

Appendix A: Atomic Data - Measurement and Sources

A.1: The Need for Atomic Data

To be able to accurately model the formation of a spectral line, various data are required, relating to the particular transition involved, the element involved, and the photospheric environment. The transition is described by the wavelength, the oscillator strength (or f-value) and the damping parameters. The atom is described by its abundance, partition function, temperature, and for NLTE cases, rates for any significant transitions which might affect level populations (or, alternatively, NLTE departure coefficients). The rest of the photosphere is then described by the abundances of the various atomic, ionic and molecular species present, and their opacities.

For any comparison to be made between the observed solar spectrum and calculated spectra, accurate observations of the solar spectrum must be used.

A.1.1: The Transition Wavelength

Ideally, we would know the *in vacuo* transition wavelength accurately, as the solar wavelength will not be the same, even after effects such as gravitational redshift of 636 ms^{-1} are taken into account, as the photospheric convective velocity field gives rise to further wavelength shifts. To determine these shifts accurately, the transition wavelengths must be accurately known.

Laboratory measurements of wavelengths can be affected by a number of factors - non-convective wavelength shifts in the photosphere may be negligible, but laboratory measurements tend to be made under very different conditions. The difficulty of accurately measuring laboratory measurements has been recognised for a

long time.¹ A review of wavelength measurements of interest in the case of the photosphere is given by Dravins *et al.*², and their wavelength shifts were used in the construction of the granular model in this work.

If the transition wavelength of a spectral line is not known sufficiently accurately, it can be adjusted to give a fit between the observed and calculated spectra, but this will obviously render it impossible to obtain any information about the wavelength shift of this line. The difficulty of, and the inaccuracy of, laboratory wavelength measurements results in this being the standard procedure used in this work. The consequences of this are discussed in chapter 8.

A.1.2: Damping Parameters

Damping constants for collisions with neutral atomic hydrogen are difficult to determine experimentally. They are also difficult to determine from the photospheric spectrum, as the line profile is dominated by Doppler shifts. For these reasons, it is important to have a reasonably accurate method for calculating damping constants theoretically. Such theoretical techniques are examined in chapter 4. The theory of collisions with simple perturbers such as electrons, protons, or neutral atomic hydrogen is simpler than that for more complex perturbers. Fortunately, such simple perturbers are the dominant types in the solar photosphere.

Experimental results for collisions with other types of perturbers are not particularly applicable to the photosphere, but could be compared to predictions from a general theory.

Accurate determination of damping constants from the photosphere is possible if the other contributions to the line profile and the qualitative effects of the interaction

¹See, for example, Babcock, H.D. "The Effect of Pressure on the Spectrum of the Iron Arc" *The Astrophysical Journal* **67**, pg 240-261 (1928), where Babcock measures line shifts due to measurements being made at pressures greater than a vacuum.

²See pg 346 in Dravins, D., Lindgren, L. and Nordlund, Å. "Solar Convection: Influence of Convection on Spectral Line Asymmetries and Wavelength Shifts" *Astronomy and Astrophysics* **96**, pg 345-364 (1981).

are well known. The first of these requirements is addressed in this work, but, as the damping contribution to the line profile is small for most lines, small errors in the velocity fields could result in quite large errors in the damping. (Conversely, an approximate theoretical prediction should be sufficiently accurate.)

The damping constants used in this work were obtained by applying the Brueckner-O'Mara theory where possible, and otherwise estimated and adjusted to fit the observed and calculated spectra.

A.1.3: Oscillator Strengths

The oscillator strength of a line transition strongly affects the total line strength. (The line strength is also strongly affected by the photospheric abundance of the element and its ionisation and excitation ratios, and is also affected to a lesser extent by broadening mechanisms (both Doppler broadening and damping).) Thus, accurate oscillator strengths are important to any quantitative study of solar or stellar spectra. At present, although f-values are available for most photospheric lines of interest, accuracy of such f-values is not as high as is desirable.

It is theoretically possible to calculate transition probabilities and thus line strengths using quantum mechanics; in practice, while this yields correct results for hydrogen atoms, the results for other (more complex) atoms are only approximately correct, due to the various simplifications necessary to produce a feasibly calculable result. High quality experimental results are usually more accurate. Theoretical and experimental determination of f-values is examined in sections A.2 and A.3.

