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SOME EFFECTS OF THE INSTRUMENTAL PROFILE IN STELLAR SPECTROPHOTOMETRY, WITH PARTICULAR REFERENCE TO THE ARCTURUS ATLAS

R. F. Griffin

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SUMMARY

A method is described of refining an instrumental profile (initially derived from emission-line observations) of a high-resolution stellar spectrograph, by using profiles of the telluric oxygen bands obtained with a solar spectrometer of still higher resolution.

Owing to the light thrown into the wings of the instrumental profile, the observed profiles of absorption lines in late-type stellar spectra are substantially shallower (by ~ 10 per cent of their central depressions) than the true profiles. It is not true that accurate photometry with a high-resolution spectrograph will result in a close resemblance between the spectrum being observed and the observations being made of it. It is not true that the resemblance can be appreciably improved by any increase in resolving power. Even with accurate photometry, the equivalent widths measured with the spectrograph here discussed must be 5–10 per cent less than the true values. Other fundamentally similar spectrographs are unlikely to be much better and may easily be much worse.

Important improvements in the observational accuracy of stellar line profiles only seem possible by the use of double-pass spectrometers, which unfortunately have low luminous efficiency.

1. PREAMBLE

The introductory text to the Arcturus Atlas (1), hereafter referred to simply as the Introduction, contains such information as the author supposed was desirable, and was able to obtain, concerning the characteristics of the spectrograph used to obtain spectrograms for the Atlas. The Introduction, however, purposely omits any discussion of the effects of these instrumental characteristics upon the spectrophotometric profiles occupying the remainder of the Atlas. The author believes that instrumental degradation of stellar spectrophotometry is quantitatively greater, and qualitatively more far-reaching, than is supposed by the majority of astronomers, and the present paper is intended to indicate some of the grounds for this belief.

In the following discussion, specific reference is made to the instrumental profile of the Arcturus Atlas, both because that instrumental profile has been published in sufficient detail to allow a reasonably complete discussion of its effects and because the results of the discussion are likely to be of value to users of the Arcturus Atlas. The writer hopes, however, that this paper will not be regarded just as a condemnation of the Arcturus Atlas—all other stellar, and almost all published solar, spectrophotometry would scarcely fare better if subjected to a similar scrutiny—but as a constructive demonstration of the various characteristics of a particular instrument and their relative importance in relation to a particular observational task. This is one of the first occasions upon which enough has become known about the characteristics of a particular instrument to permit a quantitative discussion of the neglected observational problem of the accuracy of stellar spectrophotometry.

In a recent note (**2**), de Jager & Neven, ' defending a less optimistic point of view ' than one which they quote, assert that:

(a) Even observations of line profiles made with a very good resolving power should be subjected to a careful correction for instrumental broadening.

(b) Many observations made with a moderate or even reasonably good resolving power cannot be corrected, since these corrections and the resulting profiles will appear to have no physical meaning.

Furthermore, de Jager & Neven say that a spectrograph which is inadequate for the determination of true line profiles is nevertheless suitable for ' the investigation of general properties of the lines, such as the equivalent widths '. In this, they maintain the traditional view that measured equivalent widths are, in principle at least, independent of the spectrograph used to observe them. All abundance analyses, and especially those performed with solar *f* values or with observations made with more than one spectrograph, imply respect for this tradition, which is shown below to be incorrect. Indeed, this paper will show that the problem of the instrumental profile needs to be viewed even more pessimistically than is suggested by de Jager & Neven. These authors' evidence for their assertion (b), however, consisting of the effects of attempted correction for instrumental effects of solar profiles taken from the Utrecht Atlas (**3**) and the Jungfraujoch spectrograph, will be shown in another paper (**4**) to be misleading.

2. THE TELLURIC OXYGEN BANDS

The Introduction shows the profile observed, with the spectrograph used in exactly the same form as for stellar observations, for the emission line given by a helium–neon gas laser at $\lambda 6328$ Å. This profile has a half-width of 40 mÅ, implying a resolving power higher than that claimed for any of the published solar atlases. It is, by the same standards (which may be supposed higher than would normally be applied to spectrophotometry of stars other than the Sun) a rather ' clean ' profile; it has a one-hundredth-width (whole width at one-hundredth of the peak intensity) of only 195 mÅ, and there is no satellite structure in the wings of the profile above the level of 0·3 per cent of the peak. The wings of the instrumental profile, although full of detailed structure, show a rapid general fall in intensity away from the main peak. They have been measured out to a very much lower intensity level than that to which other instrumental profiles have been published, for the reason that there is very appreciable energy in them, their large extent partly compensating for their low intensity. It should not be supposed that this is a feature peculiar to the spectrograph considered here; it is without doubt a general feature of all single-pass spectrographs and one which has been too generally ignored in the past.

A laser gives a spectrum so different from that of a star, and so difficult to determine photographically, that it is clearly worth while to check, if at all possible, whether an instrumental profile which is assumed to be identical with the measured profile of the laser line is really applicable to observations of stellar spectra.

It is evident that the convolution of the true profile of the stellar spectrum with the true instrumental profile must give (apart from photometric errors) the observed spectrum. It is not, however, possible even in principle to recover the true spectrum from the observed spectrum and the instrumental profile. In an image formed by an optical system of finite aperture, all spatial frequencies above a certain limit are altogether missing, and no amount of mathematical ' restoration ' can put them back. Even within this limitation, i.e. in attempts to recover from the observed spectrum a profile more like the true spectrum although necessarily lacking the high-frequency components which the true profile may possess, or to recover the instrumental profile (with similar restrictions) from the observed and ' true ' spectral profiles in cases where the latter may be supposed to be independently known, the practical difficulties are considerable. In particular, the accuracy required in the observed spectrum and in the instrumental profile is very great if a de-convoluted spectrum which is not rendered meaningless by noise is desired. This fact, which is only to be expected on informational grounds, effectively restricts useful de-convolution to cases in which the instrumental profile is both well-determined and ' clean ', and to spectra which are already very good in the sense of having high resolution and very low noise.

What the writer has done is to convolute assumed instrumental profiles (based closely on the measured profile) with an approximation to true stellar profiles until the results agree as closely as may be expected with the observed spectra. The laser profile is used as the basis of the initial instrumental profile. The half-width of the effective instrumental profile can be determined from the convolutions, as can the general intensity level of the wings; but the detailed wing profiles cannot be obtained from measurements of absorption spectra because the intensity of any given point in the wings of the instrumental profile is too small to have, *by itself*, any detectable effect on the resulting ' observed ' spectrum.

As will be made clear in this paper, it is exceedingly difficult to obtain the true stellar line profiles which the convolution technique requires. However, the spectra of all objects observed through the Earth's atmosphere exhibit features which arise in that atmosphere, and these features are quite independent of the spectroscopic natures of the extra-terrestrial source objects. Therefore, the profiles of telluric lines observed superposed upon the solar spectrum must be similar to those observable in the spectra of all celestial sources observed from the ground. The solar profiles can, of course, be observed with much more powerful equipment than stellar profiles owing to the much greater brightness of the Sun.

It has been realized for many years that the absorption spectrum of the telluric atmosphere includes three bands due to molecular oxygen which are of particular utility in the assessment of the instrumental profile used to observe them. They are the A, B and α bands, which have heads at λ7593 Å, λ6867 Å, and λ6276 Å respectively, and represent the (0, 0), (1, 0) and (2, 0) bands of a forbidden $^1\Sigma$–$^3\Sigma$ transition. Although they lie in a restricted region of the spectrum, and cannot give direct information about any other region, this is of little account as regards the Arcturus Atlas: shortward of λ6276 Å the K2 stellar spectrum soon becomes so crowded as to preclude the observation of unblended profiles, while to longer wavelengths the Atlas does not extend sufficiently beyond λ7593 Å for the properties of the spectrograph to have changed drastically. The merits of the oxygen bands in relation to the instrumental profile problem are, first, that each includes many lines of very different strengths close together in the spectrum, and, secondly, that the profiles of the individual lines are so exceedingly narrow that even a very good spectrograph causes substantial degradation.

