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The CHIANTI Atomic Database and Instrument Calibration: a Symbiosis

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The CHIANTI atomic database comprises a comprehensive, accurate and up-to-date database of atomic parameters, necessary for emission-line spectroscopy. The suite of user-friendly software allows plasma diagnostics to be carried out. Since its release in 1996, CHIANTI has become a standard resource for the analysis of solar spectra. Accurate atomic data can provide the foundation for in-flight instrument calibrations. Conversely, an accurate instrument calibration can provide a check on atomic parameters. The internal consistency of spectral-line intensities can be used to highlight specific anomalies. In this paper, we illustrate how CHIANTI has been used to validate the calibration of solar EUV instruments: SOHO-CDS, -SUMER, -EIT and SERTS. In addition, we show how anomalous spectral-line intensities indicate the need for more accurate atomic calculations.

18.1 Introduction

Spectroscopic diagnostics using UV, EUV and X-ray line intensities are a fundamental tool for the measurement of physical parameters of solar and stellar atmospheres, such as the electron density, temperature, plasma emission measure and chemical composition. See *Mason and Monsignori Fossi* [1994] for a comprehensive review. These diagnostics require a large amount of accurate atomic data, including energy levels, radiative transition probabilities and collisional excitation rates. The CHIANTI project [*Dere et al.* 1997, 2001, *Landi et al.* 1999, *Young et al.* 2002] aims to provide the solar and astrophysics communities with these atomic data. CHIANTI is applicable to a range of physical conditions pertinent to optically-thin plasmas in collisional ionization equilibrium. In addition, theoretical spectral-line emissivities can be used to check instrument calibrations. The accuracy of both the diagnostics and calibration results depends critically on the reliability of the atomic data used.

The accuracy of theoretical calculations can best be assessed from a direct comparison with measurements in well-controlled laboratory experiments. Unfortunately, conditions that exist in astrophysical plasmas are difficult to reproduce in the laboratory. As a result, only a small amount of the atomic data in the CHIANTI database has been verified in this way. Consequently, most of the conclusions regarding the plasma properties of the solar corona that are reported in the literature are based on comparisons between observations and ab initio calculations.

As part of the CHIANTI project, systematic comparisons have been carried out between CHIANTI emissivities and high-resolution solar spectra. The CHIANTI atomic database provides an important check on the calibration of the spectra and the broad-band filters. The method of deriving the relative radiometric calibration of solar instruments using intensity ratios of density- and temperature-insensitive lines was first proposed by *Neupert and Kastner* [1983]. CHIANTI emissivities for a number of ions, formed at different temperatures, have also been used to deduce a differential emission measure distribution for the emitting plasma. Where discrepancies between CHIANTI and measured line-intensities do exist, they point out potential mis-identifications, new identifications, line blending, possible calibration problems, data reduction errors or cases where atomic data need to be improved.

The first studies compared CHIANTI and the Solar EUV Rocket Telescope and Spectrograph (SERTS) observations [*Thomas and Neupert*, 1994] in the 17 nm to 45 nm spectral range. These studies are discussed in Section 18.2. The Coronal Diagnostic Spectrometer (CDS) on board the Solar and Heliospheric Observatory (SOHO) observes many emission lines from a large number of highly-ionised ions of the most abundant elements, covering a large range of temperatures. CDS, therefore, provides an excellent opportunity for a detailed diagnostic study of the transition-region and coronal plasma. The large number of emission lines covering an extensive wavelength range also allows an in-flight calibration to be obtained by comparison of observed and CHIANTI emissivities. A short overview of the work carried out with CDS using CHIANTI is given in Section 18.3.1. Details of the CDS in-flight calibration using CHIANTI are given in a separate paper by *Del Zanna* [2002] and a detailed paper by *Del Zanna et al.* [2001a]. A comparison has recently been made of CHIANTI emissivities with the Solar Ultraviolet Measurements of Emitted Radiation (SUMER) observations of the quiet solar corona in the 50 nm to 160 nm spectral range. Details of these results are given in Section 18.3.2. CHIANTI has also been used in the calibration and analysis of observations from the EUV Imaging Telescope (EIT) on SOHO (see Section 18.3.3). CHIANTI has been used to check which spectral lines contribute to the various EIT channels for different solar regions having different characteristic temperatures. This type of study is important for all imaging instruments: for example Yohkoh SXT (Soft X-ray Telescope) and TRACE (Transition Region And Coronal Explorer).

