Stellar Coronae in the Chandra and XMM-Newton Era
ASP Conference Series, Vol. TBD, 2001
F. Favata & J. Drake

Solar and stellar high-resolution X-ray spectra: plasma diagnostics with the CHIANTI atomic database.

G. Del Zanna and H.E. Mason

DAMTP, University of Cambridge, Cambridge, UK

Abstract. We review some of the spectroscopic diagnostic techniques that can be applied to XUV observations of the Sun and active stars. In particular, we discuss methods for the determination of temperatures and the chemical composition of the stellar transition regions and coronae.

1. Introduction

In this paper we discuss some issues that are relevant to the diagnostics of transition region (TR) and coronal plasmas from the Sun and the stars. In particular, we consider some of the methods that have been or can be used to determine temperatures, emission measures and elemental abundances. But first, we ask: can we reliably use spectroscopic observations; atomic data and models; plasma diagnostic methods; physical models, to derive useful information on the solar and stellar TR and coronal plasmas ? In this respect, there are two schools of thought:

1. No (negative). Both from theoretical considerations (see e.g. P. Judge, this issue) and from recent SOHO, TRACE observations that have shown the complexity and the dynamic nature of the solar corona.

2. Yes (positive). However, are all the older results reliable ? How can those results be revised/improved ?

Until recently, with the advent of high-resolution XUV spectroscopy, the physical characteristics of the stellar coronae could only be estimated using approximate methods, which were subject to large uncertainties. We are experiencing a new era for our understanding of the solar and stellar coronae, with new challenges:

- High-resolution spectroscopy in the XUV now allows the application of many types of diagnostics. For the Sun, the CDS and SUMER aboard SOHO have provided a wealth of spectral data covering the 150-1600 Å wavelength range. For the stars, the gratings onboard of the Chandra, XMM, FUSE, HST satellites are providing a flood of spectra from the X-rays to the ultraviolet. All these instruments provide well calibrated data. The challenge is to provide an unified view of the various phenomena of the solar TR and corona, and to relate them with those occurring in stars of different spectral types.

- For the first time it is possible to use a large number of lines from ions belonging to different isoelectronic sequences. The challenge is to find out where the atomic physics is in disagreement with the observations.
- A large number of new atomic calculations and laboratory data are being produced. The challenge is to keep up with all these new developments. In this respect, the CHIANTI project (Dere et al., 1997) provides an useful service to the astrophysics community.
- Include all the relevant atomic processes in the calculations.
- Chandra and XMM-Newton are now providing for the first time a large number of high-resolution X-ray spectra covering a wide wavelength range. The challenge is to provide: a) correct line identifications (blends); b) a complete atomic database; c) the best diagnostic methods.

A large body of literature has been written on the subject of spectroscopic diagnostics (for a general review see, e.g. Mason & Monsignori Fossi, 1994). In most stellar cases, authors used the same diagnostic methods as applied to the study of the solar atmosphere. However, in many cases approximate methods and/or inaccurate atomic calculations have been used in the past. Here, we discuss some diagnostic methods. More details can be found in Del Zanna, Landini, & Mason (2001).

2. Example of diagnostic methods. DEM

The intensity $I(\lambda_{ij})$, of an optically thin spectral line of wavelength λ_{ij} is usually written (cf. Mason and Monsignori Fossi 1994):

$$I(\lambda_{ij}) = A_b(X) \int C(T, \lambda_{ij}, N_e) N_e N_H dh \tag{1}$$

where N_H, N_e are the the Hydrogen and free electron number densities, $A_b(X)$ is the elemental abundance (assumed constant over the line of sight h), and $C(T, \lambda_{ij}, N_e)$ is called the *contribution function.* It is also common in the literature to re-write the expression in terms of an emission measure differential in both temperature and density ($DEM(T, N_e)$):

$$I(\lambda_{ij}) = A_b(X) \int_T \int_N \; C(T, \lambda_{ij}, N_e) \; DEM(T, N_e) \; dT \; dN_e \tag{2}$$

or more simply differential only on temperature ($DEM(T)$):

$$I(\lambda_{ij}) = A_b(X) \int_T \; C(T, \lambda_{ij}, N_e) \; DEM(T) \; dT \tag{3}$$