In later sections, the effects of the Arcturus Atlas spectrograph upon the profile of each of the three oxygen bands is shown in turn. The possibility of determining these effects depends entirely upon the availability of band profiles observed in the solar spectrum with an instrument very much superior to the Atlas spectrograph. Through the generosity of Drs A. K. Pierce and J. G. Kirk of the Solar Division of Kitt Peak National Observatory, very beautiful photoelectric scans have been made for the author at Kitt Peak with the McMath solar spectrometer. This instrument, used in its double-pass form with an intermediate slit little wider than the entrance and exit slits, has a profile which is both very narrow and very clean; its excellence is nowhere better demonstrated than in the oxygen bands, where residual intensities very close to zero are observed even for rather narrow lines.

2.1 *Digital procedure*

In order to approximate to the oxygen band profiles observed in Arcturus by convoluting a ' true ' profile based on the Kitt Peak observations with an instrumental profile based on the laser line, it is first necessary to modify both the Kitt Peak and the laser profiles for the reasons given below.

The intensities of the oxygen bands are not constant, but must be expected to vary with the air mass through which the observations are made. For each of the stellar spectrograms, the exposure was necessarily of such a length that the air mass changed considerably during the period of observation. Even if it is assumed (as in this paper it is) that the result of integrating spectra observed through different air masses is similar to the spectrum which would be obtained at some suitably specified mean air mass, there is a difficulty in specifying this mean without knowing the rate of accumulation of the spectral image on the photographic plate; and even if an exposure meter had been available, and its readings continuously noted during the exposure, there would be no guarantee that the photographic process is such that the effective rate of accumulation of the final image would be equal to the rate of arrival of the exposure.

An additional difficulty is that the oxygen absorption is not uniquely related to air mass but depends also upon other factors, including the temperature at every point in the telluric atmosphere traversed by the starlight. The effective telluric absorption consequently cannot, in the ordinary course of astronomical observation, be determined otherwise than from the observed spectrum itself, and must be treated for the present purposes as a disposable parameter.

Accordingly, the first step in the digital procedure is to multiply the optical depth at each wavelength step of the original Kitt Peak photoelectric scan by a constant which is chosen empirically and represents the ratio of the effective oxygen absorption exhibited in the stellar spectrum to that shown by the Kitt Peak scan. The scan is transferred from residual intensity to optical depth, multiplied, and transferred back to intensity ready for convolution.

The instrumental profile is derived from the laser profile by three successive modifications. First, the width of the laser profile is scaled in direct proportion to the ratio of wavelengths of the relevant oxygen band and the laser line. This is certainly a correct procedure as far as the grating ghosts are concerned; it is only correct for the wings of the instrumental profile insofar as they consist of diffracted light. Reasons are given in the Introduction for supposing that only about half the light in the wings is diffracted. The rest will arise from scattering in the photographic emulsion, from halation, and possibly from small-angle scattering at optical surfaces in the spectrograph. The variation of such light with wavelength, either as regards its intensity or its position on the plate, cannot be determined either theoretically or from the available observations, save that the position of the halation ring can be derived from a knowledge of the thickness and refractive index at the relevant wavelength of the glass of the photographic plate. In the case of the α band of oxygen, whose wavelength differs from that of the laser line by less than 1 per cent, these uncertainties are trivial; in the cases of the *A* and *B* bands, at wavelengths differing respectively by 20 per cent and 9 per cent, the uncertainties are much increased by the use in the stellar observations of photographic materials differing from that used to observe the laser line. These materials may, and in the case of the *A* band do, have different scattering properties from the material used for observing the laser. The intensities in the wings of the instrumental profile at the *A* and *B* bands are therefore likely to be only one order of magnitude larger than their errors as a result of the assumption implied by scaling the laser profile according to wavelength. Proportional errors of 10 per cent are, however, no greater than the error already existing in the determination of the height of the central peak of the laser profile with respect to the wings; and although higher accuracy is desirable, it is very difficult to obtain.

The second modification to the laser profile is an adjustment to the width of the main peak and the ghosts. The half-width of the main peak is used as a variable parameter in the convolutions with the oxygen bands, and the result of the convolution is so sensitive to it that its value can be accurately determined by comparison of the observed spectra with convolutions performed using different half-widths. In fact, however, the degree of modification of the laser profile required to mimic the Arcturus Atlas is not large. In the procedure used here, the main peak and the Rowland ghosts have been isolated from the rest of the profile by a process tantamount to lifting them off at their (subjectively defined) roots, scaling them in the wavelength coordinate by the factor (close to unity) representing the trial value of their half-width, and adding them back to the rest of the profile. The errors occasioned by this procedure are probably small.

Thirdly, account is taken of the fact that the energy contained within the main peak of the profile and the ghosts is scaled by the same factor as the half-width in the preceding operation. The ratio of the energy in the main peak to that in the rest of the profile should clearly not be related to the sharpness of definition of the peak; to retain the ratio at the value observed in the laser profile, the intensity at every point in the wing profile is multiplied by the same factor as that by which the main peak and the ghosts are widened. This multiplication is performed before the widened main peak and ghosts are restored to the wing profile in the operation described in the last paragraph.

The modified laser profile now represents an estimate of the instrumental profile at the wavelength of the relevant oxygen band. It belongs to a one-parameter family characterized simply by a half-width but otherwise retaining as much as possible of the information existing in the observed profile of the laser emission line. The modified laser profile is convoluted with the Kitt Peak oxygen-band profile adjusted by a suitable absorption factor; the result is for convenience displayed by a digital plotter operated directly by the computer. The horizontal and

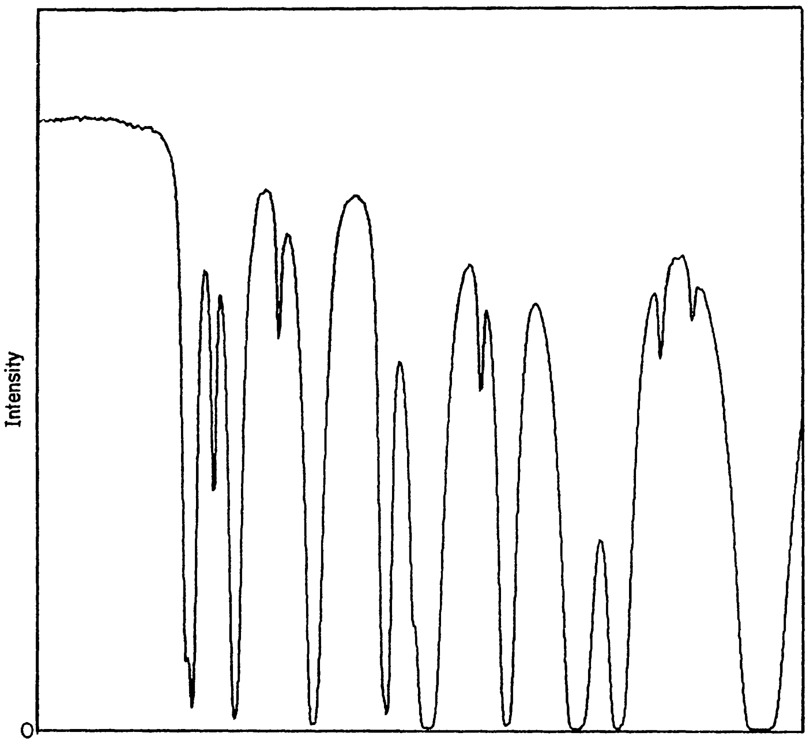


FIG. 1. *The head of the telluric A band near λ7593 Å, observed in the solar spectrum at very high resolution with the McMath double-pass spectrometer of Kitt Peak National Observatory; the optical depth has been multiplied by the factor* 0·85.

