffuse skylight this becomes 17·38. The value 17·36 given in Table II is very close to this, and we have adopted 17·4 lux per $\mu a$ as our constant for use in diffuse daylight.

Fig. 2 shows how closely the cells agreed on February 15, 1934, when the constants determined in May are used. Whereas on May 1 the vertical illumination was

* 'Phil. Trans.,' A, vol. 235, p. 20, Table III (1935).

about 90 kl and $\beta = 4$ (almost) by the selenium cell, namely a sun-sky ratio of 3 : 1, on February 15, V ranged from 17 to 4 kl, and $\beta$ was 1·24 to 1·08. Thus the readings of the three cells have given substantially the same measure of daylight over a wide range of illumination from sun and blue sky. It is not, however, claimed that the agreement would be equally close under all other conditions, for example, in some of our Dublin measurements of blue sky light differences were found, probably due to the richness of summer daylight, on certain occasions, in violet and ultra-violet. The sodium cell records also show examples of illuminations up to over 190 kl. These are partly to be explained as above and are partly due to the

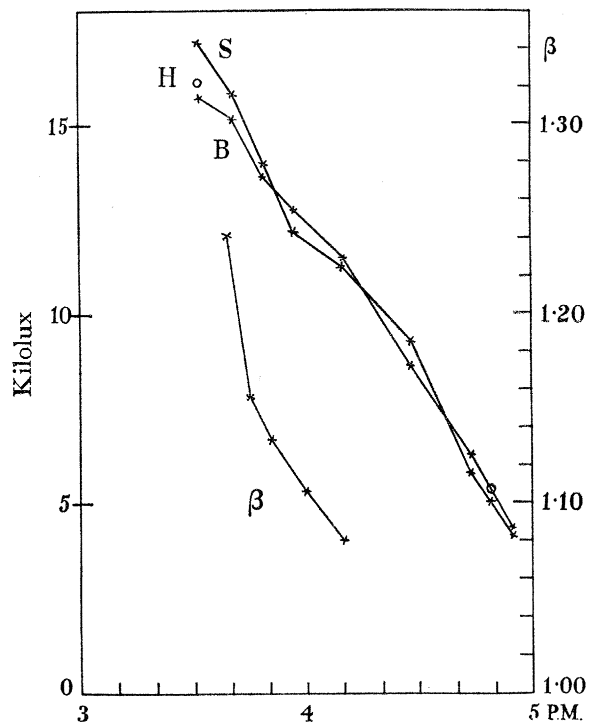



FIG. 2—Curves S and B and observations H represent vertical illumination in kilolux. The abscissae show time from 3–5 p.m. (G.M.T.) on February 15, 1934. Curve S refers to the selenium cell; curve B to the Burt sodium cell and recorder; the two circles denote observations with the potassium cell, photometer H. $\beta$ was determined with the selenium cell.

fact that we made no selenium cell measurements at these outstandingly bright moments; they occur usually after a S.W. gale with heavy rain, when the clear air and large white clouds overhead combine to produce a brief period of very intense vertical illumination.

Turning now to the daily records, it may be seen that the increase in the vertical illumination and the sudden changes it undergoes are very great, far greater than one would suppose from visual observation. The adaptation of the eye, from a moderate illumination of about 16 lux to a bright one, 500–1000 lux, only reduces the area of the pupil to about one-third ; even a very bright illumination, 10 kl, only reduces it to one-fourth. This is an adaptation for lessening the effect of sudden changes, but in addition there is a slower adaptation of the retina, so that even in the brighter light the pupils may relax and increase somewhat in diameter. Out of the very large numbers of records obtained, twenty have been selected to illustrate the daily march of events or special conditions. These are shown in Plates 23–27. With a little practice one can reconstruct the character of each day to a considerable extent from the inspection of the record.

In addition to these recorder charts we give in fig. 3 curves showing the decrease in I, in V and W from before sunset till dark. The time scale has been adjusted so that the disappearance of the upper rim of the sun is the same for all ; that is marked by a horizontal stroke on each curve ; an upper horizontal stroke shows when the sun's disc touches the hills or sea, curve D. The hills were about 50 and 80 m respectively higher than the photometers and were at distances of about 2 and 10 kilometres. Though they cut off all direct sunlight from the photometers yet the general sky illumination was thus fictitiously high for true sunset, which may be taken as being 2 or 3 minutes later. The uncorrected values for sunset are for I, curve A, 2·72 kl, and for the vertical component only, B, 0·87 milliwatt per square centimetre, C, 708 lux and D, 620 lux ; the last was with a potassium cell, A and C with selenium. The mean of the values of V is 664 lux, higher than the value 100–500 lux given in the " Dictionary of Applied Physics," vol. IV. These figures refer apparently to visual determinations made at the National Physical Laboratory, Teddington, near London, so it is not surprising that the clearer air of the sea or coast should give higher readings ; the rapidity of the change in V at sunset is also better measured by the photo-electric method than by any of the visual lamp matching instruments. In addition the general sky illumination must be raised by reflexion from the sea, curve D, or from Plymouth Sound and the sea beyond the hills in the other cases.

At sea 30 minutes after sunset small print could be read when the vertical illumination was 35 lux, but it was only possible to do so with difficulty at 34 min. after sunset with 19 lux. At 41 min. after sunset Jupiter and first magnitude stars could be seen, the illumination being 2·5 lux. Observations ceased 45 min. after sunset with 0·5 lux. The blue quality of the light probably led to the illumination being rather overrated as compared with the visual scale. On January 24, curve A, Venus was visible in the west over where the sun had set while the total illumination was as high as 35 lux at 25 min. after sunset. No stars* could be seen when observations ceased for curve C on February 22, 16 min. after sunset with V, 118 lux.

Fig. 3 shows the rapidity with which V decreases, the values in the period from sunset to about V = 100 lux being for curves D and C, 22 and 38 lux per minute respectively.

* Venus could not have been seen that night.

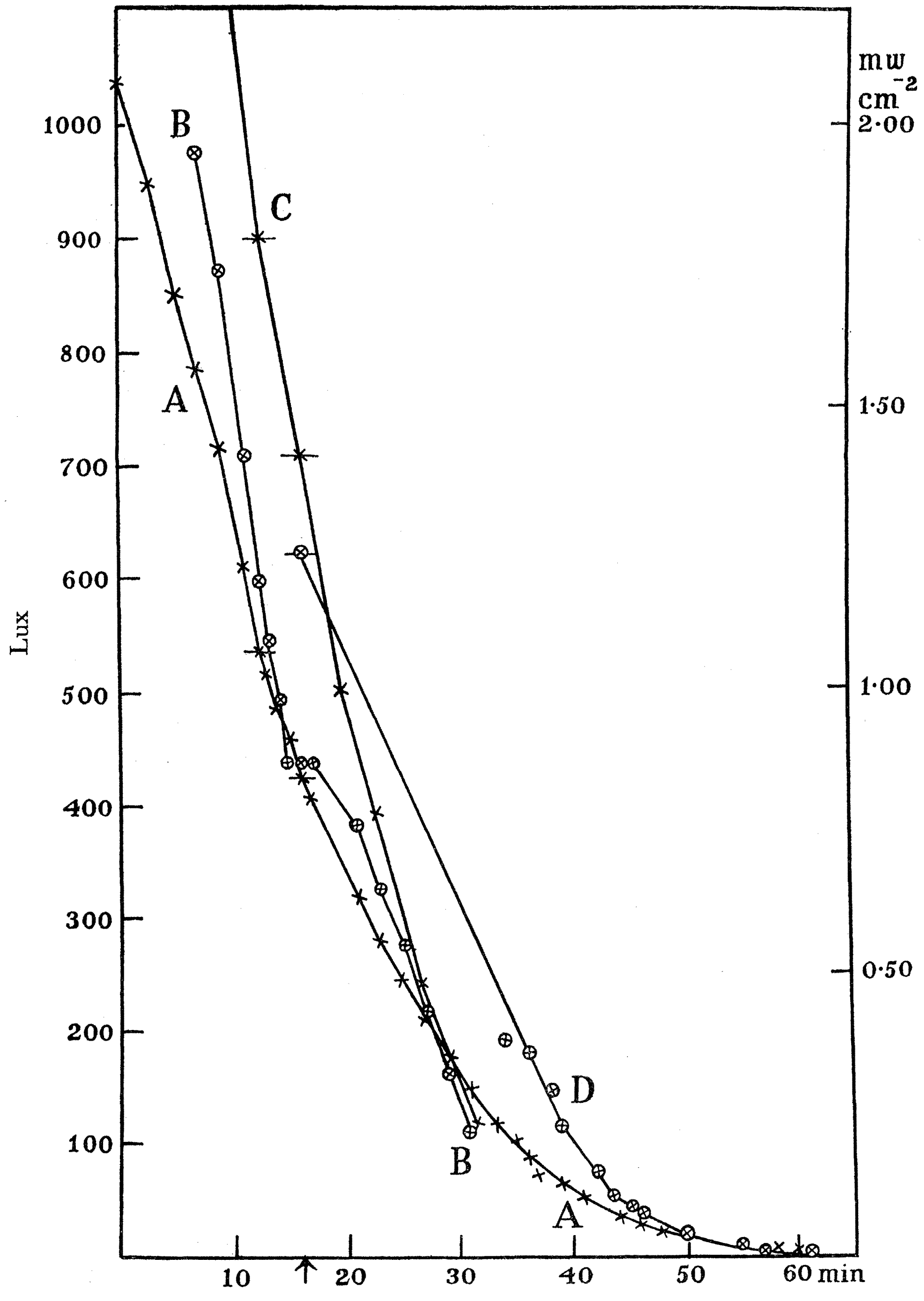



FIG. 3—The left-hand scale shows illumination in lux, for curves C and D this is vertical illumination, but for curve A it is total illumination, and the scale as shown must be multiplied by 6·44; the right-hand scale shows vertical radiation in milliwatts per cm², curve B. The abscissae show time in minutes. The three evenings were clear, almost or quite cloudless; there was a half moon on January 24 and February 22, 1934—curves A (selenium cell, globe photometer) and B (Moll solarimeter) refer to the former and C (selenium cell) to the latter date; observations made on front parapet of flat roof of laboratory at Plymouth. D was obtained on October 3, 1927, on the trawler "Salpa," using a potassium cell. The arrow at 16 minutes marks the disappearance of the sun's upper rim.



PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

## IV—Vertical Illumination Throughout the Year 1930, as Determined with a Sodium Cell

The first "thread recorder" chart obtained was for December 19, 1929. After a few days the clock stopped; records were lost owing to mechanical defects, but it has worked perfectly since February 4, 1930. In order not to lose the complete record for the year, the days missed at the beginning of January were filled in as having the average illumination of the six days following—a value a little too high. This was compensated for by filling in the six days lost at the end of the month as having the average of six previous days, and the three days lost in February as the average of the three following days. If for any reason a day was lost, as from the occurrences of a bad electrical leak in the cable, it was filled in with the value for a similar day, but such approximations are always indicated in the table. Since these lost days were usually wet days with low illumination to leave a blank would vitiate the mean. There were only four such days during 1930.