Following a workshop on atomic data requirements for SOHO [*Lang*, 1994], an international collaboration known as the Iron Project [*Hummer et al.*, 1993] was established with the aim of carrying out systematic, electron-scattering calculations for ions of astronomical interest, using the best available methods. In particular, members of the Iron Project have concentrated on the sequence of iron ions prevalent in the corona. The inclusion of these new, high-accuracy atomic data in CHIANTI is crucial to the successful analysis of solar spectra. Examples of Iron Project results and comparisons with solar observations are given in Section 18.4.

18.2 SERTS

A description of the SERTS instrument is given by *Neupert et al.* [1992]. A spectrum of an active region obtained in the first rocket flight in 1989 (SERTS-89) was published by *Thomas and Neupert* [1994]. The SERTS-89 instrument covered the 23.5 nm to 45.0 nm wavelength region in first order and 17.0 nm to 22.5 nm in second order. The spectrum is composed of optically-allowed transitions from ions formed in the 5×10^4 K to 4×10^6 K temperature range, encompassing the upper chromosphere, the transition region and the corona.

Emission-line intensities from the SERTS-89 observations have been compared with CHIANTI (Version 1) emissivities by *Young et al.* [1998]. In general, excellent agreement was found. However, at the longest wavelengths (42 nm to 45 nm), the observed intensities were found to be systematically low. The use of density-insensitive ratios and branching ratios led *Young et al.* [1998] to suggest a correction to the SERTS-89 intensity calibration for wavelengths greater than 40 nm. This demonstrates the enormous potential of the CHIANTI database as a means for checking the instrumental intensity calibration.

The version of SERTS flown in 1995 (SERTS-95) incorporated a multilayer-coated diffraction grating that enhanced the instrumental sensitivity in the second-order waveband. This gives rise to sharply-peaked response functions, which are more difficult to calibrate reliably. *Brosius et al.* [1998a] present active-region and quiet-Sun spectra derived from SERTS-95 observations. The relative radiometric calibration was derived by means of density- and temperature-insensitive line-intensity ratios [*Brosius et al.*, 1998b], using CHIANTI.

18.3 SOHO

18.3.1 CDS

CDS comprises two spectrometers: the Normal Incidence Spectrometer (NIS) and the Grazing Incidence Spectrometer (GIS). The NIS detector observes two spectral ranges (NIS-1: 30.8 nm to 38.1 nm and NIS-2: 51.3 nm to 63.3 nm), with stigmatic optics. The GIS has four detectors (GIS-1: 15.1 nm to 22.1 nm, GIS-2: 25.6 nm to 33.8 nm, GIS-3: 39.3 nm to 49.3 nm and GIS-4: 65.6 nm to 78.5 nm). CDS studies allow the simultaneous extraction of both spatial and spectral information, thus enabling quantitative, spectroscopic-diagnostic analyses to be carried out. Initial results from the CDS instrument are given in *Harrison et al.* [1997]. The CHIANTI database and software was originally integrated into the CDS software package by C.D. Pike. Figure 18.1 shows a comparison of a CDS spectrum with a CHIANTI spectrum. The plots are based on the results of the active-region analysis published in *Landi and Landini* [1998]. The synthetic spectrum is calculated using a coronal chemical composition and the DEM curves and density reported in that paper. It shows the excellent degree of accuracy and completeness of the CHIANTI database. The apparent continuum emission in the CDS spectrum is instrumental in origin. The spectroscopic diagnostic capabilities of CDS are presented in *Mason*

