THE FRAUNHOFER LINES OF THE SOLAR SPECTRUM

(*George Darwin Lecture, delivered by Professor M. G. J. Minnaert, on* 1947 *May* 9)

A lecture on Fraunhofer lines has inevitably a somewhat abstruse character. The spectroscopist could not show you any of the wonderful pictures which the telescope reveals. A spectrum looks at first sight like a rather dull succession of bright and dark stripes. But now comes the observer, using his refined methods and discovering the infinite variety of shades and halftones in that spectrum, the full richness of that chiaroscuro. And then comes the theorist, deriving by the power of his phantasy how that music of undulating spectral lines is due to the airy dance of the atoms in the fiery radiation of the Sun. Actually, the investigation of Fraunhofer lines is so fascinating, so rich in observational details and so important theoretically, that I shall have to restrict myself to one part of the subject: photometry; even then, I shall only be able to present before you some of the more important moments in the development of our knowledge and a general view of the present state of the problems involved. In this frame I shall give an account more particularly of the work done at Utrecht because with this work are connected so many personal reminiscences; but we all know that progress in this field is due to the cooperation of many scientists all over the world.*

Already the first observations of a good solar spectrum revealed, that among the individual Fraunhofer lines there is a great variety of intensity profiles. When Kirchhoff in 1860 made his drawing and catalogue of the solar spectrum †, a work in which he lost most of his sight, he with great care gave to each line a characteristic letter from *a* to *g*, indicating the *width* in 7 different grades; and similarly he had also a scale for the *darkness* inside the line, running from 1 to 6. His lithographic reproduction of the solar spectrum was printed with 6 different stones, each of them corresponding to the lines of one definite degree of darkness. It is interesting to find the green magnesium line λ5183 as a broad, shallow band with a sharp central core.

Rowland, in his Preliminary Table of Solar Spectrum Wave-lengths (1893–1896), characterized each Fraunhofer line by a number, the "intensity": a preliminary, rather qualitative estimate of the impression which the line makes, either by its width or by its darkness or by both of them. This celebrated Rowland scale, though being admittedly rough, proved of the greatest use during many years up to our day. Rowland's collaborator, Jewell, made interesting observations on some profiles.‡

Actual measurements concerning the intensity inside Fraunhofer lines were not made before 1900. An enormous amount of material was available, a vast field would be open to investigation, as soon as quantitative measurements could be made. The pioneer in this field, as in so many others, was Schwarzschild at Göttingen. His profiles of the lines H and K, determined for the centre of

* General references to the literature may be found in Unsold, *Physik der Sternatmosphären*, and in the report by Redman, *M.N.*, **98**, 311, 1938.

† "Untersuchungen über das Sonnenspectrum", *Abh. Akad. Berlin*, 1861.

‡ *Ap. J.*, **3**, 100, 1893.

the Sun's disk and for the limb, are the first profiles ever measured (1914); their precision is still comparable to that of modern measurements.

But Schwarzschild's photometric method is cumbersome, and for many years nobody followed the new pathway, discovered by him. It was only in 1927 that the tradition of reliable photographic photometry, which had been kept at Potsdam, was applied to the investigation of Fraunhofer lines by the younger generation of astronomers and physicists.*

The independent development of the Utrecht measurements† was due to the happy circumstance that Julius, professor of experimental physics, had created a heliophysical department at his institute. Since 1920 our physicists, under the lead of Ornstein, directed their efforts to the photometry of laboratory spectra; Moll constructed his microphotometer; Burger and Dorgelo discovered the multiplet rules; the photometric properties of photographic plates were investigated; van Cittert and Burger used the step reducer and developed a method for the correction of a profile for instrumental influences. It was very stimulating for an astrophysicist to take part in that development, and to apply the wonderful new methods to the investigation of Fraunhofer lines. The heliophysical department found at once a new field of activity. And I remember that our very first microphotometer record of some small part of the solar spectrum awoke at once the very ambitious plan of a complete photometric atlas. Our first steps were very cautious. In a spectrum, obtained with a focal length of many metres, we had to record the detailed profile of dark lines, not wider than a few tenths of a millimetre, surrounded by floods of light; and we wanted to measure the intensity in each point with a precision of a few per cent! It seemed almost incredible that the intensity profile recorded would have any real value. All possible sources of error were examined one by one, their influence on the measurements were minimized and the remaining effects were estimated. Gradually, we found that our results were more reliable than we could have hoped and our self-confidence increased. It was a great encouragement, that soon similar measurements were made at other institutes all over the world, and that the results from this pioneering period seemed to agree in a rather unexpected and very satisfactory way. When reading again the papers from this first period by von Klüber, Unsöld, Plaskett, Dunham, Righini, Woolley, Carroll and those of the next generation, represented by Redman, ten Bruggencate, Thackeray, Allen, and at Utrecht by Mulders and Houtgast, one is greatly impressed by their fundamental work, which became the basis for all modern spectrophotometric investigations. It may be safely asserted that astrophysicists have followed the good tradition of classical astronomy, and that they have bestowed all possible care on their method before they started measuring.

Our reward is, that we now see our naïve younger students making without any hesitation these same measurements, which for us were such a source of trouble and concern, and getting satisfactory results!

The number of Fraunhofer lines of which the profile has been studied with some precision is still astonishingly small. I mention the first four Balmer lines, H and K, the *Ca* resonance-line 4227, the D lines of sodium, the *Sr*-ion line 4078, and five heavy lines of iron in the violet, altogether sixteen lines. You will understand, that we felt a very strong desire to make available for theoretical investigation

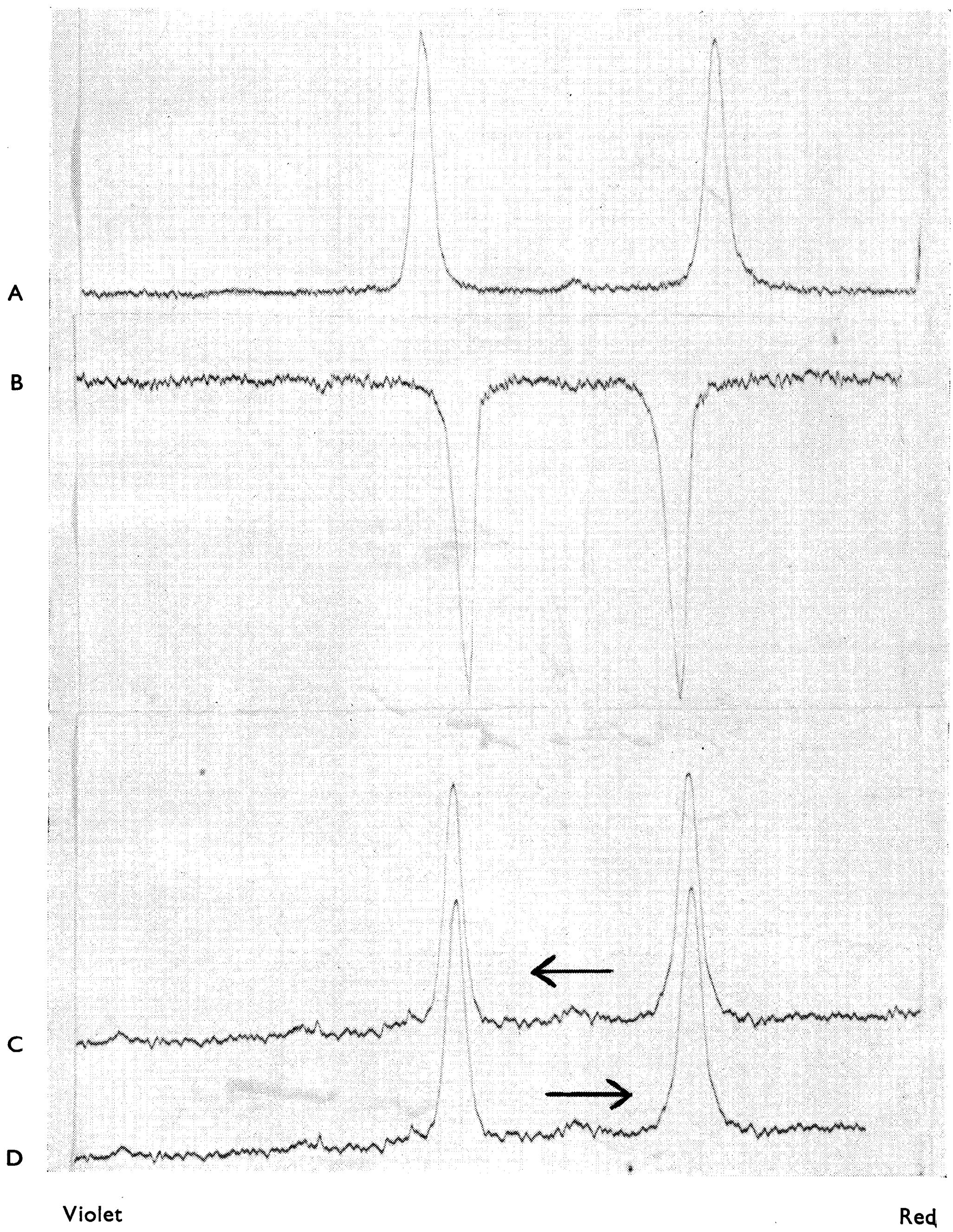
* von Klüber, *Z. Phys.*, **44**, 481, 1927.
† *Z. Phys.*, **45**, 610, 1927.

