Chapter 7

Thesis summary

This thesis addresses the problem of diagnosing and modelling optically thick structures in the lower solar atmosphere – i.e. the chromosphere and transition region. Emission from such plasmas is described by the coupled, non-linear equations of radiative transfer and statistical balance. The solution of these equations is complex since it requires in principle complete knowledge of the dynamics and structure of the plasma in question. Both of these are unknown in general and even if they were known, the solution would be computationally complex. Methods that recognise both the non-linearity and coupling of these equations exist (radiative transfer techniques) but are restricted to particular source configurations that are generally very simple such as 1-D or 2-D isobaric and/or isothermal slabs.

Presented and developed here are escape probability and absorption factor techniques for solving the radiative transfer and statistical balance equations in a regime within which they naturally linearise and decouple. These methods have the benefit of being simple to use and are easily integrated within arbitrarily complex geometric plasma models. Thus they are desirable for studying the solar chromosphere and TR which are both highly structured.

Escape probability and absorption factor techniques were introduced in chapter 2 and were applied to spectral measurements of the east solar limb made by the SUMER instrument on board the SOHO spacecraft. Using these techniques, optical depths of spectral lines of C II and C III were extracted at the limb from observed branching ratios of lines arising from a common upper level. Escape probabilities were coupled with some simple atmosphere models to predict the branching ratio variations from which optical depths at disk centre were deduced. These optical depths allowed all the lines of C II and C III to be classified according to the effects of opacity on both emergent intensities (via $\bar{g}\{\tau_0\}$) and the excited state population structure (via $\bar{\bar{g}}\{\tau_0/2\}$). It was found that certain lines were optically thin but had opacity modified upper levels due to absorption in other lines.

A predicted limb brightening curve for the C III $2s2p\,^3P_2 - 2p^2\,^3P_2$ line at 1175.711 Å was calculated based on the most effective fit to the observed branching ratios. Unlike the fits to the ratios, the fit to the fluxes, though effective on the disk and well beyond the limb, was poor in the vicinity of the limb itself. This fact, coupled with the inability of the line-of-sight escape probability to extract optical depths for the C III 1175.711 Å line in this region, illustrate weaknesses in the escape probability expressions and/or the stratified atmosphere models.

To resolve these discrepancies, and to investigate the applicability of the escape probability approach in general, the assumptions underpinning these methods have been addressed. The key areas studied relate to

1. the variation of the source function with respect to space and frequency
2. the effects of atmospheric structure
3. instrumental effects

In chapter 3 the spatial variation of the source function was considered. The source function varies spatially for two reasons: firstly, due to the spatial variation of (T_e, N_e) which leads to a dependence of the population structure on position, and secondly due to the influence of photo-absorption on the population structure. The first source of variation, though significant, was initially neglected in order to focus on the effect of opacity on the source function variation. This may otherwise be described as scattering into the line-of-sight. For a number of perpendicular optical depths, the population structure was calculated throughout model emitting layers using a spatially dependent absorption factor, $\Lambda(\tau_0, x)$. This calculation led to the identification of a disk centre optical depth regime within which the modification to the source function due to opacity impinges negligibly on the validity of the line-of-sight averaged escape probability. The maximum optical depth for which $\bar{g}\{\tau_0\}$ is valid was found to be ~ 10.

As part of this study, the quantity $\mathcal{G}(\tau_0, x) \equiv 1/2(\bar{\bar{g}}\{\tau_0^-\}+\bar{\bar{g}}\{\tau_0^+\})$, was introduced. It was found that the range of optical depths within which this quantity is valid is smaller than that for $\bar{g}\{\tau_0\}$. This is due to indirect effects which mostly influence lines that share an upper level with lines that are more optically thick than themselves. The maximum optical depth for which $\mathcal{G}(\tau_0, x)$ is effective is ~ 0.5. However, the indirect effects are most significant at the layer edges and thus the optical depth range for which $\bar{\bar{g}}\{\tau_0/2\}$ is greater (~ 1).

In chapter 4 the effects of line blending were considered. Line blending fits naturally within the escape probability/absorption factor framework from an algebraic point of view. However, it introduces non-linearity into the $\bar{\bar{g}}\{\tau_0/2\}$ expression through an explicit dependence on upper level population densities which are opacity sensitive. Consequently $\bar{\bar{g}}\{\tau_0/2\}$ must be calculated iteratively when blending is included. If it is calculated in this way then, as in the blended case, it is effective for a range of optical depths although this range is restricted in comparison with the unblended case. This restriction is dependent on the degree of blending. As before, the spatially dependent equivalent, $\mathcal{G}(\tau_0, x)$, fails at layer edge for lines that share an upper level with a thicker line.

