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The distribution of the energy over the sun's disc,

by *W. J. H. Moll, H. C. Burger* and *J. van der Bilt.*

1. The authors spent the month of August 1925 on the Gornergrat, near Zermatt (Switzerland) at an altitude of 3100 meters, with a view of measuring the distribution of the energy over the sun's disc for various wavelengths. The expedition was planned by the Executive Committee of the Eclipse-Committee of the Royal Academy of Sciences of Amsterdam. In fact, the problem to be attacked appeared on the original programme made up by this committee for the total solar eclipse of 1926 Jan. 14. Its great importance arises from the fact that reliable experimental data about the distribution of the energy over the sun's disc constitute the sharpest criterion for the soundness of any solar theory.

2. The practical solution of the problem under consideration has been aimed at by many investigators, amongst whom C. G. ABBOT, Director of the Astrophysical Laboratory of the Smithsonian Institution, has attained a general authority. His method consists in running a solar image over the slit of his spectrobolometer, and registering, for a limited spectral region, the energy received by the platinum strip.

W. H. JULIUS, as long ago as 1905, has raised objections against such measurements in a solar image. He remarked, that this image will always be covered by light, diffused by the earth's atmosphere; and, moreover, by false light originating from the imperfections of the mirrors and lenses. As a result of this, there would be, in a certain point of the solar image, not only energy from the corresponding point of the sun's disc, but also energy derived from adjacent parts.

JULIUS therefore proposed a method which has the great advantage of being entirely free from these disturbances, but the disadvantage that it can only be applied during a total eclipse and, moreover, does not yield the required distribution by *direct* measurements. This method consists in exposing a bolometer or a thermopile to the sun, without the intervention of lenses or mirrors. During the course of an eclipse the radiation gradually decreases to zero and after that rises again gradually to a maximum. By plotting the intensity of the radiation against the time, a curve is obtained, which JULIUS called an *eclipse-curve.* This curve will depend on the distribution of the energy over the solar disc. Supposing for a moment that the distribution were uniform, the shape of the eclipse curve can easily be calculated. Now the observed eclipse-curve will deviate from the curve for uniform distribution and from these deviations the true distribution of the energy can be derived.

This means, that the method is an *indirect* one; the distribution has to be derived from rather small deviations between the observed and the calculated curves. This involves that in order to get results of tolerable accuracy the observed curve must be determined with extreme precision.

JULIUS tested his method at the eclipses of 1905 and 1912 and from his measurements derived the distribution over the sun's disc for the total radiation (all wavelengths).

At the eclipse of 1914 August 21, MOLL and VAN DER BILT registered eclipse-curves for six different spectral regions, using light-filters.*) But in deriving these results they met with a serious difficulty, viz: that the first half of the eclipse-curves led to a distribution, which was essentially different from that derived from the latter half; the six curves all showing an asymmetry, which moreover had a different character for the different spectral regions.

Apparently some disturbance had been acting notwithstanding the fact, that the sky seemed to be entirely clear and the apparatus had worked splendidly. The observers are convinced that the disturbance they encountered was not accidental, but is inherent

*) *B.A.N.* I No. 30.

in the principle of the method. In fact, this method requires conditions of the atmosphere, which are hardly ever fulfilled; it implies a perfect constancy of the transparency of the atmosphere, and this during a rather long interval of time. Now, even outside an eclipse, and under the best conditions, there constantly occur noticeable fluctuations in the radiation received at the earth's surface, especially when working in the violet part of the spectrum and in those parts of the infra-red which contain strong absorption bands. Besides, in the case of an eclipse, the temperature undergoes considerable changes, which may cause increased variations of the transparency. Considering the fact that the maximum deviation between the observed and the computed curves is, along their greater part, rather small, it is obvious, that a relatively small variation of the transparency of the air will lead to erroneous results.

Against these objections, JULIUS remarked *), that his method is still available if the measurements are restricted to a short time before the 2nd contact and after the 3rd contact. During this short interval the changes in the earth's atmosphere will be small, and on the other hand for these parts of the curves the deviations from the computed curve are, relatively fairly large.

We think that, thus revised, JULIUS' method is indeed valuable, provided the measurements are made between about 2 minutes before and 2 minutes after the middle of the eclipse.