In theory	*In practice*
The kernel is differential in both T, N_e	The errors in the observational and atomic data make this approach difficult. The use of density-insensitive lines helps. A knowledge of the $DEM(T)$ distribution is needed for many purposes (elemental abundances, radiative losses, continuum).
The determination of the DEM distribution is an ill-conditioned problem where solutions are not unique (Craig and Brown 1986).	People do derive $DEM(T)$ distributions
In most cases, the plasma distribution along the line of sight is multithermal.	For years models of 1-T or 2-T EM have been used to characterise stellar coronae.
The plasma distribution along the line of sight is multidensity and 'average values' are meaningless.	Some 'average values' are needed (e.g. to calculate line emissivities). The use of a large number of line ratios of the same ions and of different ions allows a cross-check on the density distribution (Del Zanna 1999).
The DEM(T) can be derived using a large number of lines spanning a wide temperature range.	Single instruments often only provide contraints at high-T (e.g.: EUVE, Chandra/HETG, XMM/RGS) or at low-T (e.g.: IUE, HST-GHRS/STIS).
An 'accurate' DEM(T) can be derived using a relative small number of lines.	Wrong DEM(T) have been obtained (Sun, stars) due to bad selections of lines (Del Zanna, Landini, and Mason 2001).
We cannot trust atomic data because we do not know how accurate they are	Atomic data (e.g. CHIANTI) have been the primary means to suggest significant corrections to in-flight calibration of solar instruments (SERTS – Young et al. 1998; SOHO/CDS – Del Zanna et al., 2001).

On these issues, our perspective is to suggest the use of common sense and an open-minded revision of previous studies.

3. Example of diagnostic methods. Elemental abundances

There is current interest in the study of stellar coronal abundances, and the comparison with the solar ones. In particular to find out if stars present a FIP effect, as in the Sun (for a recent review of solar coronal abundances see Raymond et al., 2001). Given two elements X_1 and X_2, the ratio of the observed intensities can be written:

$$\frac{I_1}{I_2} = \frac{A_b(X_1) \int_T C_1(T, N_e) \; DEM(T) \; dT}{A_b(X_2) \int_T C_2(T, N_e) \; DEM(T) \; dT} \tag{4}$$

from which *in principle* the relative element abundance $A_b(X_1)/A_b(X_2)$ can be deduced from the observed intensity ratio $I_{\rm ob}(1)/I_{\rm ob}(2)$.

In reality, aside from the various assumptions that have already been made, *many factors affect the determination of the element abundances* (see Mason, 1992; Phillips, 1997; Young and Mason 1998; Del Zanna, 1999; Del Zanna, Bromage and Mason 2001). The factors listed below can each account for a large variation (of a factor of 2-3) in the derived elemental abundances, that is of the order of the FIP effect that we want to measure. The problems summarised here are general, that is are not instrument dependent, since we found them in Skylab, SOHO, HST and other data.

1. *Commonly used diagnostic methods are:*

   (a) Pottasch (1963) approximation. An averaged value of C(T) is extracted from the integral.

   $$I_{\rm ob} = A_b(X) \; < C(T) > \; < \int_h N_e N_H dh > \tag{5}$$

   (b) Widing and Feldman (1989) approximation. An averaged value of the DEM is extracted for each spectral line.

   $$I_{\rm ob} = A_b(X) \; < DEM(T) > \int_T C(T) \; dT \tag{6}$$

   A continuous sequence of the $A_b(Z) < EM(T) >$ or $A_b(Z) < DEM(T) >$ values, plotted at $T_{\rm max}$ (and not an effective T), are used. 'Erroneous' results can be obtained when the emissivity $C(T) \; DEM(T)$ of a line peaks at temperatures where the DEM gradient is non-negligible (Del Zanna, Bromage and Mason 2001).