Table III—Maximum Daily Vertical Illumination in Kilolux for Each Month of Year 1930, as Measured with Sodium Cell (Potassium Cell Carbon Arc Standardization)

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Greatest . | 35·1 | 43·7 | 98·8 | 196·1 | **197·6** | 174·8 | 195·3 | 193·0 | 130·7 | 98·4 | 79·8 | *31·2* |
| Date . | 25 | 28 | 29<br>30 | 27 | 6<br>14 | 24 | 29 | 2 | 10 | 30 | 3 | 11 |
| Least . | 8·7 | 11·8 | 24·9 | 53·2 | 38·0 | 41·8 | 64·6 | **77·1** | 47·5 | 20·9 | 8·6 | *6·9* |
| Date . | 24 | 19 | 6 | 8 | 26 | 10 | 20 | 29 | 17 | 28 | 15 | 6 |
| Mean . | 21·3 | 32·9 | 68·8 | 142·2 | 149·0 | 119·3 | **150·9** | 138·3 | 98·0 | 59·3 | 31·1 | *18·1* |

Table III shows the daily maxima in kilolux for the year. The maximum for the year, 197·6 kilolux, occurred twice in May; April and July come next with 196·1 and 195·3 kl respectively. The least value for the daily maximum was on December 5, 6·9 kl, but darker days have since been recorded. The brightness of April is probably not generally recognized, but it is of great importance, and the vernal diatom maximum in British coastal waters is reached during it. For some reason, as yet unascertained, June gave unexpectedly low values of daily vertical illumination. Several explanations have been put forward tentatively to account for the low values; these are given further on. As regards the least value of the maximum, it is noteworthy that neither July nor August had any day under 64 kl.

Table IV gives the "daily vertical illumination integral" in kilolux hours, as obtained by measuring the curves with a planimeter and making use of the appropriate constants. The yearly range is very great; for 1930 the values ranged from 20·7 kl h (November 28) to 1323 (July 7), namely in the ratio 1 : 64. The mean daily values go from 61·1, December to 781·4 July, the ratio being 1 : 12·8.

TABLE IV—DAILY VERTICAL ILLUMINATION INTEGRAL IN KILOLUX HOURS THROUGHOUT THE YEAR 1930. THE MINIMUM FOR EACH MONTH OR SERIES IS IN ITALICS AND THE MAXIMUM IN HEAVY TYPE

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 61·3* | 135‡ | 259 | 485 | 1131 | 260 | 850 | 508 | 672 | 152 | **317** | 82·9 |
| 2 | 61·3* | 135‡ | 140 | 792 | 796 | 888 | 413 | 744 | **743** | 237 | 255 | 45·0 |
| 3 | 61·3* | 135‡ | 216 | 425 | 1012 | 429 | 995 | 530 | 700 | 175 | 244 | 87·6 |
| 4 | 61·3* | 151 | 169 | 403 | 784 | 818 | 1068 | 895 | 556 | 105 | 207 | 69·9 |
| 5 | 61·3* | 111 | 260 | 555 | 471 | 898 | 1165 | 827 | 296 | 237 | 88·8§ | 37·6 |
| 6 | 61·3* | 143 | *74·0* | 622 | 818 | 672 | 756 | 774 | 280 | 398 | 179 | 31·1 |
| 7 | 49·4 | 164 | 149 | 755 | 722 | 892 | **1323** | 653 | 503 | 266 | 98·6 | 59·2 |
| 8 | 91·3 | 178 | 278 | 430 | 812 | 919 | 608 | 438 | 545 | 177 | 92·9 | 90·3 |
| 9 | 65·3 | 175 | 185 | *234* | 622 | 919 | 1014 | 830 | 300 | 314 | 88·8 | 66·9 |
| 10 | 82·0 | 154 | 292 | 383 | 586 | *209* | 1094 | 354 | 518 | 341 | 121 | 68·4 |
| 11 | 49·9 | 97·4 | 271 | 638 | 736 | 342 | 565 | 610 | 447 | **414** | 170 | 67·5 |
| 12 | *29·9* | 122 | 190 | 527 | 749 | 614 | 1228 | 773 | 454 | 349 | 124 | **93·8** |
| 13 | 63·9 | 125 | 219 | 346 | 293 | 783 | 895 | 407 | 385 | 266 | 142 | 71·0 |
| 14 | 46·8 | 181 | 326 | 997 | 1134 | 635 | 546 | 784 | 435 | 94 | 165 | 80·8 |
| 15 | 76·2 | 179 | 456 | 493 | 664 | 669 | 506 | 410 | 540 | 94§ | 38·8 | 52·1 |
| 16 | 82·1 | 201 | 353 | 820 | **1188** | 829 | 795 | **1023** | 250 | 240 | 42·9 | 42·0 |
| 17 | 103 | 196 | 151 | 749 | 583 | 604 | 1006 | 340 | 277 | 243 | 93·8 | 49·0 |
| 18 | 50·3 | 187 | 314 | 622 | 950 | 821 | 774 | 466 | 632 | 297 | 39·7 | 32·7 |
| 19 | 75·5 | *45·6* | 407 | 718 | 503 | 778 | 767 | 855 | 515 | 259 | 85·0 | 37·9 |
| 20 | 124 | 93·6 | 358 | 573 | 937 | 249 | *215* | 617 | 357 | 210 | 64·2 | 47·4 |
| 21 | **145** | 119 | 561 | 580 | 466 | 290 | 641 | 629 | 376 | 247 | 35·2 | 77·4 |
| 22 | 45·9 | 70·0 | 432 | **1230** | 343 | 1060 | 699 | 995 | *203* | 155 | 92·6 | 69·9 |
| 23 | 99·9 | 80·0 | 194 | 586 | 924 | 802 | 481 | 657 | 296 | 160 | 113 | 37·1 |
| 24 | 103† | 133 | 556 | 429 | 647 | 839 | 431 | 879 | 675 | 234 | 88·8§ | 45·7 |
| 25 | 103† | 51·5 | 426 | 364 | 644 | **1206** | 867 | 889 | 636 | 216 | 58·3 | *28·3* |
| 26 | 103† | 207 | 595 | 1220 | *249* | 884 | 456 | 478 | 505 | 260 | 74·9 | 66·5 |
| 27 | 103† | 106 | 156 | 1221 | 758 | 741 | 781 | 733 | 289 | 114 | 95·9 | 74·7 |
| 28 | 103† | **257** | 189 | 1123 | 832 | 887 | 759 | 598 | 431 | *88·8* | *20·7* | 59·9 |
| 29 | 103† | — | 465 | 1114 | 1043 | 749 | 709 | *295* | 289 | 101 | 42·6 | 81·0 |
| 30 | 103† | — | **717** | 1027 | 503 | 1054 | 784 | 598 | 406 | 353 | 61·2 | 80·7 |
| 31 | 103† | — | 459 | — | 392 | — | 1020 | 616 | — | 360 | — | 59·6 |
| Mean | 82·1 | 140·5 | 315·2 | 682·3 | 719·3 | 725·2 | 781·4 | 652·5 | 450·0 | 230·9 | 111·6 | 61·1 |
| Max. | 145 | 257 | 717 | 1230 | 1188 | 1206 | 1323 | 1023 | 743 | 414 | 317 | 93·8 |
| Min. | 29·9 | 45·6 | 74·0 | 234 | 249 | 209 | 215 | 295 | 203 | 88·8 | 20·7 | 28·3 |

* Average of six following figures.
† Average of eight preceding figures.
‡ Average of three following figures.
§ Bad leak, figure for similar day substituted.

Though the daily maxima are of interest, yet as far as plant growth is concerned the integrated values given in kilolux hours are more important, since in them the effect of increase in length of the day is taken into account. Fig. 4 shows the monthly values expressed as a percentage of the total value for the year. The percentages are also shown in Table V, where they are compared with the radiation as measured in

London and with the Plymouth sunshine records. One would have expected June to head the list, but it may be seen that May is slightly, and July considerably, higher. It will be of great interest to see how the values for the records obtained in subsequent years come out. The obvious explanation for the low value in June would be that the sunshine was also low ; it was, however, well above the average, an excess of 14·6 hr, whereas May, a brighter month, was 59·2 hr below the average, and July, the brightest month, was 7·0 hr below. The solution of the problem appears to lie in the character of the sky and its powers of reflexion and transmission.

It is of interest to compare the figures shown in Table V for the percentage of the annual illumination integral, as recorded in kilolux hours, occurring in each month,

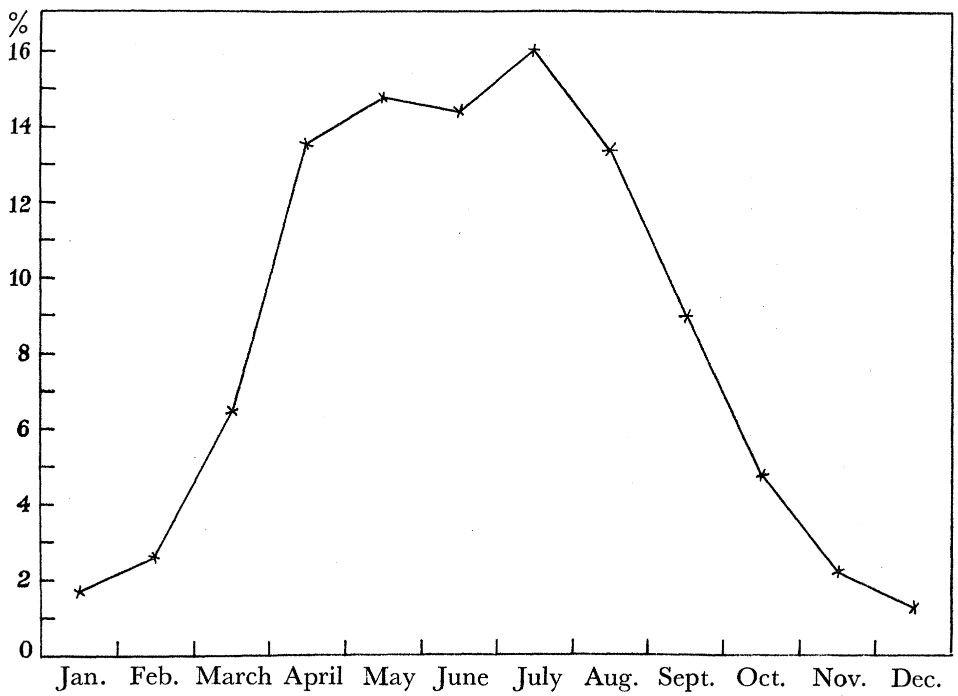



Fig. 4—The ordinates denote percentages and the abscissae months. The curve shows the percentage of the annual vertical illumination integral reckoned in kilolux hours, received during each month. The unequal lengths of the months affect these values.