Accordingly in preparing a programme for the coming eclipse, we originally intended to apply this modified method, with a view of getting data for the distribution of the energy in the immediate neighbourhood of the sun's limb; and to use for this purpose, say, six vacuum thermo-elements and six registering galvanometers.

Looking closer into the matter we began to fear that such a complicated installation must necessarily handicap a programme already crowded. Besides, in a damp tropical climate during the rainy season, the observational conditions would be far from good, whereas the duration of totality (3 minutes) would be rather long for this investigation. At the same time we became convinced, that measurements in a solar image are not so objectionable as was presumed by JULIUS, provided they could be made at a sufficiently elevated station and in good climatological conditions.

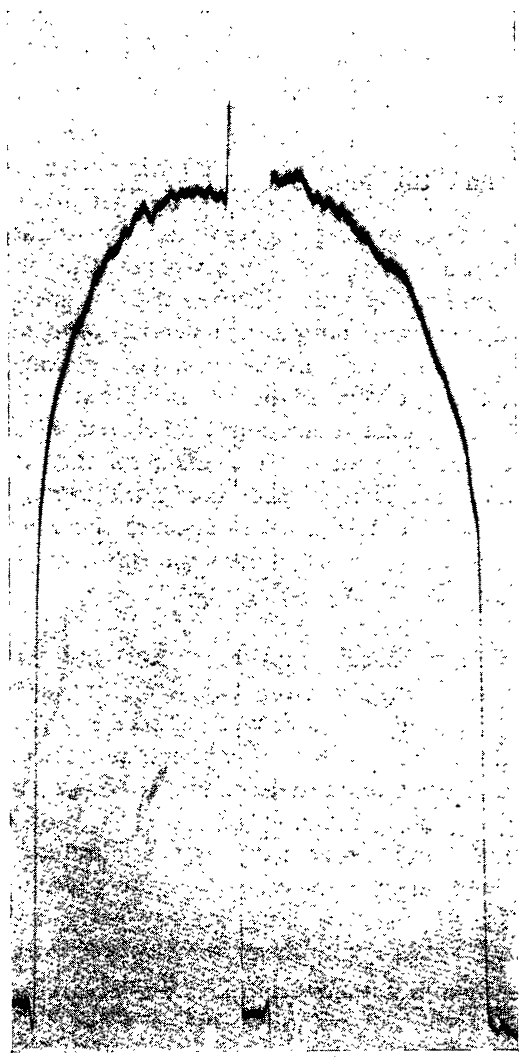
Our attention was drawn by a paper of DEMBER and UIBE on quantitative measurements of the diffusion of the atmosphere at Teneriffe, at an altitude of 2300 meters. Their result was that — under such perfect climatological circumstances — the diffusion

*) *B. A. N.* I No. 33.

is very small and, moreover, follows simple laws. We concluded from these researches, that it must be possible to eliminate the effect of the diffusion by applying corrections.

We therefore, with JULIUS' full approval, conceived the plan of ascertaining by experiments at the Meteorological Observatory at Izaña (Teneriffe) whether measurements in a solar image could give reliable results; and, if so, to collect trustworthy data.

Figure 1.



Curve, registered by ABBOT.

Later on, the Gornergrat proved a far better station than Teneriffe, this mountain ridge being especially recommended by Dr. MAURER, the Director of the Meteorological Institute at Zürich. It has against Teneriffe the disadvantage of short intervals of consecutive clear days, but, on good days, the transparency is at least of the same quality as at Teneriffe. Very important advantages of the Gornergrat are: that it can be reached by train, that there is a good hotel, and that this hotel possesses a storage battery. Moreover, we had the good luck of finding, next to this hotel, a small house with brick walls, containing three rooms, admirably suited for an observatory.

3. Our expedition intended to measure — for different spectral regions — the distribution of the energy along a solar diameter. The method consists in running a solar image over a short slit, and registering the energy received by a thermopile placed in the spectrum. This method being essentially the same as ABBOT's, it will be necessary to give the reasons which led us to repeat his work.

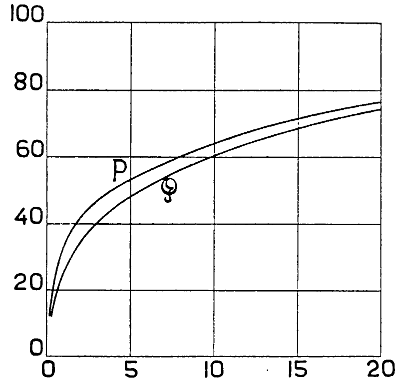
ABBOT has never given numerical data for the last 5 % of the sun's radius, whereas just this border of the sun is by far its most interesting part. We always had the impression, that he was unable to investigate this region on account of the disturbing diffusion of the atmosphere. A closer examination of his publications, however, convinced us that the reason must be a different one.

In looking at ABBOT's curves, of which Fig. 1 is a specimen*), a particularity attracts the attention: they show a certain skewness, or absence of symmetry. It seems to us, that there is but one explanation for this, viz: that the time which the bolometer needed to reach its equilibrium was too long compared with the time in which the radiation increases from zero to, say, 50 % of its maximum value. Consequently the bolometer must of necessity have considerably lagged behind the rapid increase and decrease of the radiation near the solar limbs. We presume this to be the reason why ABBOT could not give data for the borders of the sun's disc.

It is then to be feared, that also for the more central parts of the sun, ABBOT's results might have been vitiated by the same source of error. This presumption was confirmed by the following fact, revealed already by our preliminary experiments: It will be explained later on, that we slowed down the speed of the sun's image to about 1/7 of its normal value, but we also obtained records with the sun's image running at its normal speed. As will be evident from Fig. 2, the curves representing these two cases are quite different. They show the phase of increasing energy, curve P referring to the reduced motion of the solar image, curve Q to its normal speed. Evidently the latter has been seriously affected by the slowness of our instruments. Now, since these were doubtlessly much quicker in response than ABBOT's (which is evident from the absence of any perceptible skewness in our curves) his curves, which were all recorded with the sun's image at its normal speed, must have undergone a considerable deformation. No wonder, that our final measurements led to data, quite different from those given by ABBOT. (See under 7).

*) A first glance at his curve shows, that is not smooth, a fact which we ascribe to disturbances, probably of the galvanometer. One wonders how it was possible to derive, from curves like this, reliable results, and to give the data in four figures.

Figure 2.



Deformation of a curve, caused by the insufficient quickness of the instruments.

4. In 1914, we had, by means of colour-filters, isolated rather broad spectral regions; this time, wishing for a greater purity, we had to use a spectral arrangement.

A monochromator was especially devised for this purpose, and, to our full satisfaction, constructed in the Optical Institute of Dr. STEEG und REUTER at Homburg vor der Höhe (Germany). Fig. 3 gives, in a schematic way, the disposition of its principal parts.

On a rectangular ground-plate, about 1.5 meters long, two rails are mounted. One of these is fixed to the plate, the other can be rotated on an axis A. Its outer end carries an index B along a scale Z.

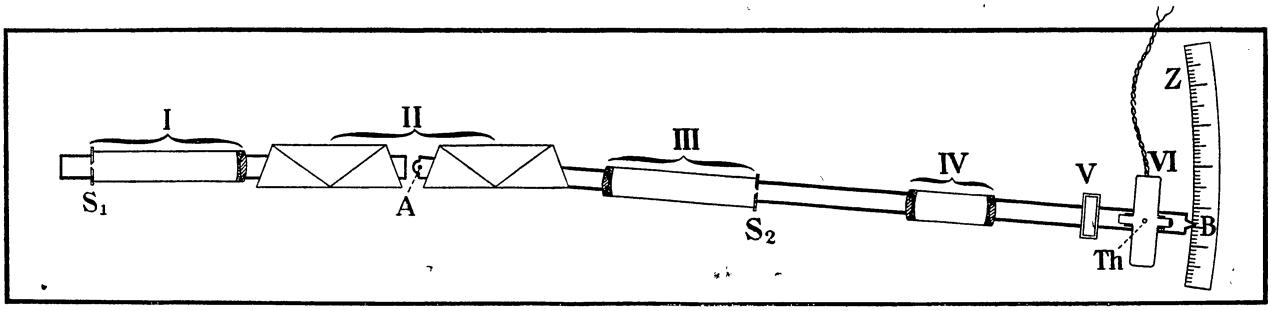
The fixed rail carries two supports I and II; the movable rail carries four supports III to VI. On these supports the following instrumental parts are mounted:

on I a collimator,
„ II two large direct vision prisms,
„ III a collimator as on I,
„ IV a combination of lenses,
„ V a light-filter,
„ VI a linear vacuum-thermoelement *), adjustable in all directions.

An image of the sun, having a diameter of 30 mm, is projected on the slit S_1, a sharp spectrum is formed in the plane of the slit S_2. By moving the second rail, the slit S_2 can be placed in different parts of the spectrum. The combination of lenses on support IV forms an image of this slit upon the linear vacuum-thermoelement Th. The light-filter

*) Described in *Phil. Mag.* 50, p. 618, Sept. 1925.

Figure 3.



Sketch of the monochromator.

on V will remove any false light of wavelengths outside the region under investigation.

The scale Z has been calibrated by means of lines of known wavelengths, partly before our departure partly during the experiments at the observing station.

Both slits S_1 and S_2 had as a rule a width of 0.1 mm. and a length of 2 mm; for the infra-red these dimensions could still be reduced.

The thermo-current generated by the radiation was photographically recorded on a rotating drum by a Moll galvanometer. The registered curve was not a continuous one, but consisted of successive dots, for reasons which will be explained under **6.** In order to produce the dots, the recording beam of light was periodically intercepted by a small screen attached to a metronome.

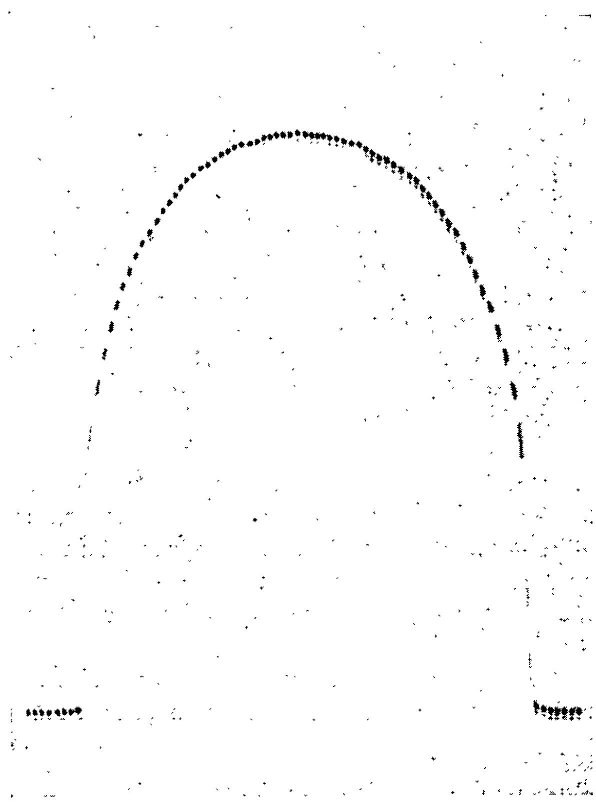
The monochromator and the registering galvanometer were installed indoors; the wall of the monochromator-room had been pierced, and outside, in front of the opening, the lens forming the sun's image was placed. This lens received the beam of sunlight, reflected by two plane silver-on-glass mirrors, so adjusted as to cause the twice reflected beam to run horizontally to the North (coelostat and second mirror arrangement). The solar image was first placed next fo the first slit of the monochromator, by adjusting the mirrors by hand; then, the mirrors being clamped, the sun's image moved horizontally over the slit, allowing a complete curve to be recorded in a little more than 2 minutes. This curve gave, for a certain spectral region, directly the distribution of the energy along the sun's diameter. As we have explained above it does not give the real distribution. Fig. 4 is the reproduction of such a curve.

5. We were prepared beforehand, as explained under **3**, to find that — unless we should succeed in slowing down the speed of the solar image — our curves would be deformed, as a result of the insufficient quickness of our indicating instruments.

We thought that, in order to obtain a reduced speed of the sun's image, it would be sufficient to reduce the speed of the driving clock of a coelostat. However, after a close examination, we became convinced, that no coelostat would be able to fulfil our requirements.

Several coelostats, and among them instruments of the very best quality, were tested as to their reliability of giving a steady image; the results were quite discouraging. Even the best coelostat gave oscillations of the image with angular amplitudes of about 8 seconds. Now, since in our arrangement the slit of the monochromator had a width of about $\frac{1}{300}$ of the diameter of the solar image, i. e. of about 6″, oscillations of that image over 8″ would have seriously affected the precision of our results. The

Figure 4.



Curve recorded at the Gornergrat station, with the solar image at normal speed.

chief oscillation had a period equal to the time of revolution of the wormscrew of the coelostat, and is therefore due to periodic errors of that screw.

We thus had to find a better method for obtaining a solar image at rest or one of reduced speed; and we succeeded in devising an arrangement, which entirely fulfilled our requirements.

This arrangement consists of *two fixed mirrors and a movable* lens. The mirrors can be turned by hand and clamped in any position. The lens, mounted on a sledge, can by means of a micrometer-screw and a driving mechanism, be slowly moved in a horizontal direction perpendicular to its optical axis. Such a motion will cause an equal displacement of the image projected by the lens. Evidently when this image has a motion of its own, it will come to rest, if the same speed in the opposite direction is given to the lens.

It is true that, in this method too, everything depends on the quality of the screw, but the errors of the screw will not have such fatal consequences as in the case of a rotating coelostat. To make this clear, let us suppose for a moment that the screw of the sledge has the same error as that of the coelostat. This error, in the first case, causes slight irregularities in the motion of the sledge, and, in the second case, affects the regular motion of the teeth of a wormwheel to the same degree. The solar image will have the same irregularities as the sledge, but in the case of the coelostat, the irregularities in the motion of the teeth will be transmitted greatly magnified to the solar image, viz: so many times as the focal distance of the lens is greater than the radius of the wormwheel. From this it may be concluded that, in cases where a really steady image of the sun is wanted during a short time, the principle of the coelostat must be rejected, that of the movable lens giving a much greater guarantee of steadiness. For obtaining a uniform slow motion of the solar image, we applied the same principle to our great advantage.

The driving mechanism of our sledge was an electromotor with speed-reducing gear, and controlled by a clock, a scheme devised by GERRISH for moving the telescopes of the Harvard College Observatory.

The strongly built sledge and the controlled motor were constructed, to our full satisfaction, by Messrs. KIPP AND SONS of Delft. Mr. HEINZELMANN of Utrecht provided a common springbalance clock with an arrangement making a reliable electric contact in constant intervals of nearly one second.

The motion of the sledge was, as a rule, such that the speed of the solar image was slowed down to about 1/7 of its normal value.

The arrangement was a complete success.

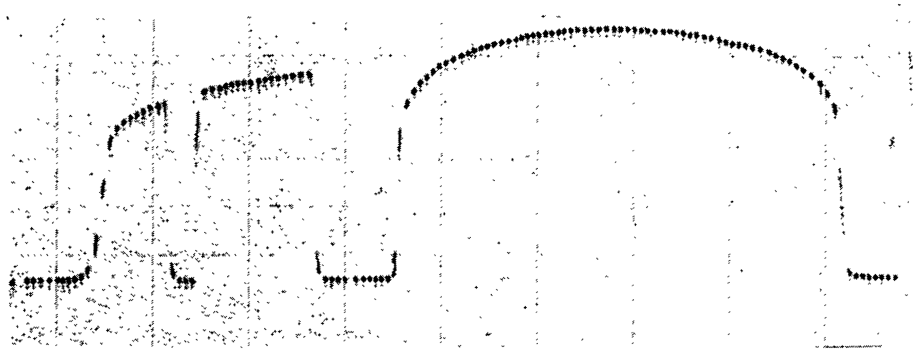
6. The horizontal beam of sunlight, reflected by mirrors of 30 cm diameter, passed through a diaphragm with an opening of 11 cm, behind which the lens, which had a diameter of 15 cm, was slowly shifted. It is obvious that, during a measurement, the lens could not be allowed to shift more than 4 cm; its usual velocity being about 1.4 cm per minute, we had slightly more than 2.5 minutes for each measurement.

The sun's image at 1/7 of its normal speed crossed the slit of the monochromator in about 14 minutes, consequently our records were restricted to a part of the sun's disc. However, it is only for the measurement at the sun's border, that a reduced speed of the solar image is required; the distribution of the energy in the central part varies so slowly, that it could easily be measured with a solar image at its normal speed.

Our definitive results were recorded in the following way:

The lens was placed, so that its western edge slightly overlapped the opening in the diaphragm. The mirrors were adjusted so as to have the centre of the solar image and the middle of the slit on a horizontal

Figure 5.



A set of curves recorded at the Gornergrat station. Left hand: Solar image at reduced speed, Right hand: Solar image at normal speed.

line, the solar limb nearly touching the slit. Then the motor was started, the registering drum opened, and a curve recorded, which gave the distribution for the first 15 or 20 percents of the sun's radius. When the motor had run for $2\frac{1}{2}$ minutes, the beam of sunlight was intercepted and the drum closed. The sun's image was again adjusted beside the slit, and once more a curve was obtained, now with the lens at rest, that is to say, with the solar image at its normal speed. This was done in order to get a value for the energy at the sun's centre. Fig. 5 is a reproduction of one of these records.

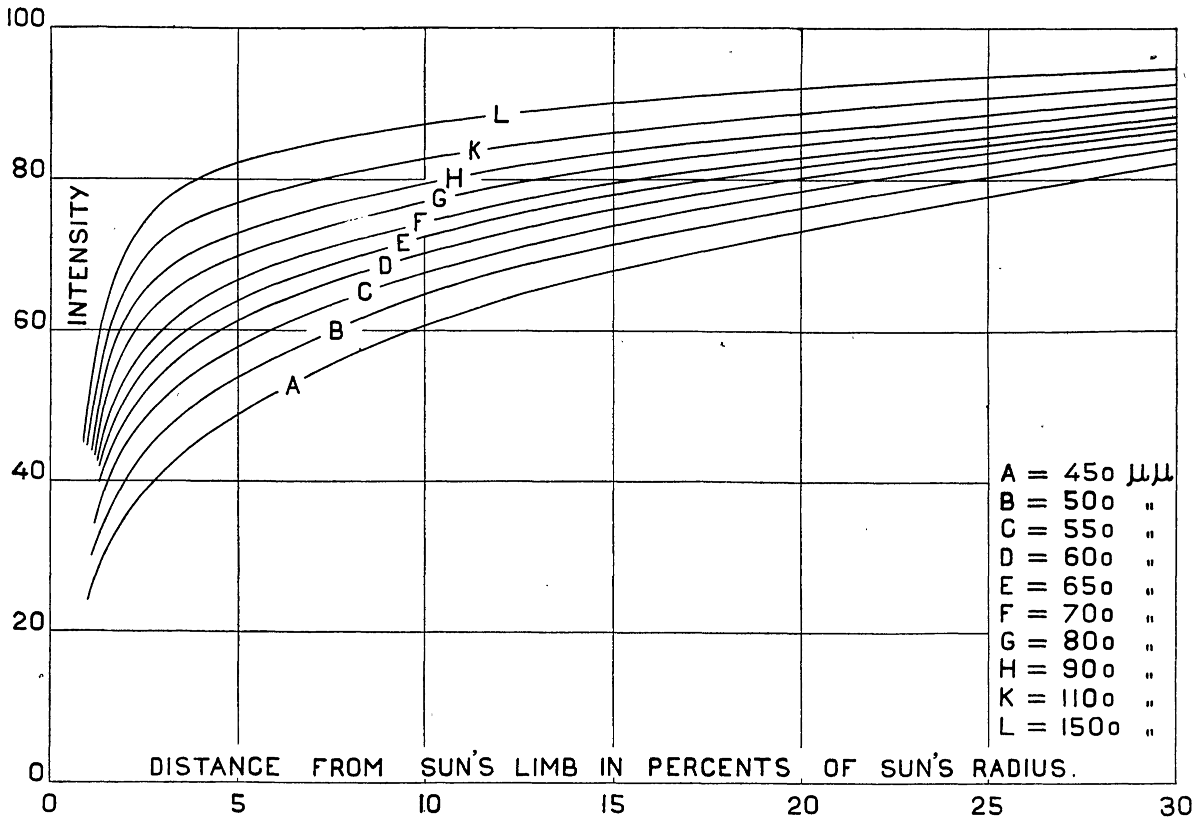
We will now explain the reason why the curves have been recorded in dots.

It is obvious that, in order to reduce our records to distribution-curves, it was necessary to calibrate the line of abscissae in percentages of the sun's radius. Since in the reduced-speed records only part of the image crossed the slit, the problem arose how this was to be effected. The difficulty was increased, by the facts, 1st that the normal speed of the solar image slightly differs on successive days, 2nd that the reduced speed undergoes an enlarged influence of this effect, 3rd that the distance from lens to slit had to be varied again and again for the various spectral regions.

These difficulties were overcome by the discontinuous way of recording, mentioned under 4. The period of the metronome, hence the time-distance between two adjacent dots on the diagram was a known quantity; the speed of the lens, too was known. The distance from lens to slit was measured, and the angular speed of the solar image derived from astronomical data. Hence it was easy to compute, for each recorded curve, which part of one percent of the sun's radius corresponded with the distance between two dots. In this way the distribution-curves, derived from the records, could be plotted with great precision. Of course, they were reduced to a normal scale of ordinates (maximum 100).

7. The first part of our stay on the Gornergrat was favoured by splendid weather. The observatory was equipped, the instruments were mounted, and the complete arrangement became ready during that time. In the installation and testing of our instruments we had the valuable assistance of Mr. P. VAN LEEUWEN BOOMKAMP of Amsterdam. Unfortunately as soon as we got ready for definitive work the sky became overcast, and we had to wait a long time before we could proceed. Consequently — being restricted in our time — we could not get quite as many records as we had planned for, and the results obtained consequently have a somewhat provisional character. But the agreement

Figure 6.



Curves, showing the distribution of the energy over 30 °/₀ of the sun's radius.

between the results on different days is such, that we think ourselves justified in considering them very reliable.

We made measurements in ten different spectral regions and so, after our return to Holland, ten different distribution-curves had to be derived from our various records. The ordinates of the numerous dots had to be measured, and reduced to percents of the energy at the centre of the sun's disc; the abscissae of the dots had to be reduced to percents of the sun's radius; corrections had to be applied in order to reduce the curves relating to the normal speed of the solar image to those relating to its reduced speed, and so on. All these measurements and reductions were made by Mr. D. VAN SUYLEN of the Astronomical Observatory, Utrecht; we wish to thank him most cordially for his disinterested and valuable assistance.

The results of our measurements are shown in Fig. 6. From these curves the proportional distribution of the energy over the sun's disc may be read off for the ten indicated spectral regions. We prefer to reseve the publication of accurate numerical data till later, because we have the intention still to refine our method and to accumulate a much larger material than could now be obtained.

8. When comparing our results with the data published by ABBOT we are led to make the following remarks:

We were able to get trustworthy values of the distribution of the energy along about 99 °/₀ of the sun's radius, against ABBOT's 95 °/₀.

Our values for the common 95 °/₀ exceed those of ABBOT. The differences attain a maximum amount of about $2\frac{1}{2}$ °/₀ at a distance of about 8 °/₀ from the sun's limb. As stated under **3**, it is easy to explain this discrepancy in a satisfactory way as a consequence of the insufficient quickness of ABBOT's instruments compared with the speed of the solar image.

It is not so easy to explain the fact that the discrepancies are less at a distance of 5 °/₀ from the sun's limb. Probably ABBOT has been under the influence of a preconceived opinion, viz: that the energy at the sun's limb must, from a finite value, abruptly fall to zero. He probably was led to this opinion by noting the extraordinary rapid increase and decrease near the sun's limbs; but we think, that these must be ascribed to the fact, that his galvanometer was periodical.

9. As stated before, our measurements do not claim to give results of the highest precision obtainable. We think that our values of the energy are trustworthy to about one hundredth of their value at the sun's centre. At the border of the sun's disc, from 2 °/₀ to the limb, the precision is less. Measurements in this region, where the energy falls off rapidly, meet with serious difficulties. Among these, the diffusion of the radiation in the earth's atmosphere (see under **2**.) is only of secondary importance. In fact, on good days our records showed a radiation practically zero outside the sun and in the immediate neighbourhood of its limb. Had there been a sensible disturbing effect of the diffusion, the sky in the immediate neighbourhood of the sun's limb would certainly have shown a perceptible radiation.

The greatest trouble in the experimental solution of this problem undoubtedly lies in the irregular refraction in the air, which causes the well-known „boiling" of the sun's limb. Nevertheless, on favourable days, and with still improved instruments, we think it possible to get reliable results, even in the immediate neighbourhood of the limb, and we have the intention to attack this problem as soon as possible.

A future publication will extensively give all the detailed information about our expedition to the Gornergrat, which could not be dealt with in this short, preliminary paper.

UTRECHT, 1925 November 1.