2. *The selection (or paucity) of spectral lines.*

   In the past, only a limited number of lines of few isoelectronic sequences were used. Some lines present anomalous behaviour in emission measure analyses. For example, those of the Li-like and Na-like ions (see Burton et al., 1971, Dupree, 1972, OSO-IV, Judge et al., 1995, Del Zanna, 1999).

Most lines are *underestimated or overestimated by factors ranging from 2 to 10*. These discrepancies cannot be ascribed to element abundance anomalies. Indeed these lines should not be used for DEM or elemental abundance analyses. More details can be found in Del Zanna, Landini, & Mason (2001).

3. *The assumption of ionization equilibrium and the ionization balance.*

   Del Zanna (1999) presented a comparison between different ionization equilibrium calculations applied to SOHO/CDS observations of a simple quasi-isothermal region. Large differences were found. Example: Ca IX and Ca X, factor of 3 difference using Mazzotta et al. (1998), as suggested by Young and Mason (1998).

Other important effects are the instrument calibration and those related to the use of density-dependent lines.

4. Atomic data for the XUV

One of the main challenges is to provide an accurate and complete atomic database to be used for diagnostics in the XUV. CHIANTI is a collaborative project involving the Naval Research Laboratory (Washington DC, USA), the Arcetri Observatory (Firenze, Italy), and the Cambridge University (United Kingdom). The database contains the most up-to-date atomic data (energy levels, A-values, electron collisional excitation rates, etc). The available atomic data are assessed before they are entered into the database. Complete references to the original calculations are given. The CHIANTI database and related software for plasma diagnostics are freely available:

- via WWW, e.g. (DAMTP, University of Cambridge, UK):

  http://www.damtp.cam.ac.uk/user/astro/chianti/chianti.html

The database (CHIANTI version 3) has recently been extended in the 1 - 50 Å wavelength region (Paper IV: Dere et al., 2001). The main new additions are the inclusion of emission lines from the hydrogen and helium isoelectronic sequences, innershell transitions and satellite lines. Many of the ions have been modified and improved with new atomic data.

The CHIANTI data are now included in many other spectral codes. For example, CHIANTI data are included in the Atomic Plasma Emission Database (APED, Smith et al., 2001), which in turn is included in various spectral analysis packages (XSPEC - general; CIAO and ISIS - specific for analysis of Chandra data). In such cases, it is important to remind the end user to cite the appropiate references, in particular those concerning the original atomic calculations. CHIANTI emissivities are also included in PintofALE (Kashyap & Drake 2000), an IDL-based software package for analysis of UV and X-ray spectra. The CHIANTI atomic data for electron excitation and radiative decays are also included in XSTAR (Bautista & Kallman, 2001), a package for modelling photoionised plasmas.

4.1. Comparison of CHIANTI data with observed solar and stellar spectra in the 1–50 Å range

There are very few published high resolution solar spectra that cover the 1-50 Å range and that can be used to benchmark the most recent atomic data. Most of these spectra do not have an accurate intensity calibration and were recorded by scanning over a wavelength range during solar flares.

Most of the line identifications were based on wavelengths, and not on intensities. Paper IV includes a comparative list of CHIANTI predicted lines and the observed lines from all published high resolution solar spectra, mostly recorded by the SMM/FCS and SOLEX spectrometers. Here, we present results of a comparison between observed solar and stellar spectra and theoretical line intensities. For the solar spectra we have considered: a) a flare spectrum of 1979 June 10 recorded in the 8 – 23 Å region by the SOLEX (USAF P78-1) spectrometer, in $\simeq$ 85s (McKenzie et al., 1980 - the observed spectrum was reconstructed based on the published line intensities); b) a flare spectrum of 1980 August 25 recorded in the 5 – 19 Å region by the SMM/FCS in $\simeq$ 18m (Phillips et al., 1982). For the stellar spectra, we have considered Chandra/HETG observations of Capella. Here, a composite of the publicly available spectra (D. Huenemoerder, priv. comm.) has been used.