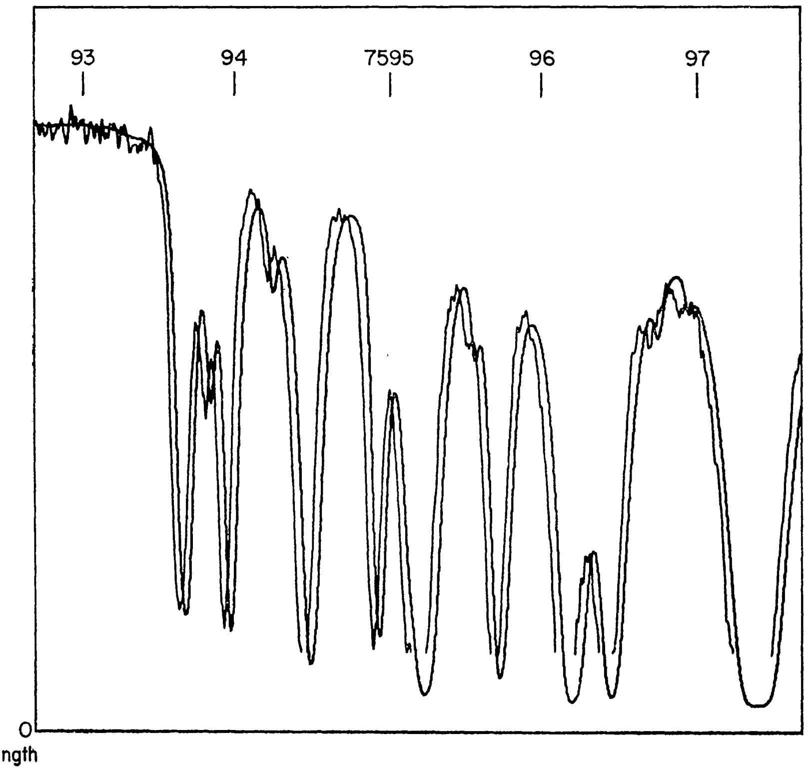


FIG. 2. *Profiles of the A band head, with a small relative horizontal displacement. Left (and wavelength scale): reproduced from the Arcturus Atlas. Right: the result of convoluting the profile shown in Fig.* 1 *with an instrumental profile, based on observations of a laser emission line and having a half-width of* 40 *mÅ, supposed to represent the instrumental profile used for the Arcturus Atlas.*

vertical scales of the plot are arbitrarily chosen to be identical with those of the Arcturus Atlas to allow comparison of the observed and synthetic profiles by superposition. In the case of each of the oxygen bands, a particular choice of the absorption and half-width parameters for the synthetic profile gives an excellent match with the observed profile, and there is no occasion to resort to any modifications of the character attributed to the instrumental profile except those detailed above.

2.2 *The A band*

Fig. 1 shows a 5 Å region of the solar spectrum in the vicinity of the head of the *A* band; this profile represents the original Kitt Peak observation after adjustment to a somewhat (15 per cent) smaller optical depth. Fig. 2 shows the same spectrum convoluted with an instrumental profile derived from the laser observations in the manner described above and having a half-width of 40 mÅ. (Although this figure is the same as the half-width of the initial laser profile, the instrumental profile it characterizes is not identical with the laser profile owing to the different wavelength to which it refers; each of the three steps of modification detailed in Section 2.1 has been applied.) For convenience of comparison, the profile observed in the Arcturus spectrum is printed in the same diagram; that profile, with its wavelength scale, is reproduced directly from the Arcturus Atlas (**1**). The synthetic and observed profiles are so similar to one another that it has been necessary to print them out of register in order to make them separately distinguishable. The relative displacement is in the horizontal coordinate, the synthetic profile (which exhibits small steps owing to its origin in a digital plotter) being shifted slightly to the right of the stellar profile. The latter is incomplete, because the photographic spectrogram is not sufficiently exposed for good photometry at points where the intensity in the spectrum is less than about 13 per cent of the continuum.

The effect of altering the optical depth parameter is of course to raise or lower every point of the computed profile; there is obviously little scope for such alteration. Changing the half-width attributed to the instrumental profile alters more particularly the turning points in the synthesized profile: increasing the half-width raises the central residual intensities of all absorption lines and depresses the maxima between them. The features most sensitive to half-width are those of moderate strength blended with strong lines, such as that observed in Arcturus in the spectrogram of Fig. 2 at a wavelength near 7593·8 Å. Weaker features, such as λ7594·2 Å in Fig. 2, close to strong lines show a similarly rapid change of amplitude with instrumental half-width, but the comparison with observation is hampered by the relatively increased importance of photographic granularity in the observed profiles of weak lines.

The agreement of the synthetic profile with the observed one, and its sensitivity to half-width, is such that a change in the assumed half-width of ± 3 mÅ makes the agreement noticeably worse, so that that figure may be regarded as the maximum error associated with the value of 40 mÅ which is the half-width used for the convolution shown in Fig. 2.

At wavelengths a few ångströms longer than those shown in Figs 1 and 2, some lines of the band due to the isotopic molecule O^{16} O^{18} form a useful subject for the present study. In the vicinity of λ7607 Å, the lines of the ^{R}R and ^{R}Q branches of the isotopic 0–0 band occur at slightly different wavelength intervals, are by good fortune visible between the immensely saturated lines of $O_{16}{}^{2}$, have nearly

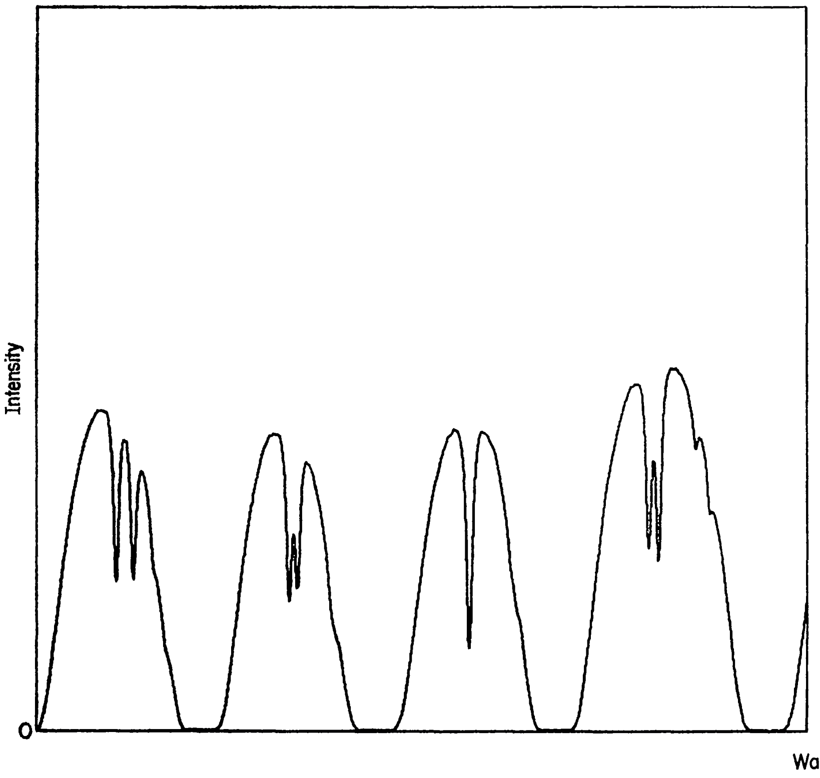


FIG. 3. *The strongest part of the telluric A band, observed in the solar spectrum with the McMath spectrometer; the optical depth has been adjusted as for Fig.* 1.

