

An appraisal of the accuracy of furnace measurements: their extension by use of a hollow cathode source

ABSTRACT

The need for a reliable assessment of the accuracy of determined oscillator strengths is stressed. A discussion is given of the various sources of error and uncertainty in the furnace method for determining relative oscillator strengths. Experiments being made at Oxford with a hollow cathode source for extending furnace results to weaker and higher excitation lines are described.

NEED FOR A RELIABLE ASSESSMENT OF ACCURACY

Since 1960 there have been great advances in almost all areas of stellar spectroscopy. There has been a corresponding progress in the accuracy and range of available atomic data, as is clear from the proceedings of this meeting, but much remains to be done. Dr Petford and I started measurements in Oxford some 20 years ago, and I propose to speak first about accuracy in relation to what we have tried to do since then. A discussion of accuracy is important because a vital part of a determination of an oscillator strength is the assessment of a probable error. If this is not done reliably then, for example, an apparent detection of non-LTE in a stellar atmosphere might only be due to errors in the adopted oscillator strengths. There are some tests that can be applied to measured oscillator strengths, which will be mentioned later, but this is the basic requirement. The history of science contains many examples of experiments with stated accuracies subsequently found to have been too optimistic. I hope that our Oxford measurements using the furnace method will not suffer the same fate when more accurate methods are developed, but part of the purpose of this talk is to show that what began as a simple direct experiment is in

practice a complex one, full of opportunities for small errors of measurement which are not easily assessed.

Supposing that it is possible, using a Fourier Transform spectrometer, to measure the equivalent width of a stellar absorption line to one per cent, then oscillator strengths are needed to at least this order of accuracy. They are needed for weak lines, high excitation lines, and of course for atoms of all degrees of ionisation. Our measurements of FeI lines were begun because we were interested in the determination of stellar masses by using strong lines in stellar spectra broadened by collision damping. Then the work developed into a general study of diagnostics for stellar atmospheres, and we added TiI, CrI and NiI, among other atoms, to the programme. The furnace method, which measures the ratios of oscillator strengths, was adopted because it was ostensibly capable of high accuracy, needing only measurements of the ratio of two equivalent widths and a temperature.

THE FURNACE METHOD

I want to say only enough about the apparatus to discuss the many difficulties of the experiments, the precautions taken, and sources of error that are not apparent from published papers (e.g. Blackwell et al., 1982), and indeed were not apparent to ourselves when we started. The Oxford furnace has a carbon tube 1m long, heated to temperatures approaching 3000 K by a current of up to 5000 A. In practice, a three-pass optical system is used giving a 3m column of metal vapour. It is run in an atmosphere of argon. One purpose of this is to contain the metal vapour in the tube, while another is to ensure that there is a state of LTE in excitation there. The temperature is measured using a photoelectric pyrometer which compares the brightness of carbon blocks in the tube with the brightness of a standard source calibrated by the National Physical Laboratory. Pairs of lines are measured simultaneously using two high resolution photoelectric spectrometers. A high degree of simultaneity (i.e. to within about 3 seconds) is required to avoid difficulties due to minor eruptions of vapour at isolated places along the tube. The accuracy of comparison of oscillator strengths varies between 0.5 per cent for small differences in excitation, to 2 per cent for an excitation difference of 3 eV for apparently unblended lines of FeI.

This basic description conceals the many

minor details of the experiment and the uncertainties that go with them; for instance, at very high temperatures a correction should be made for the emission from the furnace of a line spectrum. A basic requirement is a high photometric accuracy because all iron lines, for example, must be compared ultimately with the resonance line Fe I 3719.9, for which an accurate absolute oscillator strength is known. This is the strongest line in the furnace spectrum, and is stronger than a typical 3 eV line of comparable wavelength and $\log gf = -1$, by a factor of about 10^7 . This large ratio must be measured to good accuracy, but its determination is complicated by the need for a curve of growth correction, which is obtained theoretically. Such a calculated curve of growth must be approximate because there is only poor knowledge of collision damping, so the absorption lines must be kept weak and they then suffer from noise in the continuum. We were encouraged early in our experiments by a comparison between 0 eV oscillator strengths obtained with the furnace and those of Huber & Tubbs (1972), who used the hook method, over a range of nearly $10^6:1$. The ratios over the whole of this span, given by these two experiments using different methods, differ by less than one per cent. Both furnace spectrometers suffer from scattered light of the kind described by Griffin (1969). However, this has been allowed for through an examination of the solar spectrum obtained with each spectrometer and a comparison with the double-pass solar atlas of Delbouille et al. (1973), leading to a correction for scattered light. Such a procedure is only possible because the colour temperature of the high pressure xenon arc source used in the experiments approximates to the colour temperature of the sun.

