Chapter 7

Conclusions and further work

7.1 Summary of results and conclusions

The main findings and results of this thesis work are now summarised. During the research work leading to this thesis, many new results have been obtained. Some of these have already been published or are in press (*Mason et al.*, 1997; *Del Zanna and Bromage*, 1997; *Bromage et al.*, 1997; *Landi et al.*, 1997b; *Bromage et al.*, 1997b; *Fludra et al.*, 1997a; *DeForest et al.*, 1997a; *Fludra et al.*1997b; *Gopalswamy et al.*, 1998; *Del Zanna and Bromage*, 1999a; *Fludra et al.*, 1999a; *Gibson et al.*, 1999; *Bromage et al.*, 1999; *Landi et al.*, 1999a; *Del Zanna and Bromage*, 1999b; *Fludra et al.*, 1999b, *Del Zanna and Bromage*, 1999c), some have been presented in detail in the previous Chapters and the Appendices, whilst others are in the process of being studied in more detail.

The CDS instrument has allowed spectroscopic diagnostic techniques to be used to describe the temperature distribution, densities and elemental abundances of the plasma in the lower solar corona. This instrument has provided the opportunity of observing (for the first time with sufficient spectral and spatial resolution) a large number of emission lines from a wide range of ions of different elements, in order to achieve these analyses.

The level of accuracy and completeness of the CHIANTI atomic database, has allowed an in-flight calibration of the CDS detectors to be made. The work for this thesis has included a contribution to the testing of the various versions of this database, and to the development of software for its use (Chapter 2). CHIANTI has enabled the identification of many hundreds of lines observed in all the different CDS spectra examined here.

7.1.1 Spectroscopic diagnostic methods and the CDS

- Various diagnostic methods for emission measure, differential emission measure , and element abundance determinations have been inter-compared in a consistent way. A critical discussion and re-evaluation of previous studies has been presented.

- A diagnostic method based on the differential emission measure (DEM) analysis has been developed to allow: a) the thermal structure of the emitting plasma to be studied; b) the relative element abundances to be estimated from non-flaring solar plasmas, for the first time; and c) the detailed assessment of line blends, for the first time.

- A detailed DEM re-analysis of a Skylab coronal hole spectrum has been presented and compared to previous studies, to show how more recent atomic data and different assumptions change the results and how blending limits the applicability of the diagnostic method.

- The diagnostic method has been applied for the first time to the entire high-resolution SERTS-89 spectrum to give a complete picture of all the ions observed, point ions out which require further study to assess the identification of all the lines and the blendings in order to to help in identifying the lines that CDS also observes, and which can be used for calibration purposes.

- Detailed CDS observations of the solar corona, and in particular of coronal holes have been planned. Software has been developed (in IDL) to analyse the large body of CDS spectral observations obtained by the author and Dr. Barbara Bromage and collaborators. These data sets are still only partly analysed.

- An extensive presentation and comparison of CDS NIS and GIS spectra of many different types of solar regions and structures have been given for the first time.

- For the first time, a complete in-flight cross-calibration between all the CDS detectors has been presented. In particular, the first full in-flight calibration of the GIS detectors has been given, including an assessment of the second order sensitivities for which no pre-flight estimates were available. Also for the first time the in-flight NIS 2 second order sensitivities are presented.

  The difficulties in calibrating an EUV spectroscope have been described in detail. The GIS and NIS sensitivities have been fully assessed, and temporal variations over a period of six months in 1997 studied in detail, showing that during this period of time the relative calibrations between all the CDS detectors did not appreciably change. A comparison with the pre-flight calibration data and with other studies has been given, showing the effects of different calibrations on the results.

- An in-flight assessment of various peculiar GIS characteristics has been made. This included a study of line profiles, the wavelength calibration, and, most important, a study of the ghosting. Examples of the various effects that ghosting has on the GIS spectra have been presented in detail, to provide suggestions on which part of the detectors are usable with some accuracy.

- The usefulness of many CDS spectral lines employed in density, temperature, and abundance diagnostics has been assessed in detail (for coronal hole and quiet sun observations), in terms both of blending and impact on deduced parameters.

- Considering all the spectra presented here, several newly-observed lines have been identified for the first time, while in several other cases new identifications of previously observed lines or previously unreported blends have been pointed out.