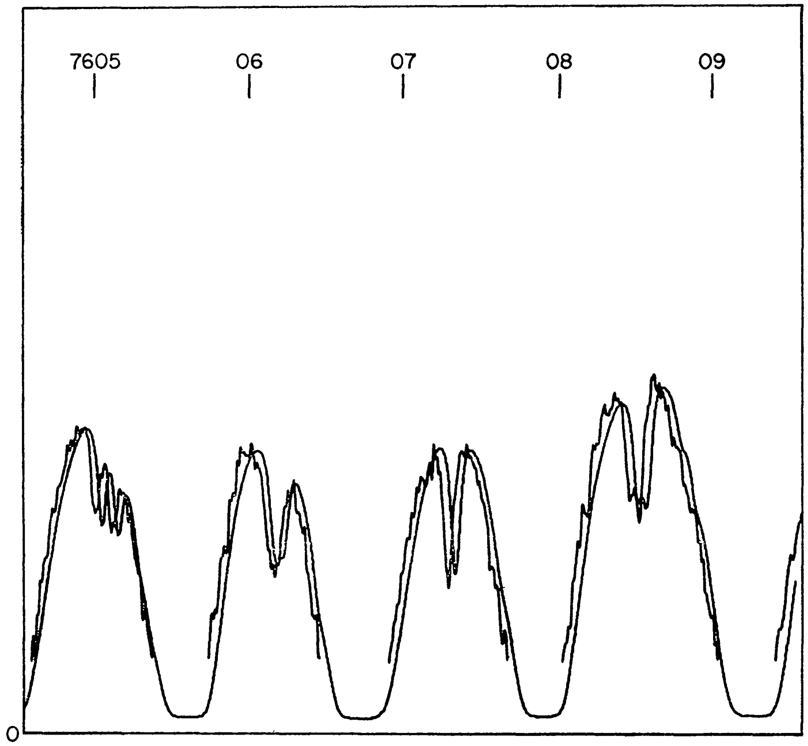


FIG. 4. *The same region as in Fig.* 3. *Left: reproduced from the Arcturus Atlas. Right: the result of convoluting the profile shown in Fig.* 3 *with the same instrumental profile as is used in Fig.* 2.

equal strengths, and pass through a wavelength coincidence. The separation of the pairs of lines near λ7605 Å and successive intervals of just over one Å are given by Babcock & Herzberg (5) as 110, 40, 0 and 56 mÅ respectively. (The Kitt Peak scan suggests that the 40 and 56 mÅ intervals have been underestimated, but the exact separation is immaterial for the purposes of this paper. The zero separation of the third pair implies simply that the separation is too small to be resolved.) In the Arcturus Atlas, the 40 mÅ pair is portrayed as an almost flat-bottomed blend, while the 56 mÅ pair is clearly resolved. The resolution of these pairs may be expected to be, and is in fact, a sensitive test of instrumental resolution. Figs 3 and 4 present profiles exactly analogous to Figs 1 and 2 respectively; the synthetic profile in Fig. 4 is based upon an instrumental half-width of 40 mÅ, which was selected as giving the best approximation to the observed profile quite independently of the identical figure derived from the convolutions of the head of the *A* band. In the λ7607 Å region, changes of the assumed instrumental half-width of ± 4 mÅ give convolutions which fit the observed spectrum definitely worse than the profile shown in Fig. 4, which is based on a 40 mÅ half-width.

2.3 *The B band*

The head of the *B* band has an ideal character for the present investigation. Fig. 5 shows the Kitt Peak scan after multiplication of the optical depth by a factor of 1·26, and Fig. 6 compares the observed spectrum of Arcturus with the result of convoluting the profile seen in Fig. 5 with an instrumental profile having

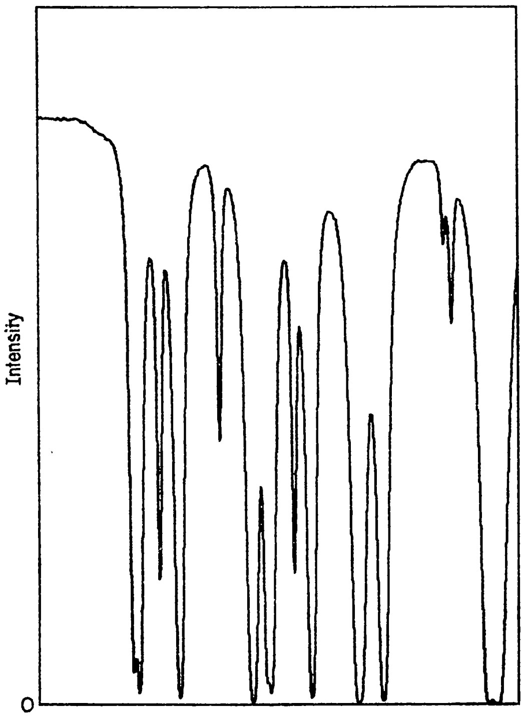


FIG 5. *The head of the telluric B band, observed with the McMath spectrometer and adjusted in optical depth by the factor of* 1·26.

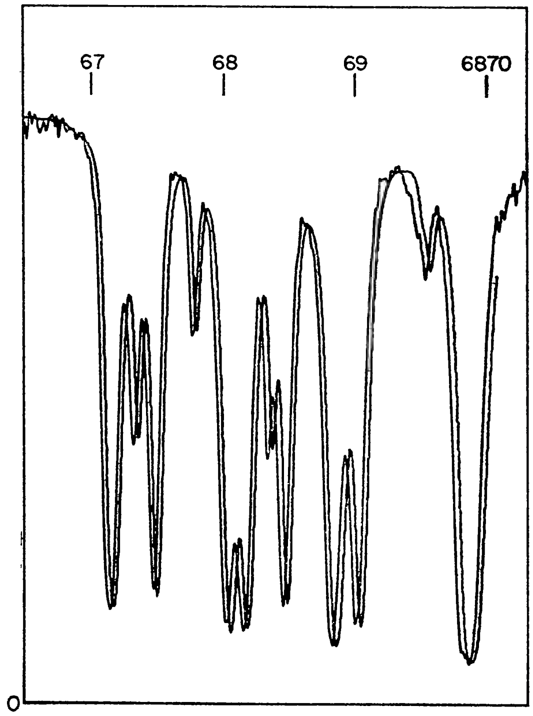


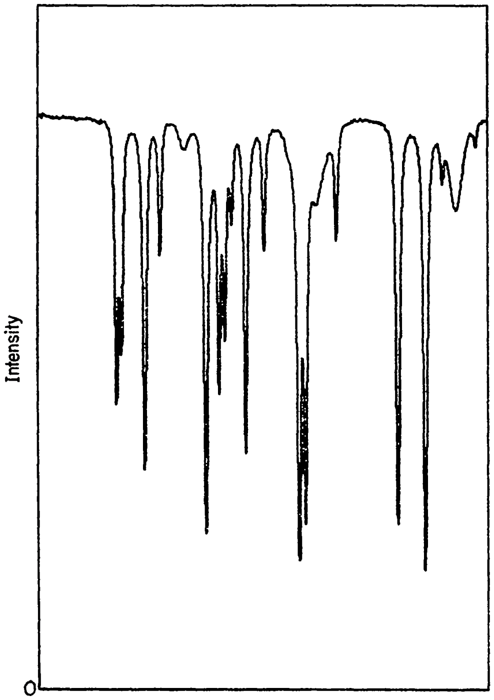
FIG. 6. *The head of the telluric B band. Left: reproduced from the Arcturus Atlas. Right: the result of convoluting the profile shown in Fig.* 5 *with a laser-based instrumental profile of half-width* 44 *mÅ.*

a half-width of 44 mÅ. There are very few points where the discrepancy between the two spectra much exceeds 1 per cent of the continuum. It should be borne in mind, in comparing the two profiles, that they not only are derived from observations with two completely independent instruments of radically different characters, but refer to two completely independent sources each of which may (and probably does) contribute features to this region of the spectrum. Shortward from the *B* band head there is probably no interval of such a length without measurable lines in the Arcturus Atlas. It is likely that Fig. 6 shows a stellar line at λ6869·4 Å, and the small discrepancy at λ6868·4 is of such a sign and character as to admit of a similar explanation.

Trial convolutions in which the instrumental profile differs from 44 mÅ by ± 2 mÅ match the observed spectrum distinctly worse than the 44 mÅ result shown in Fig. 6.

2.4 *The α band*

The Kitt Peak solar scan of the α band, after the optical depth has been increased by a factor of 1·57, is shown in Fig. 7. This band and the laser emission line are at nearly the same wavelength, and were observed on the same emulsion at Mount Wilson. Therefore, if all aspects of the Mount Wilson photometry are in order (and the optical depth factor is appropriate), a good match must be obtained between the Arcturus Atlas and the result of convoluting the profile of Fig. 7 with the laser profile modified only by a very slight change in wavelength scaling. It is.