with figures for the radiation as recorded similarly in joules per square centimetre. Since such data are not in existence for Plymouth, we have shown those obtained with the Callendar recorder in London (S. Kensington) in nearly the same latitude as Plymouth, 51·5° and 50·4°, respectively. These figures are for 1930, and for the average over eight years. For them we are indebted to the Superintendent of the Meteorological Office and to Dr. F. J. W. Whipple, of Kew Observatory, who drew our attention to the agreement between the sets of figures, which is surprisingly close for the eight year mean during the winter months. The actual figures for 1930 are, however, in some months widely divergent ; thus while vertical illumination and total vertical radiation are tolerably concordant in January, February, July, September and November, there is wide divergence in April, 13·58 and 8·67% respectively, and in October, 4·74 and 6·35%. Only in August were the monthly maxima on the same date; in June, September, and November the minima coincided. When one considers that skylight and clouds play such a large part in

TABLE V—MEASUREMENTS OF VERTICAL ILLUMINATION INTEGRAL WITH BURT VACUUM SODIUM CELL COMPARED WITH HOURS OF SUNSHINE, BOTH AT PLYMOUTH, AND WITH VERTICAL TOTAL RADIATION AT LONDON (S. KENSINGTON) AS MEASURED WITH CALLENDAR RECORDER FOR 1930, ALSO FOR MEAN OF EIGHT YEARS

| | Vertical illumination integral at Plymouth, 1930 | | Vertical radiation, London | | | Sunshine at Plymouth | | |
|---|---|---|---|---|---|---|---|---|
| | Daily mean in kilolux hours | % annual total kl. hr. | Daily mean 1930 joules/cm² | % annual total 1930, joules/cm² | Mean % annual total joules/cm² | Hours for 1930 | % annual total 1930 | % normal value 1881-1915 |
| Jan. | 82·1 | 1·68 | 158 | 1·93 | 1·77 | 46·0 | 2·88 | 3·18 |
| Feb. | 140·5 | 2·60 | 240 | 2·64 | 3·47 | 98·9 | 6·18 | 4·70 |
| Mar. | 315·2 | 6·47 | 650 | 7·91 | 6·32 | 127·6 | 7·98 | 7·98 |
| April | 682·3 | 13·54 | 736 | 8·67 | 10·53 | 169·6 | 10·60 | 10·48 |
| May | 719·3 | 14·76 | 1092 | 13·29 | 15·89 | 157·8 | 9·86 | 13·01 |
| June | 725·2 | 14·40 | 1416 | 16·66 | 16·59 | 225·6 | 14·10 | 12·65 |
| July | 781·4 | 16·03 | 1261 | 15·36 | 13·96 | 205·0 | 12·81 | 12·69 |
| Aug. | 652·5 | 13·38 | 1225 | 14·92 | 12·76 | 187·9 | 11·75 | 11·86 |
| Sept. | 450·0 | 8·93 | 741 | 8·72 | 9·70 | 161·0 | 10·06 | 9·58 |
| Oct. | 230·9 | 4·74 | 521 | 6·35 | 5·19 | 98·3 | 6·14 | 6·74 |
| Nov. | 111·6 | 2·22 | 210 | 2·46 | 2·43 | 66·4 | 4·15 | 4·19 |
| Dec. | 61·1 | 1·25 | 90 | 1·09 | 1·39 | 55·9 | 3·49 | 2·94 |
| Year, totals | 151,076·0 | 100·00 | 254,880 | 100·00 | 100·00 | 1600·0 | 100·00 | 100·00 |

determining the magnitude of the illumination it is rather remarkable that the correspondence is even as close as it is between the two sets of records, for the violet and the total spectrum. If we take the figures for the whole year in each case and assume that the radiation is the same at Plymouth and London—which is certainly to rate London rather too high—we find that one kilolux hour is equivalent to 1·69 joules per square centimetre; this is equal to 0·404 g. cal. We hope to consider the relation between illumination and radiation more adequately in another paper.

## V—THE RATIO OF SUNLIGHT TO SKYLIGHT THROUGHOUT THE YEAR

We have already, in the course of our measurements of submarine illumination, given values for the ratio β, at various times. Further, in another paper,* we have shown how β is greater when one measures the longer wave-lengths, since skylight is predominantly blue. Table VI now gives the values of $V_s/V_d$ and of $I_s/V_d$ as

* 'Sci. Proc. R. Dublin Soc.,' vol. 20, p. 13, Tables IX and X (1931).

TABLE VI—THE RATIO OF SUNLIGHT, RECEIVED ON A HORIZONTAL PLANE OR NORMALLY, TO SKYLIGHT RECEIVED ON A HORIZONTAL PLANE

| Date | Local time | Sun $\alpha°$ | $V_d$ kl | $V_s$ kl | $I_s$ kl | $\frac{V_s}{V_d}$ | $\frac{I_s}{V_d}$ | Sun-shine, hours | Wind at 1 p.m., direction and force | Sky |
|---|---|---|---|---|---|---|---|---|---|---|
| 19/12/29 | 11·46 | 14·5 | 12·5 | 7·73 | 30·9 | 0·62 | 2·46 | 7·3 | S.S.W., 6 | N |
| 8/2/30 | 11·59 | 24·4 | 22·1 | 13·5 | 32·6 | 0·61 | 1·48 | 8·1 | N.E., 5 | Bc |
| 9/2/30 | 11·42 | 24·5 | 22·1 | 17·8 | 43·0 | 0·81 | 1·95 | 7·1 | E., 5 | — |
| 9/2/30 | 12·13 | 24·5 | 23·0 | 17·2 | 41·5 | 0·75 | 1·81 | 7·1 | E., 5 | — |
| 17/2/30 | 11·52 | 27·5 | 20·1 | 19·7 | 42·6 | 0·98 | 2·12 | 8·2 | E.N.E., 3 | — |
| 18/2/30 | 9·41 | 18·2 | 17·1 | 10·8 | 34·6 | 0·63 | 2·02 | 6·7 | N.E., 5 | VB |
| 18/2/30 | 11·44 | 27·7 | 22·9 | 18·6 | 40·0 | 0·81 | 1·74 | 6·7 | N.E., 5 | CC |
| 18/2/30 | 1·52 | 22·9 | 15·1 | 12·2 | 31·4 | 0·67 | 1·73 | 6·7 | N.E., 5 | C |
| 28/2/30 | 11·0 | 30·2 | 29·8 | 16·1 | 32·0 | 0·51 | 1·02 | 9·2 | E.N.E., 4 | BcH |
| 28/2/30 | 1·30 | 28·2 | 33·5 | 17·2 | 36·4 | 0·50 | 1·05 | 9·2 | E.N.E., 4 | BcH |
| 1/3/30 | 10·30 | 29 | 22·2 | 18·9 | 38·9 | 0·85 | 1·75 | 8·8 | E.N.E., 5 | N |
| 1/3/30 | 12·0 | 32 | 23·7 | 23·3 | 43·7 | 0·99 | 1·85 | 8·8 | E.N.E., 5 | VB |
| 10/3/30 | 10·47 | 34 | 27·0 | 32·7 | 58·5 | 1·21 | 2·17 | 6·9 | N.N.W., 5 | CC |
| 10/3/30 | 11·37 | 35 | 27·9 | 35·2 | 61·1 | 1·26 | 2·19 | 6·9 | N.N.W., 5 | CC |
| 15/3/30 | 11·54 | 37 | 34·8 | 51·8 | 68·2 | 1·49 | 2·48 | 7·4 | S.W., 2 | C |
| 21/3/30 | 11·46 | 39·5 | 31·8 | 58·1 | 91·4 | 1·83 | 2·87 | 6·9 | S.S.W., 4 | C |
| 24/3/30 | 11·39 | 40·5 | 35·0 | 43·7 | 67·7 | 1·25 | 1·94 | 10·8 | N.E., 4 | Bc |
| 24/3/30 | 12·7 | 40·7 | 34·6 | 51·4 | 78·8 | 1·49 | 2·28 | 10·8 | N.E., 4 | Bc |
| 24/3/30 | 2·7 | 33·8 | 31·5 | 39·3 | 70·7 | 1·25 | 2·25 | 10·8 | N.E., 4 | Bc |
| 24/3/30 | 3·37 | 30·1 | 25·9 | 13·7 | 27·3 | 0·53 | 1·05 | 10·8 | N.E., 4 | Bc |
| 25/3/30 | 12·52 | 41·1 | 39·6 | 45·9 | 69·9 | 1·16 | 1·77 | 2·0 | S.W., 3 | CC |
| 22/4/30 | 11·49 | 52·0 | 53·3 | 114·0 | 144·7 | 2·14 | 2·71 | 12·9 | S.E., 4 | N |
| 29/4/30 | 11·41 | 53·7 | 48·9 | 101·4 | 125·8 | 2·07 | 2·57 | 13·0 | N.E., 5 | N |
| 30/4/30 | 8·36 | 35·2 | 31·1 | 59·6 | 103·2 | 1·92 | 3·32 | 13·3 | — 0 | N |
| 30/4/30 | 11·16 | 53·2 | 41·4 | 92·9 | 116·2 | 2·24 | 2·81 | 13·3 | — 0 | N |
| 30/4/30 | 11·51 | 54·4 | 44·8 | 92·5 | 113·6 | 2·12 | 2·54 | 13·3 | — 0 | c |
| 30/4/30 | 12·51 | 53·0 | 43·3 | 88·1 | 110·3 | 2·04 | 2·55 | 13·3 | — 0 | cH |
| 1/5/30 | 7·16 | 23·3 | 25·5 | 31·5 | 79·6 | 1·23 | 3·12 | 13·0 | S.S.W., 4 | N |
| 1/5/30 | 8·16 | 32·3 | 32·2 | 51·8 | 96·9 | 1·61 | 3·01 | 13·0 | S.S.W., 4 | N |
| 1/5/30 | 9·16 | 41·0 | 35·2 | 73·6 | 112·1 | 2·10 | 3·19 | 13·0 | S.S.W., 4 | N |
| 1/5/30 | 9·46 | 45·0 | 38·1 | 81·4 | 115·1 | 2·14 | 3·02 | 13·0 | S.S.W., 4 | N |
| 1/5/30 | 10·16 | 48·5 | 42·2 | 91·4 | 122·1 | 2·17 | 2·89 | 13·0 | S.S.W., 4 | N |
| 1/5/30 | 10·46 | 51·5 | 64·0 | 79·2 | 101·0 | 1·24 | 1·58 | 13·0 | S.S.W., 4 | c |
| 1/5/30 | 11·16 | 53·5 | 57·7 | 99·5 | 124·0 | 1·72 | 2·15 | 13·0 | S.S.W., 4 | c |
| 1/5/30 | 11·51 | 54·7 | 55·9 | 111·7 | 136·9 | 2·00 | 2·45 | 13·0 | S.S.W., 4 | c |
| 5/6/30 | 9·0 | 45·5 | 30·3 | 47·0 | 65·9 | 1·55 | 2·17 | 14·6 | E.S.E., 4 | N |
| 5/6/30 | 11·30 | 61·0 | 33·7 | 77·3 | 88·4 | 2·30 | 2·63 | 14·6 | E.S.E., 4 | N |
| 5/6/30 | 3·25 | 41·7 | 25·5 | 44·0 | 66·2 | 1·73 | 2·59 | 14·6 | E.S.E., 4 | N |
| 18/6/30 | 11·50 | 62·5 | 53·7 | 93·6 | 105·8 | 1·75 | 1·97 | 9·9 | S.W., 2 | N |
| 30/6/30 | 11·30 | 61·5 | 35·2 | 94·7 | 108·0 | 2·70 | 3·08 | 10·6 | S., 3 | N |
| 7/7/30 | 11·43 | 61·7 | 37·0 | 113·6 | 126·2 | 3·07 | 3·41 | 14·6 | N.W., 3 | N |
| 7/7/30 | 2·3 | 53·3 | 40·3 | 94·0 | 117·3 | 2·33 | 2·91 | 14·6 | N.W., 3 | N |
| 7/7/30 | 3·38 | 40·8 | 29·4 | 70·7 | 108·0 | 2·40 | 3·67 | 14·6 | N.W., 3 | N |
| 3/9/30 | 12·51 | 45·8 | 26·6 | 73·3 | 102·1 | 2·75 | 3·83 | 8·9 | E., 5 | N |
| 3/9/30 | 1·19 | 43·8 | 35·2 | 65·5 | 94·7 | 1·86 | 2·70 | 8·9 | E., 5 | c |
| 3/9/30 | 1·49 | 41·3 | 26·6 | 63·6 | 96·6 | 2·39 | 3·62 | 8·9 | E., 5 | c |
| 3/9/30 | 2·19 | 38·2 | 25·9 | 57·4 | 92·9 | 2·22 | 3·59 | 8·9 | E., 5 | BC |
| 3/9/30 | 3·49 | 26·0 | 19·6 | 6·29 | 14·4 | 0·32 | 0·73 | 8·9 | E., 5 | BC |