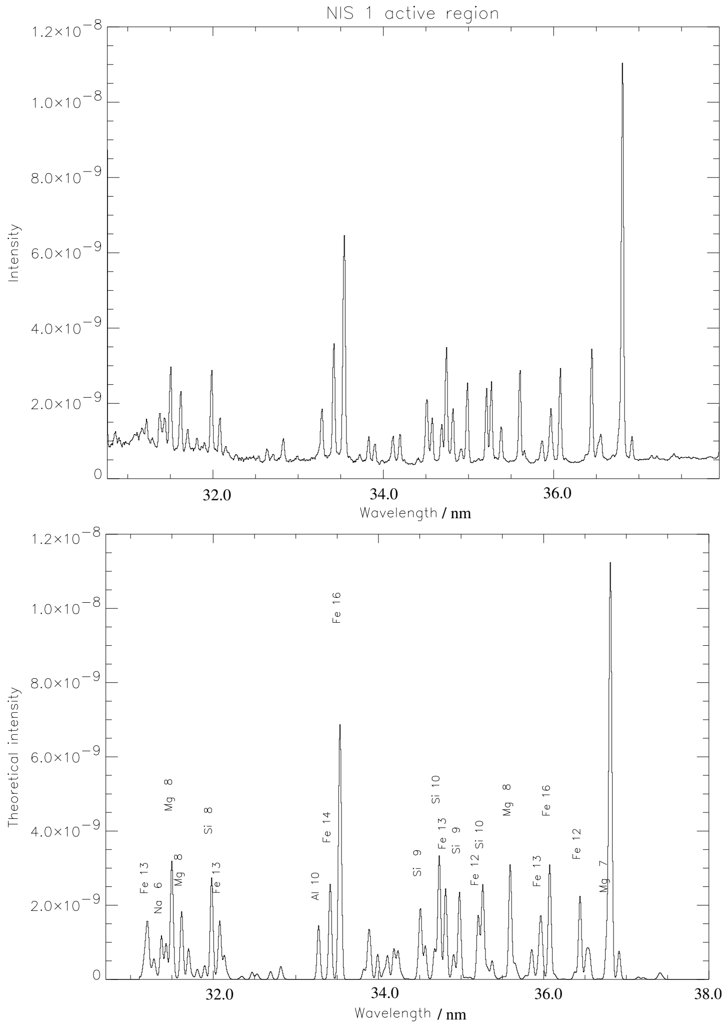

Figure 18.1: Synthetic spectrum for an active-region dataset, taken from *Landi and Landini* [1998]. Top: CDS NIS-1 observed spectrum, and bottom: CHIANTI synthetic spectrum. The intensity units are erg cm^{-2} s^{-1} arcsec^{-2}.

et al. [1997, 1999]. These require a reliable CDS calibration. In particular, the study of elemental abundances is a field of intense interest [*Mason and Bochsler*, 1999]. For example, *Young and Mason* [1997] investigated the relative elemental abundance of magnesium to neon in an active region. High electron-densities and photospheric abundances were found, which could possibly be related to emergent flux. In contrast, the footpoints of larger coronal structures show coronal abundances. These results depend critically on the CDS calibration, in particular between the two wavelengh ranges of NIS-1 and NIS-2. *Fletcher et al.* [2001] have pursued this topic and find indications that transition-region brightenings and elemental abundance variations could be closely related to changes in magnetic topology. A strong warning is given by *Del Zanna et al.* [2002] and *Gianetti et al.* [2000] that limitations of the calibration, the analysis method and the atomic data can all lead to serious errors in elemental-abundance determinations. It is best, whenever possible, to use both NIS and GIS observations for such studies.

Many Joint Observing Programmes (JOPs) have been carried out with SOHO. For example, *Gibson et al.* [2002] monitored the structure and evolution of an active region by combining SOHO, TRACE, Yohkoh and ground-based observations. These multi-instrument campaigns require careful co-alignment and an accurate cross-calibration of different instruments.