An accurate measurement of temperature is crucial. An error of 1 K at a temperature of 2500 K gives an error of about 0.6 per cent for an excitation difference of 3 eV. The standard temperature source used at Oxford has an accuracy of 0.9 K at 1900 K (3 sigma), and the furnace temperature measurements should be of comparable accuracy. A complication is that the use of radiation pyrometry depends on a negligible absorption by the metal vapour within the bandpass used by the detector. Any possible error has been reduced by choice of a suitable filter, but scans across its bandwidth are needed. A further complication is that the temperature varies along the tube. This affects the thermal excitation through the Boltzmann relation, but it also poses a problem about

the change of number density along the tube. We assume this is proportional to the vapour pressure at the local temperature, but this assumption will be vitiated if there is a flow of carrier gas and vapour along the tube.

An important defect of the experiment is that, because of impurities in the carbon tube, the absorption spectrum at very high temperature is rich in weak lines of elements other than iron. If the lines are obvious they can be avoided, but their density is such that an impurity line may well fall, undetected, within the profile of a measured line. Line profiles are fitted to synthetic profiles so that an allowance can be made for blending lines, but I am doubtful if blends of one per cent can be detected in this way. One shield against them is the warning of possible blending from study of the large number of semi-empirical gf values calculated by Kurucz and Peytremann (1975).

TESTS FOR ACCURACY

The many imponderable sources of error discussed here make other tests of accuracy desirable. One arises automatically from the reduction process. In this, the lines under investigation are placed in a two-dimensional array of excitation and $\log gf$ (e.g. Blackwell et al., 1979). If the measures of $\Delta \log gf$ were accurate, all routes between two well-separated spectrum lines on the diagram would give the same overall $\Delta \log gf$ value. This condition is satisfied by making minimum alterations to all the measured values. In practice, the individual changes that have to be made are small, typically 0.25 per cent for 0.0 eV/1.0 eV Fe I lines, and it is suggested that the average change is a measure of the photometric accuracy of the experiments. However, these changes increase with increasing temperature, to 0.53 per cent for 2.6 eV lines, probably because of undetected blending.

Two other tests have been devised. In one we compare measured ratios of oscillator strengths of lines within multiplets with those calculated by Kurucz and Peytremann (1975). The average deviation can be large, but the standard deviation of the differences is usually small. This is especially true for Ti III lines; for example, the five lines of multiplet 5 show a standard deviation of 0.003 dex (0.8 per cent). A similar test can be made using the solar spectrum. There are apparent changes of iron abundance with excitation, but the apparent abundances for lines within a multiplet can be closely

similar. As an example of this, four of the lines of TiI multiplet 104 show a standard deviation of 0.006 dex (1.5 per cent). These are encouraging tests, but they are not particularly informative because the lines being compared are always close in strength and excitation; hence they do not check for possible temperature errors. This check can only be made by comparing with the results of other, completely different methods of experiment.