Almost cloudless = N. Clouds small, c or cc; large, C or CC. Sky blue, B or very blue VB. Haze, H determined from the thread recorder charts, namely with a cell giving its maximum response in daylight at 410 $m\mu$.

It may be seen that in general $V_d$ increases with the sun's altitude as $V_s$ obviously does. $V_d$ ranges between 12·5 and 64·0 kl in the middle of the day for the clear days on which such determinations were possible and were actually made. $V_d > 50$ kl was, however, recorded five times; $V_d$, 40–50 kl six times; $V_d$, 30–40 sixteen times and $V_d$, 20–30 kl seventeen times; $V_d < 20$, four times out of 48 observations. Thus in approximately 70% of the observations $V_d$ was 20 to 40 kl.

The vertical component of the sun's light, $V_s$, naturally increases with $\alpha$; but it increases for a second reason also, namely because it suffers less scattering since its path through the atmosphere is decreased. One would therefore expect to find the maximum value of $V_s$ when $\alpha$ was a maximum. But the highest values of $V_s$, 114, followed by 113·6 and 111·7 kl, were found with $\alpha$, 52·0°, 61·7°, and 54·7° respectively, 62·5° being the highest value tabulated. The differences become even more striking when one eliminates the purely geometrical effect by considering $I_s$, when we get 114·7, 126·2, and 136·9 kl for the same observations, respectively, with three other values over 120 kl. It is obvious, accordingly, that there are variations in the transmission of the atmosphere, $f$, for $I_s/f^{\operatorname{cosec}\alpha}$ could not be a constant with almost the same value of $V_s$ at 52° and at 61·7°. ABBOT, FOWLE, and ALDRICH* give values for the transmission of the solar spectrum at Washington; these are average values for cloudless (but not necessarily hazeless) days and give, by interpolation, 0·552 for $f$ at 410 $m\mu$.

In regions where the conditions are sufficiently uniform to enable the absorption of the entire atmosphere to be deduced from measurements of the sun's radiation, made at different solar altitudes, we might evidently employ a photo-electric cell with suitable filters to find this absorption for various parts of the spectrum. The method would evidently have considerable advantages for all regions of the spectrum to which photo-electric cells are sensitive. The irregularities exhibited in our measurements show, however, that climatic conditions in these islands are as a rule insufficiently stable to enable reliable measurements of atmospheric absorption to be made in this way.

It may be seen from Table VI that not till the beginning of March is $V_s > V_d$. The maximum value of the sun–sky ratio shown here is 3·07, in July. With other Burt cells, in which a yellow stain acted as a partial minus blue filter and raised the average effective wave-length, values close to 4 have been obtained.

Even in mid-winter $I_s/V_d$ may be as high as 2·5, but the highest values observed were 3·6–3·83 in September.

## VI—THE VARIATION IN THE VERTICAL ILLUMINATION FOR A SOLAR ALTITUDE OF 45°

AURÉN† has found the *average* values for the illumination with a clear sky to be very constant. He considers that for 1928 these have probable errors of 1·2% only.

* 'Astrophys. J.,' vol. 34, p. 197 (1911).
† 'Medd. Met. hydr. Anst. Uppsala,' vol. 5, No. 4 (1930).

Accordingly as his unit for daylight he adopted the "*average value for illumination from sun and sky of a horizontal surface at 45° solar altitude, clear sky and free horizon.*" The unit thus defined is denoted by $E_s$, and the amount of light received in one hour is measured in $E_s$ H units. His photo-electric cell was of the vacuum potassium type. The cell was mounted under a 5 mm plate of yellow-green glass (Schott F. 5899, now listed as GG.11). DORNO* considers that this combination gives a sensitivity curve which is approximately equivalent to that of the eye, but it is quite insensitive to red. The outer covering was a de-polished plate of opal glass. AURÉN† has presented further data extending over the years 1928–1932 inclusive. With a total of 69 observations with $\alpha = 46°$ and 80 at $\alpha = 44°$, the annual mean values for these altitudes are in $E_s$ units 1·021 and 0·979, with extremes 1·017 to 1·024 and 0·976 to 0·983 respectively. No figures are given for the individual measurements, so one cannot see how much any individual observation was astray. AURÉN, however, appears to regard the method as more reliable than a lamp standardization, and of great value for ecological work in which a knowledge only of the altitude and a measurement with a clear sky suffice to calibrate the photometer in $E_s$ units. Apparently by clear days AURÉN means those which are cloudless or nearly so. He tested his generalization that this unit ($E_s$) should be the same over the Scandinavian peninsula by measurements at Luleå (65° 37′ N) as well as near Stockholm (59° 23′ N). Calculation of the average values for the illumination on clear days showed that the $E_s$ unit was the same at both stations. For the ultra-violet, however, a difference in intensity was found to exist, which depended upon the height above sea level.

In order to test the constancy of such a unit the records obtained on sunny days with the sodium cell and thread recorder were examined, and are summarized in Table VII. In it are included days which had some clouds in the sky. It is obvious

TABLE VII—ALL VALUES HERE REFER TO THE VERTICAL ILLUMINATION IN KILOLUX, WITH SUN AT 45° ($E_s$ UNIT); MONTHLY MINIMUM MEAN AND MAXIMUM VALUES OF THESE ARE GIVEN, ALSO SIMILAR YEARLY VALUES FOR ALL DAYS AND FOR CLOUDLESS DAYS

| Month | 45° a.m. No. of obs. | Min. | Mean | Max. | 45° p.m. No. of obs. | Min. | Mean | Max. |
|---|---|---|---|---|---|---|---|---|
| April | 7 | 84·7 | 122·6 | 137·9 | 7 | 94·6 | 122·6 | 146·7 |
| May | 3 | 88·5 | 110·0 | 119·7 | 4 | 126·9 | 130·4 | 136·8 |
| June | 9 | 62·7 | 80·3 | 105·6 | 12 | 74·1 | 86·0 | 98·0 |
| July | 5 | 91·2 | 107·2 | 114·0 | 6 | 88·5 | 104·4 | 115·9 |
| August | 4 | 82·1 | 105·6 | 123·5 | 5 | 79·0 | 107·1 | 131·5 |
| September | 4 | 82·1 | 88·5 | 93·5 | 4 | 85·9 | 93·2 | 98·8 |
| Year | 32 | 62·7 | 100·4 | 137·9 | 38 | 74·1 | 103·9 | 146·7 |
| | | | (All days) | | | | | |
| Year | 17 | 70·3 | 100·0 | 125·4 | 27 | 74·1 | 97·8 | 127·7 |
| | | | (Cloudless days) | | | | | |

* 'Met. Z.,' vol. 240 (1924).

† 'Ark. Nat. Astr. Fys.,' vol. 24–29, No. 4 (1933).





PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

that no great constancy is shown in the illuminations at 45° altitude; the monthly averages show wide variations, which are quite inexplicable in terms of the mid-day wind observations or of cloud effects. Even the April observations among themselves are hard to explain—low values on 11th, high on 14th and subsequently. A consideration of the local sunshine and wind observations and of the European pressure system at 8 a.m. on each morning of the month failed to bring out any further explanation, nor was cleansing of the air by rain a valid explanation. The pressure map showed, however, that the general air movement was on all these April dates from a northerly direction, including north-east, which would be seen likely to bring down smoke from the industrial areas of England, though more seems to come from the east. Out of the forty-two days on which observations were possible the wind had some south in it on thirty, but some high illuminations were found on the clear days with northerly winds. Purely local smoke contamination of the air is only serious in calm weather, and the one day with no wind, April 30, showed no specially low values, though the afternoon was markedly lower than the morning. The position of the photometer on the front parapet of a roof about 30 m above the sea and overlooking it is a specially favourable one. The afternoon values are in the aggregate slightly higher than those of the morning, but the relation is reversed when cloudless days only are considered. The general average is but little altered by the exclusion of days with some clouds, but the range of variation is reduced considerably.

When one considers the monthly mean values there appears a remarkable grouping. Values for April and May are notably high, while June is remarkably low. The earth is of course in aphelion early in July and in perihelion early in January, but this variation in the square of the solar distance only causes a 7% increase in January as compared with July, and is accordingly quite inadequate as an explanation.

Table VIII shows measurements made with a selenium cell with sun at or near 45°. The results are low, lower even than the June, 1930, values obtained with the sodium cell (Table VII), but the one observation with the sodium cell is higher than the mean for 1930, even allowing for $\alpha$ being 45·5°. One cannot consider these few results as showing any great constancy in spite of the general similarity of the weather conditions. The large difference between the sodium and selenium cells was chiefly due to the blue light from the summer sky which was about 2·5 times as bright here, according to the sodium cell. Under certain atmospheric conditions the transmission of the short waves which affect the sodium cell appears to be exceptionally high.