An evaluation of CHIANTI data for the CDS NIS coronal lines has been carried out by *Landi et al.* [2002]. They chose a set of off-disk observations which were found to be almost isothermal over several hours. They found very good agreement between the electron temperature and density measured from spectral-line intensity ratios and those values derived from an emission measure analysis. Overall, good agreement was found between different ions and different isoelectronic sequences. Some blends are indicated and individual cases of discrepancies between the CDS observations and CHIANTI suggest there is a requirement for improved atomic data.

18.3.2 SUMER

The SUMER spectrometer on board SOHO covers the 50 nm to 160 nm spectral range and offers a unique opportunity to check CHIANTI predictions for emission lines in this rich wavelength range. In general, these lines are either optically-allowed lines due to low-ionization stages formed in the 2×10^4 K to 3×10^5 K temperature range (typical of the solar chromosphere and transition region) or optically-forbidden and intercombination lines formed in the solar corona at $T > 3 \times 10^5$ K. When the SUMER field-of-view is on the disk, the lower-temperature lines dominate the spectrum; when SUMER observes plasma beyond the solar disk, the lower-temperature lines, to a large extent, disappear and the hotter lines become most prominent.

Landi et al. [2002] compared the CHIANTI emissivities with an off-disk coronal spectrum observed at distances from the limb between 1.03 and 1.045 solar radii, in quiet conditions. By so doing, they limited their investigation to ions having maximum fractional abundances in the temperature range $3 \times 10^5\ \mathrm{K} < T_e < 3 \times 10^6$ K. The choice of such a region had the advantage that the emitting plasma was nearly isothermal. The emission measure technique allowed a simultaneous measurement of both the electron temperature and the emission measure of the emitting plasma. An example of the emission measure technique is given in Figure 18.2, where lines from nitrogen-like ions are used. The place where the curves cross gives the derived temperature and emission measure values. Excellent agreement was found between the temperature measured for all coronal lines in the dataset and the *Feldman et al.* [1999] value for the same observations. The intensity calibration of the SUMER instrument and the elemental abundance adopted for the study were confirmed, and several blends were identified. A few areas of disagreement were found, where the problems were probably due to inaccuracies of atomic physics or

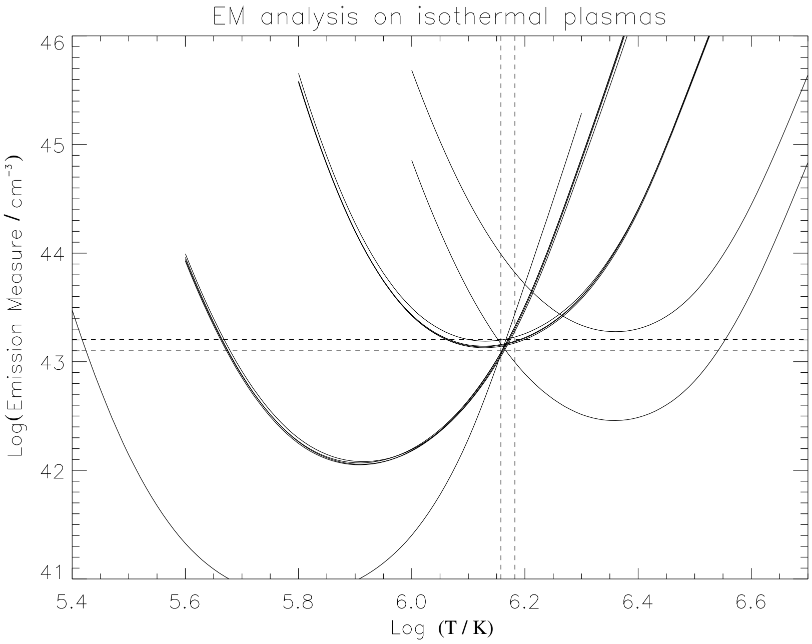

Figure 18.2: Example of the emission measure analysis applied to SUMER line intensities. The curves displayed are the $\frac{I_{obs}}{G(T)}$ functions of Al VII, Si VIII, S X and Ar XII lines, where I_{obs} is the observed intensity and $G(T)$ is the contribution function of each line calculated using CHIANTI. The crossing region, marked by the dashed lines, indicates the value of the plasma emission measure and temperature. The line missing the common crossing region clearly indicates the presence of a blend or of some atomic physics problems.

to unidentified blending. By simultaneously comparing lines of many different ions, the emission-measure technique allowed the problems in individual transitions along the entire isoelectronic sequence to be tracked, thus enabling a discrimination between blending problems and real atomic physics inaccuracies.

