The Presidential Address*

 STELLAR ATMOSPHERES AND LABORATORY ASTROPHYSICS

D.E. Blackwell

(Delivered at the Anniversary Meeting of 1974 February 8)

Although very popular as a research topic, the measurement of stellar abundances, and particularly of solar abundances, is regarded by some progressive astronomers as a mundane activity that is full of uncertainties and inaccuracies and often leads to doubtful terminal statements of the kind, '... in star X, silicon is overabundant by 0.3 dex, chromium is underabundant by 0.1 dex ...'. That the subject is full of inaccuracies is undeniable, yet it is also one of basic importance for modern astrophysics, providing information about the course of stellar evolution, about the nuclear processes taking place in stellar interiors, about the structure and history of the Galaxy and about the origin of the chemical elements. In this Address, I propose to examine it afresh and to discuss some of its more fallible areas, using for illustrative purposes some of the work that we are doing at Oxford.

The uncertainties to which I refer can be demonstrated by a study of the various determinations that have been made over the last half century of the abundance of iron, for example, in the solar photosphere. Some of these (1–27), on the scale log \( N_H = 12.0 \), are shown arranged in date order in the diagram of Fig. 1. The first point on this diagram refers to the measurement made in 1928 by Russell. He obtained the value of 7.15 using the eye-estimates of line intensities that are contained in the 1928 Revision of the Rowland Table of solar absorption lines. Actually, Russell was preceded by Mrs Payne-Gaposchkin (16) in 1925; I have not given her value because it is an average for several stars obtained by estimating positions in the spectral sequence at which weak lines of particular elements begin to appear. She obtained an abundance of 5.8.

*An up-dated and slightly expanded version of the original Address.

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Fig. 1. Determinations of the abundance of iron in the solar photosphere. The numbers against the points refer to the list of publications at the end of the paper. The bars at the right-hand side refer to determinations of the abundance of iron in the solar corona (not arranged according to date).
Russell assumed a model of the solar atmosphere in which the continuum is formed in deep layers and line absorption occurs above these in a cooler reversing layer. He was therefore effectively measuring the number of iron atoms in a column of unit cross-section in the reversing layer. The abundance relative to hydrogen was then found using a similar analysis giving the number of hydrogen atoms in the reversing layer. As we now know that this is not a correct model of the solar atmosphere, it is perhaps inappropriate to compare Russell's abundances, measured relative to hydrogen, with modern abundances. A better comparison would be between Russell's abundances, measured relative to another element such as silicon (28, 29), and modern values. The results of Russell and Mrs Payne-Gaposchkin for iron are presented in this form in Table I. From this you will see that Russell's data for

<table>
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<th>Table I</th>
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<tr>
<td>Photospheric abundance of iron relative to silicon</td>
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<tr>
<td>log ratio</td>
</tr>
<tr>
<td>iron/silicon</td>
</tr>
<tr>
<td>Mrs Payne-Gaposchkin</td>
</tr>
<tr>
<td>Russell</td>
</tr>
<tr>
<td>Modern value*</td>
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*Assuming $A_{Fe} = 7.65$, $A_{Si} = 7.55$ (28, 29)

iron are not significantly different from modern data†. Indeed, a modern research student complains that he apparently can do little better than Russell even though he measures his spectrum instead of making eye-estimates, and makes use of complex modern techniques to interpret the data.

The next two decades saw many advances in the techniques used for measurement of spectra and methods of interpretation. Among these were the development of the microphotometer for measuring photographic spectra, the idea of expressing the strength of an absorption line as an equivalent width, the concept of the curve of growth and of damping by neutral hydrogen atoms, the laboratory measurements of oscillator strengths, the discovery of the true origin of the solar continuum in the continuous absorption of the $H^-$ ion, and the use of model atmospheres. The later points in Fig. 1 show the effect of these refinements on determinations of the solar abundance of iron subsequent to Russell's measurement. Almost all of these developments were initiated and pursued by astronomers rather than by conventional physicists, presumably because the astronomers were more concerned with the absorption spectra of stars than the emission spectra of the laboratory spectroscopist. Indeed, even the measurement of oscillator strengths is still regarded as the province of the astronomer as much as the spectroscopist.

