Astronomy & Astrophysics manuscript no. paper1 December 21, 2004
(DOI: will be inserted by hand later)

How hot are the coronae of active stars ?

G. Del Zanna*

MSSL, University College London, Holmbury St. Mary Dorking Surrey RH5 6NT UK

Received / Accepted

Abstract. X-ray spectroscopic diagnostics are currently applied to Chandra and XMM-Newton observations of active stars. Among them, emission measure (EM) techniques are used to obtain temperatures and chemical abundances. Here, direct temperature diagnostics involving L-shell Fe XXIV and Fe XXIII and He-like S XV emission are discussed and applied to observations of AR Lac. The direct measurements indicate the presence of an isothermal distribution with a temperature $\simeq$ 10 MK. These results are at odds with those obtained using EM techniques and standard ionization fractions, which suggest the presence of much hotter plasma.

Key words. Stars: coronae – Techniques: spectroscopic – X-rays:stars

1. Introduction

Astrophysics of stellar coronae is enjoying a golden age, with a wealth of X-ray spectroscopic observations with Chandra and XMM-Newton. For the first time, spectral diagnostic techniques previously only applied to the solar corona have been used in the recent literature. Among them, the most popular ones are density measurements using He-like ions, and emission measure (EM) or differential emission measure (DEM) techniques. EM or DEM techniques have been used to describe the temperature distribution of stellar coronae and to obtain estimates of chemical abundances. Among the main results from the Chandra and XMM-Newton observations of active stars are the fact that their quiescent coronae appear much hotter than the solar corona, and exhibit a large range of chemical abundances, different from the solar photospheric ones. All the different EM or DEM techniques adopted in the literature have some common assumptions. The main ones are that the plasma is static, multi-thermal, in ionization equilibrium, and the filling

Send offprint requests to:
G. Del Zanna (G.Del-Zanna@damtp.cam.ac.uk)
* Previous address: DAMTP, University of Cambridge, Cambridge CB3 0WA, UK

factors are the same for all the spectral lines. As discussed in Del Zanna (1999), there are various problems associated with emission measure techniques. For example, ions of the Li and Na isoelectronic sequences (which produce strong lines in the XUV) present anomalous emission measures, when compared to ions of other sequences. This effect has been sporadically noted in the solar physics literature for more than thirty years. Del Zanna (1999) and Del Zanna et al. (2001) used Skylab and SOHO data to show that this effect is present not only for lines formed at transition region temperatures (say T=0.2–0.7 MK), but also for coronal lines ($T \geq 1$ MK). Also, to show that this effect is more pronounced than previously thought (with intensities under- or over-estimated by factors of up to 10). Del Zanna et al. (2002) have later shown for the first time that this anomalous behavior also occurs in stellar transition regions, not only in the Sun. All previous emission measure results based on UV line intensities measured by IUE, HST-GHRS/STIS largely overestimated emission measures, electron densities (by an order of magnitude) and incorrectly derived chemical abundances.

It therefore makes sense to ask whether the emission measure techniques currently used to interpret Chandra and XMM-Newton data provide meaningful results. In particular, if emission measure techniques can reliably be used and if the coronae of active stars are as hot as it is currently believed. In fact, in most of the recent literature, large emission measures at temperatures well in excess of 30 MK have been reported. For example, high temperatures were found in: the young star Θ^1 Ori C, the hottest in the Trapezium (see Schulz et al. 2003); the RS Cvn stars σ^2 CrB (cf. Osten et al. 2003), AR Lac (cf. Huenemoerder et al. 2003), II Peg (cf. Huenemoerder et al. 2001), just to mention a few.

These high temperatures are at odds with one of the main results from X-ray diagnostic techniques applied to solar flares, that temperatures rarely exceed 20 MK, even for the largest flares (see, e.g. the review of Doschek 1990). This somewhat surprising result was obtained with the use of satellite lines in a way independent from any assumption on the ionization state of the plasma, and could be fundamentally related to the physical processes that heat the plasma in the first place. Much higher temperatures in other stars could therefore be related to different scenarios of energy release.

There are many reasons why EM techniques for the solar corona and stellar transition regions could break down. The most simple one is that the plasma is not in ionization equilibrium. The standard assumption is that electron densities are so high that ionization/recombination times are short (tens of seconds), compared to the other plasma characteristic times, so the plasma that emits the lines should be predominantly in ionization equilibrium. Note, however, that small departures can have a dramatic effect on line intensities (Bradshaw et al. 2004).