If $\bar{\bar{g}}\{\tau_0/2\}$ is not calculated iteratively its range of validity is severely reduced and is most markedly in error for the most severely blended lines.

Again a disk centre optical depth regime was identified within which the line-of-sight averaged escape probability, $\bar{g}^{(i)}\{\tau_0\}$ is valid. The upper optical depth limit was found to be ~ 4.

Spectral line profiles were considered in a blended context and it was found that opacity can lead to significant distortion of individual line profiles and can severely alter the intensity envelope of multiplets affected by blending. Opacity can also lead to perceived Doppler shifts in overlapped components.

In chapter 5 the effects of atmospheric structure and plasma flow were addressed.

It was demonstrated that for a structured, dynamic, optically thick plasma, an appropriate stratified, static model can be found from which an optical depth regime may be identified within which $\bar{g}^{(i)}\{\tau_0\}$ is valid in *both* the stratified, static and the structured, dynamic cases. This follows since the presence of structure and flow serve to minimise the effects of photo-absorption on the source function.

The spectral data discussed in chapter 2 was reconsidered from both a modelling and diagnostic perspective in chapter 6. Revised models were constructed that include correct treatment of line-of-sight optical depths, line blending and instrumentally scattered light. The resultant fits to observed limb-brightening curves and branching ratio variations were partially improved and partially worsened compared with the fits achieved in chapter 2. It was concluded that the structural detail ignored in the stratified models is critical for modelling effectively the emergent fluxes. It was also concluded that at heights above $\sim$ 970 arc sec, the signals are not dominated by instrumentally scattered light as had been expected. Rather structural issues are responsible for the failure of the models at and beyond the limb.

Observed fluxes were analysed in comparison with $f_{los}\{\tau_0\}\bar{g}^{(i)}\{\tau_0\}$ from which it was discovered that the quantities $f_{los}\{\tau_0\}$ show no dependence on optical depth. This implies that the spatial variation of the source function due to the variation of (T_e, N_e) with position may be neglected in the moderate optical depth regime of interest here, as asserted in chapter 3. It follows that $\bar{g}^{(i)}\{\tau_0\}$ is accurate for moderate optical depths.

The $f_{los}\{\tau_0\}$ terms, which may be written simply as f_{los}, are interpreted as filling factors, representing the area of the slit occupied by emitting structures. The variability of these factors for the two multiplets of C II and the multiplet of C III considered in this work, indicates that at all pointing positions, both on disk and off-limb, there exist emitting structures that are observationally unresolved. In an attempt to resolve these structures, the data was separated based on the visual identification of spicular and intra-spicular regions. The stratified models were found to be much more effective for the intra-spicular data than in both the spicular and combined cases. However, filling factors were deduced from both sets of data suggesting the presence of structures within both regions that have diameters less than $\sim$ 1 arc sec

The effectiveness of the line-of-sight escape probability demonstrated here illustrates its potential for use within structurally complex, dynamic plasma models. Moreover, the applicability of $\bar{g}^{(i)}\{\tau_0\}$, and its independence of model structure make it a powerful tool for diagnosing plasma parameters such as optical depth, and filling factors of emitting structures. It is possible to extend such techniques to incorporate bound-free absorption factors (Loch, 2001) and to consider the effects of opacity on ionisation balance. This fact, coupled with the flexibility of escape probability and absorption factor techniques from a structural perspective, suggest that these models may be applied to the study of radiative power loss from complex plasma geometries.

The branching ratio analysis is effective for diagnosing optical depths and filling factors providing the corresponding optical depths at disk centre are not too great. The cut-off is $\sim \tau_{0,dc} = 10$ for unblended lines. For blended lines this cut-off is lower and is dependent on the degree of overlap. Currently no simple formula exists to compute the cut-off for blended lines but further studies may reveal a simple connection between it and the optical depth of the line in question, along with those of the overlapped components and their overlap parameters $((\nu_0^{(i)} - \nu_0^{(n)})/\Delta\nu)$. Disk centre optical depths may be obtained by direct measurement or by model based extrapolation as demonstrated in chapters 2 and 6.

The filling factor diagnostic may be used in conjunction with a line-of-sight filling factor analysis such as that of Mariska et al. (1978). Such methods compare electron densities deduced from emission measure analyses which yield the line-of-sight integrated electron density, and local density diagnostics using line ratios. Together the two could be used to diagnose the 3-D structure of spicule-like features.

The escape probability methods presented in this work are not limited to use with quiet sun observations at the limb but may be applied anywhere, both on disk and off-limb and to features such as active regions and prominences. Furthermore, there are not restricted to use with stratified static models but may be coupled with complex geometric and dynamic plasma models to predict optically thick emission for comparison with observation. Providing the optical depths are moderate, such predictions represent realistic solutions to the radiative transfer and statistical balance equations.