- The first comprehensive compilation of line lists and identifications for the whole CDS NIS and GIS wavelength region, including second order lines and GIS 'virtual' lines (ghosts) has been presented. However, a complete CDS spectral line list of identifications is virtually impossible, due to the moderate CDS resolution, the overlapping of first and second order lines, and the GIS ghosts and other peculiar characteristics. The complexity of the observed structures seen along the line of sight , together with the moderate spatial resolution, inevitably means that contributions to most CDS lines are highly variable from case to case. In addition, for GIS, different instrument settings yield different ghosting patterns. Some examples of how these differences affect a line identification have been presented here.

- Many cases of disagreement between theory and CDS observations have been highlighted. These occur either for all the lines in some ions (e.g. Mg V), or for single lines of other ions (e.g. Mg IX). These differences cannot be explained by instrument calibration problems, and could be due to inaccurate ionization equilibrium calculations or atomic physics. In fact, in various cases, the re-analyses of previous spectra (e.g. Skylab and SERTS-89) presented here, has shown analogous problems, indicating that solutions have to be sought in improvements to the theory, rather than in experimental calibrations or measurement errors.

- It has been shown with the use of the DEM analysis, that in most of the spectra examined (and presented throughout this thesis) the lines of Li-like ions have large discrepancies (by factors of 2 or more) compared with all the other lines. Some of these discrepancies were already pointed out by other authors.

- A comparison of the results of three different published ionization equilibrium calculations (presented in Chapter 3) has pointed out that large variations (by factors of 2-3) in the calculated intensities of the lines can simply be due to the use of a different ionization equilibrium. Some of the peculiar observed intensities (e.g. the

Ca IX and Ca X lines) can easily be explained in terms of an inaccurate ionization equilibrium calculation, rather than due to a variation of the element abundance. Some of the reported discrepancies for the Li-like ions can also be partly explained in terms of ionization equilibrium. The *Arnaud and Rothenflug* (1985) calculations were found to produce more consistent results for most of the ions.

- A detailed CDS - EIT comparison is presented for the first time, showing how important it is to compare observations from EUV filter images with detailed spectra of the same bandpass, in order to assess the possibility of using filter images for diagnostic purposes.

7.1.2 Solar physics results and conclusions

During 1996 the Sun was at minimum activity, and coronal conditions were at their most favourable for the study of coronal holes. Most of the CDS observations taken for this investigation were made in coronal hole regions. Considering that in the EUV only one previous set of coronal hole spectra for line intensities had ever been measured (by Skylab) before the advent of SOHO, the latter (and CDS) can be regarded as a coronal hole 'discovery mission'. Thus, many new exciting results have been produced. Some of the unanswered questions described in Chapter 1 are now finding answers from the SOHO observations. The solar physics results from the present work are now summarised.

- In all the observations analysed, temporal and spatial variations of all the measurable quantities were common.

- Average line-of-sight *coronal electron densities* in coronal holes and the quiet sun have been presented, in both on-disc and off-limb observations. Reliable measurements based on a number of unblended density-sensitive coronal lines, have been presented for coronal hole regions for the first time. Coronal holes are found to have densities about a factor of two lower than the quiet sun areas.

- Average line-of-sight (isothermal) *electron temperatures* in the same coronal holes and quiet sun regions were deduced using lines emitted by different stages of ionization of the same element, thereby eliminating uncertainties due to element abundance variations. This was the first time that this had been done for coronal hole plasmas.

- A large *equatorial coronal hole*, the Elephant's Trunk, was identified and a series of CDS observations carried out during the last week of August 1996.

- The on-disc CDS observations of both the Elephant's Trunk and polar coronal holes during 1996, 1997 and 1998, have shown average coronal electron densities $N_e \simeq 1 - 2\text{x}10^8$ (cm^{-3}). This is about a factor of two lower than in the quiet sun areas.

- *Transition region electron densities* also appear to be lower, by a factor of two, in coronal hole areas, with quiet sun values $N_e \simeq 1\text{x}10^{10}$ (cm^{-3}). This is also a new result, only suggested by some Skylab observations, and recently confirmed by SOHO SUMER observations (*Doschek et al.*, 1998a).