For solar flares, it has been possible to have some information on the spatial extent, densities, filling factors and characteristic times (e.g. related to flows) of the emitting plasma. Hence, to provide some estimates of ionization/recombination times, and to assess the validity of ionization equilibrium. Also, diagnostics involving comparisons between spectral lines formed by direct and inner-shell excitations have been used to check the ionization state of the flaring plasma and independently measure plasma temperatures (Doschek 1990). Departures from ionization equilibrium have been observed, but contradicting results have been obtained. In the stellar case the above details are not known, so it is possible that conditions occur where departures from ionization equilibrium are present. EM techniques can also break down if the plasma emission is predominantly isothermal. In this case, most spectral lines can be formed at temperatures largely different from those of the maximum ion abundance in ionization equilibrium. Obvious examples have been provided for solar coronal plumes and active region loops by Del Zanna et al. (2003) and Del Zanna (2003). Inaccurate results can also be obtained because the current ion fractions are not accurate. Large uncertainties in the calculated rates are well known. Significant variations due to the effects of high densities on dielectronic recombination and on the formation of metastable levels are also known but currently not taken into account properly. Indeed ionization fractions calculated in the low-density limit are normally used (Del Zanna et al. 2002).

It is also possible that the simple EM techniques are not appropriate for a highly structured, dynamic stellar atmosphere. Finally, further errors can be associated with the atomic data that are used, and line blending [the X-rays are still relatively un-explored]. Below, a direct method to measure temperatures for 'hot' plasmas is described and applied to one example case.

2. Method and atomic data

Measuring electron temperatures in a way that is independent from the assumption of ionization equilibrium is not a trivial task. There is a large body of literature on the use of satellites of the H- and He-like lines to obtain electron temperatures of solar or laboratory plasmas. These diagnostics have a great potential, but are beyond the capabilities of Chandra and XMM.

One viable alternative is to use the L-shell emission from Fe XXIV and Fe XXIII. This was previously known but only applied for the first time by Del Zanna (2004) and Del Zanna et al. (2004). The lines are optically-allowed and are much brighter than the satellite lines.

Fe XXIV and Fe XXIII L-shell emission is prominent in spectra of solar flares (see, e.g., Neupert et al. 1967). Chandra and XMM-Newton satellites have also shown that a large number of 'hot' astrophysical sources produce Fe XXIV and Fe XXIII L-shell emission ($n = 3, 4, 5 \rightarrow 2$) in the 6–13 Å range. Fe XXIV and Fe XXIII $n = 2 \rightarrow 2$ spectral lines fall instead in the EUV, and have been observed in solar flares (e.g. Kastner et al. 1974) and in EUVE spectra of stars (see, e.g. Monsignori Fossi et al. 1996).

Fe XXIII and Fe XXIV have a peak emission in ionization equilibrium at log $T \simeq$ 7.15,7.3, however there is no reason why Fe XXIII and Fe XXIV lines cannot be formed at different temperatures. In fact, they can be used to estimate plasma temperatures in the log T=7 – 7.5 range. Here, the Fe XXIII atomic data benchmarked by Del Zanna et al. (2004) are used. They included the new collision strengths for excitations to the $n = 2, 3, 4$ levels in Fe XXIII produced as part of the IRON Project by Chidichimo et al. (2004). For Fe XXIV, the atomic data benchmarked by Del Zanna (2004), which include the IRON Project collision strengths calculated by Berrington & Tully (1997) are used here. Note that blending with lines from different ions is often significant.

Transition probabilities (A_{ji} values) are used, together with the electron excitation data, to calculate the fractional population $N_j(N_e, T_e)$ of level j (relative to the total number density of the ion), as a function of electron temperature T_e and density N_e assuming collisional excitation and steady-state conditions. Collision strengths have been thermally-averaged assuming that the electrons have a Maxwellian distribution. Note that these two assumptions would break down if the processes that drive the formation of the lines are shorter than the level decay times (typically of the order of ps) and free electron relaxation times. Ionization and recombination effects occur normally on much longer timescales, hence in first approximation are decoupled from the excitation and de-excitation processes. The spectral line intensities, proportional to $N_j A_{ji}$, are compared to the observed intensities I_{ob}, by plotting the emissivity ratio values:

$$F_{ji}(N_e, T_e) = C \ \frac{I_{ob} N_e}{N_j(N_e, T_e)\ A_{ji}} \tag{1}$$

calculated at a fixed density $N_e = N_0$ as a function of the electron temperature T_e. The proportionality constant C is chosen for each dataset so that the emissivity ratios are close to unity. If agreement between theory and observations holds, the F_{ji} values for different spectral lines should overlap. If the curves cross at one temperature, then the plasma emission is isothermal, and the value directly gives the temperature of the plasma in a way that is independent from any assumption on the ionization state. Even in solar flares electron densities are significantly lower than the values ($\sim 10^{14}$ cm^{-3}) at which densities affect the Fe XXIII and Fe XXIV level populations. Therefore, the diagnostics are independent from the plasma density ($N_e = 10^{12}$ cm^{-3} is assumed here).

Another possibility, first shown by Gabriel & Jordan (1969), is to use the ratios of the intercombination (x+y) and forbidden (z) lines with the resonance lines in He-like ions. There is ample literature, but no applications to stellar observations yet. The diagnostics are more complex because of blending with the satellite lines, and the (small) dependence from the ion fractions and the density. S XV is an excellent example because at log $N_e < 14$ is in the low-density regime, and lines are quite resolved and bright.

Both ratios of the intercombination and forbidden lines with the resonance line are basically only temperature-dependent. Emissivities of S XV have been calculated using recent R-matrix calculations of Kimura et al. (2000), adding the contribution of the satellite lines, calculated with the CHIANTI 4.2 data [results are similar to those of previous calculations].

3. One example: AR Lac

Del Zanna et al. (2004) and Del Zanna (2004) provided some examples of the emissivity ratio technique applied to Chandra and EUVE observations of 'hot' stars. Results were not always consistent with those obtained with emission measure techniques.

As a further example, we consider here the excellent spectral data obtained by the Chandra and EUVE gratings on the RS CVn star AR Lac and described by Huenemoerder et al. (2003). The two satellites observed simultaneously AR Lac. We use here the averaged Chandra and EUVE line intensities published by Huenemoerder et al. (2003) [the EUVE intensities were corrected for interstellar H, He absorption]. Huenemoerder et al. performed a DEM analysis using the APED atomic data and the Mazzotta et al. (1998) ion fractions. The DEM analysis showed the presence of two peaks, at log T[K] $\simeq 6.9, 7.4$ (cf. Fig. 1). Only the highest-temperature peak is considered here. Note that most of the recent literature on RS Cvn or 'hot' stars shows similar distributions. Fig. 1 shows the EM loci curves (cf. Del Zanna et al. 2002 for definitions) obtained from a selection of lines, the atomic data in the CHIANTI[1] atomic database version 4 (Young et al. 2003), and two ion fractions, Mazzotta et al. (1998) and Arnaud & Rothenflug (1985). The lines selected are the brightest (un-blended) lines for Fe ions: 11.77 Å (Fe XXII); 11.74 Å (Fe XXIII); 11.17 Å (Fe XXIV). Four curves for the Fe XXV emission are also shown. Two only include Fe XXV emission, and two also include the satellite lines. Note that the contribution from the satellite lines is important, and that even at the highest Chandra HETG spectral resolution these lines are not resolved. A similar situation occurs for Fe XXVI, and is therefore not appropriate to use Fe XXV and Fe XXVI lines for EM analysis.

Fig. 1 shows that there is consistency between the EM loci curves (when the Mazzotta et al. ion fractions are used) and the T[K] $\simeq 7.4$ peak obtained by Huenemoerder et al. (2003). This also indicates that differences in the atomic data contained in CHIANTI and APED are not large (as discussed in Del Zanna 2002). It is worth noting the difference in the EM loci curves calculated with the Arnaud & Rothenflug (1985) ion fractions. Also, and more importantly, the large range of temperatures over which these Fe lines can be formed. This produces a large uncertainty in any EM method.