A.1.4: Partition Functions

The partition function was defined in equation (2-15) as

$$U(T) = \sum_{\text{all } j} g_j e^{-E_j/kT}. \quad (\text{A-1})$$

At solar temperatures, only the lower energy levels (up to $30\,000\text{ cm}^{-1}$)³ contribute significantly to the partition function. For most (but not all) elements, the energies and multiplicities of levels are known sufficiently accurately.

The greatest problem with partition functions is that it is generally desirable to use the smallest amount of time and data storage when performing calculations. Thus, a method of calculating partition functions without large amounts of atomic level data is useful. In practice, this reduces either to the case of calculating the partition functions for all atoms and ions of interest for a particular photospheric model, and then using these partition functions for spectral synthesis, or using simple approximation formulae (obtained from curve fits to calculated values) to calculate them as required.

The ionisation fractions are also determined by the ionisation energies. For most cases, these are well known. It is important that very accurate ionisation energies are used, as errors in ionisation energies will result in systematic errors in abundances or photospheric models, as all lines of a particular ion will be affected similarly.

A.1.5: Abundances

Photospheric element abundances can only be measured from the solar spectrum. Abundance measurements are affected by errors in damping, Doppler broadening, and oscillator strengths. Errors due to broadening mechanisms can be reduced by using weak lines which are less sensitive to such errors. Unfortunately, f -values for weak lines tend to be less accurate. One solution is to simply use as many lines as possible, and if there are no systematic errors in the f -values used, the mean abundance will be close to the actual value.

Element abundances in the solar system as a whole can also be measured from meteorites. The abundances for most elements relative to each other should be very

³Grevesse, N. "Accurate Atomic Data and Solar Photospheric Spectroscopy" *Physica Scripta* **T8**, pg 49-58 (1984).

similar in the photosphere. This is generally observed.⁴ Meteoric abundances are generally known to within 10%. The most important difference between meteoric and photospheric abundances is that of iron. The “standard” value of 7.67 is quite high compared to the meteoric abundance of 7.51. Significantly, many determinations (including this work) of the solar abundance of iron find an abundance lower than this standard value, but comparable to the meteoric abundance.

Photospheric abundances are briefly discussed in section 2.2. Abundances determined in the course of this work are given in section 5.8.3. The problem of finding solar and stellar abundances (particularly iron abundances in view of the spectroscopic importance of iron, and the abundance discrepancies) accurately occupies a significant part of the literature.⁵

A.1.6: Opacities

The calculation of opacities is discussed in detail in chapter 5. The calculation of continuous opacities for the visible solar spectrum is simpler than the general case (for other stars or wavelengths) as the opacity is dominated by the H^- ion absorption. The other contributions to the opacity are quite small in comparison, and thus, the total error due to their inaccuracy will be small.

When large sections of the spectrum are being examined, such as when determining atmospheric models, the opacity due to lines needs to be considered. Large numbers of weak unresolved lines can also effectively add to the continuous opacity.

⁴Anders, E. and Grevesse, N. “Abundances of the Elements: Meteoric and Solar” *Geochimica et Cosmochimica Acta* **53**, pg 197-214 (1989).

⁵See Milford, P.N., O’Mara, B.J. and Ross, J.E. “A Determination of the Solar Abundance of Iron from Faint Fe I Lines” *Astronomy and Astrophysics* **292**, pg 276-280 (1994), Blackwell, D.E., Lynas-Gray, A.E. and Smith, G. “On the Determination of the Solar Iron Abundance using Fe I Lines” *Astronomy and Astrophysics* **296**, pg 217-232 (1995) and Holweger, H., Kock, M. and Bard, A. “On the Determination of the Solar Iron Abundance using Fe I Lines - Comments on a Paper by D.E. Blackwell et al. and Presentation of New Results for Weak Lines” *Astronomy and Astrophysics* **296**, pg 233-240 (1995) for recent examples.