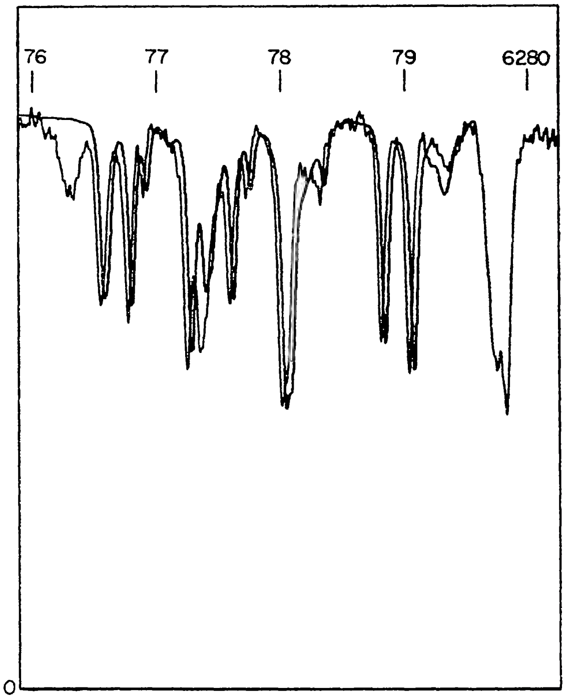


FIG. 7. *The head of the telluric α band, observed with the McMath spectrometer and adjusted in optical depth by the factor 1·57.*

FIG. 8. *The head of the telluric α band. Left: reproduced from the Arcturus Atlas. Right: the result of convoluting the profile shown in Fig. 7 with a laser-based instrumental profile of half-width 42 mÅ.*

However, the full treatment such as has been applied to the other oxygen bands shows that the unmodified laser profile (40 mÅ half-width) is near the lower bound of the range of half-widths which give convolutions matching the Atlas profile practically equally well; the central value of this range is 42 mÅ, and the excellence of fit begins significantly to decrease at 3 mÅ on either side of it. The observed profile is compared in Fig. 8 with the 42 mÅ convolution; the difference between the latter and the direct laser-profile convolution is scarcely appreciable.

Fig. 8 shows several features which do not arise in the telluric atmosphere but in one or both of the stars. In some cases the same feature (though not with the same strength) can be recognized in both profiles; in these cases a relative displacement of about 57 mÅ, due to the radial velocity of the star, is seen, and of course the solar profiles are distorted by the optical-depth adjustment which is only correctly applicable to telluric lines.

2.5 *Discussion*

Two important results are obtained by the trial convolution procedures described above: the first consists of the numbers which the process yields, and the second, to which we shall shortly return, is that the scheme works at all.

Before leaving the numerical results, however, we must point out that the half-widths derived in the previous sections are optimistic values in that they take no account of the fact that even the McMath spectrometer at Kitt Peak lacks the virtue of infinite resolution; and the profiles seen in Figs 1, 3, 5 and 7, exquisite though they are by any reasonable (and especially any practical) standard, are nevertheless already somewhat degraded from the true profiles of the telluric bands. The half-width of the Kitt Peak instrumental profile is slightly narrower than 20 mÅ at the *A* and *B* bands, and is near 15 mÅ at the α band. If the half-widths of convoluted profiles added quadratically, the corrections to the derived Mount Wilson instrumental half-widths at the three bands would be about 4, 4 and 3 mÅ respectively. But the assumption of quadratic additions is quite unjustified, and has in the past led to important errors in this very field of instrumental half-widths (**4**); so all we can say with certainty is that the half-widths derived for the Mount Wilson instrumental profile are subject to some upward revision on account of the limited resolution of the original oxygen-band scans. Perhaps we may, however, expect the order of magnitude of the revision to be 3 or 4 mÅ; and even a considerable percentage error in this estimate does not amount to very much.

In addition to specific information on instrumental half-widths, three other important conclusions (two of them strictly qualitative) may be reached by inspection of the foregoing diagrams. They are as follows:

(a) The agreement between the observed and computed profiles seen in Figs 2, 4, 6 and 8 is of the general order of 1 per cent of the intensity of the continuous spectrum. Since the computed spectra were derived from accurate observations by the application of a minimum number of very simple assumptions and the use of only two free parameters (absorption and half-width), it is unlikely that this agreement is artificial or illusory. The remaining discrepancies (apart from those caused by solar or stellar absorption lines) must be principally due to photometric errors in the Arcturus Atlas and to errors in the instrumental profiles used in the respective convolutions. Errors of the order of 1 per cent of the continuum confirm the order of accuracy indicated by internal comparisons within the Arcturus Atlas. They represent a standard of photographic photometry which has probably not been achieved previously in stellar spectroscopy. However, it is proper to observe that systematic errors which would influence profiles in the Arcturus Atlas in much the same way as a change of effective optical depth influences profiles of telluric absorption bands would escape attention in the comparisons with computed profiles as well as in internal comparisons. Such errors cannot be ruled out at present, but their discussion involves the methods of photometric calibration of stellar spectra and will be deferred to a subsequent paper.

(b) Since the discrepancies observed in Figs 2, 4, 6 and 8 are no larger than the minimum to be expected on the basis of internal consistency in the Atlas, they provide no evidence of any errors in the assumed instrumental profiles. This may be taken, on the one hand, as indicating that the instrumental profiles are perfectly correct; or, on the other hand (as it has been shown in Section 2.1 that the assumed instrumental profiles are of limited accuracy), that the method of convolution is so insensitive to the instrumental profile that there is nothing to be gained from it. No doubt the truth lies between these two extreme points of view: the convolutions are certainly sensitive to the fundamental characteristics of the instrumental profile, but, for reasons given in Section 2, cannot give information on the details of the wings of the profile. It is these details which are only approximately represented in the assumed profiles.

(c) Comparisons of Figs 1 and 2, 3 and 4, etc. demonstrate very cogently that the Mount Wilson spectrograph, however excellent it may be by the ordinary standards of stellar spectrophotometry, nonetheless can produce profound modifications of the spectra which it is used to observe. Of course, the telluric oxygen lines are particularly narrow and especially vulnerable to instrumental degradation; but the Figures certainly show the desirability of investigating the effect of the spectrograph on stellar lines. Unfortunately there is no line in the spectrum of Arcturus whose true profile is accurately known; so in Section 3 the effect of the instrument on an arbitrarily chosen profile is assessed.

The writer suggests that the diagrams reproduced in this paper may be regarded as largely vindicating the Mount Wilson photometry both of Arcturus and of the laser spectrum, and also as a caution against supposing that good photometry with a high-resolution spectrograph implies also a close resemblance between the spectrum being observed and the observation made of it.

3. GENERAL EFFECTS OF THE INSTRUMENTAL PROFILE

To provide a tangible starting point for the discussion of the effects of the instrumental profile, Fig. 9 shows its effect upon a gaussian absorption line. The half-width and equivalent width of this line correspond roughly with the parameters of medium-strength lines in the red region of the spectrum of Arcturus, so the effects of the instrument on stellar lines will be qualitatively similar to the effects shown in Fig. 9; but no suggestion that stellar lines are approximately gaussian is implied.

The half-width of the gaussian absorption shown in Fig. 9 is 188 mÅ and the central residual intensity is 20 per cent. The equivalent width is 160 mÅ. After convolution with the instrumental profile—here taken to be the same as the observed laser emission profile—the absorption appears to be of half-width 198 mÅ and has a central intensity of 29·3 per cent.

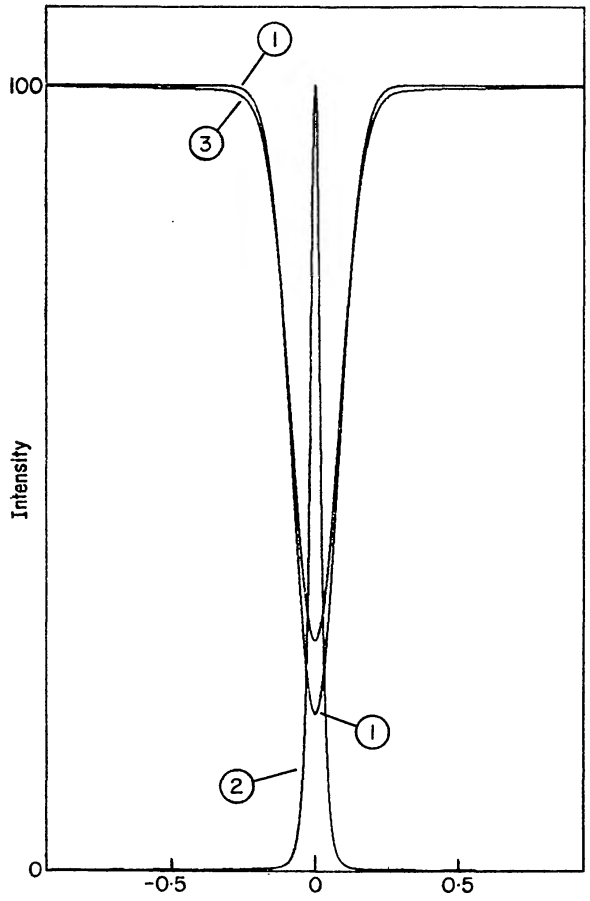


Fig. 9. *Convolution of the instrumental profile with a gaussian absorption line.* (1) *Gaussian absorption line, half-width* 188 *mÅ, central residual intensity* 20 *per cent.* (2) *Observed profile of laser emission line (taken to be the instrumental profile). The half width of this profile is* 40 *mÅ.* (3) *Result of convoluting* (1) *and* (2); *the half-width is* 198 *mÅ and the central intensity* 29·3 *per cent.*

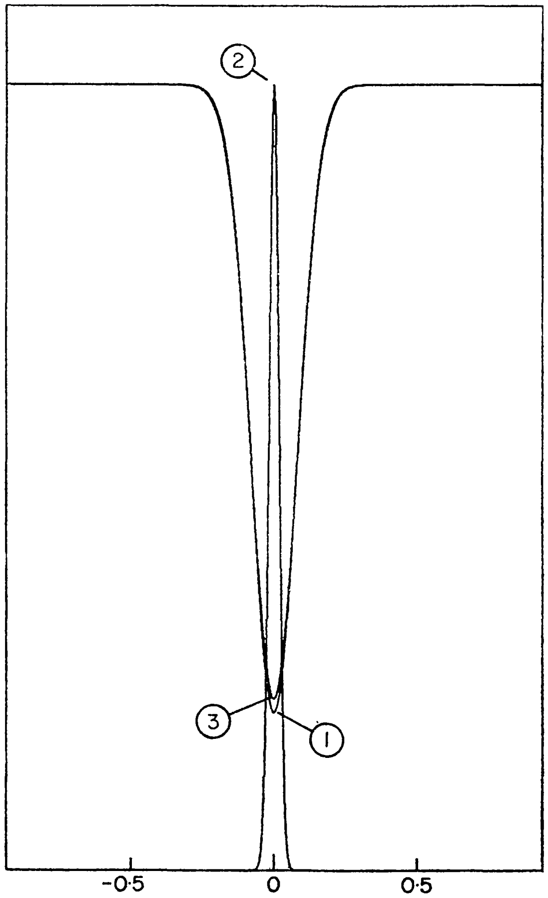


Fig. 10. *This figure is exactly analogous to Fig.* 9, *but the instrumental profile is a gaussian of half-width* 40 *mÅ. The convoluted profile has a half-width of* 192 *mÅ and a central intensity of* 21·8 *per cent.*

It must not be supposed that these numbers convey the full extent of the damage done by the instrumental profile to the original gaussian. The damage is largely caused by the wings of the profile, whose primary and most obvious effect is to feed light from the continuous spectrum into the absorption line, thereby filling it up. The extent to which this infilling is caused by the wings is well demonstrated by comparing Fig. 9 with Fig. 10, which shows the effect of a gaussian instrumental profile (having the same half-width of 40 mÅ as the real one but relatively negligible wings) on the same gaussian absorption. The half-width of the resulting absorption profile is 192 mÅ (gaussians do add quadratically) and the central intensity is 21·8 per cent. The instrumental profiles of Figs 9 and 10 are practically identical in the region above 25 per cent of the peak intensity; but the gaussian instrumental profile is seen to cause infilling of an absorption line more than five times smaller than that caused by the real profile, while its effects outside the line core are very small indeed.

However, the spectrophotometric damage seen in Fig. 9 extends far beyond the limits of the original absorption line. Although the raising of the central intensity is the most conspicuous effect of the instrumental profile, the transference of light into the absorption line from outside involves even more undesirable effects in the places from which the false light is removed than in the absorption line which it tends to fill up.

Suppose the observed spectrum is used for the elementary purpose of determining equivalent widths. The measured equivalent width of every line will be subject to considerable errors arising in two distinct ways from the modification of the absorption profile by the instrument. The root of the trouble is that the absorption is redistributed by the spectrograph in such a manner that every line has enormously broad, weak wings. These contain a non-trivial fraction of the total absorption, a fraction which is completely lost so far as measurement is concerned. Furthermore, the total effect of the overlapping wings of all the lines in a given neighbourhood is to depress the apparent continuum, causing additional loss of measured equivalent width.

As an example, we will consider what percentage of the equivalent width would be likely to be lost in a measurement of the line shown in Fig. 9. The quantitative effect will depend to some extent on whether the line exists in isolation in an otherwise featureless spectrum or is only one line among many. The latter is the situation in the spectrum of Arcturus, and it is relevant to consider the case in which lines such as the one under consideration occur at 1 Å intervals. Such a frequency of lines of this strength implies a blanketing coefficient of 16 per cent—a value characteristic of the blue region of the spectrum; the blanketing in the red is considerably smaller and the figures derived below for the loss of equivalent width are in consequence worse than may be expected to apply to the Arcturus Atlas at wavelengths greater than 5250 Å. The convoluted profile in Fig. 9 shows a rather constant shallow slope in its outer parts, and this starts well within ± 0·5 Å of the line core. It is clear, therefore, that the overlapping wings of a pair of lines 1 Å apart will cause a considerable stretch of the intervening spectral profile to be almost perfectly flat. It is, of course, not at the level of the true continuum; but nobody will suspect that, because there will be no higher points anywhere else near strong lines. Although the true continuum will be more closely approached far from strong lines, no one who is aware of the limitations of photographic photometry will care to draw a continuum between occasional regions, perhaps tens of ångströms apart, which are well removed from strong lines, just missing, as he does so, plenty of perfectly flat intervening plateaux where no lines are visible. There is no doubt that these plateaux will be accepted as the true continuum. Even when one is fully alert to the difficulty, there is no escape from it unless one is able and willing to take detailed numerical account of the whole spectrum over a range of tens of ångströms. In practice, the only thing to do is to draw the continuum where it appears to be, and to regret the misfortune by which equivalent widths are so sensitive to its height.

Additionally, the greatest overall width which the measurer will attribute to the line—the distance between the points at which the profile appears to reach the apparent continuum—is 0·5 Å or at the utmost 0·6 Å.

The total loss of equivalent width will therefore include, first, all the absorption which is thrown beyond ±0·3 Å of the line centre, and, secondly, the absorption within this distance but above the level of the apparent continuum. We are now in a position to put in the numbers, as follows:

(i) At ±0·5 Å from the line centre, the apparent absorption profile is at a height of 99·58 per cent of the true continuum. Midway between two similar lines 1 Å apart, therefore, it will be at 99·16 per cent. 0·2 Å blueward and redward of this midpoint the heights are 98·89 and 98·95 per cent respectively, the slight difference being due to the asymmetry of the instrumental profile. These figures show that a substantial region, at least 0·4 Å wide, between the two lines will appear (on a tracing having the appreciable noise that all observed stellar profiles do) absolutely flat; the height that will be attributed to it must be put at no more than 99·1 per cent. If the spectrum consisted of identical lines all at 1 Å intervals the more distant ones would contribute a further 0·2 per cent or so to the depression of the continuum; but the spectrum is not like that, and as we cannot in any case derive a quantitative result which is accurately applicable to the real spectrum, we will be content with the figure of 99·1 per cent.