[1] http://www.chianti.rl.ac.uk/

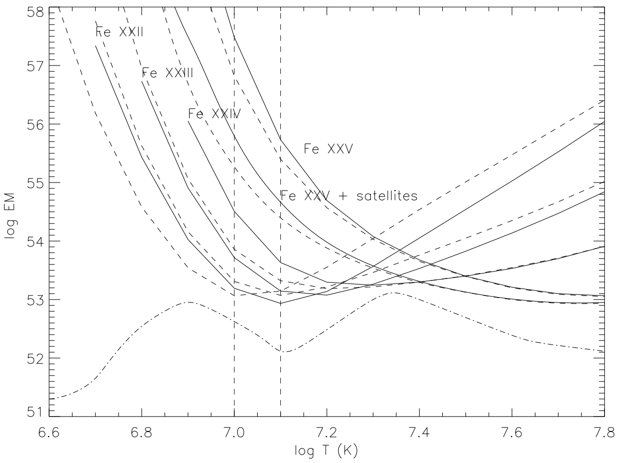

Fig. 1. The emission measure loci curves for a selection of lines, obtained with the Mazzotta et al. (1998) [full lines] and Arnaud & Rothenflug (1985) [dashed lines] ion fractions. Below [dot-dash curve], the DEM obtained by Huenemoerder et al. (2003) using the Mazzotta et al. (1998) tables.

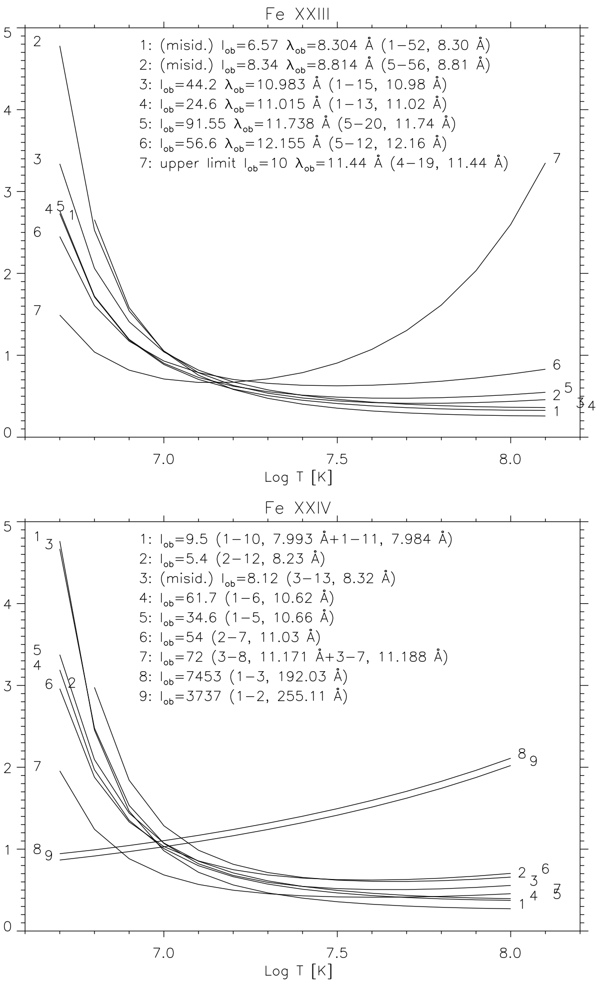

Fig. 2. The emissivity ratio curves relative to the $n = 2, 3, 4 \rightarrow 2$ Fe XXIII and Fe XXIV transitions

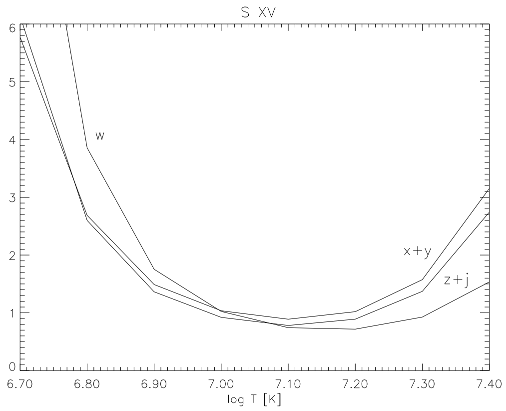

Fig. 3. The emissivity ratio curves for the S XV triplet, including the satellite lines.

On the other hand, the emissivity ratio curves for Fe XXIII and Fe XXIV, shown in Fig. 2, present a different picture. Both ions consistently indicate a much lower (and isothermal) temperature, log T[K]=7.0 $\pm$ 0.1. Note that three of the lines were incorrectly identified by Huenemoerder et al. (2003) [for a full description of the line blending see Del Zanna et al. (2004) and Del Zanna (2004)].