Overall, the CHIANTI database has been very successful in reproducing the SUMER coronal spectrum. Future studies will be devoted to the cooler part of the spectrum, by comparing CHIANTI emissivities with on-disk observations of quiet Sun from SUMER.

18.3.3 EIT Plasma Response

The EIT instrument has been designed to be sensitive to the solar spectrum in four narrow wavelength-bands. These wavelength bands have been chosen to correspond to four strong lines that are produced in four distinct, narrow temperature-regimes. The wavelength bands are listed in Table 18.1. In order to understand the response of the EIT to coronal and transition-region plasmas at various temperatures, it is necessary to have a model of the solar spectrum at the wavelengths where EIT is sensitive. The CHIANTI database and spectral code provide an accurate and comprehensive model spectrum for calculating the EIT plasma response. They provide good predictions of the strong primary

Table 18.1: EIT Wavelength Bands

Wavelength	Dominant Ion	Characteristic Temperature
17.1 nm	Fe IX, X	9×10^5 K
19.5 nm	Fe XII	1.3×10^6 K
28.4 nm	Fe XV	2×10^6 K
30.4 nm	He II	8×10^4 K

lines in the EIT passbands as well as the weaker lines and the continuum. These various components can be significant contributors at temperatures outside the contribution function of the principal lines.

The primary calibration of the EIT spectral response is based on measurements, taken at the Orsay synchrotron, with flight components of the EIT. This work has been reported by *Dere et al.* [2000]. An integration of the solar spectrum using the CHIANTI database is shown in Figure 18.3. These calculations are based on the instrument response function given in *Dere et al.* [2000]. The three curves refer to three positions of the EIT filter wheel. The solar variability model of *Warren, Mariska and Lean* [1998] suggests that the CHIANTI models can underestimate the intensities of He II 25.6 nm and 30.4 nm by factors of two and six respectively. However, they do seem to reproduce correctly the He I intensities, although this may just be fortuitous. *Newmark* [2001] has reanalysed the EIT preflight calibration data and found that the second-order mirror reflectivities of the He II 30.4 nm channel should provide a non-negligible reflectivity at wavelengths just longward of 17 nm. To produce the response curves included in the EIT calibration software, Newmark has included this change to the He II 30.4 nm bandpass as well as extending the wings of the EIT response functions. The helium line intensities were calculated with CHIANTI using standard active-region and quiet-Sun differential emission measures from OSO-6 observations. It is assumed that collisional excitation is dominant and that the line is optically thin.

Del Zanna et al. [2002] have made a direct comparison of CDS-GIS and EIT. Plumes were found to exhibit a quasi-isothermal distribution, which peaks at a lower temperature ($T = 7$ to 8×10^5 K) than the surrounding coronal-hole region. Elemental abundances in the plumes exhibit only a small departure from photospheric values. A comparison was made with the broad-band images of EIT, showing that, in the plume, the low temperature Fe VIII emission is the dominant contribution to the 'Fe XII 19.5 nm' EIT filter.

The 17.1 nm and 19.5 nm EIT filters have been used by various authors to deduce that plumes are about 30 % cooler than the surrounding coronal-hole regions. In order to confirm this result, a comparison was made between the GIS scans and the EIT 17.1 nm and 19.5 nm images. A direct comparison is possible because GIS spectrally resolves the emission lines observed by the EIT filters. The observed and calibrated GIS spectra were multiplied by the EIT effective-areas [*Dere et al.*, 2000], to simulate the EIT observed bandpasses. GIS spectra of the three regions were chosen as representative of plume, coronal-hole and quiet-Sun areas. These spectra were multiplied by the EIT filter response. The three spectra of the various solar features show how different lines, formed at a range of temperatures, contribute to the emission seen by the EIT. The transmission of the EIT