  Moreover, in the transition region, the cell-centres show consistently higher densities (by a factor of 2) compared to those at the network boundaries. This observation confirms the (only) earlier suggestion (*Dupree et al.*, 1976) of increased densities at the cell-centres, an observation that was based on Skylab HCO C III data.

- On-disc coronal hole observations (including the Elephant's Trunk) have shown, on average, isothermal coronal temperatures $T \simeq 8 - 9\text{x}10^5$ K, about 10% lower than the quiet sun, although the precise values obtained depend on the region examined.

- For the first time, a complete DEM analysis of a near-disc-centre observation of a coronal hole has been performed, including high-temperature emission lines, something that was not possible with the Skylab HCO instrument, due to the low sensitivity at the lower wavelengths where these lines are observed. The Elephant's Trunk and a nearby quiet sun region showed different thermal distributions, with peaks of the DEM at $T \simeq 8\text{x}10^5$ K and $T \simeq 1.1\text{x}10^6$ K, respectively.

- Some results from on-disc coronal hole observations performed during the rising phase of the solar cycle in 1997, have shown that coronal hole observations are significantly affected by the presence of foreground over-lying quiet sun plasma, in particular if lines that are emitted above a million degrees are used for coronal hole diagnostics.

- Analogously, off-limb coronal hole observations have shown that the presence of diffuse background emission from non-coronal-hole regions can affect coronal hole measurements.

- The variation of averaged densities and temperatures *with distance from the Sun* has been obtained from off-limb observations. This was performed for both coronal hole regions (distinguishing between plume and inter-plume regions), and equatorial quiet sun regions, up to a radial distance of 1.2 $R_\odot$.

  Observations (in 1996, 1997, and early 1998) of equatorial quiet sun regions have shown similar general characteristics from year to year, with densities decreasing from $4 - 5\text{x}10^8$ in the lower corona, to $\simeq 1\text{x}10^8$ cm^{-3} at 1.2 R$_\odot$. Densities in inter-plume coronal hole regions showed a decrease from $1 - 2\text{x}10^8$ in the lower corona, to $\simeq 5\text{x}10^7$ cm^{-3} at 1.2 R$_\odot$.

Temperatures were more difficult to establish, because the plasma has rarely been exactly isothermal, so that referring to 'a temperature' is not correct, and only a DEM analysis is appropriate to describe the temperature distribution of the plasma along the line of sight . However, measurements of line ratios, together with DEM analyses for off-limb quiet sun and coronal hole regions have all confirmed the Elephant's Trunk measurement, that coronal holes are much 'cooler' than the quiet sun. Temperatures in quiet sun areas are about $T \simeq 1.0 - 1.1\text{x}10^6$ K and then tend to increase with distance, up to 1.2 R$_\odot$, where they appear to reach a constant level.

In coronal holes, the temperatures have a much shallower gradient (as already known from Skylab observations), increasing slightly from $T \simeq 8\text{x}10^5$ K, to $T \simeq 0.9 - 1\text{x}10^6$ K. It should be noted that these isothermal temperatures vary depending on which structure is observed, and by the amount of foreground and background line of sight. However, these variations with height are consistent with the recent results of *David et al.* (1998), up to 1.2 R$_\odot$, the limit of the observations presented here. In fact, *David et al.* (1998) also derive from CDS and SUMER observations that the temperature gradient (from O VI ratios) in coronal holes is only slightly increasing up to about 1.15 R$_\odot$, after which they measure a decrease in the electron temperature.

- An examination of intensity ratios of lines of different elements but which have similar contribution functions, over a range of solar structures, has shown that in some cases the results are the same, while in others large variations are found. These variations appear to be correlated with the supergranular pattern, both in coronal hole and quiet sun regions, something that has never been reported before. Some of these variations could be due to different temperature gradients in the cell-centres and the network regions.

Coronal hole plumes

- For the first time, spectroscopic analyses of on-disc EUV observations of *coronal hole plumes* have been performed. This allowed a spectroscopic characterisation of plumes to be obtained for the first time. As for many other coronal structures, plumes have also shown a wide range of characteristics. Here, only typical faint plumes as observed by CDS during the minimum of the solar cycle are considered. Their main characteristics are lowered temperature and an enhanced Mg/Ne intensity ratio.