†It is of interest to compare the modern value for this ratio given in Table I with the values given by Urey (30) for the various bodies in the solar system.
Among the many astronomers who made distinguished contributions to these advances was Professor Allen, who recently retired from University College London. He and Sir Richard Woolley (31) made another important contribution in 1948 when they determined the coronal abundance of iron. They found a value that was at least ten times greater than the generally accepted photospheric value at this time, and the anomaly did not begin to be resolved until some five years ago when it was realized by, among others, Garz & Kock (35) that there was a large error in the existing oscillator strengths of photospheric iron lines. On the diagram of Fig. 1 three bars show recent measures (32, 33, 34) of the coronal abundance of iron. It is still of interest to know whether there remains any significant difference between the photospheric and coronal measures of abundance. However, my purpose in assembling the diagram of Fig. 1 has only been to give a first view of the uncertainties and difficulties of solar photospheric abundance determinations and I do not propose on this occasion to present a critical discussion of the various measures shown there. It is perhaps sufficient to say that the spread in the more recent determinations is attributable chiefly to a corresponding spread in oscillator strengths (including the absolute scale), and in the solar model used, including the microturbulence. My present belief is that the most reliable photospheric determinations so far give a value in the region of 7.65 (the value adopted for Table I). The coronal abundance is probably in the region of 7.75.

We see that in spite of all the advances that have been made since Russell's time there has been a disappointingly large spread of abundance values. This still persists to a smaller extent in recent measures, which over the last four years have shown a total spread of nearly a factor three. In addition, there may also be a standing error contributing to a possible difference between photosphere and corona. In the time that remains to me I propose to discuss in outline the various stages in the determination of an abundance, using a model atmosphere technique rather than a differential curve of growth analysis, and perhaps to demonstrate qualitatively that the observed spread is not unreasonable. My remarks apply to the Sun in particular and to stars of type F and later. The earlier type stars are a special case, and their peculiar problems are, in some ways, easier to solve.

The abundance A of an element in a star is obtained from measurements of the equivalent widths of absorption lines W in the spectrum of the star. These equivalent widths are related to the atmospheric model for the star and the atomic parameters for the element through a formal scheme of the kind outlined in Fig. 2. The section denoted
The equivalent width of a spectrum line depends upon—

The atmospheric model ($T_{\text{eff}}$, $\log g^*$, abundances, microturbulence) +

Atomic parameters (wavelength, $\log g^{**}f$, damping constant) +

Theory

*acceleration due to gravity
**statistical weight

FIG. 2.

‘theory’ refers to such problems as the mechanism of line formation and calculations of ionization equilibria and excitation made without the assumption of local thermodynamic equilibrium.

The Sun is unique among stars in that it is the only one for which a basic atmospheric model is obtainable by direct observation. The primary data that are required are the intensity of radiation at the centre of the solar disk and the variation of intensity across the disk from centre to limb. To construct a complete model we also need to know the various sources of atmospheric opacity, the most important for the Sun being the H$^-$ ion. It is essential to be sure that all the sources of opacity are included in the list, but even for the Sun there is still some doubt about whether the list is complete for the ultraviolet region, as has been discussed by, for example, Tarafdar & Vardy (36). To investigate this point, Mr Peter Craven has made a series of limb-darkening measurements at the Gornergrat Observatory of the Department of Astrophysics, in Switzerland, using a new technique. He suspends a 25-cm plane mirror in a magnetic field which can be modulated in a controlled fashion so that the mirror is caused to oscillate about an equilibrium position in a pre-determined waveform at any frequency up to 50 c s$^{-1}$. With this arrangement he scans a portion of the solar disk and builds up a complete scan extending across a complete solar diameter. The method is particularly useful for making fast scans near the limb when an effort is made to rectify the consequences of imperfect seeing*.

*At this point one of Mr Craven’s scans, at a wavelength of 402.9 nm was shown in the form of a slide. The diagram showed that the mean observed curve and a limb darkening curve calculated from the Harvard Smithsonian Revised Reference Atmosphere are indistinguishable, although there are deviations at other wavelengths.
Turning now to the atomic parameters, we need principally the variation of the atomic absorption coefficient, at each depth in the atmosphere, over the wavelength range of the observed line profile. This is determined chiefly by the oscillator strength of the transition, together with the broadening due to the thermal Doppler effect and to any microturbulence, and to damping. This spread in the atomic absorption coefficient then determines the absorption line profile. I use the word ‘microturbulence’ with reserve because it is a vague concept, and its amount and even its existence is questionable (see, for example, the discussions of Wilson and of Worrall (37, 38)). When presently available oscillator strengths are used, a parameter must be introduced to equalize the abundance values derived from weak and strong lines. This is usually interpreted as a microturbulence, and we shall continue this as a description of the parameter. The effect of microturbulence on the equivalent width of a strong line is shown in Fig. 3. If the line is already highly saturated at the centre, the addition of microturbulence will merely broaden the line while only slightly relieving the saturation at the centre, and the equivalent width is

\[ W_m > W_0 \]