A.1.7: The Solar Spectrum

The basic requirements for accurate solar spectral data are high photometric accuracy and high spectral resolution. This is very difficult to achieve with the spatial and temporal resolution needed to provide suitable spectral “snapshots” of the solar surface. Instead, observations must be made over a larger area of the solar surface and over a longer time. It is important that the area and time are both large enough for the spectrum obtained to be a truly representative average spectrum.

In addition to the solar spectrum, such observations also contain features due to absorption in the terrestrial atmosphere (i.e. telluric lines). A number of important solar lines are blended with such telluric lines, such as the sodium D lines.

Section A.4 examines such spectral observations and the variation between them. High spatial and temporal resolution spectra are not discussed in depth. Generally, such spectra are of lower photometric accuracy, and are of much smaller spectral regions, often only a single line, or a few lines, and the surrounding spectrum. As a result, such observations are usually made when required for a particular purpose.

A.2: Theoretical Determination of Oscillator Strengths

The calculation of oscillator strengths is a difficult problem in quantum mechanics. The wavefunctions of the atom are found from Schrödinger’s equation

$$H\psi = i\hbar \frac{\partial \psi}{\partial t}. \quad (\text{A-2})$$

The eigenstates for the unperturbed system are

$$\psi_j(t) = \psi_j(0)e^{-iE_j t/\hbar} \quad (\text{A-3})$$

where E_j is the energy of the state j . The system can be described in terms of these eigenstates by

$$\psi(t) = \sum_{\text{all } j} a_j(t) \psi_j(t) \quad (\text{A-4})$$

where the probability of the system being in state j is $a_j^* a_j$. When the system is perturbed by an incident electromagnetic field, the transition probability can be found in terms of the rate of change of these probability coefficients.

The Schrödinger equation for the perturbed system is

$$(H_0 + V)\psi = i\hbar \frac{\partial \psi}{\partial t} \quad (\text{A-5})$$

which reduces to

$$i\hbar \sum_{\text{all } j} \dot{a}_j \psi_j = \sum_{\text{all } j} a_j V \psi_j \quad (\text{A-6})$$

where V is the perturbing potential. As the $\psi_j(0)$ are orthogonal, this can be written as

$$\dot{a}_j(t) = \frac{1}{i\hbar} \sum_{\text{all } k} a_k e^{i(E_j - E_k)t/\hbar} V_{jk} \quad (\text{A-7})$$

where V_{jk} are the appropriate matrix elements of the perturbation V . This can be considerably simplified if it is assumed that the atom is initially in an eigenstate k and consider a short time interval (so that the state is virtually constant). Then,

$$\dot{a}_j(t) = \frac{1}{i\hbar} a_k e^{i(E_j - E_k)t/\hbar} V_{jk}. \quad (\text{A-8})$$

In this case, the initial state is k , and the desired result is the (small) probability that the transition to state j has occurred. To find this, equation (A-8) can be integrated with respect to time. All that is necessary is to describe the perturbation of the atom by the incident field appropriately.

If the incident field is described as a plane harmonic wave, $\mathbf{E} = E_0 \cos \omega t \hat{\mathbf{i}}$, the potential of the electrons in this field is

$$V = \sum_{i=1}^N e \mathbf{E} \cdot \mathbf{r}_i. \quad (\text{A-9})$$

This proves to be accurate for hydrogen, but for more complex multi-electron atoms, it becomes difficult to adequately describe the atom-field interaction.

A.2.1: Theoretical Hydrogen Oscillator Strengths

For a simple system such as the hydrogen atom, it is possible to obtain an analytical solution for the transition probabilities. The procedure is somewhat involved, and only the results will be given here.⁶ The usual selection rules are derived as these are found to be the only transitions with non-zero rates.

The resultant oscillator strength for hydrogen for a transition from i to j is

$$f_{n'n} = \frac{32}{3} n'^2 n^4 \frac{(n-n')^{2n+2n'-4}}{(n+n')^{2n+2n'+3}} \times \left\{ \left[F\left(-n', -n+1, 1, \frac{-4n'n}{(n-n')^2}\right) \right]^2 - \left[F\left(-n'+1, -n, 1, \frac{-4n'n}{(n-n')^2}\right) \right] \right\} \quad (\text{A-10})^7$$

where $F(a, b, c, x)$ is the hypergeometric function

$$F(a, b, c, x) = 1 + \frac{ab}{c} x + \frac{a(a+1)b(b+1)}{2!c(c+1)} x^2 + \dots \quad (\text{A-11})$$

A classical treatment of the problem gives an oscillator strength of

$$f_k(n', n) = \frac{32}{3\pi\sqrt{3}} \left(\frac{1}{n'^2} - \frac{1}{n^2} \right)^3 \frac{1}{n^3 n'^5} \quad (\text{A-12})$$

and equation (A-10) is often written in terms of this value as

$$f_{n'n} = g_1(n', n) f_k(n', n) \quad (\text{A-13})$$

where g_1 is the **Gaunt factor**, given by

$$g_1(n', n) = \pi \sqrt{3} \frac{nn'}{n-n'} \left(\frac{n-n'}{n+n'} \right)^{2n'+2n} \Delta(n', n) \quad (\text{A-14})$$

where

$$\Delta(n', n) = \left\{ \left[F\left(-n', -n+1, 1, \frac{-4n'n}{(n-n')^2}\right) \right]^2 - \left[F\left(-n'+1, -n, 1, \frac{-4n'n}{(n-n')^2}\right) \right] \right\}. \quad (\text{A-15})$$

These also provide a starting point for bound-free and free-free transition rates used to calculate the continuous hydrogen opacity (see section 5.3).

⁶See pg 98-106 in Mihalas, D. "Stellar Atmospheres" Freeman (1970) for details.

⁷This is equation (4-167), pg 105, in Mihalas, D. "Stellar Atmospheres" Freeman (1970).

A.2.2: Theoretical Oscillator Strengths for Other Elements

The difficulty in calculated oscillator strengths for complex atoms is in adequately describing the interaction between the atom and the incident radiation field. Generally, in multi-electron atoms, the contribution of the interaction between the electrons to the total energy cannot be neglected. The resultant N -body problem cannot be solved analytically. A combination of approximations and numerical techniques must be used to obtain solutions.

The simplest useful approximation is the Coulomb (or hydrogenic) approximation, where only one electron is assumed to be important. The electron is assumed to move in the coulomb potential resulting from the nucleus screened by the remaining electrons. (See section 4.5.2 for the use of the hydrogenic approximation in damping constant calculations.) Due to the simplicity resulting from this approximation, it is commonly used, but is not particularly accurate.

If more sophisticated approximations are used (such as using Hartree-Fock or Thomas-Fermi-Dirac wavefunctions), the problem becomes correspondingly more difficult to calculate.

Calculations of oscillator strengths for strong lines are generally more reliable than those for weak lines. Accuracies of 30%, or even better, are attainable for strong lines⁸, while errors in oscillator strengths of weak lines can be much greater. Neutral iron, while spectroscopically important, proves to be unfortunately resistant to accurate calculation of oscillator strengths. Investigation of theoretical oscillator strengths for Fe I shows that the difference between theoretical and experimental values is similar for transitions within the same multiplet, but the errors vary greatly between multiplets. This could be used to calculate reasonably accurate theoretical values, given experimental oscillator strengths for at least some of the lines within the multiplet.

⁸See Gustaffson, B. "The Future of Stellar Spectroscopy and its Dependence on YOU" *Physica Scripta* **T38**, pg 14-19 (1991).

A.3: Experimental Determination of Oscillator Strengths

The accurate experimental determination of oscillator strengths is not an easy task. There are many different techniques which can be used, and have been used for such measurements. Each technique has its own advantages and disadvantages.

Briefly, the experimental methods can be divided into two groups: those that yield absolute oscillator strengths and those that give relative oscillator strengths (the ratios between two transitions). Relative measurements can be used to obtain absolute oscillator strengths if absolute oscillator strengths are available for appropriate transitions or if the lifetimes of suitable levels are known. The experimental techniques can be further divided into lifetime measurements, emission line measurements and absorption line measurements.

An experiment designed to measure relative oscillator strengths is described in Appendix B.

A.3.1: Absolute Oscillator Strengths

If the lifetime of an energy level is known, the sum of all spontaneous emission rates from this level is then known. Then, if the relative strengths of all of the spontaneous transitions (or at least, all of the significant transitions) from this level are known, the absolute oscillator strengths of all of the transitions can be found.

The rate at which spontaneous decay to lower levels occurs is

$$\Gamma_R = \sum_{\substack{\text{all lower} \\ \text{levels } k}} A_{ik} \quad (\text{A-16})$$

where A_{ik} are the Einstein spontaneous emission coefficients. The level lifetime is thus

$$T_i = \left(\sum_k A_{ik} \right)^{-1}. \quad (\text{A-17})$$

From equations (3-34) and (3-42), the oscillator strength is

$$f_{ij} = \frac{\lambda^2 m_e c}{8\pi^2 e^2} A_{ij}. \quad (\text{A-18})$$

If the Einstein spontaneous emission coefficient for the transition can be found, the oscillator strength is then known. There are various techniques which can be used to

measure the level lifetime, such as measuring the radiation emitted by an atomic beam, and thus determining the dependence of the population of the level along the beam, which can, by using the beam velocity, be converted to the time dependence of the level population. The level lifetime can thus be determined. This, however, only gives the sum of all of the Einstein spontaneous emission coefficients from the level.

If relative intensities for all of the spontaneous transitions from this level are measured, their sum can be normalised to give this lifetime. The intensity of a particular (spontaneously emitted) transition will be measured to be

$$I_{ik} = C_{\lambda} A_{ik} \quad (\text{A-19})$$

where C_{λ} is a constant (dependent on wavelength). The wavelength dependence of the constant C_{λ} can be determined from the wavelength calibration of the system. If the lines are measured in emission, the level population for the initial state (the upper level) will be the same for all transitions. The intensity, after calibration for wavelength dependence of intensity measurements, can then be written in terms of a wavelength independent constant, so

$$I_{ik} = CA_{ik} \quad (\text{A-20})$$

where the intensity I_{ik} is measured in photons per unit time.

The sum of such intensities is then

$$C \sum_k A_{ik} = \frac{C}{T_i}. \quad (\text{A-21})$$

The constant C can then be determined from the intensity measurements and the level lifetime. It should also be noted that it is not strictly necessary to include all the possible transitions in order to achieve a reasonable accuracy. As long as the strongest transitions are measured, the sum of these transitions can be quite close to the sum of all transitions.

As the sum of the spontaneous emission rates is important in this process, relative line intensities are often given as **branching ratios** R_b , defined as

$$R_{ij} = \frac{A_{ij}}{\sum_k A_{ik}} = \frac{I_{ij}}{\sum_k I_{ik}} \quad (\text{A-22})$$

where the intensities are, again, measured in photons per unit time. Branching ratios are a convenient form to use, as the branching ratio for a transition is proportional to the intensity (and thus ratios of branching ratios are equal to intensity ratios) and, if the

level lifetime is known, can be readily converted to Einstein coefficients and oscillator strengths.

As long as the intensities are measured sufficiently accurately, and the relative intensity calibration with respect to wavelength is accurate, the branching ratios can be accurately measured. Care should be taken in choosing the source of emission lines, as self-absorption in the source can be a serious source of error. If this is avoided, the intensity calibration is likely to be the greatest source of error in the branching ratios.

It is also possible to define an upwards branching ratio (as opposed to the downwards branching ratio defined in equation (A-22)) in terms of the intensities of upwards transitions. Given a comprehensive set of upwards and downwards branching ratios, it is in principle possible to determine a complete set of relative intensities for all transitions, regardless of the upper and lower levels involved. A set of absolute oscillator strengths can be obtained from a single lifetime (or absolute oscillator strength). Perhaps more usefully, a number of lifetime measurements can be combined in order to reduce errors.⁹

It is also possible to measure absolute oscillator strengths directly from emission or absorption lines. The basic process of the formation of spectral lines, either in absorption or emission, is well described in chapter 3. The problem is reduced to fitting parameters in the radiative transfer in order to reproduce the observed spectrum. This, in turn, requires accurate knowledge of the population of the initial state of the transition (the upper level for emission measurements and the lower state for absorption measurements). This is difficult to achieve if the line source is not in LTE or if the temperature is not known accurately. For a stable source in LTE, the temperature is usually not particularly high, so only the lowest energy states have significant populations. Shock tubes can be used to obtain higher temperatures, but measurements must be made faster, so photometric accuracy can suffer, particularly for weak lines. Sources using non-thermal excitation rarely have known populations,

⁹For an example of the use of such a process, see Cardon, B.L., Smith, P.L., Scalo, J.M., Testerman, L. and Whaling, W. "Absolute Oscillator Strengths for Lines of Neutral Cobalt between 2276 Å and 9357 Å and a Redetermination of the Solar Cobalt Abundance" *The Astrophysical Journal* **260**, pg 395-412 (1982). The basic procedure had been suggested at least as early as 1970. (By Ross in Ross, J.E.R. "The Solar Abundance of Iron" University Microfilms, Ann Arbor, Michigan (1970).)

so arc and hollow cathode sources are not particularly useful for such measurements. Thus, methods of this nature are usually restricted to absorption line measurements from low energy states or to strong lines. This can be a useful method to obtain absolute oscillator strengths for resonance lines. If conditions in the source are sufficiently well known, self-absorption can be corrected for.

A.3.2: Relative Oscillator Strengths

The oscillator strength of a transition can be measured relative to the oscillator strength of another transition. This is a simpler process than measuring absolute oscillator strengths. If intensities of unknown lines are measured relative to lines with known oscillator strengths, then, from equation (A-18), the unknown oscillator strength is

$$g_i f_{ij} = g_0 f_0 \frac{I_{ij} \lambda_j^2}{I_0 \lambda_0^2} \quad (\text{A-23})$$

where the lines are measured in emission and share a common upper level. Absorption intensity measurements can be used if the lines share a common lower level.

Alternately, if sufficient lines are measured, either upwards or downwards branching ratios can be found.

A.3.3: Spectroscopic Intensity Measurements

Spectroscopic intensity measurements requires two basic items: a light source and a spectroscope. While the light sources for absorption and emission measurements are very different, the spectroscope systems required have many features in common.

The basic requirements are sufficient accuracy and resolution in both wavelength and intensity determination. In order to meet the wavelength requirements, a resolution high enough to resolve the lines in the source is needed. A higher resolution is desirable, as it will enable self-absorption or other effects which will alter the line profile to be detected more easily.

To meet the intensity measurement requirements, a detector sensitive enough to give good photometric accuracy for the weakest lines measures is needed. The noise in the system must also be low enough so as not to mask small signals. Background noise from scattered light within the spectroscope is a more serious problem when making absorption measurements than when measuring emission lines, as it is more difficult to measure. When measuring emission spectra, the background noise can be measured at any wavelength point sufficiently far from any line, and can then be subtracted from the data.

The spectroscopic requirements for measurement of emission line intensities is discussed in more detail in Appendix B.

The variation in the refractive index of a gas in the neighbourhood of a spectral line can also be measured to find the line strength. This is the anomalous dispersion or hook method. An interferometer is used to measure the speed of light in the medium. The interference fringes show a characteristic hook shape near a spectral line, and the separation of the peaks of the hooks depends on the line strength.

A.3.4: Absorption Spectroscopy

A source of absorption consists of a light source and an absorbing medium. As the photosphere consists of neutral atoms and ions rather than molecules, an absorbing medium composed of such atoms is desirable if photospherically interesting transitions are to be measured. As a result of this, either high temperatures or some other method of producing such atoms is required if transitions in elements such as titanium through to nickel are to be measured. These elements form the bulk of the unblended solar lines (see Appendix C). A high temperature furnace is a typical absorbing medium.¹⁰ A furnace is also typically in LTE, so if the temperature is stable and known accurately, the population ratios for different levels can be found.

As furnaces are usually limited to temperatures of about 3000°K or lower, it is difficult to measure high excitation lines. Conversely, as absorption lines are measured, excitation to the lower level of the transition is required rather than the

¹⁰The furnace used by Blackwell *et al.* was operated at 2000°K.

upper level as would be the case in emission measurements, so the excitation energies required are lower.

The absorbing medium can in principle be placed anywhere along the light path, and could even be between the spectroscope and photodetector. The usual arrangement is to use a continuous light source to pass the light through the absorbing medium and then into the spectroscope and photodetector, but other arrangements could be used if desired. In particular, light from a narrow bandwidth tunable source could be passed through the medium straight into the photodetector.

As the strength of absorption lines is measured relative to the local continuum, no intensity calibration for wavelength variation is required. Thus, one of the largest sources of error in emission measurements is absent. This also makes it difficult to accurately measure the intensities of weak lines where the difference between the line and the continuum can be quite small. (This is compounded by the difficulty of measuring the background noise.)

A.3.5: Emission Spectroscopy

A wide variety of sources are used in emission spectroscopy. An emission source requires a method to obtain excited single atoms of the element being measured. Common sources are shock tubes, arcs, and hollow cathode lamps.

Shock tubes can provide high temperatures (and thus populate high excitation energy levels) of up to about 8000°K.¹¹ Shock tubes are also generally in LTE, as at the temperatures and pressures attained, collisional processes are dominant. As the high temperature is only maintained for a short time, it can be difficult to measure line intensities accurately. Instead, the hook method is often used with shock tube measurements.

Other emission sources tend to not be in LTE and are thus suitable only for relative intensity measurements. The source must be stable over the time in which measurements are made. As this time can be several hours, or even days, long when

¹¹Huber, M.C.E. "Hook-Method Measurements of *gf*-values for Ultraviolet Fe I and Fe II Lines on a Shock Tube" *The Astrophysical Journal* **190**, pg 237-240 (1974).

measuring weak lines, this can be an important criterion. There are a large number of different arc sources that can be used, with their individual advantages and disadvantages. Many arc sources are susceptible to self-absorption, and care should be taken to avoid this, or least to detect when it occurs. A hollow cathode lamp source is described in Appendix B.

As self-absorption is a serious problem with emission measurements, efforts should be made to check whether it significantly affects the lines being measured. In the case of a line with strong self-absorption, it will be detectable from the line profile, which will show an absorption line superimposed on the emission line (see figure A-1). Note the resemblance of the self-absorbed line to a doublet.

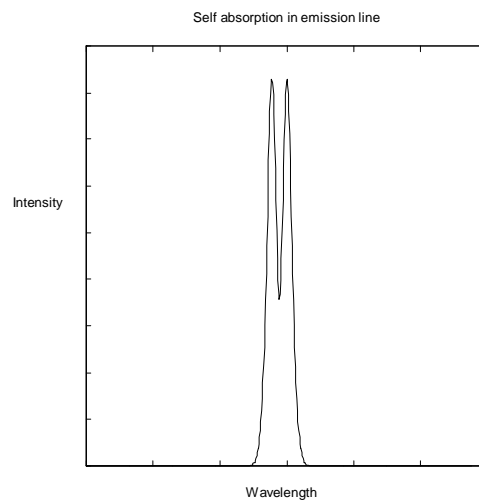


Figure A-1: Strong Self-Absorption

A lesser case of self-absorption will be harder to detect. If the intensity ratio between two lines with a common upper level is dependent on the conditions in the source, it is likely that self-absorption affects one of the lines.

The other major problem with emission measurements is the need to calibrate the spectroscope and detector system for the wavelength dependence of intensity measurements. This generally requires a source with a known variation of intensity with wavelength. The source can either be a line source where the line strengths are well known, or a continuous source with known behaviour. The wavelength dependence of the intensity measurements is a result of wavelength dependence of the behaviour of the optical components of the spectroscope and the wavelength dependence of the photodetector. At some wavelengths, atmospheric absorption can be important.

A.4: Observations of the Solar Spectrum

The solar spectral observations used to compare synthetic spectra to must be of sufficient quality. The photometric accuracy must be high enough so that the strengths and profiles of weak lines are accurate, and the resolution must be much higher than the widths of Fraunhofer lines in the solar spectrum. A number of solar spectral atlases are available that easily exceed the minimum requirements.

The major spectral atlas used in this work is the Jungfrauoch Solar Atlas.¹² As matching synthetic spectra to the observed spectrum to a greater degree of accuracy than possessed by the observational data is fairly meaningless, it is useful to know how accurate the observed line profiles are. A number of lines in the Jungfrauoch Solar Atlas are compared to the same lines from the Kitt Peak Solar Atlas¹³ in figure A-2.

¹²Delbouille, L., Roland, G. and Neven, L. "Photometric Atlas of the Solar Spectrum from 3000Å to 10000Å" Institut d'Astrophysique, Liege (1973).

¹³The National Solar Observatory (NSO)/Kitt Peak FTS data used here (the Kitt Peak Solar Atlas) were produced the National Science Foundation (NSF)/National Optical Astronomy Observatories (NOAO).

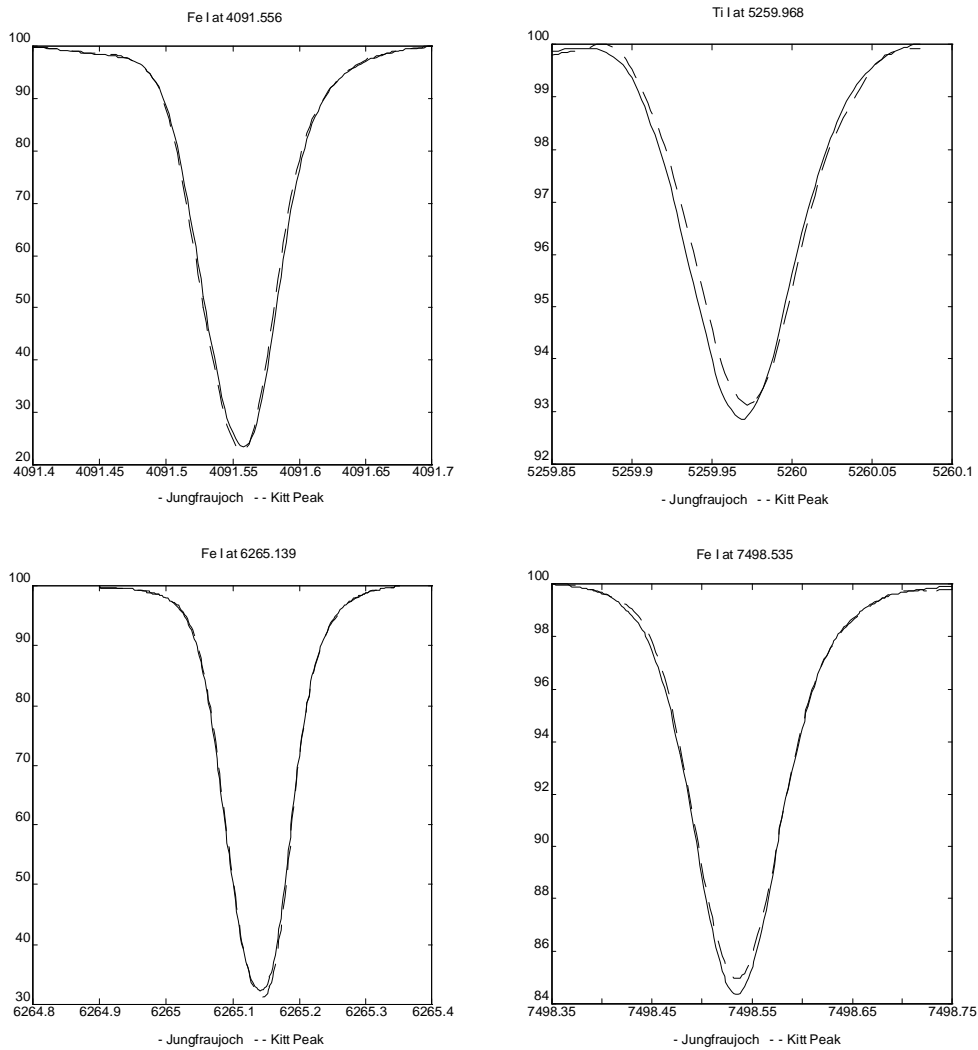


Figure A-2: Comparison between Jungfrauoch and Kitt Peak Atlases

It can be seen that the two atlases are quite similar, but there are differences between them. The differences between the atlases and the differences between synthetic and observed spectra is examined in chapter 8. The differences are more noticeable for the weaker lines (the lines on the right in figure A-2).

Fewer spectral atlases of such quality are available for disk positions away from disk centre.