Dorno* states that the intensity of the sun's radiation at Davos, received normally, is never a maximum when the sun is at its greatest altitude; the annual maximum occurs in the spring, in March or April; even the clear autumn days do not have such a powerful sun. This, however, may probably be explained by the water-vapour

* 'Davos Inst. for Alpine Physiol. and Tuberculosis Res.' Pt. I, 33. Brunswick (1924).

content of the air. Again, volcanic eruptions have on occasion produced marked effects upon the radiation received at widely different places on the earth's surface, as for example those due to the eruption of Mt. Katmai, in Alaska, on June 6 and 7, 1912. The effect reached its maximum in August when the total direct radiation

Table VIII—Determinations of the $E_s$ unit, made upon the buildings of the Royal Dublin Society, on eastern edge of Dublin city. Upper roof has entirely free exposure; lower roof has low angle obstructions all round, but these reflect some light. Selenium cell used save in last line of table, which shows results with sodium cell. Sun and sky clear

| June, 1934 | G.M.T. | $\alpha$ | Roof | Sun, kl | Sky, kl | Total = $E_s$ |
|---|---|---|---|---|---|---|
| 1 | 3·13 | 45° 0′ | Lower | — | — | 68·3 |
| 2 | 9·31 | 45° 0′ | Upper | 33·8 | 34·7 | 68·5 |
| 4 | 3·21 | 44° 20′ | ,, | 64·9 | 17·3 | 82·2 |
| 11 | 3·20 | 45° 10′ | Lower | 54·9 | 20·9 | 75·8 |
| 4 | 3·12 | 45° 30′ | Upper | 76·1 | 44·9 | 121·0 |

of the sun was reduced by nearly or quite 20%.* Alterations in the anti-rachitic ultra-violet, shown by Dobson and his partners to be due to absorption by a variable amount of ozone, must be very nearly without effect upon our sodium photometer, and entirely without effect upon the selenium cell.

There is also the possibility that variations in the sun's radiation may have some part in such changes as have here been observed, more especially those relating to the variations in the violet. It is known from the work of Abbot† and his co-workers at Mt. Wilson that such variations exist, up to 5–10% in the radiation of the total spectrum and in irregular periods of 5–10 days. It is possible that this effect may be more pronounced in the short wave-lengths.

Aurén gives his $E_s$ unit as 131 kl, based on the Hefner unit and his standardization of his cell, with filter, against a gas-filled lamp. His value, 118 kl on the international candle basis, materially exceeds the values obtained by others under similar conditions, but these other values are, according to Aurén, not at all concordant. It seems probable that the filter used may not cope adequately with the great preponderance of yellow and red light in the gas-filled lamp, as compared with daylight, since the function of a yellow-green filter on a potassium cell is to reduce its blue sensitivity, but naturally it remains quite insensitive to red. Our own average value for the $E_s$ unit is 102 kl, on the basis of all values in Table VII, or taking the cloudless days only 99 kl; these are, of course, as ascertained with the sodium cell standardized against the potassium arc scale and the selenium mean noon sunlight scale, which

* Abbot, Fowle and Aldrich, 'Ann. Astrophys. Obs., Smithson. Inst.,' vol. 3, p. 229 (1913).

† 'Ann. Astrophys. Obs., Smithson. Inst.,' vol. 3, p. 14 (1913).

give identical values in bright mixed daylight as shown in our Table III.* A determination of the 45° illumination on the roof at Plymouth on May 1, 1934, using the selenium cell gave 79·5 kl, which though rather low exceeds twelve of the values grouped in Table VII, and lies among the Dublin values for the selenium cell in Table VIII. The mean of the five selenium cell determinations of $E_s$ is 74·9 kl. The June values with sodium cell average 83·1.

## VII—Horizontal Illumination

Horizontal illumination is what affects our eyes in their normal position, and for diffuse light we may note that $V_d = 2H_d$, and where $H_s$ refers to a vertical surface set in azimuth normal to the plane of the sun's rays, $V_s \operatorname{cosec} \alpha = H_s \sec \alpha = I_s$. For known conditions, therefore, $H_s$ and $H_d$ can always be calculated from $V_s$ and $V_d$, but we must not forget that whereas $V = V_s + V_d$, $H = H_s + H_d + H_r$, and $H_r$ may be quite considerable, as for example, over snow or at sea. Measurements of $\overline{H}$, viz., $H_d + H_r + H_s/\pi$, were made at sea by means of uranium oxalate tubes†, and $\overline{H}_{calc.}$ was obtained from V, using the same potassium cell employed in the calibration of the uranyl oxalate tubes and neglecting the reflected light. The ratio $\overline{H}/\overline{H}_{calc.}$ varied from 1·52 to 1·11, between July and October, and was 1·19 on November 30, with V = 7·3 kilolux, as against V = 118 kl in July. There was a general tendency for the ratio to fall as the sunlight decreased in intensity ($\beta = 1 \cdot 0$ on November 30), due, it seems, partly to a decrease in the violet and ultra-violet and partly to a fall in the sensitivity of the uranyl oxalate solution with fall in temperature.

## VIII—The Globe Integrating Photometer and Total Illumination

A photometer of this type has been described by Bennett.‡ The receiving surface is a wide mouthed opal flask, inside which is another flask, necessarily much smaller. Below the mouth of this the aperture of an emission cell is placed. By moving the inner flask up and down a position could be found such that the resulting current from the cell was independent of the altitude or azimuth of the illumination. On this model but using a more sensitive potassium-hydride neon-filled cell Hill§ was able to get sensitivity adequate for the operation of the Cambridge thread recorder, so that records of the total illumination were obtained. The small size of the diameter of neck of the inner flask limits the effective aperture of the cell, so a different type was evolved as follows.

* 'Phil. Trans.,' A, vol. 235, p. 1 (1935).

† 'Sci. Proc. R. Dublin Soc.,' vol. 19, p. 321 (1929).

‡ 'Proc. Phys. Soc.,' Lond., vol. 40, p. 316 (1928).

§ 'Photo-electric Cells and their Applications,' Phys. and Opt. Soc. Joint Discussion; p. 138, London (1930).

An opal globe with a metal seat or "gallery" 9·5 cm high was obtained; this globe was 15·2 cm in diameter, with aperture 6·8 cm in diameter, such as is ordinarily supplied for holding an electric lamp, the globe being fixed in the gallery by three screws. Inside the gallery a rectifier selenium cell was set, with its opal disc horizontal; the leads ran down the neck of the gallery. The globe was then placed in position and illuminated with a test lamp run at carefully controlled voltage, and mounted in a metal cup, so that the sensitivity of the arrangement could be tried at various altitudes and azimuths. The constancy was not, however, satisfactory. An additional diffusing surface was then introduced, using an opal hemisphere, 6·4 cm in diameter, which just fitted over the opal disc above the cell which was 6·3 cm; the diameter of the sensitive surface of the Weston cell was 4·0 cm. For this hemisphere one end of an old Ediswan "Fullolite" electric lamp bulb served. Volatilization of the tungsten filament had darkened the bulb, but it was cleaned by immersing in potassium nitrate fused in a platinum crucible.

The diffusing surfaces now were (*a*) the opal glass globe, (*b*) the thin opal hemisphere, (*c*) the surface flashed opalized plate. On testing with the lamp the current from the cell was found to be sensibly constant and quite independent of the altitude and azimuth of the lamp. Small and irregular variations were found, due apparently to lack of uniformity in the globe; these were of no practical importance, especially as they were more numerous and larger near the rim of the globe than elsewhere, namely in the region which received only the relatively unimportant light reflected upwards. The optical arrangements having been thus perfected, the cell was bedded down on a bituminous insulating compound and the gallery mounted on a suitable wooden base. This could be weighted down when the globe photometer was exposed on the parapet of the flat roof of the Laboratory at Plymouth.

It was not possible to standardize this globe photometer on a photometer bench because of the uncertainty as to the distance from source to photometer, owing to the curvature of the latter. An approximate value could of course be obtained, using a special source of high intensity and operating at a distance relatively great as compared with the radius of the globe. It seemed preferable, however, to standardize in the open air by direct sunlight as follows.

The globe photometer was set up in clear high-angle sunlight on the parapet a few feet from a selenium cell, whose sensitivity happened to be remarkably close to that of the selenium cell in the globe. The second cell was mounted horizontally as usual under a plane opal disc. The equality of sensitivity makes it probable that these two cells did not differ very greatly in either curvature corrections or colour sensitivities.

Readings of the two photometers were made in rapid succession (*a*) with both freely exposed, and (*b*) with the direct sun screened off by means of as small an object as possible held at a distance of a few feet from the cells. Each reading was corrected for curvature, and the difference between the corrected readings found for each photometer. This difference for the plane photometer, when multiplied by the known constant of that instrument and by the obliquity correction factor for the given solar altitude, gives the vertical sunlight, $V_s$, whence $I_s = V_s$ cosec $\alpha$, the solar altitude, $\alpha$, being known from the time. Hence the constant of the globe photometer for direct sunlight can be found.

The diffuse light readings would give an alternative method of standardization if we could ensure that (*a*) reflected light travelling upwards were negligible and (*b*) the sky were uniformly bright all over; since we should then have $I_d = 2V_d$. The former condition, however, is in our case not realized, and the chief use of this diffuse light comparison is to obtain an estimate of the reflected light. For this we must choose a day with a fairly uniform sky, and be certain that the differences, if any, in the colour sensitivities of our photometers are too small to produce sensible differences in their relative sensitivities to sunlight and skylight.

It would probably be better, though slightly less convenient, to set the plane photometer normal to the sun's rays when making this comparison. This would avoid the introduction of $\alpha$ and of the obliquity correction into the equation, and would enable reasonably accurate standardizations to be made with low sun.

As an example of the method, on May 1, 1934, at 2.47 p.m. with $\alpha$ 43°, the selenium cell W 21104–2 under plane opal glass gave, after making the necessary corrections, $V = 75{\cdot}2$ kl, $V_d = 24{\cdot}6$ kl, and $V_s = 50{\cdot}6$ kl. Hence $I_s = V_s$ cosec $\alpha$ = 74·1 kl. Nearly simultaneous readings with the globe photometer gave for the currents, corrected for curvature, sun plus sky 1178 $\mu a$, sky alone 516 $\mu a$, hence sun alone 662 $\mu a$. Thus 1 $\mu a$ corresponds to 74,100/662, *i.e.*, to 112 lux. Using this constant we get for the total diffuse light as measured by the globe 57·8 kl, whereas $2V_d = 49{\cdot}2$ kl, assuming the sky to be uniform. The difference, 8·6 kl, representing the reflected light, is 6·9% of the total incident light. If we assume that the reflected light was perfectly diffused, as was probably approximately true with this fairly high sun, we get the upward vertical light as 8·6/2, *i.e.* 4·3 kl, or 5·7% of the downward vertical light. With low sun in February, reflexion off the sea greatly increased the relative importance of the upward light.