**Fig. 3.** Demonstration of effect of microturbulence on the equivalent width of a strong line.
Fig. 4. Demonstration of effect of damping on the equivalent width of a strong line.

thereby increased. The effect of damping is shown in Fig. 4, from which you will see that it increases the equivalent width of a strong line. So, some knowledge of microturbulence and damping are needed for the interpretation of the equivalent width of a strong line. We shall discuss later how much knowledge is actually needed. However, the equivalent width of a weak line is little affected by either microturbulence or damping.

Unfortunately, our knowledge of both microturbulence and damping is poor. The damping is due to interaction between neutral hydrogen atoms and the absorbing atom, with a smaller contribution due to interaction with neutral helium atoms. The interaction with hydrogen atoms, although a commonplace phenomenon in the solar atmosphere can scarcely be measured in the laboratory because of the difficulty of obtaining a spectroscopic source that contains a sufficient and known concentration of atomic hydrogen. Neither is it usually possible to make an accurate calculation of the interaction. So far, only one reasonably satisfactory calculation has been made; this is by Lewis et al. (39) for the case of the damping of the D-lines of Na I. That this calculation is probably reliable is shown by the good agreement between observations of the wings of the D-lines in the solar spectrum and calculations using the Lewis theory (40). For this and other spectrum lines, empirical studies (41, 42) of damping constants using solar line profiles for their determination show that the constant may
be expected to lie between the value, $\Gamma$, given by the Unsold relation (43) and the value $3.16 \times \Gamma$. The microturbulence may be expected to lie between the values of zero and 2.0 km s$^{-1}$. The effect of uncertainties such as these on the interpretation of equivalent widths has been considered by Blackwell, Calamai & Willis (44) who have given curves relating the errors involved to the equivalent widths and excitation potentials of lines; a typical relation between error due to uncertainty in damping, and equivalent width, for Fe I lines of 2.0 eV excitation potential at 600 nm lines, is shown in Fig. 5.

**Fig. 5. Effect of damping on error of interpretation of an Fe I line.**

The next step in our argument runs as follows. It is surely possible to obtain the equivalent width of a well-defined and unblended solar line to an accuracy of about 1 per cent. In an interpretation of such a line it is desirable to use an oscillator strength of comparable accuracy. But we would not wish to have this accuracy spoilt by a larger inaccuracy due to uncertainties in microturbulence and damping. The curves referred to above now tell us the maximum equivalent width that we may use without incurring errors of this magnitude. They show, for example, that at a wavelength of 600 nm and for an excitation potential of 0.00 eV, if an error of not more than 1 per cent is to be incurred through the uncertainties in damping and microturbulence, the
maximum equivalent width is roughly 9 mÅ for the damping uncertainty and 4 mÅ for the uncertainty in microturbulence. Of course, if one were to be content with a poorer accuracy, the maximum permissible equivalent widths would be greater than these.

Now we come to practicalities; what are such lines like and is it possible to measure them? Certainly a low noise spectrum is needed, and the technique of obtaining such spectra is a topic on which we have concentrated some effort at Oxford over the last few years. It would be appropriate at this stage to say that many people in Oxford have been concerned with this work and with the oscillator strength work that I will speak about later. I cannot give all of their names, but would like to mention David Petford (who has taken a large measure of responsibility), John Peach, David Emerson, Peter Ibbetson, Ted Mallia, Brian Collins, Geoffrey Smith and latterly Richard Ellis. Fig. 6 shows typical solar spectra obtained with the low noise spectrometer at the Gornorgrat Observatory (45). Equivalent widths of some

![Diagram](image-url)

**Fig. 6.** Typical solar spectra obtained at Gornorgrat Observatory.
of these lines are given on the diagram in order to show the appearance of lines of strength that we are speaking about. In this diagram, the lowest spectrum is of the centre of the solar disk, and the other two are of positions between centre and limb. The rms noise level in all of these spectra is of the order of 0.03 per cent, a value which is ordinarily used in our work, and it is clear that such spectra can be used for the measurement of very weak lines. A remarkable feature of this series of spectra is the change in their appearance between centre to limb, in that the spectra at the limb appear to have been recorded with a smaller wavelength resolution. In fact, the change is due to an increase in line width towards the limb, a phenomenon which has not so far been explained satisfactorily.