(ii) 3·4 per cent of the total absorption lies above 99·1 per cent of the true continuum and within 0·3 Å of the line centre.

(iii) 5·3 per cent of the absorption lines beyond ±0·3 Å of the line centre.

(iv) The total loss of absorption from the measured line is therefore 8·7 per cent.

(v) But, since the apparent continuum is drawn at 99·1 per cent of the true continuum, the apparent unit of equivalent width is 99·1 per cent of the true unit: the equivalent width which is observed will be attributed a value about 0·9 per cent greater than we know it really has. Thus the observed area of the absorption line (91·3 per cent of the total area) will be attributed an equivalent width of 91·3 (100/99·1) or about 92·1 per cent of the true area.

(vi) The nett loss is 7·9 per cent.

The discussion in this section is not limited in its applicability to gaussian absorption lines of a particular central intensity. The ordinate scale for the absorption lines in Fig. 9 may be altered (provided the continuum level remains fixed and the scale remains linear) without in the least affecting the rest of the figure, or the results derived from it with the exception of the value of the minor correction described in paragraph (v). Although these results are obtained from calculations based on a highly artificial spectrum, they are certainly of the correct order. The quantity given in (ii) above is expected to be quite sensitive to the local complexity of the spectrum; in the relatively empty parts of the red and infrared spectrum, the loss of measured equivalent width occasioned by an erroneous estimate of the continuum height will be small. The underestimation of the equivalent widths of particular strong lines in the Arcturus Atlas may accordingly be expected to run from about 5 per cent (for lines much stronger than any nearby, in uncrowded parts of the spectrum) to 10 per cent or so (in moderately complex regions); it is nearly independent of the strengths of the lines concerned except for very wide lines. But the only way of determining the effect fully in any given case would involve a detailed treatment of a considerable length of the spectrum aimed at recovering, as nearly as possible, the true profile of the middle part of that region. It is doubtful whether spectrophotometry of a standard high enough to warrant such a treatment is yet possible for any star except the Sun.

The above discussion serves to indicate the damaging effect of the distant wings of the line profile in spectrophotometry. It is worth observing that the figure of 5·3 per cent given in (iii) above reflects approximately the amount of light in the wings of the instrumental profile beyond ±0·3 Å of the main peak; yet the intensity in this region is everywhere more than 2½ orders of magnitude less than the peak intensity.

It has already been shown in Fig. 10 that a gaussian instrumental profile of the same half-width (40 mÅ) as the observed one would have relatively insignificant effects in degrading the profile of an absorption line. The analogous Fig. 11 shows a gaussian profile which raises the apparent central intensity as much as the real instrumental profile does. This gaussian is just 100 mÅ wide, and although it causes a modest increase in the degradation of the half-width of the absorption line (to 213 mÅ) it still has absolutely no effect upon the height of the continuum or on equivalent widths. If such an instrumental profile—not possible for instruments of finite aperture—were available, it could be expected to provide spectrophotometry at least as acceptable as that in the Arcturus Atlas in exposure times about one-third as long, other things being equal.

4. HIGHER RESOLUTION IS NO ADVANTAGE

Stellar spectroscopists are apt to suppose that it is always possible to make the observed profile of a stellar spectrum more like the true one by increasing the resolving power. This is correct in cases where the degradation of the observed

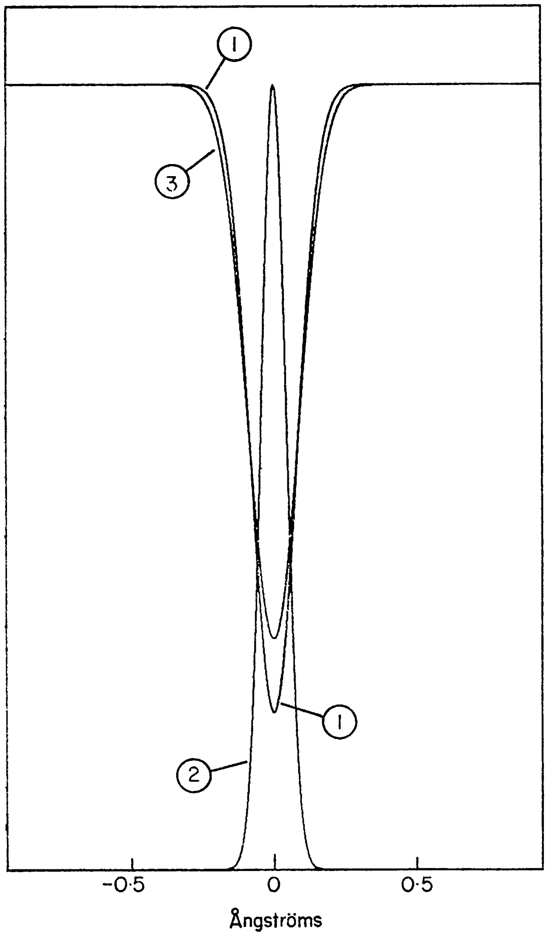


FIG 11. *This figure is exactly analogous to Fig. 9, but the instrumental profile is a gaussian of half-width 100 mÅ. The convoluted profile has a half-width of 213 mÅ and a central intensity—almost identical with that shown in Fig. 9 despite the very much wider instrumental profile—of 29·4 per cent.*

spectrum is largely due to inadequate resolution. In the present case, as Figs 9 and 10 demonstrate, the resolving power is quite adequate and it is the wings of the instrumental profile which are very largely responsible for the degradation. In this case, increased resolution, whether it is obtained by using the diffraction grating in a higher order, by using a camera of longer focal length, or by narrowing the entrance slit, is of little advantage. The effects of these three methods of obtaining higher resolving power are discussed separately below. For the purpose of the discussion, we shall need to consider the instrumental profile (here supposed identical with the observed laser profile shown in the Introduction) as consisting of several components which may be treated separately, viz:

(i) The main peak.
(ii) Rowland ghosts.
(iii) Diffracted wings.
(iv) Small-angle scattering in the optical system.
(v) Halation, and scattering in the photographic emulsion.
(vi) True scattered light, in the sense defined in the Introduction.

The Introduction shows that (vi) is negligible in this spectrograph, but for completeness it will be retained in the discussion. The total intensity of the Rowland ghosts has been measured as 0·5 per cent of the light in the whole profile. The infilling of the centre of the absorption line of Fig. 9 is 9·3 per cent of the continuum. Of this amount, the percentage attributable to heading (i) of the above breakdown of the instrumental profile is seen from Fig. 10 to be 1·8 per cent or about a fifth of the total; heading (ii) contributes 0·5 per cent and heading (vi) none. The difficulty of separating the contributions of (iii), (iv) and (v) has already been alluded to in Section 2.1; there is some reason to attribute about half the wings of the observed laser profile to heading (iii), and half therefore of the remaining 7 per cent of infilling of the hypothetical absorption profile. The relative importance of headings (iv) and (v) simply cannot be estimated at all, except to the extent that (v) must be appreciable because halation rings are clearly seen in all over-exposed spectrograms of emission sources.

A property of the wings of the instrumental profile, and one which is needed in the discussion below, is their inverse-square nature. This is sufficiently demonstrated in Fig. 12, where the wings are plotted on a log–log scale. The Mount Wilson instrument is not alone in exhibiting inverse-square wings (**6**).

4.1 *Use of a higher grating order*

The effect of a higher order is considered in relation to each of the six components of the instrumental profile defined above. Where distances from the main peak are used, they refer to wavelength separations and not to linear distances on spectrograms.

(i) The main peak is made narrower and hence distorts observed absorption profiles less. But the advantage is not great because most of the distortion, as has been shown, is not caused by the width of the main peak in the original case.

(ii) Rowland ghosts are increased in intensity by the factor n_2^2/n_1^2 where n represents grating order and the suffices 2 and 1 refer to the new grating order and the former one, respectively. Since $n_2 > n_1$, the ghost intensities are higher

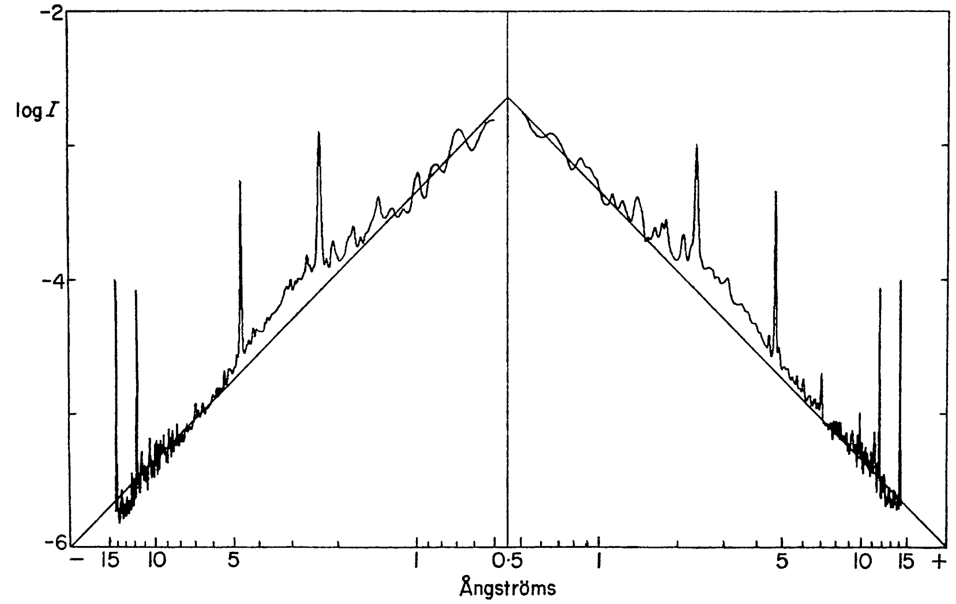


Fig. 12. *The wings of the instrumental (laser) profile. The central ångström of the profile is omitted. Both ordinates and abscissae are on logarithmic scales, and the diagonal straight lines represent inverse-square relationships. The instrumental profile as a whole does not differ very much from these lines; the humps near* ± 3 *Å represent the photographic halation ring which is quite conspicuous on the original spectrograms.*

than they were before. The ghosts are also closer to the main peak by the factor n_1/n_2; but, as they are still more than far enough away to feed completely extraneous light into an absorption line, this is of no advantage. Thus the nett result of using the higher order is to make the effect of the ghosts worse.

(iii) The diffracted wings behave like the ghosts: they are brought nearer to the main peak by the factor n_1/n_2 and strengthened by n_2^2/n_1^2. But since the general character of the wing profile is an inverse square one, a point on the *original* profile nearer to the main peak than any arbitrary point by a factor of n_1/n_2 is also more intense by n_2^2/n_1^2. Thus, although the details of the new profile are moved up nearer to the main peak, the general trend of the profile is exactly the same and there is no nett effect on the performance of the instrument.

(iv), (v) Because the linear scale of the spectrum is increased, while there is no reason to expect any change in the linear scale or intensity of (iv) and such change is definitely absent in (v), the higher order results in a compression of (iv) and (v) in wavelength terms and therefore an improvement in the performance of the instrument. The improvement only occurs, however, for the central part of that component of the wing profile represented by (iv) and (v). The part of the instrument profile which is well within the width of an absorption line of the main peak has less effect in distorting the observed absorption profile than the distant part. But it does not much matter how far the more distant part of the instrumental profile may be spread: the light it feeds into an absorption line is wholly false light, whether it comes from 1 Å away or 100 Å. Thus the halation ring, of the order of 2 mm from the parent line, will continue to be just as damaging to absorption profiles until increasing dispersion makes absorption lines more than 2 mm wide. For typical lines in late-type spectra this implies a reciprocal dispersion of the order of 0·1 Å mm^{-1}.

(vi) Changing the grating order will not affect the amount of scattered light; thus there is no change under this heading.

The result of the above discussion is to show that modest improvements may be made, by increasing the grating order, as regards the effects of the main peak of the instrumental profile and that part of the wing profile which is close to the main peak and is not due to light diffracted into the wrong place by grating errors; and even this modest improvement is partially offset by the increased intensity of Rowland ghosts. The smallness of the expected nett effect is borne out by observation: the Arcturus Atlas shows tracings of the region $\lambda\lambda 5520$–35 Å observed in both the second and third orders, and they are exceedingly similar to one another. The only noticeable photometric improvement gained in the third order (requiring three or four times the exposure needed in the second) is the superior resolution of unequal blends—which have already been noted in Section 2.2 to be particularly sensitive to resolving power—such as that at λ 5533·0 Å.

4.2 *Use of a longer camera*

(i) Slight advantage is again obtained by further reduction of the already rather small effect of the main peak, provided that the projected width of the spectrograph entrance slit is maintained unchanged.

(ii), (iii), (iv) These properties of the instrumental profile have unchanged angular relationships with the main peak, and the linear scale at which they are imaged by the camera varies with that of the spectrum; thus their effect is independent of the camera focal length.

(v) The same modest advantage is gained, and for the same reasons, by increasing the camera focal length as by increasing the grating order.

(vi) Again, there is no change.

However, this discussion does less than justice to the use of higher dispersion which, at great cost in exposure time, provides (if nothing else) better signal-to-noise ratio owing to the greater acreage of emulsion exposed, and also less susceptibility to photographic adjacency effects owing to the reduced density gradients in the emulsion.

4.3 *Use of a narrower entrance slit*

The only significant change obtained by altering the width of the entrance slit is an alteration of the width of the main peak of the profile. It has been made clear already that any narrowing of the main peak of the instrumental profile can only slightly reduce the degradation caused to an absorption spectrum by the complete profile. If, as is usually the case, the ‘ normal ’ width of the entrance slit has been decided on the basis of matching the projected slit width to the possible resolving power of the spectrograph as a whole (taking into account photographic resolution), narrowing the entrance slit will scarcely even narrow the main peak of the instrumental profile. Therefore, narrowing the entrance slit is not usually likely to be an effective way of increasing the resolving power of the spectrograph; and even in cases where improvement in resolving power is obtainable in this way, minimal improvement in the performance of the spectrograph in relation to an absorption spectrum can be achieved.

5. CONCLUSIONS

Regrettably, it seems impossible at present to observe stellar line profiles, at least in late-type stars, in such a manner as to obtain a good approximation (error $\gtrsim 1$ per cent of the continuum) to the true profiles; and this is true of the Arcturus Atlas, although the Atlas probably provides profiles as good as any yet obtained. Furthermore, no appreciably better spectrophotometry could be achieved by using the same grating in any other spectrograph, of no matter what design. The grating is, nonetheless, one of the finest in existence; how much light is thrown into the wings and ghosts of the instrumental profile by large gratings recently ruled under interferometric control does not appear to have been published, but evidence available to the writer suggests that the best of such gratings are comparable in these respects with the Babcock grating used for the Arcturus Atlas. Certainly, few gratings approach the valuable combination of large blaze angle ($\sim 33°$) and luminous efficiency of Babcock's masterpiece, which is now over ten years old.

Probably the only way of obtaining photometry much better than that of the Arcturus Atlas is to use a double-pass system with an intermediate slit scarcely wider than the half-width of the instrumental profile. This effectively means the use of a monochromator having the same characteristics as those of the spectrograph itself; the instrumental profile is thereby squared, rendering the wings of the profile negligibly weak. Since only one element of the spectrum is observable at a time, photoelectric recording is indicated. Such instruments are in use for observations of the solar spectrum at several observatories, and one was employed to make the scans of the oxygen bands described in Section 2 of this paper. Unfortunately, double-pass instruments are inevitably rather inefficient as regards light transmission, and the recording of a high-resolution spectrum one element at a time is also a very inefficient procedure. It appears scarcely practicable to use a double-pass spectrometer to observe large regions of stellar spectra with resolving powers much in excess of 100 000 without enormously larger optical elements than astronomers have so far envisaged; yet that is the only direction in which substantial progress in the field of high-resolution stellar spectroscopy seems possible.

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The Observatories, Madingley Road, Cambridge.

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