not only these sixteen lines out of 20,000, but many more, and even all of them, if possible. The plan for a general photometric atlas of the whole solar spectrum gradually took shape and seemed more and more possible through the experience, accumulated at Utrecht and increased by information from other workers in the field. Of course, in such an undertaking it is impossible to give full care to each of the lines, as may be done in individual investigations. But if the work is done in a systematic way, one may be able to correct afterwards in a relatively simple way the errors left. The plan was carried out by Houtgast, Mulders and myself, each taking for his share a part of the work.* A great deal of the credit is due to the generous help of the Mt. Wilson Observatory, where Mulders was allowed to take the whole series of spectral records with the splendid equipment there available. The spectra have a dispersion of 3 mm./A. in the second order, beautiful definition, and a reliable standardization; their full length is about 12m. In the very first period of spectrophotometric research, one would have had to measure by eye the density of all consecutive surface elements of the plate by means of a Hartmann photometer. Since the invention of the microphotometer, this whole process of deriving the transmission of the plate all along the spectrum is solved by an entirely automatic apparatus. However, the second step involved, the conversion of the transmission curve into an intensity curve, is still now generally made by tedious measuring and reading from graphs and plotting point by point, exactly in the same cumbersome way as we formerly did when we determined transmission with the Hartmann. In our case, it would have been utterly impossible to follow such a lengthy procedure. The total length of the microphotometer records amounted to 120m. When handling such extensive material, a completely automatic and direct registration of the intensity curve is necessary.† This was solved by adding a relatively simple auxiliary apparatus to the ordinary microphotometer; a diaphragm is inserted, cut out in the form of a characteristic photographic curve, corresponding to the plate which we are investigating. The instrument works remarkably well and has been in full operation for the whole of our atlas. For a similar purpose an entirely different instrument of great ingenuity has been devised by Williams and Hiltner at Michigan; it was used by them for their wonderful Atlas of Stellar Spectra. I have the impression that both of these instruments are adapted to their particular problem. The Michigan apparatus can be used without complications even if the characteristic curve changes quickly along the spectrum, as is generally the case in stellar spectra of moderate dispersion; but it has the disadvantage that it increases the graininess of the plate. The Utrecht device is only practical when the characteristic curve remains the same over a considerable distance along the plate, so that the same diaphragm can be kept in use, but it reduces the graininess to a minimum.

It was a real thrill to develop the intensity curves recorded, to see in the red light of the darkroom how the graphs appeared and how the profiles of the well-known Fraunhofer lines were revealed one by one for the first time in their true intensity values.

When turning the leaves of the atlas, many striking features of spectral lines become at once apparent. The shallow hydrogen lines and the Ca^{+}-lines in

* Minnaert, Houtgast, Mulders, *Photometric Atlas of the Solar Spectrum*, Amsterdam, 1940.
† Minnaert and Houtgast, *Z. Astrophys.*, **15**, 354, 1938.



A—Mount Wilson. B, C, D—Evershed.

The Fraunhofer Lines of the Solar Spectrum, M. G. J. Minnaert.

the infra-red, the broad wings of the sodium and magnesium lines, the deep iron lines in the violet, the complicated blends in the ultra-violet are striking. Shortly after the publication, Mulders described the faint ultra-violet hydrogen lines up to H17, which Unsöld also remarked; they can only be seen on the microphotometer records and not by looking at the original plate.*

It is very important to examine the narrower lines of the atlas and to find out how far their profiles have to be corrected for instrumental distortion and broadening. From plates taken for that purpose, we determined the instrumental curve: we found that a truly monochromatic line would be broadened into a line with a width of 61mA. (in the second order, $\lambda = 6000$ A.). However, van de Hulst, from a careful analysis of the atmospheric oxygen lines, showed that our instrumental width had been overestimated a little, and that the width should rather be taken as 51mA.† Let us now consider the influence of this effect upon the narrow solar lines. From a random selection of well isolated lines, recorded in the atlas, we draw typical mean profiles. To correct these for instrumental broadening, several methods are available. In our experience, that of Burger and van Cittert ‡ is still very reliable; but van de Hulst § has described other and quicker procedures. We find now the corrected profiles as drawn in Fig. 1.

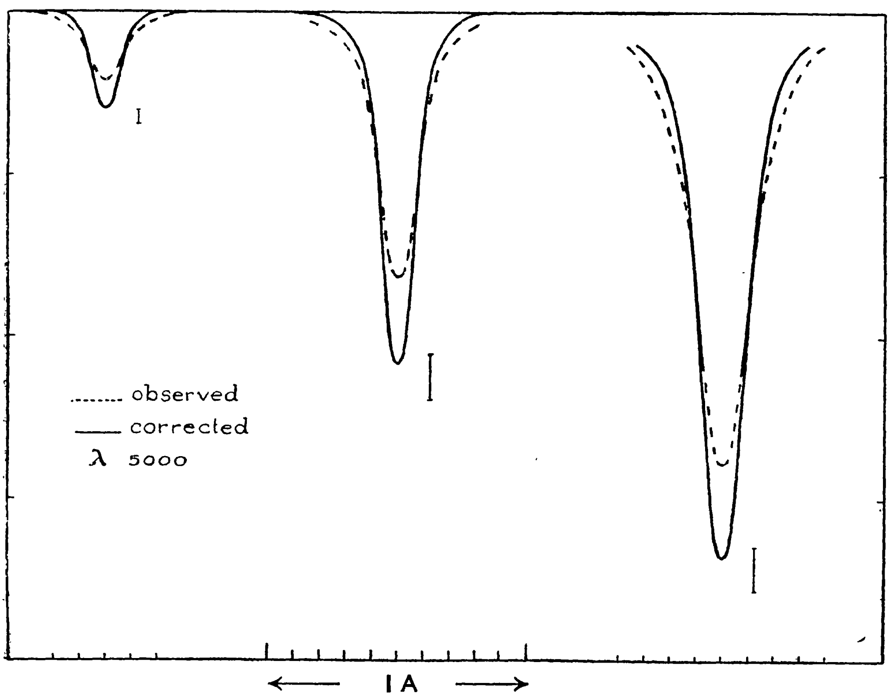


FIG. 1.