Fig. 3 shows the emissivity ratio curves for the S XV triplet, indicating log $T \simeq 7.0$, in good agreement with the Fe XXIII and Fe XXIV results. Note that the temperature of S XV maximum abundance in ionization equilibrium is log T= 6.85.

He-like Ar XVII could also be used. However, the forbidden line is blended with S XVI and S XV, and the signal-to-noise is much lower.

4. Summary and conclusions

L-shell ($n = 2, 3, 4, 5 \rightarrow 2$) Fe XXIII and Fe XXIV transitions are an excellent temperature diagnostic for 'hot' astrophysical plasmas, over a wide temperature range. These lines are relatively bright (compared to e.g. the satellite lines of the H- and He-like ions) and are easily observable by current and future instruments. Accurate temperature measurements that are independent from any assumption on the ionization state of the plasma can be obtained (obviously, values would still be spatial and temporal averages).

For AR Lac, Fe XXIII and Fe XXIV lines indicate an isothermal plasma distribution, with a temperature $T \simeq 10$ MK, at odds with the results that are obtained using current ionization equilibrium tables and standard EM techniques. The same temperature is obtained from the S XV lines. Del Zanna et al. (2004) and Del Zanna (2004) also found temperatures below 20 MK and some inconsistencies with EM results for the RS CVn stars σ^2 CrB, II Peg, and the young star Θ^1 Ori. These results question the use of current EM techniques to infer plasma temperature distributions (and indirectly chemical abundances). More detailed studies are needed before reaching some firm conclusions, however.

Analysis of 'hotter' emission (e.g. Fe XXV) is beyond the capabilities of Chandra and XMM. Although the presence of a small amount of 'hotter' plasma cannot be ruled out, it is tempting to extend to stellar plasmas the solar result, i.e. that the bulk of the emission has temperatures that do not exceed 20 MK. This could have important implications for our understanding of the plasma heating.

Acknowledgements. Support from PPARC is acknowledged.

References

Arnaud, M. & Rothenflug, R. 1985, A&AS, 60, 425

Berrington, K. A. & Tully, J. A. 1997, A&AS, 126, 105

Bradshaw, S. J., Del Zanna, G., & Mason, H. E. 2004, A&A, 425, 287

Chidichimo, M. C., Del Zanna, G., Mason, H. E., & et al. 2004, A&A, in press

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

—. 2002, proc. MSSL workshop on X-ray Spectroscopy

—. 2003, A&A, 406, L5

—. 2004, A&A, submitted

Del Zanna, G., Bromage, B. J. I., & Mason, H. E. 2001, AIP Conf. Proc. 598, 59

Del Zanna, G., Bromage, B. J. I., & Mason, H. E. 2003, A&A, 398, 743

Del Zanna, G., Chidichimo, M. C., & Mason, H. E. 2004, A&A, in press

Del Zanna, G., Landini, M., & Mason, H. E. 2002, A&A, 385, 968

Doschek, G. A. 1990, ApJS, 73, 117

Gabriel, A. H. & Jordan, C. 1969, MNRAS, 145, 241

Huenemoerder, D. P., Canizares, C. R., Drake, J. J., & Sanz-Forcada, J. 2003, ApJ, 595, 1131

Huenemoerder, D. P., Canizares, C. R., & Schulz, N. S. 2001, ApJ, 559, 1135

Kastner, S. O., Neupert, W. M., & Swartz, M. 1974, ApJ, 191, 261

Kimura, E., Nakazaki, S., Berrington, K. A., & Norrington, P. H. 2000, J Phys B, 33, 3449

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

Monsignori Fossi, B. C., Landini, M., Del Zanna, G., & Bowyer, S. 1996, ApJ, 466, 427

Neupert, W. M., Gates, W., Swartz, M., & Young, R. 1967, ApJ, 149, L79

Osten, R. A., Ayres, T. R., Brown, A., Linsky, J. L., & Krishnamurthi, A. 2003, ApJ, 582, 1073

Schulz, N. S., Canizares, C., Huenemoerder, D., & Tibbets, K. 2003, ApJ, 595, 365

Young, P. R., Del Zanna, G., Landi, E., et al. 2003, ApJS, 144, 135