Fig. 5 shows the results obtained on the front parapet of the laboratory roof at Plymouth on January 24, 1934, using the globe integrating photometer, the Moll solarimeter, and the sodium cell with thread recorder to measure I, W, and V, respectively. In the forenoon of January 25 the selenium cell was also used to find V. The scale has been chosen so as to bring I/2, which for diffuse light from a uniform hemisphere is equal to V, to lie near W. I/2 lies close to V from 4–5 p.m. when the sunlight is relatively unimportant or nil. For the observations concerned with direct sunlight W apparently follows I more closely than V, but this seems to be a more or less fortuitous balancing of effects. The low sun contributes much more to I/2 than it does to V; sunlight is also more important, relatively to skylight, to W than to V, since its luminous efficiency (as determined on the photo-electric scale) is much lower, especially for low sun. Thus as the sun sank and became relatively less important, I/2 approached V, and W also approached V. There were only three readings of W with sun obscured, and these, like I, showed much greater falls below the sunshine values than did V, but for different reasons—the low luminous efficiency of sunlight and the low angle of the sunlight, respectively.

We have seen that a comparison of the globe with the plane selenium photometer for high-angle sunlight carried out in May, 1934, gave as a constant 112 lux per $\mu a$ on the selenium mean noon sunlight scale, which in mixed bright sunlight and skylight agrees with the potassium arc scale used for calibrating the sodium photometer.

Fig. 6 shows results on this scale obtained on the parapet of the laboratory roof at Plymouth as the sun was sinking and setting on February 22, 1934. The sun's altitude, which is used as abscissa, was obtained from the noted times of the readings, and corrected for the average refraction at low angles. This agreed to within about

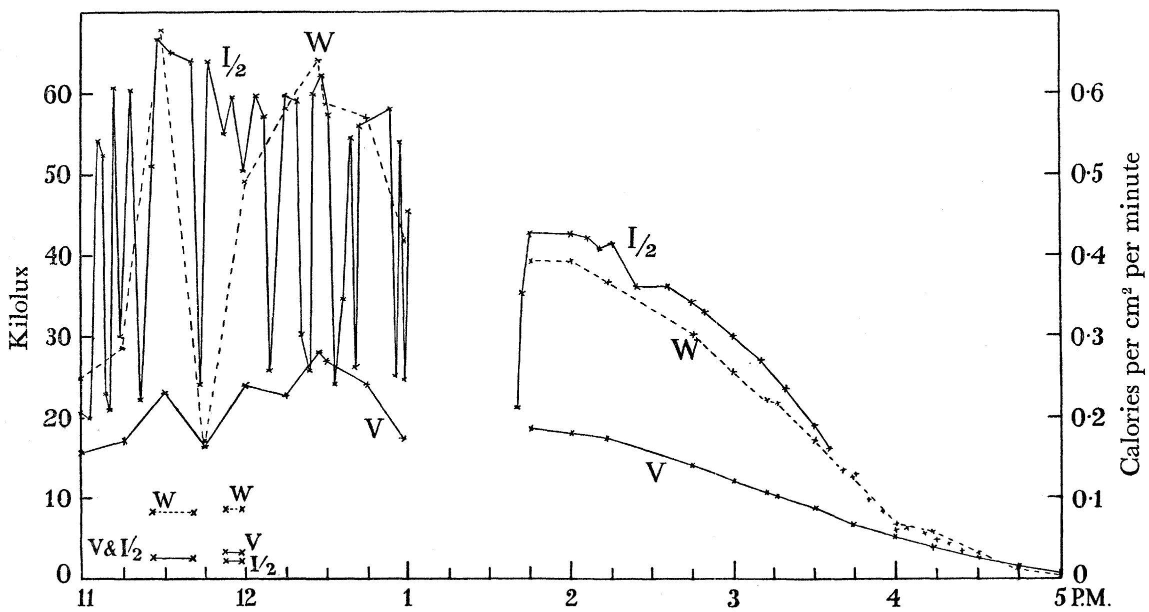



FIG. 5—The left-hand ordinates show illumination in kilolux; the right-hand show radiation in gram calories per cm² per min. ($0 \cdot 1$ cal. cm$^{-2}$ min$^{-1}$ = $6 \cdot 97$ mw. cm$^{-2}$). The upper curves relate to January 24, 1934, at Plymouth, wind E, blue sky and numerous small clouds which disappeared later. V measured with sodium cell and recorder, W with solarimeter and I, plotted as I/2, with globe photometer. For the evening, I/2 is represented by crosses only on account of similarity to curve W. The lower lines show averages over periods in fore-noon of January 25, strong S.E. wind, grey sky, lighter overhead; rain stopped work after second set of observations. On January 25, V by sodium and selenium cells agreed so closely as to be indistinguishable, as was also I/2 for the earlier period, viz. :—I = 2V as required by theory for uniform hemisphere neglecting reflexion upwards.

$0 \cdot 2°$ with the altitude as estimated from the height of the land horizon at sunset. The legend explains the significance of the various observations and curves plotted. The curve for V as found by the sodium cell was taken from the recorder. Individual readings for $V_d$ and $V_s$ were made at frequent intervals, and lay nicely along the curves but they have not been shown separately. Readings with the globe photometer and with the solarimeter were less numerous, and have been marked in, so that the extent of the interpolation used in plotting the corresponding curves may

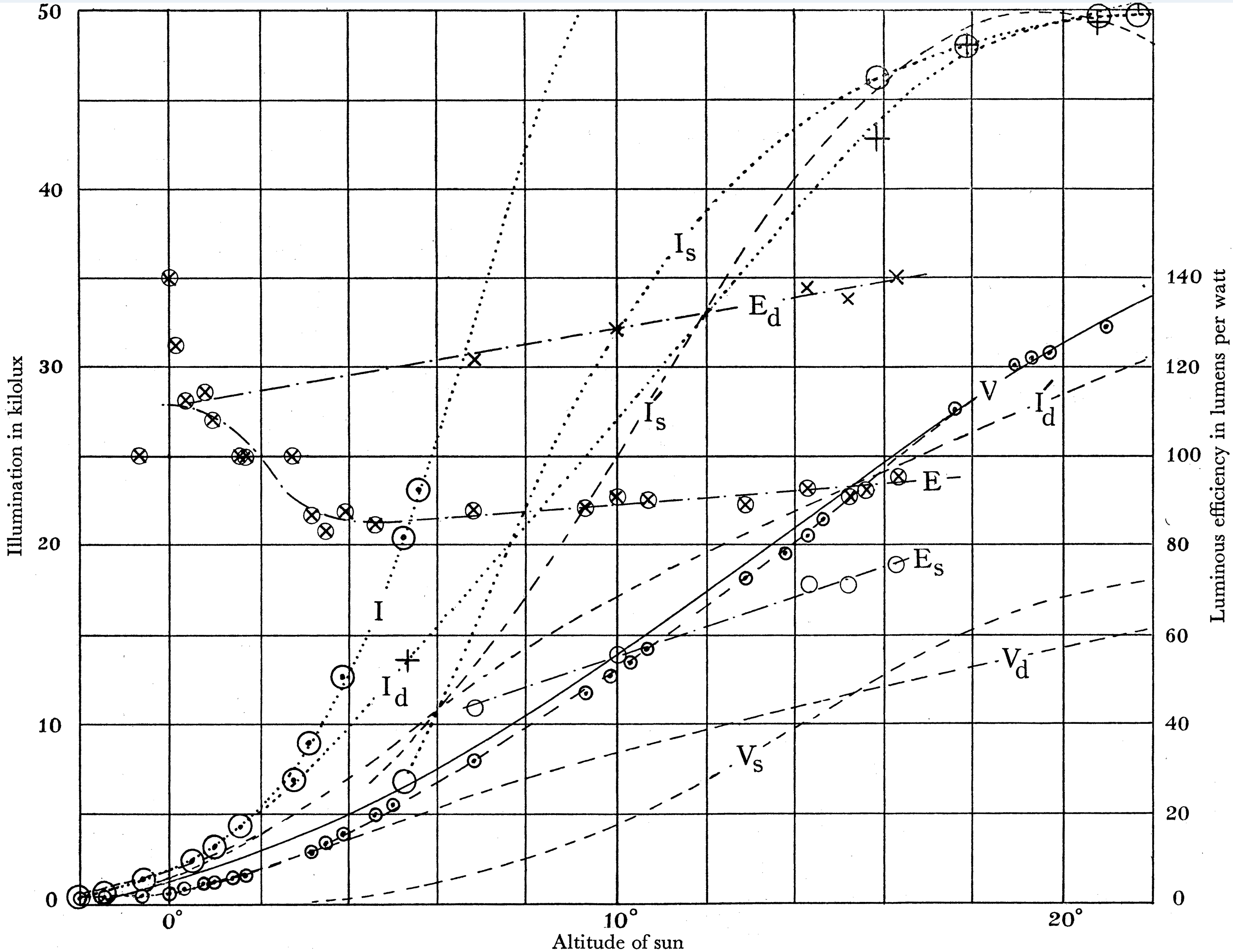



FIG. 6—Comparative measurements, with various photometers and with solarimeter, for low angle sunlight and diffuse light on evening of February 22, 1934; sky clear. On front parapet of roof of laboratory. Considerable reflexion off water of Plymouth Sound affected globe photometer only.

V, Vertical mixed light (sodium cell)
V, ,, ,, ,, (selenium cell)
$V_d$, ,, diffuse ,, ,, ,,
$V_s$, ,, sunlight ,, ,,
$I'_d$, Total diffuse light excluding reflexion (= $2V_d$)

I, Total mixed light by globe (selenium cell)
$I_d$, ,, diffuse ,, ,, ,,
$I_s$, Normal sunlight ,, ,, ,,
E, Luminous efficiency, vertical mixed light (selenium cell)
$E_d$, ,, ,, ,, diffuse ,, ,, ,,

be gauged. Instead of the energy measurements made with the solarimeter we have plotted the luminous efficiencies obtained by dividing these into the corresponding selenium cell measurements of the vertical illumination.

It will be seen that the selenium and sodium cells agreed perfectly so long as the sun's altitude exceeded 18°, but that at low altitudes the preponderating effect of blue skylight caused the latter to read higher by 6% at 10°, by about 25% at 4° and by nearly 100% at sunset. This difference decreased again after sunset, which may have been due to the reddening of the diffuse light, though the smallness of the readings with the sodium cell renders this result rather indefinite. The measurements of pure perpendicular sunlight at about 20° with the globe photometer agreed excellently with the results obtained from the readings of $V_s$, but the single globe reading at 5·3° is appreciably lower than the value found from the plane photometer. The latter is not very well suited for measurements of very low angle sunlight owing to the large and somewhat uncertain obliquity correction. For such readings the advantages of the globe become evident.