Profiles of faint Fraunhofer lines from the Utrecht Atlas.

A valuable check on these results is obtained from measurements by Shane ||, who carefully determined with his interferometer the true central intensity of some weak lines. By comparison with the Utrecht atlas, he finds that the correction varies somewhat from plate to plate; according to his curves, the central

* Mulders, *P.A.S.P.*, **53**, 38, 1941.
† *B.A.N.*, **10**, 79, 1946.
‡ *Z. Phys.*, **79**, 722, 1932 and **81**, 428, 1933.
§ *B.A.N.*, **9**, 225, 1941; and **10**, 79, 1946. See also: Kremer, *B.A.N.*, **9**, 229, 1941.
|| *P.A.S.P.*, **53**, 200, 1941.

intensities of the lines considered should fall within the range indicated in our diagrams by vertical bars (Fig. 1).

The excellent agreement shows that such corrections can be made in a quite reliable way. If the corrected central intensity is about right *, the other points of the profile will be still better. It is well known that in principle, given an accurate instrumental curve and precise measurements, arbitrarily narrow lines can be fully resolved. In practice there are very definite limits. But apparently the instrumental curve of our atlas is sufficiently narrow, compared to the rather considerable width of all solar lines, to make a reliable correction possible for all of them. The profiles thus obtained, similar to those drawn on Fig. 1, are the *true* shapes of the faint Fraunhofer lines. The atlas is sufficient for a full resolution of all solar lines.

The origin of the instrumental broadening is still not fully understood. For a part it is due of course to diffraction by the finite size of the grating; but other effects must be certainly involved also. As far as present experience goes, the width of this instrumental curve seems to be proportional to the wave-length, as might be expected for a diffraction phenomenon. It would be important to check this for different spectrographs.

Another interesting problem is the slight asymmetry toward the red, observed in a great number of the isolated lines throughout our atlas (Plate 9A). It is of course necessary to ascertain whether this effect must be ascribed to a real asymmetry in the Fraunhofer lines, or to an asymmetry in the spectrograph, or to inertia in the microphotometric apparatus.

1. We begin by recording a Mt. Wilson plate near λ6100 with an ordinary microphotometer, without cylindrical lenses or intensity apparatus, just in order to have clean and simple experimental conditions. The asymmetry shows again, towards the *red*, apparently as strong as in the atlas.

2. The microphotometer is run in the reverse direction; the asymmetry remains, always towards the *red*; the records forward and backward are identical. This proves that inertia of the microphotometer is excluded (*cf.* Plate 9C and D).

3. We now investigate a plate of the same spectral region, taken with the grating spectrograph at Hale's private observatory, Pasadena. The asymmetry is again present, to the *red*, and by about the same amount as in the Mt. Wilson plate. One would almost suspect that the phenomenon is a true solar effect!

4. Fortunately, Evershed was so kind as to send us a few very fine plates, taken by means of his autocollimating spectrograph with liquid prisms, its dispersion is equivalent to that of ten 63 deg. flint glass prisms. Here the asymmetry in the spectral lines is small, but distinctly toward the *violet* side. (Plate 9B). In a second series of plates from Evershed the asymmetry is still more reduced (Plate 9C and D).

5. From these records it is now clear that the asymmetry in our atlas has an instrumental origin, which is to be found in the spectrograph. Let us now compare a spectrum taken at Hale's laboratory with the left side and another with the right side of the grating. The records show that the asymmetry is towards the *red* in both cases. It may be that the grating itself is the source of the trouble. It may be that in big spectrographs the objective does not always

* The central intensities found agree reasonably well with those of ten Bruggencate, *Z. Astrophys.*, **18**, 327, 1939. Those of Allen are appreciably lower, *Ap. J.*, **85**, 165, 1937.

concentrate the rays in a perfectly symmetrical image. In any case it is clear that all care should be given to such instrumental imperfections. A true asymmetry of Fraunhofer lines, mentioned sometimes in the literature, cannot be considered as established unless confirmed by very precise experiments.

It must be possible to account for the asymmetry of the atlas lines by considering the influence of the instrumental curve.* This curve, as it was determined from neon lines and published in the introduction of our atlas, shows indeed some asymmetry; a slight increase of this asymmetry would already be sufficient to explain the asymmetric line-wings; and this modification seems reasonable, considering the difficulties of determining an instrumental curve.

Fig. 2 finally presents the best available mean curve. It embodies: (*a*) our original determinations from neon lines; (*b*) a slight contraction after van de Hulst; (*c*) the asymmetry, as derived from the wings of well isolated lines.

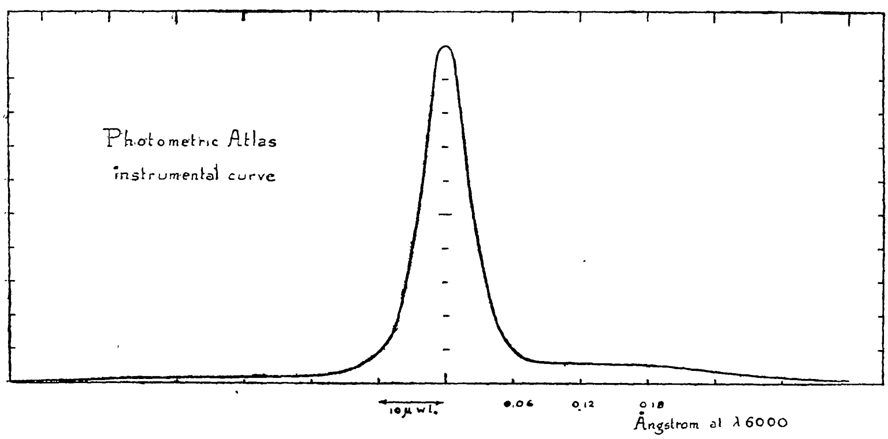


FIG. 2.

It will certainly prove very interesting to undertake a detailed investigation of solar line profiles either by means of the interferometer or by precise corrections to the atlas curves. For only this method gives information on the *individual* shape of each particular line, independent of any theory.

Apart from such a detailed and always difficult analysis, it is important that from each profile, however distorted by the instrument, we are able to derive a most valuable characteristic: the area, which is a measure for the energy absorbed in the line. This area, which we express as an equivalent width†, is a more precise definition of what was formerly called rather vaguely the "line intensity". The introduction of this concept proved very useful, both from a descriptive and a theoretical point of view. Already in 1934, Allen presented a beautiful catalogue of equivalent widths, which was extensively used.‡ After the publication of our atlas, we thought that it would be useful to derive a similar catalogue from our graphs. This work was undertaken in the difficult years of the war by a team of older and younger Utrecht astronomers, and I can inform

* This subject has been fully investigated by Messrs Buys and Ongering; I thank them for a preliminary communication of their results, which are being published in *B.A.N.*

† First introduced: *Versl. ned. natuur-geneesk. Congres*, 1923. From theoretical results of Allen and Menzel, it proved afterwards useful to measure widths in micro-wave-lengths $= 10^{-6}\lambda$. (Dunham, *Publ. Amer. astr. Soc.*, **7**, 215, 1933.) This is the more so, because the width of the instrumental curve is also proportional to λ.

‡ *Mem. Commonw. Obs. Austr.*, **1**, No. 5, 1934 and **2**, No. 6, 1938; *Ap. J.*, **88**, 125, 1938.

you that the infra-red spectrum, recorded in the first order, is now practically ready for publication. This is the part most urgently needed, because it has not yet been treated by Allen and supplements his work. It is curious how many difficulties have to be solved in an apparently so simple undertaking. Thus the faint lines, with equivalent widths below 20mA., are difficult to measure with sufficient precision by means of a planimeter. We found a much better and quicker method in making glass scales with a great variety of standard profiles, once for all accurately measured, and to which the atlas lines are easily matched. Another very frequent difficulty is the question whether a small inflexion in the graph is due to a Fraunhofer line or to graininess of the photographic plate. Then for many strong lines there is doubt concerning the precise run of the continuous background. Abnormally broad lines may be considered as single and widened, or as a close doublet of normal lines. The analysis of blends is again a special problem; for this purpose, well isolated lines of the atlas were corrected, theoretically compounded into a great variety of blends, and finally blurred again by the instrumental curve into model blends, thus furnishing reliable standards for comparison. So there are many questions involved which can be solved only by much experience and discrimination.

As Miss Farnsworth at Mount Holyoke kindly offered the help of her observatory for this programme, we asked her to make independent measurements of several series of selected dubious lines. At the same time I am informed, by the courtesy of Babcock, that a very complete catalogue of the infra-red solar spectrum has nearly been finished at the Mount Wilson Observatory. Both sets of American measurements will furnish an excellent check on our catalogue and a very useful estimate of the possible errors, due to differences in interpretation.

In all these considerations we have mentioned "the" equivalent widths of Fraunhofer lines, as if their intensities were invariable and once for all fixed. It is absolutely necessary to investigate whether the solar spectrum is really constant, by comparing plates, taken with the same instrument at different times during a series of years. Such a fundamental investigation was made by van der Meer *, using the collection of spectrograms taken at Utrecht. His method, being purely differential, is at the same time very simple and very sensitive; it can be used for plates without any calibration. I would like to see it applied to the material of other observatories. The result was: an astonishing constancy of the solar spectrum, which means also constancy of the solar temperature; a difference of 25 deg. would have been detected, by comparing lines of very different excitation potentials. This is fully in line with the well-known constancy of the solar radiation. The variations in the far ultra-violet, ascertained from geophysical observations, apparently do not affect the gases which absorb the Fraunhofer lines, probably because the far ultra-violet radiation originates in the chromosphere. At the same time this is a very happy circumstance for all of us who are engaged in measuring intensities and making catalogues, because now we are sure that the equivalent widths have fixed values; values found at different times and by different observers can be directly compared, and the care given to precise measurements is justified.

While the methods of measurement were improved and while a huge amount of data accumulated, the theory also of Fraunhofer lines was developed, and it

* *Variaties van Fraunhofer-lijnen*, Dissertation, Utrecht, 1936; *Z. Astrophys.*, **13**, 157, 1937.

has reached at this moment a more or less classic form. For the sake of a systematic exposition, I have described first the observations, and I will consider now the theoretical side of the subject. Actually both methods of investigation have continually influenced each other and their interaction has been a great stimulus towards progress. Already the first and most primitive intensity measurements have contributed to the solution of that fundamental question: "how does a Fraunhofer line actually originate?" It is perhaps not generally known that Kirchhoff and Stokes each stressed part of the phenomenon. When Kirchhoff assumes that the solar gases have a greater absorption coefficient for light inside the line, and also a greater emission coefficient, he apparently means that there is purely thermal absorption: the absorbed radiation is converted into heat, and reversely the atom is again excited by collisions. But when Stokes pictures the vibrating atoms and resonators which re-emit the arriving waves *, he has in mind the process which we now call selective scattering: the absorbed radiation is at once re-emitted, without an interaction of other atoms. Kirchhoff's celebrated experiment on the reversal of the sodium lines shows the effect of selective absorption and emission, because it is made at a relatively high pressure and in the presence of many molecules. Stokes was not able to illustrate his view of the matter by an experiment; actually it was only in 1924 that Dunoyer by means of modern vacuum technique demonstrated the pure resonance radiation of sodium. It is interesting that these two theories even now each hold part of the field, and that their relative importance has not yet been entirely settled. For a long time the conception of Kirchhoff generally prevailed. The model of Stokes was taken up much later by Julius, Stewart and Schwarzschild and is now considered a better description of the phenomena.† That scattering plays an important rôle became at once clear when some measurements of profiles became available, made by Schwarzschild, von Klüber and at Utrecht. By thermal absorption the core of a Fraunhofer line could never become darker than 30 or 20 per cent of the continuous background, whereas many lines have central intensities of only 5 per cent and less.‡ Unsöld made a great step § by showing quantitatively that *scattering by damped atoms* accounts in broad lines for the profile of a strong Fraunhofer line. This profile is practically a resonance curve, one of these well-known curves which our students have been recording for many years in practical work on electrical circuits. These same curves now explain also why Fraunhofer lines are not sharp and black, but broad and hazy.

Originally only very few lines could be measured in a reliable way. It was important to make the bulk of all the fainter lines useful for theory, avoiding at the same time all difficulties and uncertainties of the instrumental curve and the correction for finite resolving power; this was the more necessary, because it was proved soon that the most interesting lines had only an equivalent width of a few hundredths of an angstrom. This problem was solved by making use of the equivalent widths, and when the relation between these equivalent widths,

* *Phil. Mag.*, **19**, 196, 1860.

† Selective scattering is identical with the anomalous scattering advocated by Julius. His work remains of historical importance, though the anomalous refraction in density gradients, also considered by him, is now known to be negligible.

‡ Thackeray, *M.N.*, **95**, 293, 1935; Redman, *M.N.*, **95**, 742, 1935 and **97**, 552, 1937; Allen, *Ap. J.*, **85**, 165, 1937; Shane, *Lick Obs. Bull.*, **19**, 119, 1941.

§ *Z. Phys.*, **44**, 793, 1927.

from the very faintest to the very strongest lines, was found. The method was introduced by Russell and proved wonderful.* Comparing the components of multiplets, we find a *curve of growth*, indicating how the lines increase in strength when the concentration of the resonators or of the absorbing atoms augments. Russell had considered the increase of the Rowland intensity. It was clear that more significant data could be obtained by plotting the equivalent widths.† We found remarkable curves, drawn at first in a purely empirical way, but which we at once recognized when, just in time, a paper of Schütz was published on the curves of growth of laboratory lines.‡ Curves of growth are very insensitive to the stellar model, but they give full information concerning the profile of the spectral lines. Just as these profiles can be deduced from a blurred spectrum by correcting for the instrumental curve, similarly they may be found from the curve of growth, in both cases by solving an integral equation. From our curves, Mulders and I were able to conclude that the damping of Fraunhofer lines is about ten times the classical damping, and that apart from this there is also a broadening due to the Doppler effect of thermal motion and appearing especially in the faint lines. The curve of growth for solar lines has been constructed later on the basis of much more material and with considerably increased accuracy by Righini, Menzel, Allen, R. B. King, K. O. Wright, and our original results have been mainly confirmed.§ From this work and from that of many other observers and theorists, it is possible now to picture already in detail the behaviour of the atoms in the radiation field of the Sun.

Let us consider a volume element of the solar atmosphere, containing some milliards of corpuscules. These we have never observed individually, we only hear the ether music emitted by the buzzing swarm, but the refined analysis of these waves reveals each motion, each adventure happening to any single atom. We see before our eyes that there are about 10,000 hydrogen atoms against one metal atom; more uncertain is the abundance of helium, carbon, nitrogen, oxygen, which together perhaps may be put equal to 2000 particles. The metals are for a great part ionized; a few per cent of them are excited. Some free electrons shoot through the swarm, about one to the thousand particles, most of them having been ejected from hydrogen atoms. All are moving quickly by thermal agitation. Moreover there are turbulent motions of the order of 1 km. a second. When ether waves arrive, these atoms start resonating; but why are they damped in doing so? This question has stimulated extremely interesting investigations on atomic behaviour. We first considered classical radiation damping: a string gives only a pure tone when vibrating in a vacuum, but then I cannot hear it; as soon as I perceive a sound, the chord must have transmitted energy to the air; so it has experienced some friction; so it is damped; so its tone is not pure any more. The curve of growth showed that the damping in Fraunhofer lines is actually ten times the classical radiation damping. Now an atom is not identical with a classical resonator. We calculated what

* Russell, Adams, Moore, *Ap. J.*, **68**, 1, 1928.

† Minnaert and van Assenbergh, *Z. Phys.*, **53**, 248, 1929; Minnaert and Mulders, *Z. Astrophys.*, **1**, 193, 1930 and **1**, 300, 1930; Minnaert and Slob, *Proc. Acad. Sci. Amst.*, **34**, 543, 1931. General review in *Observatory*, **57**, 328, 1934.

‡ Schütz, *Z. Phys.*, **64**, 662, 1930.

§ Righini, *Mem. Oss. Arcetri*, Fasc. 48, 1933; *Mem. Soc. astr. Ital.*, **7**, 1933; Menzel, Baker, Goldberg, *Ap. J.*, **87**, 81, 1938; R. B. King, *Ap. J.*, **87**, 40, 1938; Allen, *Mem. Commonw. Obs. Austr.*, **1**, No. 5, 1934; K. O. Wright, *Ap. J.*, **99**, 249, 1944; Rubenstein, *Ap. J.*, **92**, 114, 1940.

a quantum atom would do; it could be sometimes more, sometimes less damped than a resonator, but a factor 10 could certainly not be expected.

The other possibility was collisional damping. Physicists and astronomers are familiar with the idea, that the spectral lines become hazier by pressure. But could this effect operate at 0·01 atm.? And if so, how precisely does it work?* The kind of disturbance mostly considered by the physicists is a typical collision, which quenches the energy of the excited atom. But this is identical with what we called thermal absorption, and which we have already excluded because of the central intensities. Then Weisskopf and Lenz discovered another, a much more subtle disturbance.† Particles passing along had only to modify the frequency of a vibrating atom during a very short moment now and then, in order to confuse the phase coherence of the scattered wave-train. So this was the solution; there could be disturbance and still no quenching of the energy! The precise theory of this effect was developed later by Lindholm ‡ and in a more general form by van de Hulst.

But we ask further. *How* does a passing atom accelerate or retard the vibration? Are all atoms equally effective in this respect, and how effective are they? Here also, different possibilities have been considered. It may be that the quadratic Stark effect of the electrons plays a rôle. But Strömgren, calculated from atomic theory §, and ten Bruggencate and Houtgast || showed from observations that in the Sun the most important effect is due to the Van der Waals forces of the hydrogen atoms, forces which act proportionally to the inverse sixth power of the distance. This then seems to be the ultimate explanation for the haziness of Fraunhofer lines: *phase disturbances by hydrogen atoms.*

To the hydrogen lines themselves this theory does not apply. They are different from all other lines, because hydrogen atoms are the only ones which experience a linear Stark effect. In their case the statistical broadening by the Stark effect of neighbouring ions is the most efficient perturbation.

Finally there is the important fundamental question, whether after each absorption by an atom there follows an emission in the same frequency. A physicist would be astonished to hear the question put that way and he would reply: "Of course not; the returning electron can fall back just as well in steps as directly". Astrophysically speaking such processes are nearly irrelevant, because they are to a great extent balanced by the reverse processes; for nearly each quantum of light, split into pieces, there is a new quantum welded together. But owing to the anisotropy of the solar radiation field, the balance is not perfect, and a small amount of continuous radiation is pouring down into the strong Fraunhofer lines, so that their cores become less dark.¶

Also in another way there could be a difference between the radiation absorbed and the radiation emitted. We know that the atomic energy levels are not perfectly sharp, but may be pictured as groups of numerous narrow-spaced sub-levels. An electron, starting from one of the sub-levels, may fall back to

* A general review is found in Unsöld, *Vjschr. astr. Ges., Lpz.*, **78**, 213, 1943.

† Weisskopf, *Z. Phys.*, **75**, 278, 1932 and **77**, 398, 1932; Lenz, *Z. Phys.*, **80**, 423, 1933; Burkhardt, *Z. Phys.*, **115**, 592, 1940.

‡ Lindholm, *Ark. Mat. Astr. Fys.*, **28**, B, No. 3, 1942; van de Hulst, in course of publication.

§ E. Strömgren, *Stromgren. Festschr.*, 1940.

|| ten Bruggencate and Houtgast, *Z. Astrophys.*, **20**, 149, 1941.

¶ Woolley, *M.N.*, **94**, 631, 1934; *Observatory*, **57**, 345, 1934; Pannekoek, *M.N.*, **95**, 725, 1935; Strömgren, *Z. Astrophys.*, **10**, 237, 1935; Dempster, *Ap. J.*, **96**, 295, 1942.

another one, and a wave-length shift is observed.* A special case of this is the "interlocking", studied by Woolley. It was assumed that this effect would be absent in resonance lines, because the ground level is perfectly sharp. But Houtgast made plausible that a level disturbed by collisions must be considered as unsharp just as well as a naturally widened level. † Quantum mechanical calculations made by Zwaniken under the direction of my colleague Rosenfeld seem to confirm this view, but at the same time show the complications involved.

Having studied our volume element we proceed to the investigation of the solar atmosphere as a whole, and we have to consider how the interaction of all its volume elements explains the observed Fraunhofer spectrum. Our study of the properties of solar gases was actually atomic physics. The interaction of all the infinitely numerous layers is a typical astrophysical problem. These problems of transfer in immense atmospheres have a beauty of their own, which you only feel when you have worked in this field. The infinitely complicated paths of the radiation, with all their turns and bends and loops, are grasped by the power of mathematics into simple, impressive equations. The whole architecture of a stellar atmosphere may thus be studied in detail, with its temperature, pressure, ionization at each level.‡ In the last few years the work of Wildt and other scientists, culminating in that of Chandrasekhar and his collaborators, has furnished a most important basic contribution to this description of the Sun.§ If I could show you a sample of the solar gases, you would perceive that this mixture has a striking green-blue colour. It is due to the continuous absorption by negative hydrogen ions, of which there is only one against millions of ordinary hydrogen atoms. This gas, practically unknown on Earth, was discovered from the study of the solar spectrum; the calculation of its optical properties was carried out entirely by theory. Now for the first time it is possible to find the true relation between pressure and temperature in the successive layers. And this again is the basis for all calculations on the Fraunhofer line profiles.

There remains an uncertainty concerning the exact temperature distribution in the outer layers of the Sun. Part of the energy, absorbed by the Fraunhofer lines, is used in raising the temperature of the gas. This is the blanketing effect discovered by Milne. For its computation we ought to know how much energy is taken away from the solar spectrum by the whole of the Fraunhofer lines. Years ago I determined for this fraction 0·15. Mulders made a much more accurate measurement and found 0·08.|| A few years ago however the French astronomers have shown that our energy curve has to be changed considerably in the ultra-violet; taking this into account, and repeating the computation, we come now to a coefficient 0·10. But the blanketing effect is more complicated than it was thought at first. It is different according to the height where the

* Eddington, *M.N.*, **89**, 633, 1929; Woolley, *M.N.*, **91**, 979, 1931 and **98**, 624, 1938; Pannekoek, *Proc. Acad. Sci. Amst.*, **34**, 1352, 1933; Weisskopf, *Z. Phys.*, **85**, 451, 1933; *Observatory*, **56**, 302, 1933; Spitzer, *M.N.*, **96**, 794, 1936 and *Ap. J.*, **99**, 107, 1944; Zanstra, *M.N.*, **101**, 273, 1941.

† Houtgast, *Variations in the profiles of strong Fraunhofer lines along a radius of the solar disk*, Dissertation, Utrecht, 1942.

‡ Strömgren, *Tables of model stellar Atmospheres*, Copenhagen, 1943.

§ *Ap. J.*, **104**, 430, 1946 and **104**, 446, 1946.

|| Minnaert, *Z. Phys.*, **45**, 610, 1927; Mulders, *Aequivalente breedte van Fraunhofer-lijnen*, Dissertation, Utrecht, 1933.

Fraunhofer lines originate and according to their mode of formation, either by scattering or by thermal absorption; and even according to their spacing along the spectrum. Another source of uncertainty is turbulence, which was shown by Plaskett to modify the general temperature distribution.

Fortunately for many problems concerning Fraunhofer lines these doubtful points are not essential. I would like to show you how easy and straightforward the calculation of the intensity becomes if it is applied to the important case of faint lines or to faint wings of strong lines. We are able to express the dip of the intensity in the line as a simple integral over the scattering and over the absorbing material, the contribution of each layer being weighted by a function of depth computed once for all *:

$$\frac{i_0 - i}{i_0} = \int_0^\infty \frac{\kappa_\nu}{\kappa} g_1(\tau) d\tau + \int_0^\infty \frac{\sigma_\nu}{\kappa} g_2(\tau) d\tau.$$

The integrals of $\frac{\kappa_\nu}{\kappa}$ and $\frac{\sigma_\nu}{\kappa}$ may be taken for practical purposes over the optical depth τ, but they are equivalent to integrals of κ_ν and σ_ν over the gas mass. So it is clear that the weighting functions simply express how effective are the scattering and selectively absorbing atoms at each depth: the highest layers are distinctly visible, whereas the deeper layers are veiled more and more and are finally lost in a luminous fog of continuous radiation. The computation of this weighting function can be made, independently of assumptions about the temperature distribution, by making use of the direct observational data on limb darkening. Making use of the analysis already carried out by Chalonge and Kourganoff †, this computation is easy and straightforward. We select wave-lengths where no influence of neighbouring Balmer lines is to be feared and we express the dip of the profile relatively to the continuous background. The weighting curves, thus computed for the centre of the Sun, expressed in units $E_{0\nu}$, are presented here as a practical help for the use of our atlas and for other work (Fig. 3). They are based on Abbot's measurements of 1906–08, those of the same author in 1913, and those of Raudenbusch in 1937. Several of the curves have been independently derived from two or three of these sets of data; it will be seen that the resulting differences, indicated by vertical bars, are small, and that the curves apparently are reliable to a fairly high degree. It is interesting to see how small is the difference between the effects of scattering and of thermal absorption, how the first is gradually getting more important the more we proceed to the red.

For a practical application of these formulae, it is necessary to divide once for all the functions $g(\tau)$ by $\kappa(\tau)$, and it is easier to integrate over $\bar{\tau}$ than over τ:

$$\frac{i - i_0}{i_0} = \int_0^\infty \kappa_\nu(\bar{\tau}) \, . \, h_1(\bar{\tau}) d\tau + \int_0^\infty \sigma_\nu(\bar{\tau}) \, . \, h_2(\tau) \, . \, d\bar{\tau}.$$

The discovery of the H^- absorption furnishes us with the data needed. As an illustration we assume the calculations of Barbier ‡ on the electron pressure and temperature, and use the variation of κ with wave-length as computed by

* Unsöld, *Z. Astrophys.*, **4**, 339, 1932 and **8**, 225, 1934; Minnaert, *Z. Astrophys.*, **12**, 313, 1936. A special case is studied by ten Bruggencate in *Naturwiss.*, **33**, 91, 1946; and more detailed calculations by the author are found in *B.A.N.*, **10**, 339, 1946.

† Chalonge and Kourganoff, *Ann. Astrophys.*, **9**, 69, 1946.

‡ Barbier, *Ann. Astrophys.*, **9**, 173, 1946.

Chandrasekhar. Fig. 4 now shows the weighting curves in their ultimate form, in units which are absolute and the same for all curves. Multiply the ordinates by $\sigma_\nu(\bar{\tau})$ and $\kappa_\nu(\bar{\tau})$, expressed per neutral hydrogen atom, integrate, and you get the dip of the line profile, expressed as a fraction of the continuous spectrum