17.1 nm filter can be regarded as almost isothermal with contributions mainly from Fe IX and Fe X for all three solar regions. In the EIT 19.5 nm filter, the situation is quite different, as Figure 18.4 shows. In the quiet-Sun spectrum the main contribution is from Fe XII lines, mixed with some Fe X, Fe XI and Fe XIII emission. However, in the coronal-hole and plume spectra, the cooler lines (Fe VIII, Fe X, Fe XI) become increasingly dominant in comparison to the Fe XII lines. This shows that it is incorrect to assume that the observed emission in the EIT 19.5 nm filter is predominantly from Fe XII, and explains why plumes are visible in the EIT 19.5 nm images. Since the lines observed in the EIT 19.5 nm filter are formed over such a wide range of temperatures, it is dangerous to use this filter for temperature diagnostics.

18.4 The Iron Project: Fe XIV, Fe IX and Fe XII

The comparisons of CHIANTI with SERTS and SOHO observations highlighted some inconsistencies, which indicated the need for better atomic data. The iron ions are particularly difficult to represent with an accurate atomic model. Some examples are presented here of new calculations from within the Iron Project for Fe IX, Fe XII and Fe XIV.

Fe XIV is one of the most important diagnostic ions in the solar corona. Transitions within Fe XIV give rise to spectral lines in the visible (green line, 530.3 nm) and extreme-ultraviolet wavelength ranges. *Storey et al.* [1996, 2000] calculated new atomic data for Fe XIV. The electron-scattering calculation was more sophisticated than any previous work on this ion. Significant differences with earlier work were found in the excitation rates for many transitions. A comparison was made between predicted line-intensity ratios and those observed in solar-coronal spectra, including those from SERTS-89 and CDS. Several long-standing inconsistencies between the theoretical and observed intensity ratios, as detailed by *Young et al.* [1998], were resolved by these new atomic data.

Recent analyses of SERTS-89 data have been carried out for Fe IX by *Storey and Zeippen* [2001]. They have show that their new atomic data lead to significant changes in line-intensity ratios. These new data resolve some major inconsistencies between the observed and theoretical Fe IX spectra.

Fe XII also plays a key role in diagnostic studies because of its wealth of strong spectroscopic lines covering a wide wavelength-range in the UV and EUV spectral regions, spanning several instruments on SOHO. A new set of atomic data for Fe XII was calculated by *Binello et al.* [1998a, 1998b]. In *Binello et al.* [2001] a comparison is made between the theoretical line intensities and solar observations for a range of plasma densities and temperatures. The SERTS-89 and SERTS-95 observations of quiet Sun and solar active-regions provided a useful means of testing the quality of the atomic data. For the Fe XII density-insensitive ratios, they found generally good agreement between theoretical and observed ratios. However, the electron densities derived from the Fe XII spectral lines for SERTS-89 and SERTS-95 show persistently greater densities than those from other ions formed at similar temperatures. This highlights a serious discrepancy. Further improvements to the atomic model may help to resolve this problem for this troublesome and complex ion.

18.5 Conclusions

Imaging instruments can provide high spatial and time resolution observations. They have clearly demonstrated that the solar atmosphere contains dynamic, filamentary structures. Spectroscopic instruments provide good diagnostic capabilities for plasma parameters. Both imaging and spectroscopic instruments require accurate calibrations to obtain reliable scientific results. In-flight calibrations can and have been performed for solar instruments using high quality atomic data. The CHIANTI package (atomic database and supporting software) has contributed significantly to this effort. It is freely available and is now widely used by the solar-physics community.