There is a large difference between $I_d$, as measured by the globe, and $I'_d$, as found from $V_d$, since the former includes all the reflected light off the water and off the lead roof. The tendency to a maximum near 20° shown by $I_d$, $I_s$, and $I'_s$ must apparently be ascribed to a clearing of the sky having taken place near the time when the observations were commenced, as there can be no doubt that otherwise the values would increase steadily with the sun's altitude. The approximate equality of $I_d$ and $I_s$ over a wide range of altitudes on this occasion is of interest.

The luminous efficiency of the diffuse light decreased slightly, and that of the sunlight considerably, as the sun sank. For the combined light, however, the fall in the proportion of sunlight maintained the average efficiency almost constant until the sun sank so low as to become unimportant, when this average rapidly rose to that for diffuse light. There can be no doubt that after sunset a fall in efficiency must occur, but the solarimeter readings became so small that only very approximate values could be calculated.

We desire to acknowledge our indebtedness and to express our thanks to the Government Grant Committee of the Royal Society for a series of grants for purchasing much of the apparatus used. For general laboratory facilities we are indebted to the Royal Dublin Society and the Marine Biological Association, Plymouth. We are further indebted to Dr. E. J. Allen, C.B.E., F.R.S., and other members of the staff of the Plymouth Laboratory for assistance in obtaining the daily records during the last five years. We have also to thank the Director of the Meteorological Office, London, and Dr. F. J. W. Whipple, of the Kew Observatory, for data supplied.

## IX—Summary

The exposure of plane, tubular, and spherical surfaces are considered in relation to the measurement of daylight by sodium, potassium, and selenium cells, and by photo-sensitive liquids. Curves are given showing the variation of the sensitivity

of the cells with wave-length in a mean noon sunlight spectrum. The scale used is the selenium mean noon sunlight standardization, with which the potassium cell standardized against the carbon arc is in close agreement for bright mixed daylight. The sodium cell carbon arc standardization does not differ much from these, but a daylight standardization against the potassium cell was adopted.

A Burt sodium cell and a Cambridge " thread recorder " have been used to get records of the vertical illumination over a period of five years. The results for 1930 are presented, showing daily maximum values, and the curves have been integrated with a planimeter to give the vertical illumination integrals in kilolux hours. The daily maxima ranged between 6·9 and 197·6 kilolux during 1930, and the illumination integrals between 20·7 and 1323. A sudden snowstorm was found to reduce the vertical illumination from 82·2 to 1·9 kilolux within 25 minutes. A selection of records illustrating various types of weather is reproduced. The illumination at sunset on clear days was found to be about 0·6–0·7 kilolux at sea or on the coast.

The monthly percentages of the annual illumination integral in kilolux hours ranged from 1·25 for December to 16·0 for July.

The ratio of sunlight received on a horizontal surface to skylight similarly received ranges up to about 3·0, as measured with a sodium cell having a maximum response at about 421 $m\mu$ in a mean noon sunlight spectrum. Much larger ratios are found with the selenium cell.

For the vertical illumination, from sun at 45° altitude and a fairly clear sky, values ranging from 62·7 to 146·7 kilolux were found, as measured with a sodium cell, but the mean of seventy observations was 102 kilolux. For cloudless days forty-four observations gave a mean of 98·9 kilolux. The mean of five determinations with the selenium cell is 74·9 kilolux. The sodium and selenium cells usually agree well in their rating of sunlight, but the former rates the blue light of the summer sky much more highly under some conditions.

A globe photometer is described, which by means of a horizontally mounted selenium cell and triple diffusing surfaces gives readings independent of the altitude and azimuth of the source. When exposed in the open this gives a measure of the total light, such as is received on the small sphere, and has a sensitivity of 112 lux per microampere when standardized in sunlight.

## Description of Plates

### Plate 23

| | | Sun, hours | Wind direction and force | Remarks |
|---|---|---|---|---|
| A | December 21, 1929 . . | 6·2 | N.N.W. 3 | Max. V, 17·2 kl. |
| B | December 21, 1930 . . | 3·8 | N.W. 3 | „ 19·9 „ Note dark current in early morning. |
| C | January 14, 1930 . . . | 0·1 | S.S.W. 6 | A bright morning thickening up. |
| D | February 13–14, 1930 . | 3·2 | S.E. 3 | A dull morning; sun breaks through at noon. 14th to 10 a.m. |

A break in the top line of frame draws attention to a record near or slightly beyond the line. The ordinates show current in micro-amperes.


PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

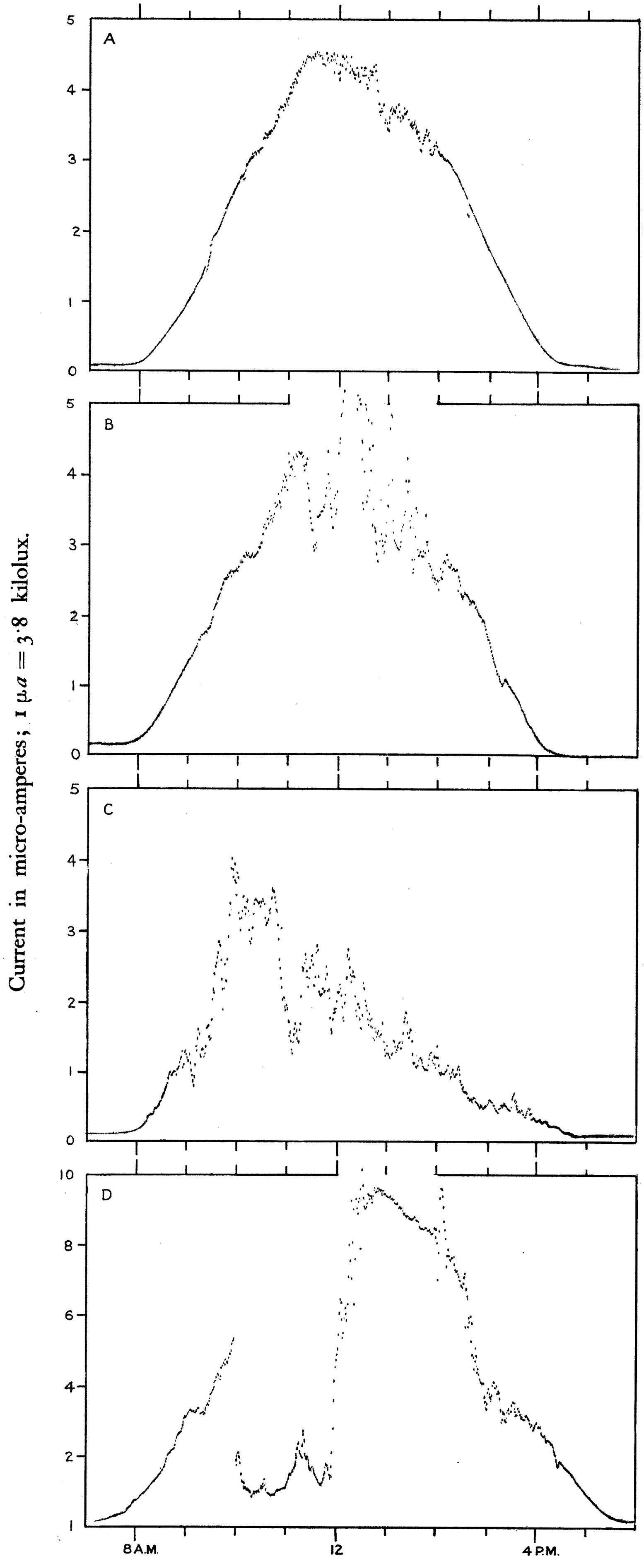

A
B
C
D
Current in micro-amperes; 1 μa = 3·8 kilolux.
0
1
2
3
4
5
10
8
6
8 A.M.
12
4 P.M.

PLATE 24

| | | Sun, hours | Wind | Remarks |
|---|---|---|---|---|
| A | February 23, 1930 . . | 0·0 | N.E. 2 | Thin veil of gray cloud gives a noon maximum. |
| B | February 24 & 25, 1930 | 0·8 | E. 3 | Sun breaks through at times. 25th to 10 a.m. |
| C | February 28, 1930 . . | 9·3 | E.N.E. 4 | Max. V, 43·7 kl. Clear blue sky, a few small clouds and some haze. |
| D | February 28, 1931 . . | 3·8 | N.W. 3 | A bright morning with heavy clouds and almost total darkness at 1·38 due to sudden snow storm. Note max. V, 82·5 kl, far above February 28, 1930, an almost cloudless day. |

A break in the base line draws attention to the position of a zero check marking, or very low illumination.

The records in Plates 23–27 were usually changed at 10 a.m. or 9 a.m. in summer, accordingly the morning portion normally refers to the following day ; the discontinuity is not always evident.



PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

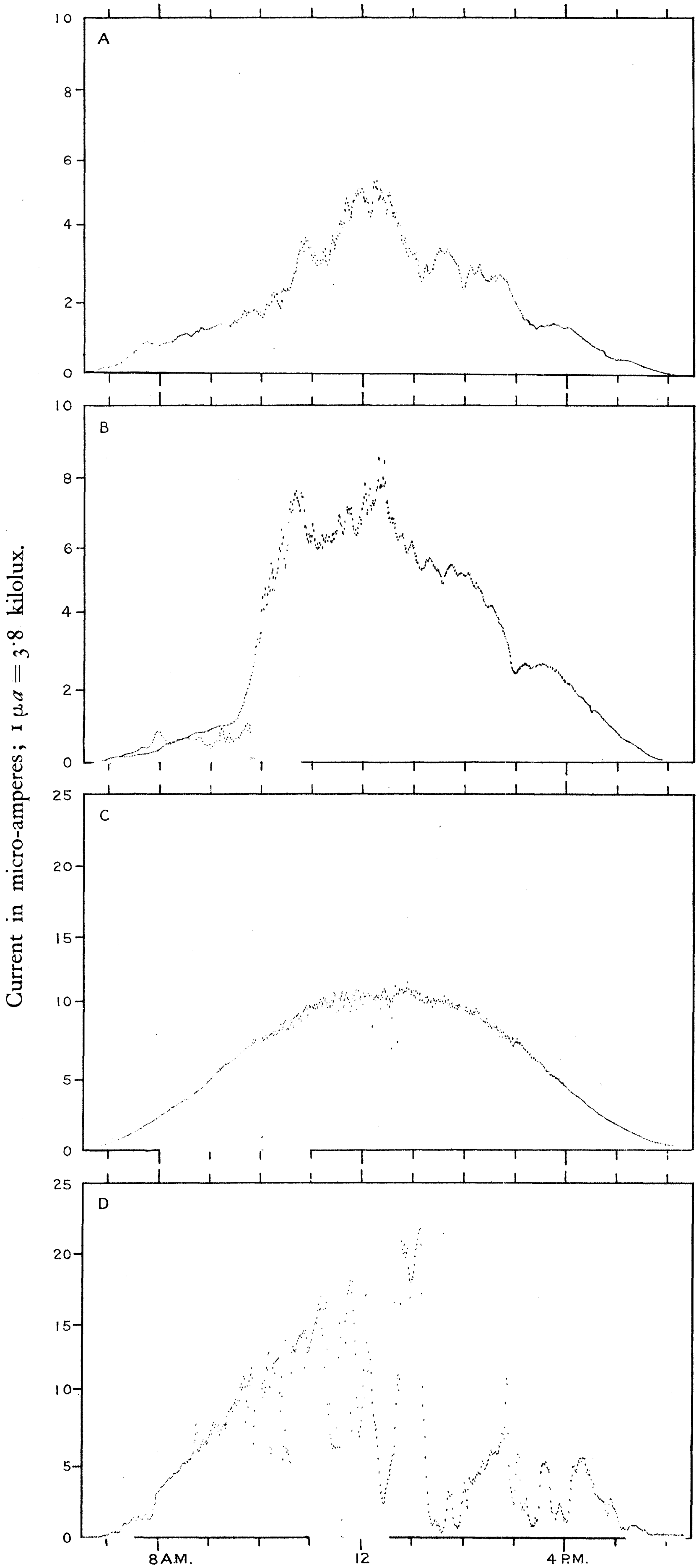
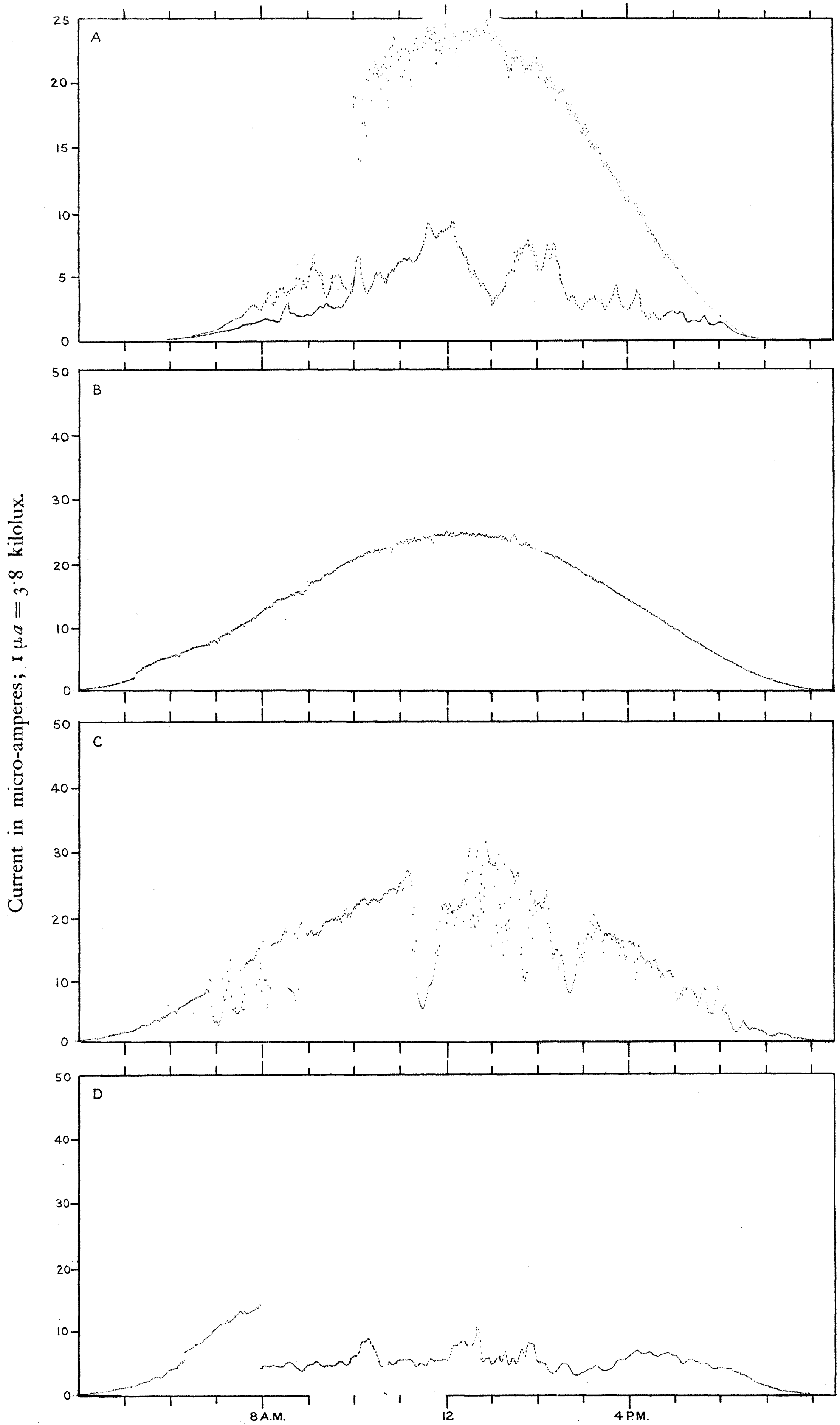

A
B
C
D
Current in micro-amperes; 1 μa = 3·8 kilolux.
10
8
6
4
2
0
25
20
15
5
8 A.M.
12
4 P.M.

PLATE 25

| | | Sun, hours | Wind | Remarks |
|---|---|---|---|---|
| A | March 26, 1930 . . . | 11·1 | N.W. 3 | Day almost cloudless. |
| | March 27, 1930 . . . | 0·0 | 0 | Sea fog intense to 1·30, lifted in afternoon. |
| | March 28, 1930 . . . | — | — | The upper morning curve to 10 a.m. |
| B | May 23, 1933 . . . . | 14·3 | N.W. 4 | Cloudless day, save for small wisps, one at 1·30. Afternoon curve even more regular than morning. |
| C | May 24, 1933 . . . . | 11·1 | W.S.W. 4 | Regular curve interrupted by some clouds, reflected light raises maximum to 118 kl as against 95 kl for 23rd. |
| D | May 26, 1930 . . . . | 0·0 | S.W. 2–0 | A remarkably constant low illumination. Unbroken curve indicates little wind. 27th to 8 a.m. |






PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

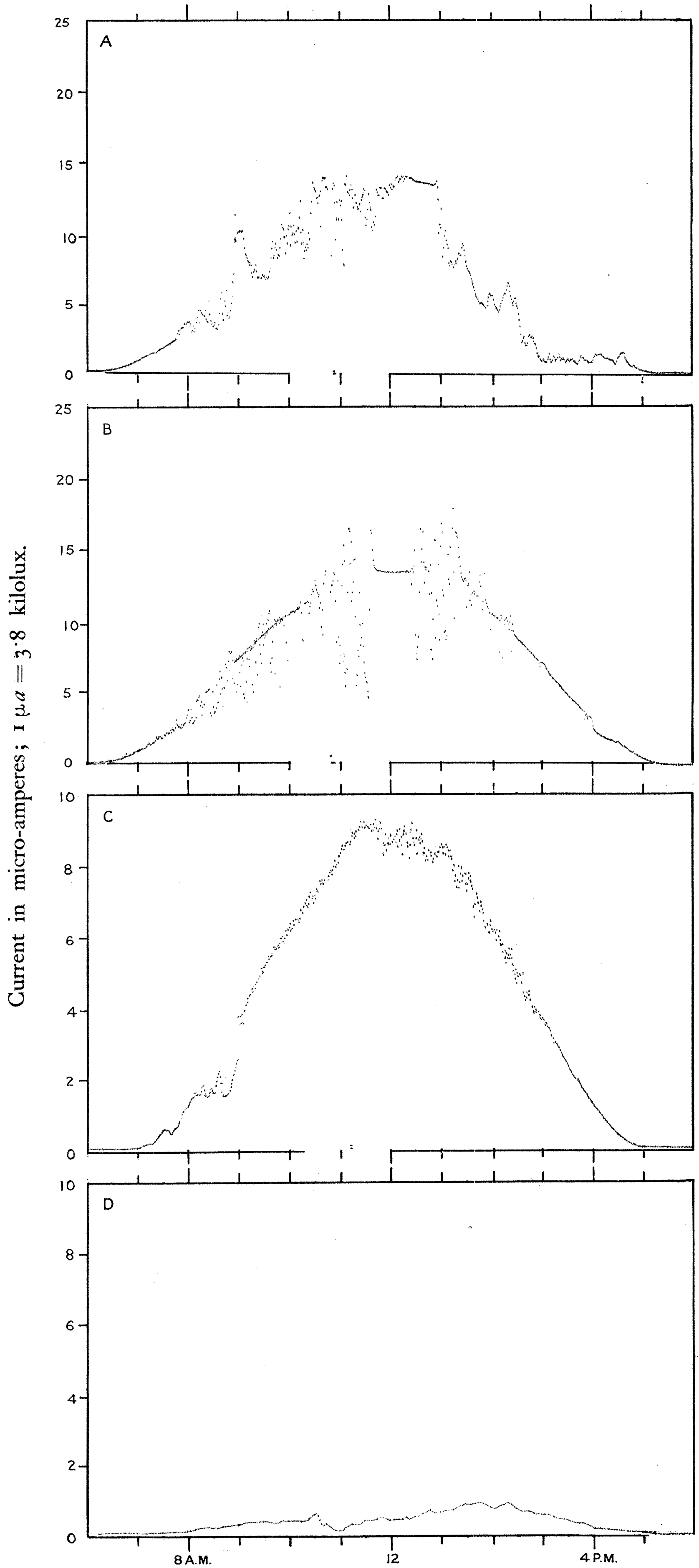
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

PLATE 26

| | | Sun, hours | Wind | Remarks |
|---|---|---|---|---|
| A | July 22, 1930 . . . . | 5·1 | N. 4 | A very windy day with sunshine, note irregular dots. |
| B | August 16, 1930 . . . | 12·1 | S.S.W. 3 | Cloudless almost all day. Note great regularity of afternoon curve, which is at all points well above that of May 23, 1933, though noon altitude of sun was 60·4° then and on 16th was 53·9°. |
| C | August 25, 1930 . . . | 8·7 | S.E. 4 | Noon to noon. A cloudless day followed by one with thin cloud, as shown by irregular curve with noon maximum, *cf.* February 23. |
| | August 26, 1930 . . . | 0·1 | S.S.W. 3 | |
| D | October 9, 1930 . . . | 7·5 | N.W. 2 | A bright windy day with large clouds. |

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
THE ROYAL SOCIETY A
PHILOSOPHICAL TRANSACTIONS OF

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
THE ROYAL SOCIETY
PHILOSOPHICAL TRANSACTIONS OF





PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES