

Chapter 7: Modelling Granulation

7.1: A Basis for Modelling Granulation

When considering modelling of the solar granulation, two goals should be kept in mind: a successful model describing the **behaviour of granules** in terms of well-known physics, and a successful model describing the **effect of granules** on the solar spectrum. Although the ideal model will achieve both of these aims, it will not necessarily be possible to develop such a model. Modelling the effect of granulation on the emergent spectrum is the main aim of this work; if the model requires making use of the gross characteristics of the granulation rather than the model predicting these features, this is the price that must be paid for insufficiently well-developed fluid dynamics and incomplete knowledge of the conditions beneath the photosphere.

For the model to be considered “correct”, it must satisfy some basic conditions. The model must be physically reasonable¹, and the model must match observations of granular behaviour and observations of the emergent spectrum. Ideally, the spectrum predicted by the model will be the same as the observed spectrum. At this point, some difficulties will intrude; namely, that there are too many gaps in our knowledge of the photosphere to claim that all of the difference between the calculated and observed spectra are due to the granular model. To bypass this, many modellers have not aimed to duplicate the spectrum, but have been content to predict spectral line bisectors² rather than profiles. A similar approach is to use equivalent widths of lines rather than profiles. Both of these techniques give some independence from line broadening processes.

¹Although this may seem a rather obvious point, some suggested models in the literature are overtly unrealistic physically. For example, the velocity field is sometimes assumed to be symmetric.

²The bisector of a spectral line is the line drawn half-way between points of equal intensity. The bisector of a symmetric line would be straight; as spectral lines in the sun are asymmetric, the bisectors typically are of a distinctive “C” shape.

7.1.1: A Parametric Granular Model

In order to relate observed and calculated spectra, a model should be sufficiently simple so that it is feasible to compute spectra. This is difficult with direct numerical simulation of granulation, from which spectra can be found (essentially using a Monte-Carlo technique) by finding a space and time average of instantaneous emergent spectra. This, unfortunately, takes a great deal of time, even on fast computers.

To easily compute spectra, a simple parametric model is desirable. The granulation can be described in terms of a small number of parameters, where the parameters reflect the basic properties of the granulation. The physical properties represented in such a parametric model must include the flow velocities, the small-scale turbulent velocities, the size of upflows and downflows, and the temperature variation.

In order to make the model as simple as possible, the only effect of temperature variations to be considered will be the intensity difference between the upflow and downflow continua.

In general, it is desirable to have as few free parameters as possible in such a model. With more free parameters, it becomes easier to find multiple sets of values for these parameters that give a good fit between theory and observations, so fewer reliable results can be determined.

There are three main aims to be addressed in the construction of such a model. Firstly, it should allow the cause of asymmetry in solar spectral line profiles to be reliably determined. Secondly, it will allow the model parameters affecting the line profile to be more accurately determined. Lastly, it will allow solar line profiles to be readily reproduced theoretically, allowing parameters unrelated to the granulation such as damping constants and abundances to be more accurately determined.

7.2: The Effect of Granulation on the Solar Spectrum

7.2.1: The Effect of Vertical Mass Flows on the Solar Spectrum

As seen in chapter 6, the vertical mass flows produce blue-shifts of average line profiles. While, in any case, granular motions would act to broaden spectral lines, the asymmetry of the granular velocities (as the downward velocities are greater than the vertical velocities) will produce asymmetries in spectral lines; asymmetric Doppler shifts will result in asymmetric lines.

The large scale granular velocity field is due to the fairly uniform upward flow of the granular centre, and the more rapid downward flow at the edges. The type of effect this will produce will be a combination of a slightly blueshifted spectral line and a (smaller due to the smaller area involved in the downflow and lower continuum intensity) more strongly redshifted line (see figure 7-1).

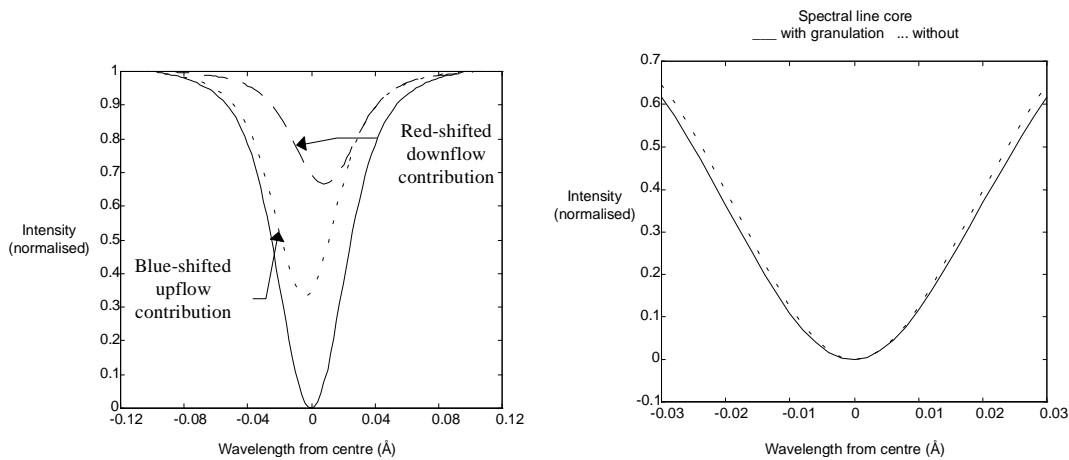


Figure 7-1: Effect of Granule on Spectral Line

As the granular flow velocities are small, their effect should be mainly visible in the core of the spectral line. It is encouraging to note that spectral line cores show the expected shape (see figure 7-2).

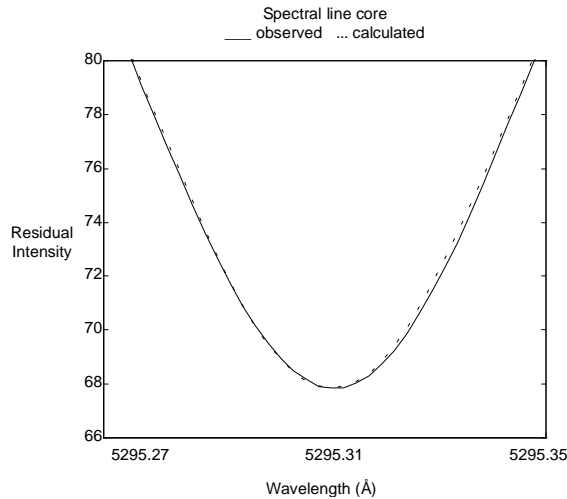


Figure 7-2: Spectral Line Cores: Core of Fe I at 5295.306Å

As the granular flow does not merely consist of a uniform upflow and a uniform downflow, the real case will not be quite this simple. This uniformity will be absent in the real photosphere, so a complete solution would require a continuum of small regions to be added together in order to reproduce an exact result. A similar, sufficiently accurate result should also be obtained from adding together a reasonable number of contributions from sufficiently uniform regions of the photosphere.

It should, therefore, be sufficient to consider a number of plane-parallel regions of the photosphere, each with its own vertical flow velocity (which can depend on height). This is highly desirable, considering the relative simplicity of plane-parallel spectral synthesis.

7.2.2: The Effect of Small Scale Granular Motions on the Solar Spectrum

The variation in the small scale turbulent field will also affect spectral line profiles. The small scale turbulence will act to broaden the contribution to the spectral line arising from a particular region of the photosphere. As the small scale velocity field is not uniform, contributions to the spectrum from different regions within the granule will have differing amounts of Doppler broadening as well as differing red and blue Doppler shifts.

7.2.3: The Effect of Horizontal Mass Flows on the Solar Spectrum

The horizontal mass flow velocity will have no effect on spectra observed at disk centre. It will, however, affect spectra from near the limb. As the horizontal flow velocity field is symmetric, it should not contribute to the asymmetry of the line, but will only act to broaden it instead. The line will also not be shifted by the horizontal flows.

It should also be noted that if horizontal motions were to be taken into account (such as for spectral line formation away from disk centre), the problem of trying to represent the granulation by a small number of plane-parallel regions becomes difficult. This will greatly complicate the calculation of theoretical spectra away from disk centre, except at disk positions very close to the limb, where the vertical motions can be ignored instead.

7.2.3: Pressure and Temperature Variations

If the temperature and velocity are known throughout the granular cell, the pressure and its fluctuations can be determined from these. The pressure variations can, and should be, taken into account if the temperature variations and the flow velocity of the granular cell are well known, otherwise, as they have relatively little effect on the spectrum, they can be neglected. Therefore, the pressure variations will be ignored in this work.

The temperature variations cannot be ignored. Their most obvious effect is on the continuum intensity from the regions of different temperature at the base of the photosphere. This can be simply taken into account by adjusting the contribution from a portion of the solar surface by the brightness as well as its area. As the temperature variation falls rapidly with increasing height, temperature variations will be smaller in the regions where spectral lines are formed. This simple treatment of temperature variations should then be an adequate first approximation.

To fully account for the different temperatures, a different model atmosphere is required for each region of different temperature structure. This gives a much greater

number of parameters that can be adjusted in order to produce a fit between calculated and observed line profiles, and greatly increases the likelihood of a spurious fit.

7.3: Modelling the Effect of Granulation on the Spectrum

7.3.1: Microturbulence and Macroturbulence

The simplest model of velocity fields in the photosphere is the traditional microturbulence-macroturbulence model. Both the microturbulent and macroturbulent velocity fields are assumed to be Gaussian in distribution. They are distinguished from each other by their effect on the spectrum; macroturbulent motions do not affect the equivalent width of a spectral line, while microturbulent motions do affect the equivalent width. Both affect the line shape. As a simple method to calculate emergent spectra, it is reasonably successful, although it predicts symmetric spectral line shapes.

The microturbulence is usually physically identified as the small-scale turbulent motions in the photosphere. Due to the very high Reynold's numbers for flows in the photosphere, the flow must be highly turbulent, so this identification seems quite reasonable. If the turbulent velocity field was in equilibrium, it would possess a uniform almost exactly Gaussian distribution across the entire photosphere.

Many model atmospheres assume depth dependent microturbulence, but as the variation of microturbulence across the heights at which spectral lines form is not overly large in such models, uniform microturbulence is often assumed. As the atmosphere is assumed to be plane-parallel, the microturbulence is assumed to be horizontally uniform.

The macroturbulence is identified with large scale flows. These are assumed to be symmetric and Gaussian in the standard microturbulence-macroturbulence model.

The simplistic treatment of large scale flows, and the assumed horizontal uniformity of microturbulence are not physically realistic.

7.3.2: Beyond the Standard Microturbulence-Macroturbulence Model

The major defects in the standard model are readily identifiable. They can also be readily corrected with a simple parametric model of granulation. This requires accounting for the horizontal variation of microturbulence, and replacing macroturbulence with a more physically representative model.

The starting point for the representation of the vertical mass flow must be observations of granulation (see chapter 6). The resultant model can then be fine-tuned to match observed and computed spectra.

The horizontal variation of microturbulence must also be grounded in observations. Good quantitative results for the variation of small-scale motions is scarce. Qualitative results indicating where microturbulence is greatest and least are more reliable. We can also take into account that the average photospheric microturbulence of 0.845 kms^{-1} is fairly well determined.³

7.4: Structure of the Parametric Model

7.4.1: Model Parameters

In order to sufficiently describe a region of the photosphere, information on the temperature structure and both the large and small scale velocity fields (i.e. the large scale flow field and the microturbulence) must be included. If all types of regions contributing to the mean spectrum are described in this manner, the expected mean spectrum can be calculated, and if necessary, the values chosen for the parameters can be modified so as to produce better agreement between observed and computed spectra.

³See 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).

7.4.2: Plane-Parallel Regions

Each region must be sufficiently uniform so as to allow its treatment as plane-parallel. While this could be readily achieved by simply dividing the photosphere into a large number of small regions, this would be computationally inefficient, and, by the large number of resultant parameters, would virtually guarantee non-unique sets of parameters producing a match between observed and computed spectra.

Thus it is desirable to use as few regions as possible. As the greatest variation within the granule is of the large scale flow velocity, this will be the main determining factor in choosing appropriate regions.

7.4.3: Area

As granules vary significantly in size and shape, a suitable dimensionless parameter characterising the area occupied by a region should be used. The natural choice is the fraction of the total area occupied by the region. The fractional area A will be normalised so that

$$\sum_{\substack{\text{all regions} \\ i}} A_i = 1. \quad (7-1)$$

7.4.4: Brightness

If temperature fluctuations are assumed to be small except at great depth, the temperature structure in the line formation region is adequately described by a standard plane-parallel atmosphere. The temperature at depth can be described by a brightness parameter B , where the continuum intensity emergent from the region is $B\bar{I}_\lambda$, where \bar{I}_λ is a suitable mean continuum intensity. The contribution of the region to the mean spectrum is proportional to both its area and the brightness parameter. With the fraction of the total area of the solar surface under consideration occupied by the

region in question represented by an area parameter A , the mean intensity at a given wavelength will be

$$I_\lambda = \sum_{\substack{\text{all regions} \\ i}} A_i B_i I_{\lambda i} \quad (7-2)$$

if B is normalised so that

$$\sum_{\substack{\text{all regions} \\ i}} A_i B_i = 1. \quad (7-3)$$

The brightness parameter will vary with wavelength. The continuous intensity can be represented by the Planck radiation function assuming a suitable mean temperature.

$$I_\lambda = B_\lambda = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1}. \quad (7-4)$$

The intensity variation with temperature is then

$$\frac{dI_\lambda}{dT} = \frac{1}{\lambda k T^2} \frac{1}{1 - e^{-hc/\lambda kT}} B_\lambda, \quad (7-5)$$

or, in terms of a mean intensity, ignoring the exponential term which can be neglected for any low order approximation at photospheric temperatures and visible wavelengths,

$$\frac{\Delta I_\lambda}{I_\lambda} = \frac{\lambda_0}{\lambda} \frac{\Delta I_0}{I_0}. \quad (7-6)$$

The brightness parameter at various wavelengths can thus be found from the brightness parameter at a particular wavelength. A convenient wavelength to choose is 5000\AA . We can note that, from the area normalisation (equation (7-1)),

$$\sum_{\substack{\text{all regions} \\ i}} A_i (B_i - 1) = 0. \quad (7-7)$$

The brightness parameter B for a particular region at any wavelength is then

$$B = 1 + \frac{5000}{\lambda} (B_{5000} - 1) \quad (7-8)$$

where the wavelength λ is in \AA ngstroms.

7.4.5: Vertical Mass Flow Velocity

Suitable regions can be chosen so that the large scale flow is simply described for the region. As discussed in section 6.3, there are three major regions within a granular cell - the granule centre, which rises with a roughly uniform velocity, the descending intergranular space, and the transition region where the upflow meets the downflow.

The vertical mass flow velocity in the upflowing granular centre can be readily described by a velocity V_u , which will be dependent on the height within the photosphere, but can be assumed to be constant otherwise within the upwards moving region. Likewise, the downflow can be characterised by a velocity V_d . The downflow velocity is expected to be less uniform than the upflow velocity, a fact which will need to be taken into account when dealing with non-uniformities of chosen parameters. The flow velocity in the transition region will vary from the upflow velocity V_u to the downflow velocity V_d , depending on the horizontal position within the region. To simplify the variation of velocity, it can be assumed that the velocity varies linearly with distance from the edges of the transition region.

The upflow and downflow velocities are related by the area parameters A (A_u for the granular centre, A_d for the intergranular space, and A_t for the transition region between them). From conservation of mass flow,

$$A_u V_u + A_d V_d + A_t \frac{V_u + V_d}{2} = 0 \quad (7-9)$$

and

$$V_d = -\frac{A_u + A_t/2}{A_d + A_t/2} V_u \quad (7-10)$$

if the transition region is assumed to be small enough so that the linear distances along the borders with the upflow and downflow are approximately the same, or

$$A_u V_u + A_d V_d + \left(\frac{2}{3} A_t + \frac{1}{3} A_u - \frac{1}{3} \sqrt{A_u^2 + A_u A_t} \right) (V_d - V_u) + A_t V_u = 0 \quad (7-11)$$

if the granule is assumed to have a circular shape, allowing for a broader transition region, which gives the downflow velocity

$$V_D = - \frac{A_U - \left(\frac{2}{3} A_T + \frac{1}{3} A_U - \frac{1}{3} \sqrt{A_U^2 + A_U A_T} \right) + A_T}{A_D + \left(\frac{2}{3} A_T + \frac{1}{3} A_U - \frac{1}{3} \sqrt{A_U^2 + A_U A_T} \right)} V_U. \quad (7-12)$$

The large A_T circular case reduces to equation (7-10) for small A_T . The error due to shapes of real granules (which tend to be somewhat irregular) can be estimated from the difference between these two cases (calculated with $A_U = 3A_D$), which is shown in figure 7-3.

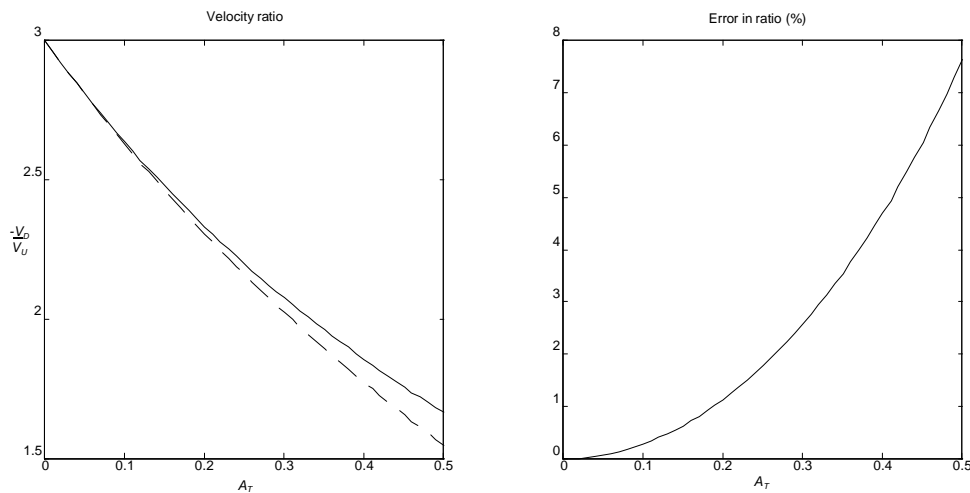


Figure 7-3: Downward to Upward Velocity Ratio

The error should be acceptably small, as even if the transition region is large, the difference between these two cases is less than 8%. As the downward velocities are greater than the upwards velocities by a significant margin (estimates vary from 2 times greater to 3 times greater⁴) it is clear that the transition region cannot be overly large. If the transition region is large, the contributions to the upflow and downflow from the transition region become large, and tend to reduce the downflow to upflow velocity ratio (as predicted by equations (7-10) and (7-12)). This effect can be seen in figure 7-3, where the ratio falls as the transition region area rises.

The velocity distribution within the transition region will be flat in the former case, and will rise linearly towards the outer edge of the transition region in the latter (see figure 7-4).

⁴Roudier, Th. and Muller, R. "Structure of the Solar Granulation" *Solar Physics* **107**, pg 11-26 (1986).

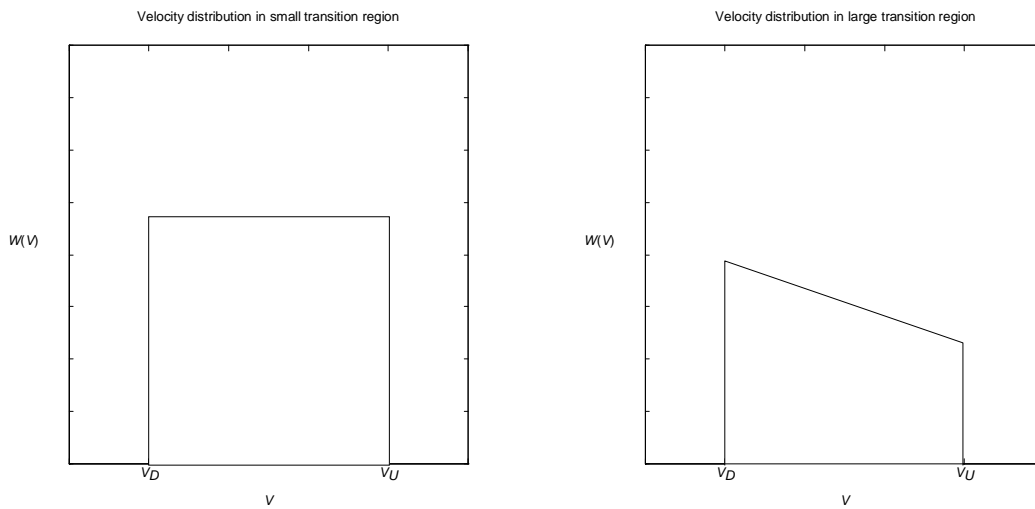


Figure 7-4: Flow Velocity within the Transition Region

For any small transition region, the flat distribution will be sufficiently correct, and it can be approximated as such.

The horizontal variation of the vertical flow velocities thus depends on the granule geometry (as represented by the area parameters A for the regions) and a single velocity parameter. The most convenient choice is to use the upwards flow speed V_u as the velocity parameter, from which the flow velocities in other regions can be determined.

The vertical variation of the flow velocities can, for a particularly simple treatment, be ignored, or the flow velocities can be described as simple functions of height. The particular functional form of the variation should be determined from available data, but we can note that the mass flow speeds are expected to decrease with increasing height, and that as the flow results from the penetration of convective flows into a convective stable region, the decrease in speeds is likely to be exponential, in common with numerous dissipative processes. Section 7.5.1 investigates the height variation.

7.4.6: Microturbulence

The microturbulence is observed to vary with horizontal position. This can be seen in high spatial resolution spectra where the width of lines emergent from downflows and the transition regions between downflows and upflows is greater than that of lines emergent from the upflows.⁵ The change in width must be due to differing small-scale velocities. (Temperature differences can be readily ruled out, since, if the difference was caused by differing temperatures, lines emergent from upflows should be broader.)

Such differences in turbulent velocities are expected from the nature of the granular flow. The other expected variation is that turbulent velocities should decrease with increasing height. This is taken into account in a number of plane-parallel model atmospheres which use depth-dependent microturbulence. It is not possible to observe the depth dependence directly, and it is liable to be difficult to determine.

The turbulent velocities for different regions of the granulation are not inter-related in the same manner as the flow velocities. Separate turbulent velocities ξ_u , ξ_r , and ξ_b will be needed to represent the turbulence in the granular cell. The turbulent velocities in the transition region and the downflow should be similar, while that in the upflow will be substantially smaller.

In the absence of further information regarding the height variation of turbulent velocities, the turbulent velocities can either be assumed to be independent of height, or can be assumed to vary with height in the same manner as the flow velocity. The differences between these approaches will be investigated in chapter 8.

⁵See Kiselman, D. "High-Spatial-Resolution Solar Observations of Spectral Lines Used for Abundance Analysis" *Astronomy and Astrophysics Supplement Series* **104**, pg 23-77 (1994).

7.4.7: The Granular Model

The granule is therefore represented by a small number of parameters. The parameters describing the temperature variation at depth and the geometry of the granule depend only on the region. The granule is divided into three regions - the upflow, the downflow, and the transition region between them, so each of these parameters will have a different value for these regions. As these parameters are suitably normalised, only two from each set of three can be freely chosen. These depth-independent region-dependent parameters are listed in table 7-1.

Table 7-1: Depth-Independent Region-Dependent Parameters

Parameter	Upflow	Downflow	Transition region
Area A	A_u	A_d	$A_r = 1 - A_u - A_d$
Brightness B	B_u	B_d	$B_r = (1 - A_u B_u - A_d B_d)/A_r$

The large scale flow velocity can be characterised by a single depth dependent parameter V_u which can be identified with the upwards flow velocity in the granular centre. The height variation can be described by representing V_u as a function of height and depth independent velocity parameters. These depth independent velocity parameters will be determined by the functional form of the height dependence. In general, unless V_u is constant, at least two such parameters will be needed (one giving V_u at some reference depth, and at least one other parameter to describe the rate of change with respect to height).

Separate turbulent velocities ξ_u , ξ_r , and ξ_d are used to represent the small-scale turbulent velocities. The treatment of the turbulent velocities will yield two separate granular cell models. The first of these will assume that the turbulent velocities are independent of depth. The second will assume that they vary with the same scale height as the flow velocities. All other parameters have identical forms for these two models (although precise values may differ).

7.4.8: Modelling Variation between Granules

So far, the representation of a “typical” granule has been considered. As granules are not uniform, the variation between granules must be represented in the model. Most of the granule model parameters can be replaced by suitable averages over a number of granules. The area, brightness, and turbulence parameters will be so replaced.

The flow velocities, however, resist such simple treatment. Variation of flow velocities between granules will cause broadening, whereas the flow velocity of a single granule region only causes a wavelength shift. It is therefore necessary to assume a simultaneous shift and broadening for the region. This will be very similar in formulation to macroturbulence, as used in the plane-parallel model.

A Gaussian variation will be assumed. To represent this, a further parameter must be introduced into the model. The parameter used will be the rms variation ΔV of the velocity in the region.

The rms variations for the upflow and downflow will be different. The ratios of the rms variation in the flow velocity to the mean velocity will be more similar, but may still be different in the different regions. It is possible to estimate the “macroturbulent” variations for the various regions from high resolution velocity measurements.

It should be noted that this treatment is not strictly correct, as it assumes that the velocity gradients remain the same between granules. Unless the variations prove to be large, this should be a sufficiently accurate assumption, and will greatly simplify calculation of spectra. If differences in velocity gradients were to be taken into account, different regions would need to be used to represent the variations.

If the observed data is broadened by any other mechanism, such as instrumental broadening, and such broadening does not affect the equivalent width of the line, such broadening will be identical to this “macroturbulent” velocity variation, and will therefore be indistinguishable from it.

7.5: Determining the Model Parameters

It is useful to determine the values of the parameters as well as possible from direct measurements before resorting to fitting the computed spectrum to the observed spectrum. This will greatly reduce the likelihood of spurious fits, thus increasing the confidence in the parameter values produced through fits.

7.5.1: Vertical Mass Flow Velocity

The wavelength of a spatially average spectral line should be very close to the wavelength of the spectral line in the upflow at the height which most strongly contributes to the formation of the line (see section 6.3.5). This can be used to determine the depth dependence of the velocity parameter V_v . This depth dependence is expected to constitute an exponential decrease with increasing height.

The wavelength shifts of solar Fe I lines measured by Dravins et al.⁶ can be plotted against the heights of formation of the lines⁷ (see figure 7-5).⁸

⁶Dravins, D., Lindegren, L. and Nordlund, Å. "Solar Convection: Influence of Convection on Spectral Line Asymmetries and Wavelength Shifts" *Astronomy and Astrophysics* **96**, pg 345-364 (1981).

⁷The heights of formation used here are from Stathopoulou, M. and Alissandrakis, C.E. "A Study of the Asymmetry of Fe I Lines in the Solar Spectrum" **274**, pg 555-562 (1993).

⁸See table C-5 in Appendix C for the values. All lines in common between the two works are used.

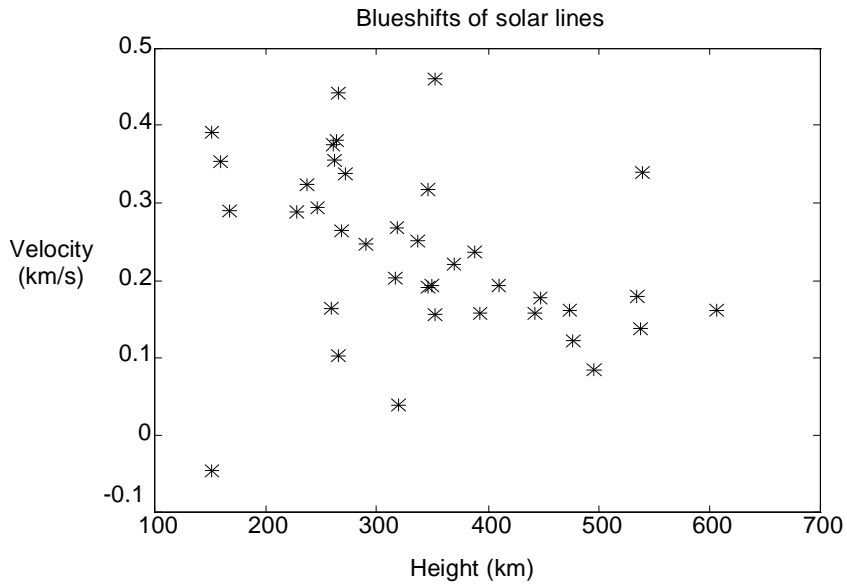


Figure 7-5: Wavelength Shifts

The wavelength shifts, as expected, fall off exponentially with increasing height. A least squares fit can then be performed to an exponential function of the form

$$V_U = V_0 e^{-\frac{h}{V_s}} \tag{7-13}$$

where V_s is the velocity scale height, and V_0 is the upflow velocity at height $h = 0$ (i.e. at $\tau_{5000} = 1$). The results of such a fit are shown in figure 7-6.

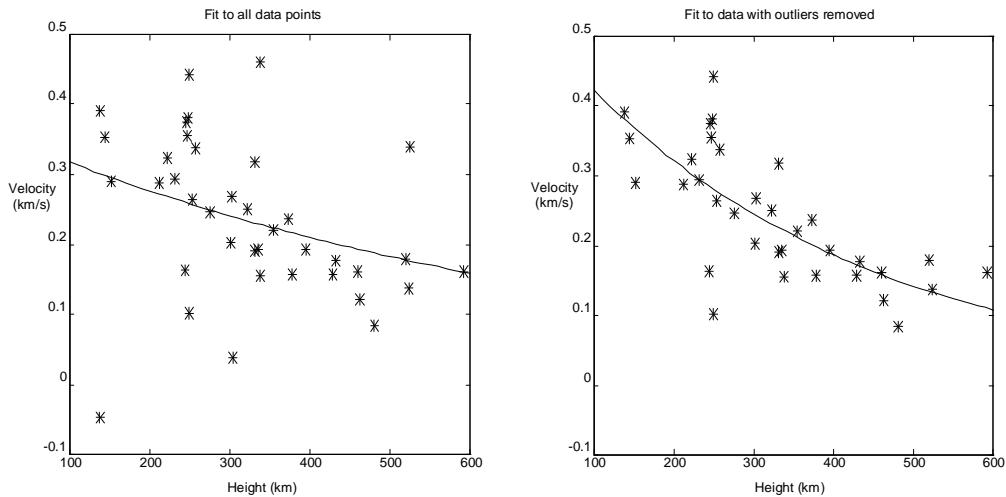


Figure 7-6: Velocity Parameter Height Dependence

The fit to the data is rather poor. As some of the points lie far from the others, these points are probably in error. Removing the four furthest outliers, the fit to the data is much improved. The results are summarised in table 7-2.

Table 7-2: Velocity Parameter Height Dependence

Velocity Parameter	All data	Outliers removed
V_0	0.373 kms ⁻¹	0.577 kms ⁻¹
Scale height V_s	726 km	368 km

As the fit to the data obtained with the outlying points removed seems much closer, the values obtained from this fit are probably much closer to the true values. It can be seen that the flow velocity varies significantly in the range of heights responsible for the formation of these lines, so it is likely to prove inadequate to approximate the velocity as being depth independent.

As the flow velocity varies by a large amount, the velocity gradient also varies. Any measurement of velocity gradients which assumes that the gradient is independent of height (i.e. a linear fit) will produce a result dependent on the height for which the data was obtained. Not surprisingly, there has been disagreement between velocity gradient measurements in the past, with scale heights of 80 km to about 2000 km being obtained.⁹

These values obtained here for the flow velocity parameters provide a suitable starting place; further refinement is investigated in chapter 8.

⁹Keil and Yackovich compare velocity gradient measurements in Keil, S.L. and Yackovich, F.H. "Photospheric Line Asymmetry and Granular Velocity Models" *Solar Physics* **69**, pg 213-221 (1981). Some of the disagreement undoubtedly results from using rather different techniques to determine the velocity gradient, such as some measurements using line shifts (as here) and others using line asymmetries. The use is liable to be quite inaccurate, due to the numerous factors influencing the asymmetry, unless very good spatial resolution is obtained, and only the spectrum emergent from a uniform upflow is used, strongly restricting the other factors which influence asymmetry.

7.5.2: Area

Estimates of the areas occupied by upflows and downflows vary due to the difficulty in identifying and measuring such flows accurately. A typical value of 45% of the area being occupied by the upflows will be used.¹⁰

From the ratio of the downflow velocity to the upflow velocity, it can be estimated that downflows occupy 15% of the area.

The initial adopted values for the area parameters are then $A_u = 0.45$, $A_r = 0.4$ and $A_d = 0.15$.

7.5.3: Brightness

Intensity measurements of granular regions are strongly affected by instrumental broadening. Thus, there is wide variation among observed results. As an average brightness for a region compared to the mean for all regions is desired, a suitable value can be chosen, based on observations (see chapter 6).

As variations of 10% above and below the mean seem to be usual, this variation can be used to find initial values for the brightness parameters, which after suitable normalisation, become $B_u = 1.07$, $B_r = 0.97$ and $B_d = 0.87$. The respective contributions to the emergent spectrum are then $AB_u = 0.48$, $AB_r = 0.39$ and $AB_d = 0.13$.

7.5.4: Microturbulence

Exact values of microturbulence are difficult to determine. At the depth where the bulk of the lines examined fall, the mean microturbulence should be approximately equal to the plane-parallel microturbulence of 0.845 km s^{-1} . As an initial approximation, it can also be assumed that the microturbulence in the transition region

¹⁰See pg 15 in Roudier, Th. and Muller, R. "Structure of the Solar Granulation" *Solar Physics* **107**, pg 11-26 (1986).

is the same as in the downflow. The difference between the upflow and downflow turbulence is large, as seen from the width of high-spatial resolution lines.

The values adopted here for depth-independent turbulent velocities are $\xi_v = 0.3 \text{ kms}^{-1}$, $\xi_r = 1.35 \text{ kms}^{-1}$ and $\xi_b = 1.35 \text{ kms}^{-1}$. These values give the correct mean.

The depth-dependent values (given at height $h = 0$) will be greater. From the data used to determine the scale height for flow velocities, the scale height V_s was found to be 368 km, while the mean height of formation was 424 km. This gives velocities at $h = 0$ of $\xi_v = 0.95 \text{ kms}^{-1}$, $\xi_r = 4.27 \text{ kms}^{-1}$ and $\xi_b = 4.27 \text{ kms}^{-1}$.

7.5.5: Intergranular Variation

From measurements by Bumba and Klvana,¹¹ the variation in flow velocities can be estimated. The variation in the upward flow is about 0.1 kms^{-1} and the variation in the downward flow is about 0.2 kms^{-1} . These values are likely to be an underestimate of the actual variation, due to resolution limits in the observations from which the velocity variations were determined.

In the absence of more reliable data, the intergranular variation can also be estimated from the plane-parallel macroturbulence and the flow velocity difference between the upflow and downflow. As the mean flow velocity difference is about 0.9 kms^{-1} , the variation should be such that the total broadening is roughly the same as that given by plane-parallel macroturbulence. This indicates that the value obtained from the measurements made by Bumba and Klvana is too low.

Values of $\Delta V_u = 0.25 \text{ kms}^{-1}$ and $\Delta V_b = 0.50 \text{ kms}^{-1}$ were chosen as initial values, and from a weighted mean of these, $\Delta V_t = .30 \text{ kms}^{-1}$. As these parameters are quite uncertain, they are a likely candidate for improvement by fitting computed spectra to the observed spectrum.

¹¹Bumba, V. and Klvana, M. "Doppler Velocity Measurements Made with a Scanning Photoelectric Magnetograph" *Solar Physics* **160**, pg 245-275 (1995).

7.6: Use of the Granular Model

The initial values chosen for the granular model parameters are liable to be inaccurate. By fitting the profiles of calculated and observed spectral lines, more reliable values can be obtained. This procedure is examined in chapter 8. More accurate knowledge of the statistical behaviour of granules, as predicted by this model, can thus be obtained. This can have two important results. Firstly, results from theoretical calculations of granulation can be compared to those determined from the spectrum. Secondly, if the results from the parameterised model do not match reliable observations, the differences can give information on why the simple model is inadequate, and indicate what further details must be considered when modelling granulation.

With a simple parametric model of granulation that reproduces line profiles well (for lines with well determined line parameters), the line parameters for other lines can be readily determined. In this way, theoretical and observed damping constants or line strengths can be compared.

In addition, once the vertical flow parameters and area parameters are determined, the horizontal flow can be found.

These are investigated in chapter 8.