In a properly designed apparatus the noise is due to the random emission of photoelectrons from a photocathode and it can be progressively reduced by integrating for longer periods of time. The spectrometer at the Gornergrat, and the low noise one in the Department, which employs a different principle (46), do indeed give a progressively lower noise as the integration period is increased. No limit to the noise level has yet been observed, but a level of $10^{-8} \times \text{signal}$ is quite readily obtainable*.

Having shown that it is possible to measure lines of the required weakness in the solar spectrum, although care must still be taken over hidden blends, we now enquire whether their oscillator strengths can be measured, preferably to an accuracy of about 1 per cent. The problem of the measurement of oscillator strengths has been studied for several decades, but it is one of such extraordinary difficulty that reasonable accuracy has been achieved only quite recently. It is not my purpose to review recent developments but I would like to mention the work of the Kiel group, and that of Huber and his colleagues at the Harvard College Observatory, as representative of the more accurate work that is now being done. Broadly speaking, such a measurement

*At this point there was shown a film, made by Dr David Petford at Oxford, which demonstrated the effect of integration on noise level. The first frames of the film show the random arrival of photoelectrons in a solar spectrum in which some deep absorption lines can just be discerned against the high noise level. Subsequent sequences show the decrease of noise and the gradual appearance of weaker absorption features as the effect of progressive integration at constant signal. The first frames were photographed at normal speed but as the improvement continues as $\sqrt{T}$, and so gradually slows down, the film jumps first 5 min, and then 30 min. By this time the noise has become too small to be seen, and the next sequence shows the scale expanded by a factor of 30; from this it will be apparent that the noise level is now only a few parts in $10^5$. Following sequences show the integration of successively weaker signals. The effect of integration is shown in Fig. 7, compiled from frames taken from Dr Petford's film.
Fig. 7. Effect of integration on signal/noise ratio in a part of the solar spectrum. The successive spectra have been obtained with an increasing integration period.

is often made in two parts. In the first part, the oscillator strength of one line, usually a very strong line originating in absorption from the ground state, is measured absolutely. There are techniques for doing this, which are only applicable to strong lines, giving an accuracy of some 10 per cent: as an example, Bell & Tubbs (47) discuss the measurements that have been made on the resonance lines of copper.
and iron. In the second part, all other oscillator strengths are measured relative to this one, so that these also are obtained on an absolute scale. At Oxford we make these relative measurements by the absorption method using an improved version (48, 49) of the technique first used by King & King (50, 51). In the apparatus used at Oxford the absorption spectrum is produced in a 1.2 m long column of the vapour of the element under examination, generated by an electric furnace of 300 kW power. The vapour column can be raised to any temperature up to nearly 3000 °C, the temperature being measured by sighting on carbon blocks situated in the vapour with an optical pyrometer. The advances incorporated in the Oxford experiments comprise chiefly the use of an improved furnace giving a longer column of vapour which is of more uniform temperature; the use of an improved spectrophotometric system which is low-noise and employs a large modern echelle grating of high quality, with a consequent reduction in scattered light, and, not least, the use of computing techniques to analyse the data without sacrifice of accuracy. Our aim is to attain an accuracy of 2 per cent or better in relative oscillator strengths over a wide range of oscillator strength.

In principle, the ratio of the oscillator strengths of two lines is found from the ratio of the equivalent widths of the lines formed in absorption, and the temperature of the furnace. In practice, the experiment is much more difficult than this, especially if an accuracy of between 1 and 2 per cent is required. The first hurdle is the design and construction of a furnace that will run at high temperatures continuously and reliably over a period of months. The second is the development of the low-noise spectrometers needed for the measurements. In the latest version of the apparatus, two low-noise spectrometers are used simultaneously in an arrangement shown in Fig. 8, each spectrometer

![Fig. 8. Optical arrangement of spectrometers used with furnace.](image)

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Fig. 9. Profiles of a pair of lines formed in furnace, plotted using twin spectrometers.
plotting the profile of one absorption line of a pair. A typical graph plotter output from the two spectrometers is shown in Fig. 9. Each pair of lines is scanned many times at various temperatures, and then the lines are reversed between the spectrometers. Great care must be taken with the photometry and the measurement of the curve of growth correction, especially if we are obliged to bridge a large gap between two lines; then, either one line must be very weak, in which case it is affected by noise and requires knowledge of the form of the continuous background, or else the other line must be so strong that a good knowledge of the curve of growth is needed. The whole gap between the strongest line of a series, which has been measured absolutely, and the weakest line, might be a factor of $10^6$ or more, and its bridging to an accuracy of 1 per cent is a formidable task. Measurement can proceed only very slowly, so that the production of one good comparison between two oscillator strengths takes one whole day. Although the apparatus is now working well, much effort, frustration, heartbreak, and even tears, have gone into its development; in all, more than 10 years have been spent in bringing the apparatus to its present state. The long period of preparation may be regarded as an indication of our belief in the importance to an understanding of stellar atmospheres of having oscillator strengths of the accuracy that we are aiming at.

One important aspect of the experiments is to decide on the accuracy that has been achieved. This is not easily accomplished. Some assessment of it can be obtained by comparing results with those obtained by other groups using very different techniques. Such a comparison is given for some ground state lines of Fe I in Fig. 10.

![Graph comparing oscillator strengths](image-url)

**Fig. 10.** Comparison of measures of oscillator strengths for ground state lines of Fe I.
This comparison is between Oxford data (so far unpublished) and the data of Corliss & Bozman (52), and that of Corliss & Warner (53), both of which have often been used in analyses of stellar spectra, and with the data of Huber & Tubbs (54). The data of Corliss & Bozman, and of Corliss & Warner, were obtained using an emission technique, whilst those of Huber & Tubbs were obtained using a combination of the absorption method and the ‘hook’ method (55). The diagram shows that for progressively weaker lines the discrepancy with Corliss & Bozman, and Corliss & Warner becomes quite large, up to a factor of 3, but the discrepancy with Huber & Tubbs never exceeds about 5 per cent. As these lines originate solely from the ground state, the accuracy of the comparisons does not depend on a measurement of an excitation temperature or any assumption about thermodynamic equilibrium. The Oxford data depend only weakly on temperature measurement through the curve of growth correction, but in the main the comparison between the Oxford data and that of Huber & Tubbs represents a test of the accuracy of photometry of spectrum lines. The comparison with the data of Corliss & Bozman, and that of Corliss & Warner, tests in addition the amount of self-absorption present in the emission sources used by these authors. It is to be expected that comparisons such as these will be worse for excited lines because of their great temperature sensitivity. In general, the dip in the solar abundance curve of Fig. 1 is largely attributable to the kind of inaccuracies in oscillator strengths that are beginning to be shown in Fig. 9. We believe at Oxford that we are beginning to get the accuracy that we set out to achieve (0.01 dex), but we do not know yet whether our data or those of Huber & Tubbs are the more accurate*.

We have already noted that the absolute scale of oscillator strength is known only to an accuracy of 10 per cent, and it might therefore be thought inappropriate to try to measure relative oscillator strengths to a much better accuracy. In addition, there is perhaps a need to justify accurate measurements of Fe I oscillator strengths when it is known that about 95 per cent of the iron in the solar photosphere is in the form of Fe II and only 5 per cent in the form of Fe I; in these circumstances, a slight error in the assessment of the equilibrium will lead to a large error in the abundance of iron derived from measurements on Fe I lines. The answer to these points is that we are now going beyond the needs of an abundance determination, for which an accuracy of 10 per cent in the measurement of oscillator strengths is amply sufficient. The prime purpose of our measurements is to develop the use of accurate oscillator strengths as a tool for the investigation

*At this point a slide was displayed showing a solar curve of growth constructed from Gornergrat data and Oxford oscillator strength data.
of the properties of stellar atmospheres. Our first step in this work is to check whether or not there is a state of local thermodynamic equilibrium in the solar atmosphere, and more particularly, to ask how accurately the Boltzmann law describes the relative populations of the energy levels of an atom. For, using our measurements of solar equivalent widths and oscillator strengths we can determine the population of each level of the Fe I atom and check whether there is equilibrium to an accuracy that is close to 1 per cent. This is a problem which worried even Russell nearly half a century ago and which concerns astrophysicists much more now. Direct observational evidence for the Sun and similar stars is still very uncertain, but I would like to draw your attention to one piece of evidence from sunspot spectra (56).

It is a well-known feature of sunspot spectra that they often show lines of ionized metals that are much too strong for the low temperature of the umbra. This is demonstrated by Fig. 11 which shows the example of two Cr II lines in a part of the sunspot spectrum in the region of 530 nm; the especially prominent anomalous line of Cr II at 531.36 nm is clearly shown (56). This spectrum was obtained using the low-noise spectrometer at the Gornergrat on 1971 September 30. The anomaly for this line is very great, the measured equivalent width being 52 mA, whilst the calculated equivalent width is only 1.4 mA. The large observed equivalent width for the line makes it unlikely that it is wholly attributable to blending, whilst a study of the amount of light scattered into the image of the Sun by the Earth’s atmosphere and the telescope, made at the time of observation, shows that it cannot be accounted for by light scattered from the photosphere or penumbra. That the line is likely to be a real part of the umbral spectrum is shown by its Zeeman splitting, assuming that this is real; this splitting corresponds to the same magnetic field in the umbra that is obtained from the splitting of other lines measured on the same spectral scans. This is additional evidence that the line cannot be due to scattering from the photosphere, where there is zero magnetic field, or from the penumbra, where the magnetic field is smaller than in the umbra; this latter is shown in the diagram of Fig. 11 by the observation that the line is widened only in the penumbral spectrum and not split. It might be thought that the anomalous lines are due to the presence of a hot component in the umbra, but this is not a feasible explanation because it leads to an unacceptably large value for the continuum intensity. There remains only the explanation that there is not a state of equilibrium in the atmosphere of a sunspot umbra. If this is correct, there should be a great uncertainty about abundance measurements in magnetic stars, the atmospheres of which are usually assumed to be in equilibrium. Of course, the physical conditions in a sunspot umbra
are very different from those in the solar photosphere, and we must not draw any firm conclusions from these observations about the state of equilibrium in the photosphere. A full investigation for the photosphere must wait until accurate oscillator strengths are available for weak lines. Meanwhile, it is of interest to note that the abundance of manganese derived from lines of different excitation potentials, using Oxford data, are closely similar (57); data for these lines are shown in Table II. Although the equivalent widths of these lines are large, their wide hyperfine structures render them weak lines.

<table>
<thead>
<tr>
<th>Line</th>
<th>Transition</th>
<th>Excitation potential (eV)</th>
<th>Equivalent width (mA)</th>
<th>Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>5394·67</td>
<td>$d^8 S_{3/2}^o - z^8 P_{7/2}^o$</td>
<td>0·00</td>
<td>74·9</td>
<td>5·39</td>
</tr>
<tr>
<td>5432·55</td>
<td>$d^8 S_{3/2}^o - z^8 P_{5/2}^o$</td>
<td>0·00</td>
<td>45·9</td>
<td>5·38</td>
</tr>
<tr>
<td>5420·36</td>
<td>$d^8 D_{7/2}^o - y^6 P_{5/2}^o$</td>
<td>2·13</td>
<td>79·5</td>
<td>5·38</td>
</tr>
<tr>
<td>5407·42</td>
<td>$d^8 D_{7/2}^o - y^6 P_{7/2}^o$</td>
<td>2·13</td>
<td>62·0</td>
<td>5·48</td>
</tr>
<tr>
<td>5516·77</td>
<td>$d^8 D_{9/2}^o - y^6 P_{3/2}^o$</td>
<td>2·17</td>
<td>41·4</td>
<td>5·48</td>
</tr>
</tbody>
</table>

When good solar spectra are also available there are other important uses to be made of accurate oscillator strengths. Among these is an application to the study of damping processes. In the solar spectrum, the wings of the stronger lines are due to interaction between the absorbing atom and neighbouring hydrogen atoms. Such interactions are well known in atomic physics, and may be investigated in the laboratory for perturbers other than atomic hydrogen. The diagram of Fig. 12 shows as an example the damping of the Ca I 422·7 nm line by argon as measured by Petford & Smith (58) at Oxford*. Unfortunately, it is exceedingly difficult to perform this experiment with atomic hydrogen, which is responsible for damping in the solar photosphere, for if the temperature were high enough for the molecular hydrogen to be dissociated into atomic hydrogen, then ionization would leave almost no neutral calcium atoms to absorb at the wavelength of 422·7 nm. But in the Sun there is exactly the right environment. Almost all of the hydrogen is in the atomic state, and there is a sufficient concentration of calcium atoms to form a reasonably deep