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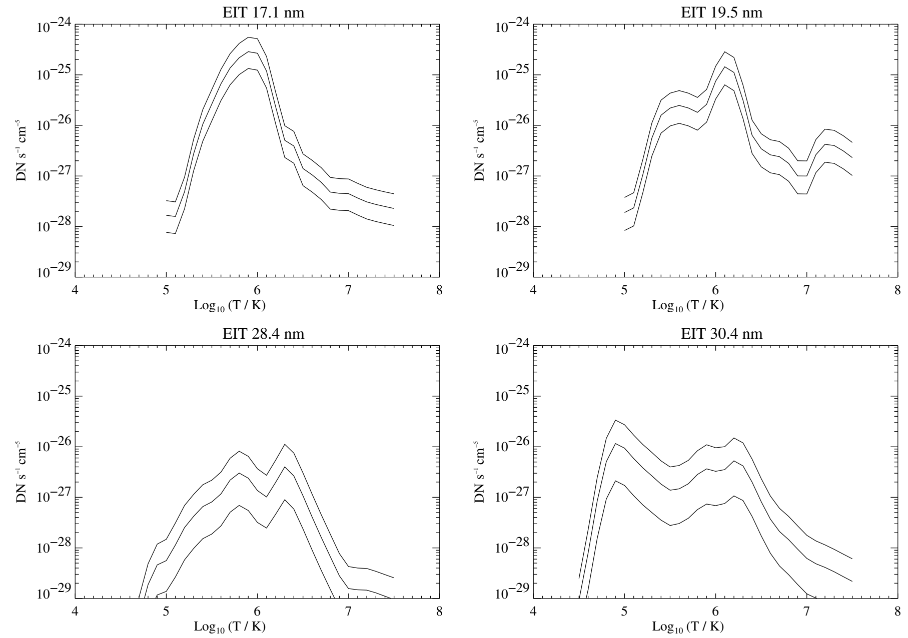

Figure 18.3: An integration of the solar spectrum obtained with the CHIANTI database based on the EIT response function given in *Dere et al.* [2000], with DN s^{-1} per unit emission measure plotted as a function of electron temperature for each of the four EIT channels. DN is simply the 'digital number' output by the instrument electronics. The CHIANTI spectrum was derived using the *Mazzotta et al.* [1998] ionization equilibria and the coronal abundances of *Feldman and Laming* [2000].

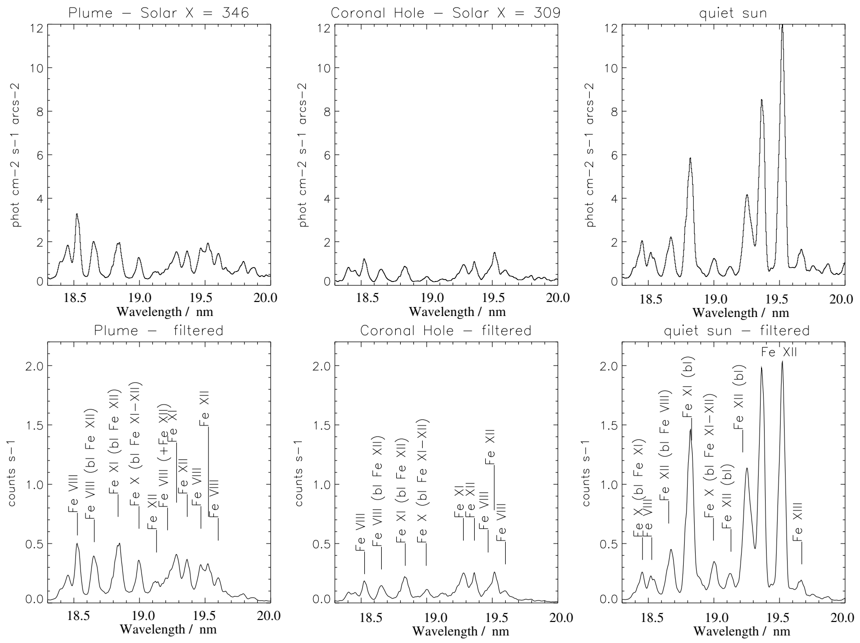

Figure 18.4: Top: GIS-1 spectra of plume, coronal hole and quiet sun. Details of the parameters used in CHIANTI to produce these spectra are given in *Del Zanna et al.* [2002]. Bottom: same as above, but multiplied by the EIT 19.5 nm filter response.