- For the first time, a low-latitude plume in a coronal hole (Elephant's Trunk) has been identified from its spectroscopic characteristics, rather than from its morphology.

- These plumes show lower temperatures (derived from line ratios) than the ambient coronal hole regions. No emission in high-temperature lines, formed above 1.2x10^5 K, was observed. DEM analyses have shown that plumes have an almost isothermal plasma distribution at coronal heights, with a peak in the differential emission measure at $T \simeq 7-8$x10^5 K, very similar to the temperatures deduced from line ratios. The surrounding coronal hole regions are less isothermal, at least at low heights. Off-limb observations suggest that plumes have even shallower radial temperature gradients than the coronal hole, and that these temperature differences tend to disappear with distance, as all the coronal hole plasma becomes almost isothermal.

  In terms of densities, measurements at lower-corona heights ($T \simeq 8-9$x10^5 K; e.g., Mg VIII, Si IX) have rarely shown significative differences between plume and inter-plume regions ($N_e \simeq 2$x10^8 cm^{-3}). However, due to low signal, the uncertainties are large and do not exclude the possibility of slightly higher density in plumes. A more detailed analysis is required, for example taking into account all the possible effects that a different temperature distribution can have on the evaluation of the densities from line ratios. At lower temperatures ($T \sim 7$x10^5 K), where plumes have their maximum emission measures and visibility, the density (Mg VII) is $N_e \simeq 1-4$x10^9 (cm^{-3}), higher than in the coronal hole regions, but similar to quiet sun values. At even lower temperatures ($T \sim 2$x10^5 K), in the lower transition region (O IV), plumes are not visible. Indeed, they appear to have the same densities as in the nearby coronal hole network regions ($N_e \simeq 5$x10^9 cm^{-3}). However, as well as exhibit enhanced Mg/Ne intensity ratios, plumes also show an enhancement in the O IV/Ne IV intensity ratios (reported here for the first time).

  The large FIP effect in plumes (reported by *Widing and Feldman*, 1992, in terms of Mg/Ne relative abundance), could be checked. For the first time, the relative abundances of many other elements have also been estimated. The observed large increases of the Mg/Ne intensity ratios at the base of the plumes, compared to the nearby coronal hole regions, can largely be explained by the plumes having a slightly *lower Ne abundance* (compared to oxygen), together with a much steeper temperature gradient in the upper transition region, thus confirming the *Phillips* (1997a) suggestion that the previously reported high-FIP in plumes could be due to a temperature effect. However, after taking into account the DEM distribution of the plume, a small FIP effect does appear to be present, although other high-FIP elements (such as S) have also shown increased abundances, compared to the photospheric values. This small FIP effect suggests that plumes may not be the source of the fast solar wind.

For the first time, it has been shown that the continuum observed in GIS 4 can be used to constrain the *absolute abundances of the elements* (relative to hydrogen). The measurements are consistent with coronal holes having absolute abundances which are photospheric.

7.2 Further work

CDS has produced a wealth of data that still requires a more detailed analysis. Now that clearer understanding of the instrument behaviour, calibration and line identification has been achieved, it is possible to extend the spectral analysis of the solar corona in much greater detail. It is very important to continue to perform comparisons of results obtained from different instruments in co-spatial and co-temporal observations, in order to remove remaining uncertainties due to instrument calibration or the diagnostic method adopted.

A more detailed study should be undertaken of the CDS absolute calibration, as a function of time throughout the mission. All CDS analyses, that were based on the preliminary calibrations (that were available until the end of 1998), will have to be revisited.

A more detailed analysis of the GIS spectra is still required, now that the various instrumental problems, including the ghosting problem, are better understood.

Atomic physics studies

Although atomic databases such as CHIANTI have proved to be extremely valuable in the EUV spectral region, there are still many unidentified lines, and many others that require more research. The recent case of Fe XIV has shown how more refined atomic physics calculations can bring theory into agreement with observations.