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*In this diagram, absorption is plotted upwards.
absorption line. Yet, there is an important difference between the methods needed for the interpretation of the laboratory and the solar spectra. The laboratory profile can be analysed directly into a Doppler and damping component. The reason for this is that although the line is weak, it is also highly damped because the pressure of perturbing gas is high. On the other hand, the pressure in the solar photosphere is low, and a highly damped line is observed only because the path length is great. As a result, highly damped lines in the solar spectrum are usually strong lines with small residual intensities (highly excited

**Fig. 11.** Anomalously strong Cr II lines in a sunspot umbral spectrum.
lines are exceptional in that they can show a damping profile even when weak), and their profiles cannot be interpreted directly to give damping components unless accurate abundances and oscillator strengths are available. Now that good values for these quantities are becoming known, accurate damping constants for damping by atomic hydrogen are being derived.

Such damping constants will be of interest to the atomic physicist, but additionally so to the astrophysicist because they will provide an extra parameter that can be used in the interpretation of stellar spectra, and give information about surface gravity. It is possible that they may lead to other information about the star also, for as the damping constant depends upon the nature of the damping atom, and is different for helium and hydrogen, examination of damping profiles might lead to an abundance for helium in cool stars.

Our final need is for a model stellar atmosphere, defined principally by the effective temperature and the acceleration due to gravity. None of the methods available for finding the effective temperature are free from criticism. The most direct method uses the total flux from the star integrated over all wavelengths. Although the integration is now possible with reasonable accuracy for the brighter stars, as the infrared and ultraviolet contributions to the flux can be measured, the inadequacy of angular diameter data for later type stars either prevents the use of the method or severely limits its accuracy. In principle, the measurement of the distribution of flux with wavelength offers a better method. The slide* gives an illustration of the method, using data for the

*To be published.
distribution of the continuum flux for Arcturus between wavelengths 350 nm and 15 μ. All of the available data have been plotted here, including some that the Oxford department recently obtained in Israel using a spectrum scanner there. Among the data are the results of 13-colour photometry from Arizona (59). Examination of these points suggests that where scanner data are not available, 13-colour photometry of the quality obtained in Arizona makes an excellent substitute. The plot also shows that the broad band colours I, J, K, L, etc. (60) may be useful for showing the continuum distribution. Notwithstanding the work of Walker (61) there is an obvious scarcity of data in the near infrared, due to atmospheric absorption. Even the best ground-based sites are scarcely suitable and observations using aircraft are almost essential. A theoretical distribution calculated for an effective temperature of 4167 °K is also plotted. The agreement is not at all good, both theory and observation show the existence of a peak near 1.67 μ, corresponding to a minimum in the absorption coefficient for the H⁻ ion. In common with other comparisons, the agreement in the ultraviolet is not good, the calculated curve lying above the observed one. Unfortunately, it is rarely clear whether these discrepancies are due to inaccuracies in the model atmosphere, arising from inadequacies of the technique, or to lack of full knowledge of the opacities in the region, and it seems best to restrict the comparison to wavelengths above 450 nm*.

The acceleration due to gravity is another very uncertain parameter. A promising method for its determination uses the wings of line profiles employing damping coefficients derived from the solar spectrum. However, there is not time to discuss this further now.

In conclusion, I hope I have said enough to demonstrate that even for the Sun, for which we have good spectra and a reasonably good model atmosphere, abundances are very uncertain. The spectrum of iron as shown by the solar photosphere, and in laboratory experiments, has been studied more intensively than that of any other element; yet, we still do not know the solar abundance of iron to better than a factor of at least three. Abundances must be still more uncertain for a star like Arcturus, for which we do not have low noise spectra and for which an atmospheric model is less accurate. For other stars, for which we have even less precise data, the uncertainty is even greater. For all of these studies we depend on solar data, and because of this I hope that solar studies will continue to prosper in Britain.

*Arcturus is a crucial test object for the model atmosphere technique applied to later type stars because of the fine spectra that have been obtained by Griffin (62) and it is therefore important to obtain an accurate effective temperature.
REFERENCES