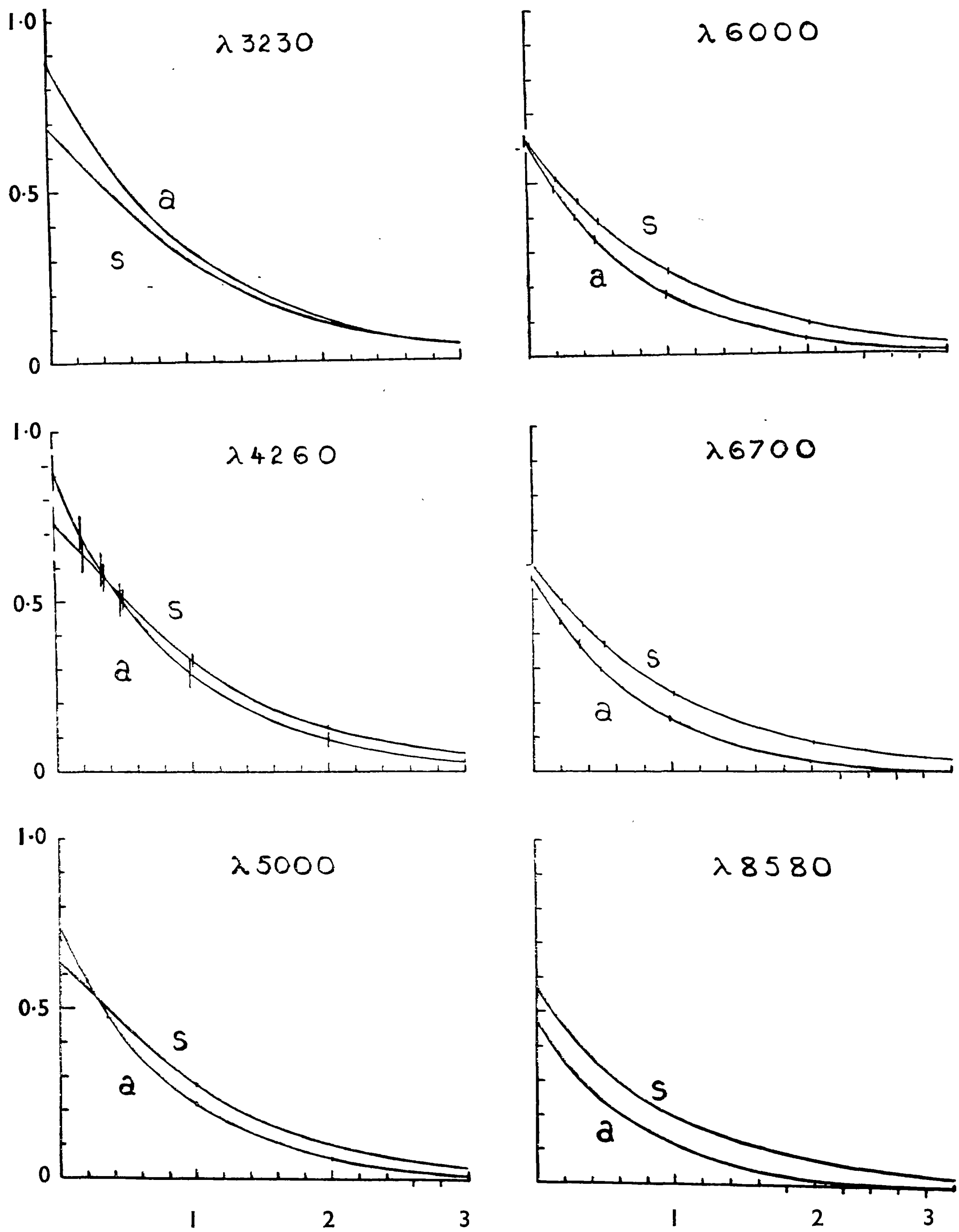


FIG. 3.—*Weighting functions* $g_1(\tau)$, $g_2(\tau)$.
Ordinates : g
Abscissae : τ

at the centre of the Sun. For such lines as H and K, for example, σ_ν is constant with depth and κ_ν is probably small, so the integral over our second weighting function is directly a measure for the dip. It is now still more apparent that only a small depth of the solar atmosphere contributes to the line formation; and this may be understood, because the effect of the rapidly increasing general

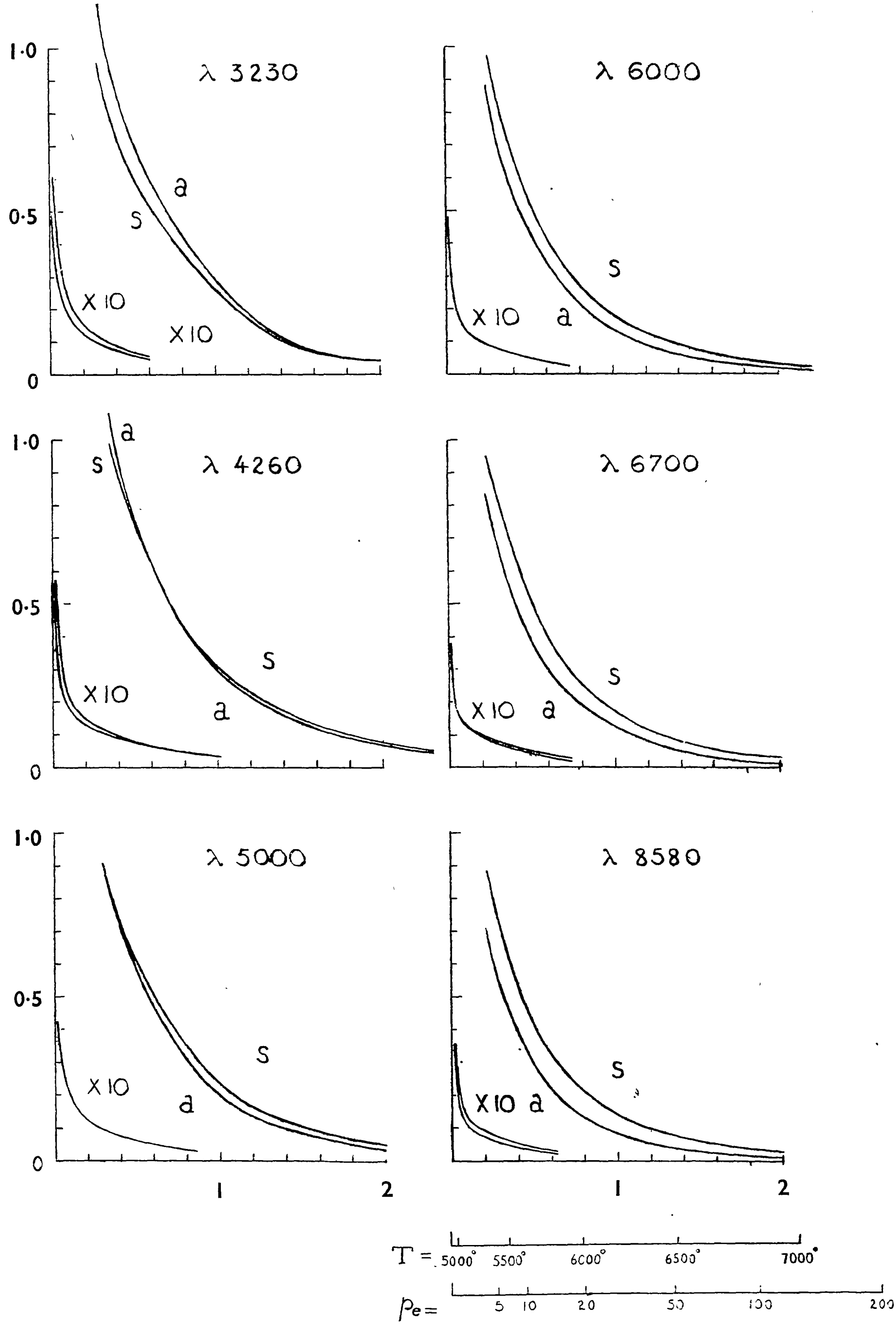


FIG. 4.—*Weighting functions* $h_1(\bar{\tau})$, $h(\bar{\tau})$.
Ordinates: $10^{-24}h$
Abscissae: $\bar{\tau}$

absorption has been brought into account. The effect of a given number of scattering or selectively absorbing atoms is now clearly seen to diminish towards the red, because the general absorption of H^- increases so that the deeper layers become invisible.

The theoretical calculation of profiles is less simple when the dip becomes more than about 15 per cent. Several simplified models have been proposed as approximations; but for many investigations, as for example the centre to limb variations, they will not be sufficiently precise. Fortunately a detailed calculation is always possible without real difficulties, according to the method initiated by Pannekoek *: (1) We start from Eddington's equations:

$$\frac{dJ}{d\tau} = \left(1 + \frac{\kappa_\nu}{\kappa} + \frac{\sigma_\nu}{\kappa}\right)H,$$

$$\frac{dH}{d\tau} = J - E,$$

and make a table of the functions κ_ν/κ, σ_ν/κ, E, as derived from our present theory of the solar atmosphere. (2) We assume a certain value for H_0 and $J_0 = 1{\cdot}8H_0$ at the surface, and integrate by finite steps, proceeding toward greater depths. If the initial value has been selected right, J tends toward E, or, more precisely, toward $E + \frac{1}{3}d^2E/d\tau^2$. (3) Knowing E and J at each depth, the emergent intensity in any direction is obtained by a well-known general formula. Since the discovery of the H^- absorption has given a considerably modified but consistent picture of the solar atmosphere, and since the selective effects are better understood now than before, a systematic calculation as here explained would be very interesting. This has not yet been made.

I have tried to give you a bird's eye view on the development of profile measurements and on the present state of theory. I would like now to show the crucial points where the cooperation of observers and theorists will be most necessary and where great progress in the next years will have to be made. I think there are two such primarily important fields for future research, and it was for this purpose that I left these for the end of my lecture, in order to give them the full stress.

The first crucial point is the variation of Fraunhofer lines over the Sun's disk. In studying this, we investigate the influence of a new variable, which is the direction of observation relative to the solar surface. Actually we look at the same layers of the Sun, but literally speaking from a new point of view, and we are able to check whether we have pictured aright our object and its structure in space. In principle the method is remarkably similar to a parallax measurement: we shift the position of our eye, and at once the world around us shows depth and becomes three-dimensional.

In the very first period of solar research, after Fraunhofer but before Kirchhoff, the difference between the spectrum in the centre and near the limb had been already considered and had given the greatest trouble to astronomers. They pictured the Sun as a glowing solid body, surrounded by a selectively absorbing atmosphere, and they expected to see the Fraunhofer lines increase in strength toward the limb, just as the atmospheric lines of the Earth do toward sunset. But nothing of that kind happened. Already in 1836 Forbes had noticed during an annular eclipse that the Fraunhofer lines looked just the same as in the centre spectrum †: an interesting anticipation of similar eclipse observations with modern quantitative technique, made by me in 1929 and by Redman in 1943.‡ One hundred years ago this difficulty was considered so insuperable that scientists

* Pannekoek, *M.N.*, **91**, 139 and 519, 1930; and *Publ. astr. Inst. Univ. Amst.*, No. 4, 1935. The method was applied to the general case by Minnaert and Houtgast, *Z. Astrophys.*, **12**, 96, 1936.

† *Phil. Trans.*, **126**, 453, 1836.

‡ Minnaert, *B.A.N.*, **6**, 151, 1931; Redman, *M.N.*, **103**, 173, 1943.

were about to reject the whole idea of the solar origin of Fraunhofer lines! The question was solved at that moment in a very sound way—by forgetting about it; so overwhelming was the evidence of Kirchhoff and Bunsen's discoveries, which followed a few years later.

It is since the work of Schwarzschild that we have understood that things are not so simple as was thought in the early 'fifties. At the limb of the Sun we look less deep into the photosphere; if the selective gas is mixed all through the continuously absorbing and emitting material, the effective path of the light decreases because of the smaller effective depth at the same time that it increases because of the greater inclination. Moreover, there is an important contribution of scattered light at right-angles to the direction of vision. The result will depend on the position of the selective layer, on the ratio between thermal absorption and scattering, on the wave-length, and on the part of the Fraunhofer line which is studied. All such different possibilities make this a subject of great and absorbing interest. Plaskett and the Oxford astronomers have done very important work in this field.* They have tried to take as a starting-point the direct observations and to derive by stepwise induction the properties of the solar atmosphere. At Utrecht, Houtgast and I have followed a more deductive method, making models of the atmosphere, calculating how the line profiles should be in the escaping radiation, trying to get a close fit to the observations.† Both methods have their advantages and their danger. In the use of the inductive method, small errors of measurement may have an unexpectedly great effect on the calculated solar model. The danger of the deductive method is that one gets a more or less satisfactory agreement with a certain model, and does not look for other models equally acceptable. It is evident that both methods must supplement each other.

It is remarkable that up to now there is not a single well-studied case in which the centre to limb variations have been quantitatively explained on the basis of the classic model of the solar atmosphere. But we must admit that most calculations have been made in an over-simplified way, and that the recent determinations of the H^- absorption and their consequences for the structure of the solar atmosphere have not yet been included. Among the most interesting new assumptions which have been tried, there is the non-coherent scattering considered by Houtgast. He showed that variations in the profiles occur in a systematic way all over the disk, and not only at the extreme limb; and he could only account for them by assuming non-coherent scattering. Several other investigations are being made now at our observatory on the centre to limb variation; in the first place for the hydrogen lines, which have such a specific importance; and secondly for the faint lines, where the theory is remarkably simple. Our observers always compare the profiles on at least six points, at increasing distances from the centre.

From the combined efforts of the workers in this field we must be able to derive the *stratification* of the solar atmosphere: the distribution of its atoms and ions over the consecutive layers, but also the variation with depth of the damping and the thermal absorption. The conception of a "reversing layer"

* Plaskett, *M.N.*, **91**, 870, 1931, and **101**, 3, 1941; M. G. Adam, *M.N.*, **98**, 112, 1937, and **100**, 595, 1940; Evans, *M.N.*, **100**, 156, 1940, and **101**, 21, 1941.

† Minnaert and Houtgast, *Z. Astrophys.*, **12**, 81, 1936; Houtgast, *Z. Astrophys.*, **16**, 43, 1938, and Dissertation, Utrecht, 1942.

has definitely disappeared. We see the integrated effect of the selective gases up to optical depths of about 2, when looking at the centre of the Sun, and only up to 0·5, when looking at the limb.

The second crucial point where observation and theory ought to cooperate closely, is the individual comparison between the several spectral lines of an element. Up to now we have worked more or less statistically, but in future a detailed study will be necessary. Génard and I have made measurements on the P-D lines of magnesium, which then found a beautiful explanation by Unsöld. Righini, when working at Utrecht, compared the individual sodium lines to their predicted intensities. Allen and K. O. Wright showed that the iron and titanium lines in the Sun are in better agreement with laboratory intensities than with the elementary multiplet rules. Allen tried to find the line to line variations of the Stark effect in the solar iron spectrum.*

The use of a mean curve of growth is too crude a method for such researches, and should be replaced by assigning to each line the individual curve of growth to which it belongs. This is possible. For each element, we can determine the *concentration* from faint lines, which are hardly influenced by the damping. To these faint lines we compare each of the stronger lines, and are then able to derive their individual *damping* constants. In this way both factors may be separated.

It is especially in view of this whole programme of research that our atlas was published and that we are working out now our intensity catalogue.

I hope that this *aperçu*, limited to essential problems which almost all are related to the Utrecht investigations, will have convinced even the non-specialist astronomers here present that the spectrophotometry of Fraunhofer lines is a beautiful and fruitful field of investigation. It is often said that we use the stars as cosmic laboratories where matter is found in conditions unknown on Earth. Indeed, the curve of growth, the damping by phase disturbances, the non-coherent scattering, the van der Waals' forces, the existence of H^-, they all have been discovered in the Sun or they have found there their first extensive applications. The International Astronomical Union intends to publish a table of atomic transition probabilities, based on the Fraunhofer lines, on data of experimental physics, and on theoretical calculations. Such a table would be of the greatest importance for physics and for astrophysics. It will have become clear that these contributions from solar spectroscopy have only become possible after we are more or less able to discern the factors, determining the line profiles.

With respect to our knowledge of the Sun, the main object of all our work will be to reduce a great diversity of apparently incoherent facts into logical consequences of a few fundamental physical laws, the ultimate result for astronomy proper being : the relative abundances of the several elements. In this stage of our science we remember a sentence of Auguste Comte † in his *Cours de Philosophie Positive of* 1835 : "There are questions which for the human mind will remain for ever unknown, for example the composition of the celestial bodies".

Once again we see that no one should try to restrict the grand sweep of science or of human progress.

* Minnaert and Génard, *Z. Astrophys.*, **10**, 377, 1935; Righini, *Z. Astrophys.*, **10**, 344, 1935; Allen, *M.N.*, **96**, 144, 1936, and **100**, 4, 1940; K. O. Wright, *Ap. J.*, **99**, 249, 1944.

† *Cours de philosophie positive*, **2**, 8, Paris, 1835.