The model adopted for producing the theoretical spectra includes: CHIANTI version 3.01; the photospheric abundances of Grevesse and Sauval (1998); the ionization equilibrium of Mazzotta et al. (1998); a constant density of 10^{11} and 10^{12} (cm^{-3}) for the solar spectra, and a constant pressure of 10^{16} (cm^{-3} K) for the Capella spectrum. A differential emission measure analysis (Del Zanna, 1999) was performed, and synthetic spectra constructed convolving the line intensities with gaussian profiles, as a first approximation. Figure 1 shows an example.

5. Conclusion

- A large body of work in terms of stellar outer atmospheres should be revisited with the appropiate spectroscopic diagnostics, now that more accurate atomic and observational data are available. We should learn from the long-term experience of plasma diagnostic for the solar corona before performing detailed studies of the stellar coronae.

- The X-ray wavelength region is relatively *unexplored.* Much work is still required in order to have more accurate line identifications. For this, high-resolution, high S/N well calibrated spectra are needed.

- We have to understand the high spectral resolution X-ray spectra, before considering the interpretation of low-resolution spectra, that represent the majority of data taken by Chandra and XMM.

Acknowledgments. G. Del Zanna and H.E. Mason acknowledge support from PPARC.

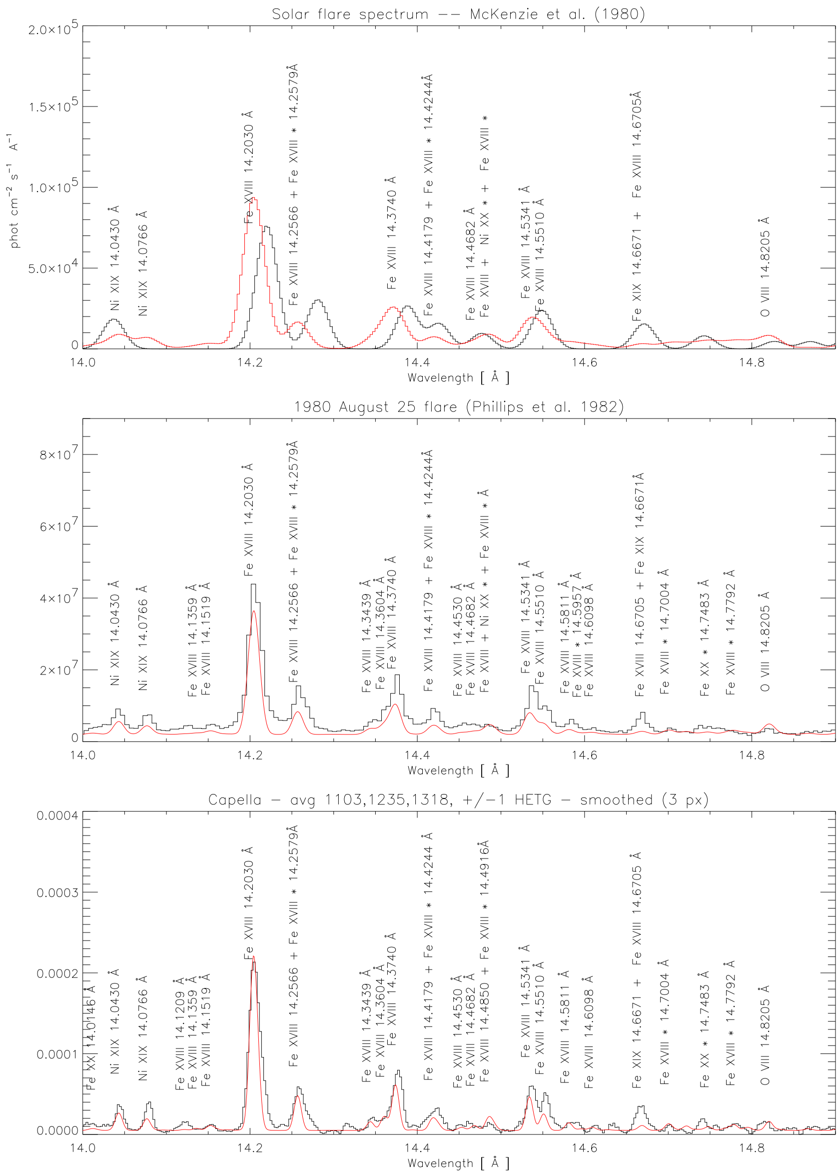

Figure 1. A comparison between observed solar and stellar high-resolution X-ray spectra, and synthetic spectra calculated with the CHIANTI emissivities. Note that the McKenzie et al. (1980) spectrum did not have a very accurate wavelength calibration. The lines indicated with an asterisk only have theoretical energy levels.

References

Bautista, M.A., & Kallman, T.R., 2001, ApJS, 134, 139

Burton, W. M., Jordan, C., Ridgeley, A., & Wilson, R. 1971, Phil. Trans. Roy. Soc. Lon. A, 270, 81

Craig, I. J. D. & Brown, J. C. 1986, Inverse problems in astronomy: A guide to inversion strategies for remotely sensed data, Adam Hilger eds.

Del Zanna, G., Landini, M., Mason, H. E., 2001, A&A, submitted

Del Zanna, G., Bromage, B. J. I., & Mason, H. E. 2001, Proc. SOHO-ACE workshop, in press

Del Zanna, G., Bromage, B. J. I., Landi, E., & Landini, M., 2001, A&A, in press

Del Zanna, G. and B.J.I. Bromage, 1999, Space Science Reviews, 87, 169

Del Zanna, G. 1999, PhD thesis, Univ. of Central Lancashire, UK

Dere, K. P., Landi, E., Mason, H. E., Monsignori Fossi, B. C., & Young, P. R. 1997, A&AS, 125, 149

Dere, K. P., Landi, E., Young, P. R., & Del Zanna, G. 2001, ApJS, 134, 331

Dupree, A. K. 1972, ApJ, 178, 527

Grevesse, N. & Sauval, A. J. 1998, Space Science Reviews, 85, 161

Judge, P. G., Woods, T. N., Brekke, P., & Rottman, G. J. 1995, ApJ, 455, L85

Kashyap, V. & Drake, J.J., 2000, BASI, 28, 475

Mason, H. E. & Monsignori Fossi, B. C. 1994, A&A Rev., 6, 123

Mason, H. E., 1992, Proc. of the First SOHO Workshop, pp. 297–304

Mazzotta, P., Mazzitelli, G., Colafrancesco, S., & Vittorio, N. 1998, A&AS, 133, 403

McKenzie, D.L., Landecker, P.B., Broussard, R.M., Rugge, H.R., Young, R.M., Feldman, U., & Doschek, G.A., 1980, ApJ, 241, 409

Phillips, K.J.H., Leibacher, J.W., Wolfson, C.J., Parkinson, J.H., Fawcett, B.C., Kent, B.J., Mason, H.E., Acton, L.W., Culhane, J.L., & Gabriel, A.H., 1982, ApJ, 256, 774

Pottasch, S. R., 1963, ApJ, 137, 945

Phillips, K. J. H., 1997, Adv. in Space Res., 20, 79

Raymond, J. C., et al., 2001, Proc. SOHO-ACE workshop, in press

Smith, R. K., Brickhouse, N. S., Liedahl, D. A. and Raymond, J. C., ApJL, 556, L91–L95

Widing, K. G., and Feldman, U., 1989, ApJ, 344, 1046

Young, P. R., and Mason, H. E., 1998, Space Science Reviews, 85, 315

Young, P.R., Landi, E. and Thomas R.J.,1998, A&A,329, 291