The coronal hole observations have shown the presence of many low-temperature lines that were not previously reported in quiet sun or active region solar spectra, including Fe VIII, Ca IV, and Ca VIII spectral lines. In particular, a detailed atomic physics study of Fe VIII is needed, since many instruments such as SOHO/EIT and TRACE (Transition Region Coronal Explorer) observe the solar corona with EUV filters in wavelength regions where Fe VIII line intensities are not negligible.

More work should also be undertaken on the validity of the ionization equilibrium and its relation to the problem of the Li-like ions. One possible method of comparing different ionization equilibria has been suggested here. Another possibility is to study the observed emission at high spatial and temporal resolutions. A preliminary analysis of the high-cadence (5s) GIS studies performed has suggested the presence of large temporal variations. However, observations with new instruments with much higher sensitivities is required to further study non-equilibrium effects on such short time-scales.

Short-time-scale events

Many wide-slit CDS observations have been performed and analysed by the author in order to create 'movies' of various solar regions, with a time resolution of the order of a minute (but with no spectral resolution). Some of these movies were created in an attempt to correlate Bright Points in coronal holes, observed with the Nobeyama radio-heliograph at 17 GHz (*Gopalswamy et al.*, 1998), with the chromospheric and transition region brightenings observed with CDS. No direct correlation was found. However, most of the brightenings observed with CDS were very brief events, lasting for only one or two exposures. Therefore, a more detailed analysis will require new instruments that will be able to measure intensities on time-scales much less than a minute.

Also worth noting is that in most cases these brightenings were almost simultaneous, in the transition region and in the lower corona. In order to understand the relation between the transition region and the corona, more detailed studies are needed, with improved spectroscopic capabilities. These need to be able to provide measurements of line widths and line shifts, and to have diagnostic capabilities, in order to give co-temporal information on density variations.

The future SOLAR-B mission, due to launch in 2004, should be able to address these issues.

Coronal holes, the transition region and the plumes

The off-limb and on-disc coronal hole observations presented here have shown that the Elephant's Trunk was an ideal subject for coronal hole studies, because of the near-disc centre, and solar minimum conditions. Hence, a full study is needed of all the remaining observations of this feature that are not yet fully analysed.

A more extended analysis of the transition region characteristics is required, to confirm the abundances, temperature, and density variations presented here. The fact that the transition region densities in the network seem lower than in the cell-centres, together with the fact that the emission measures there are much higher, indicates that the cell-centres have higher plasma pressures, as one would anyway expect, since the magnetic pressure there is lower. It also indicates that the filling factors in the transition region are highly variable (although much higher spatial resolution than CDS has is required in order to estimate the volume from which the observed emission originates).

Other information should be added, in order to constrain the various physical models of the transition region, and relate the transition region to the outer solar atmosphere. One possibility is to use the DEM distributions presented in this thesis to test models of the transition region such as the study presented by *Dowdy et al.* (1987), which compared the DEM curves derived from Skylab data, with model calculations.

Another possibility is to use the FIP effect. In fact, the processes that take place in the chromosphere/transition region may create a fractionation of the elements that follows the structure of the cell-centre regions. Once this fractionation has taken place, the abundance characteristics of a structure should not change much with height (although gravitational settling might play a role), and should therefore not only be visible at transition-region and coronal heights (with spectroscopic instruments), but should also exhibit a signature in in-situ observations of the solar wind. For example, the near-photospheric element abundances found here in the coronal hole network could represent the signature of the fast solar wind originating from the chromospheric network and propagating through coronal funnels (see the model of *Marsch and Tu*, 1997, and references therein), which from in-situ measurements does not show a significant FIP effect. Recent SUMER observations (e.g., *Hassler et al.*, 1999) have also confirmed that the fast solar wind appears to be originating at the junctions of the chromospheric network.

Coronal hole plumes deserve much more detailed investigation. This is not only for the reasons outlined in the introduction, but also because CDS observations have shown that, among the complex zoo of coronal large scale structures, they are probably the simplest ones to model. This is because: (1) their geometry is relatively well defined, which for example helps theoretical modelling, and estimates of the filling factors (a preliminary analysis indicates that plumes have filling factors close to 1.); (2) they are long lasting quasi-stationary structures; and (3) they are almost isothermal. Studies of their peculiar element abundances should surely also shed some light on the wider coronal abundance problems, and address the question of why coronal abundances appear to be different from the photospheric ones.