LIMITATION OF FURNACE MEASUREMENTS

Because the furnace method depends on thermal excitation, it is limited to low excitations. For the Oxford furnace, with its effective tube length of 3m, the limit is about 3eV for 'weak' solar FeI lines having equivalent widths of about 80 mÅ at 6000 Å. The limit for the strongest solar lines is about 3.5eV. The furnace cut-off in excitation cannot easily be extended. It would be useless to try to increase the temperature, for this would result in a rapid destruction of the tube. A doubling of the tube length, to 2m, would only increase the maximum excitation by 0.16eV for FeI, whereas we would like to increase it by nearly 2eV. However, it is desirable to measure FeI lines that are both weaker than these limits and of higher excitation. For example, it is not easy to measure 'weak' FeI lines in the Arcturus spectrum, where they are stronger than in the sun because of the smaller degree of ionisation. Also, stellar lines of higher excitation are of great interest. They can be expected to be formed closer to LTE in excitation, so that the corresponding stellar abundances should be more representative of true abundances. This is illustrated by the results we have found for TiI (Blackwell et al., 1987), where the low excitation lines show a somewhat erratic variation of derived abundance, but the high excitation lines show a levelling off to a more constant abundance value which we may suppose to be closer to the true abundance value. Also, the influence of collision damping on line profiles for cooler stars increases quite rapidly with excitation, so that even weak solar lines show extended damping wings. There is scope here for investigation of surface gravity using such lines.

MEASUREMENTS USING A HOLLOW CATHODE

In order to extend the furnace measurements, we started a programme of hollow cathode

measurements some years ago. The use of this source for oscillator strength measurements is well known, and important and accurate work has been done with it, for example by Whaling and colleagues (Whaling et al., 1985). Our own application is linked to a continuing use of the furnace, and is illustrated by the schematic energy level diagram of Figure 1. In this, A represents a transition measured in absorption with the furnace. The corresponding transition in emission is represented by B, where $\log gf(B) = -\log gf(A)$. Another transition C is compared with B to give $\log gf(C)$ by comparing the fluxes in B and C from the hollow cathode, for which of course an absolute calibration of flux is needed. As the two transitions B and C originate from the same upper level, no knowledge of excitation conditions in the lamp is needed. Now, if D is the absorption line corresponding to the emission line C, $\log gf(D) = -\log gf(C)$. Line A might be a measured furnace line of excitation 3.3eV, say, so that D becomes a measured line of higher excitation. Of course, A is of shorter wavelength than D, but there is

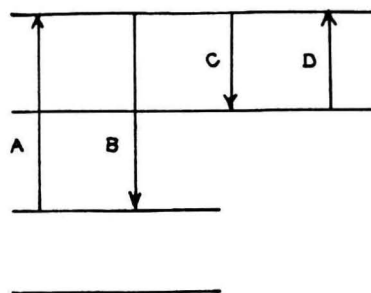


Fig. 1 Energy level diagram showing relation between furnace line A and final measured absorption line D

little disadvantage in this. The temperature measurement needed for the furnace is replaced here by an absolute flux measurement, using a standard lamp, which itself is based on the measurement of the temperature of a standard flux source. The same arrangement of two spectrometers used for the furnace work is adopted for the hollow cathode experiments. This enables a simultaneous comparison of the emission lines B and C to be made, followed by a measurement of the flux from a standard lamp using each

spectrometer. This technique has the advantage that very weak lines can be measured by using long integration periods.

USES OF THE HOLLOW CATHODE TECHNIQUE

Our use of this technique is based entirely on existing and future furnace results. We have used it to see how far its results follow those obtained using the furnace, although it is not clear whether we are testing the hollow cathode or furnace methods. We are also using it to check the temperature scale of the furnace results. An important application is to the measurement of weaker FeI, CrI, TiI and NiI lines, among others, than can be obtained with the furnace. We are making a particular effort to measure lines of high excitation, and have so far reached an excitation of 5.1eV for an FeI line that is apparently unblended in the solar spectrum.

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The furnace measurements published so far are listed in Table 1, together with the range of excitation potential studied.

Table 1. Furnace measurements of oscillator strengths

Atom	Excitation range	Reference
FeI	0.0 - 2.6	Andrews et al., 1979 Blackwell et al., 1979a, b; 1982a, b; 1986a
TiI	0.0 - 2.3	Blackwell et al., 1982c, d; 1983
TiII	0.0 - 0.1	Blackwell et al., 1982e
CrI	0.0 - 3.5	Blackwell et al., 1984, 1986b; 1986c
MnI	0.0 - 3.0	Booth et al., 1984
NiI	0.0 - 0.4	Blackwell et al., 1989
CaI	2.5 - 3.0	Smith & Raggett, 1981; Smith, 1988

Work is continuing on these and other elements.

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