Advances of plasma diagnostics with high-resolution spectroscopy of stellar coronae

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Abstract

X-ray emission from cool stars is an important tracer for stellar activity. The X-ray luminosity reflects different levels of activity and covers four orders of magnitude in stars of spectral types M-F. Low spectral resolution provided by X-ray observations of stellar coronae in the past allowed the determination of temperature distributions and elemental abundances making use of atomic databases (listing line emissivities and bremsstrahlung continuum for a given temperature structure). The new missions XMM-Newton and Chandra carry X-ray gratings providing sufficient spectral resolution to measure the fluxes of strategic emission lines. I describe the different approaches applicable to low-resolution and high-resolution spectra, especially focusing on the new grating spectra with X-ray lines. From only a few lines it is possible to determine plasma temperatures and associated densities, to check for any effects from resonant scattering, and to identify particular abundance anomalies. Line-based temperature- and density measurements represent only a fraction of the total plasma, but the pressure environment of different fractions can be probed simply by selection of specific lines. Selected results are presented covering all aspects of line-based analyses.

Key words: Stellar atmospheres, Stellar activity, Main-sequence: late-type stars
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1 Introduction

The term activity for the Sun and for late-type stars summarizes phenomena in the outer atmosphere. Important connections are known between sunspots (places where magnetic fields pierce the surface and suppress convection) and active regions in the corona (regions with particularly high temperature and strong X-ray emission). Also, the appearance of active regions is more frequent with solar maximum and the X-ray output exhibits the same cycle

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as the sunspots. The interface between the surface and the upper corona is the chromosphere, where Ca\textsc{ii} emission originates. The intensity of the Ca\textsc{ii} emission (measured in the middle of the Ca\textsc{ii} photospheric absorption line) sensitively reacts to changes in the solar activity cycle, and is at present (with few exceptions) the only tracer for stellar activity cycles.

It took severe efforts to actually discover the extreme physical properties of the solar corona (extremely high temperatures and very low densities). Measurements of the optical corona revealed that the spectrum is almost identical to the spectrum of the solar photosphere at all heights, suggesting scattering of photospheric light by electrons. Since most Fraunhofer lines could not be identified and the strongest lines were found smeared out, Grottrian [1931] concluded that the electrons must have extremely high mean velocities, which are not consistent with photospheric temperatures. However, only the identification of emission lines from highly ionized species led to the undoubted conclusion of the million degree corona (e.g., Edlén, 1943; Grottrian, 1939). This high temperature requires X-ray observations in order to directly look into the million degree plasma of stellar coronae; no contamination from the stellar photosphere needs be dealt with in this wavelength region. Past X-ray missions like Einstein and ROSAT were able to discover the ubiquitous occurrence of hot, tenuous coronae around late-type stars by detection of considerable X-ray luminosities for all late-type stars within the immediate neighborhood of the Sun (e.g., Schmitt, 1997). The X-ray luminosity is a classical activity indicator and a relation between the X-ray luminosity and the rotational velocity $v\sin i$ (Pallavicini et al., 1981) has been established. This suggests magnetic dynamo generation to be involved in the creation of stellar coronae and therefore also for the solar corona.

Common practice in analyzing X-ray spectra has been based on global fit approaches (see Sect. 2). With this method a general trend of plasma temperatures increasing with activity was found (e.g., Jordan and Montesinos, 1991). Since the causes of the heating phenomena have still today not been discovered, this is an important contribution towards a complete future understanding of the formation and heating of stellar coronae and the solar corona. In this spirit, the detailed physical description of stellar coronae is the next step in order to approach this aim. X-ray spectroscopy of the solar corona has been applied to measure temperatures and densities in specific active or quiescent regions. The solar corona was found to be essentially optically thin and the X-ray spectrum is thus dominated by emission lines. Important diagnostics tools have been developed, e.g., the density diagnostics with He-like triplets (Gabriel and Jordan, 1969). All these diagnostics can in principle also be applied to stellar coronae, however, very sensitive instruments are required in order to provide a decent S/N at the required spectral resolution. Also, the results have to be interpreted with the limitation that only average coronal properties can be obtained, because no spatial resolution is possible. The X-ray missions Chandra and XMM-Newton provide the ideal instrumental setup with their slitless grating spectrometers. With these gratings, spectra
have been obtained in the last four years which clearly confirmed that the X-ray spectra of stellar coronae are also dominated by emission lines originating from highly ionized atomic transitions. For more active stars continuum emission is found which is dominated by the bremsstrahlung mechanism (e.g., Ness et al. 2002). While the continuum can be used in order to obtain the plasma temperature of the hottest regions in the corona, the formation of each individual line reflects the physical conditions of the plasma regions emitting the respective lines. Since no individual emission region can be isolated in a stellar corona the line diagnostics will return averages of all visible emission regions, weighted with the brightness of each region. This limitation implies that only typical activity-related physical properties can be identified. When samples of stellar coronae are investigated, trends between coronal properties and stellar parameters can be found, uncovering the underlying physical processes.

This paper will give a review of coronal physical parameters that can be deduced from spectral line analysis. While in the past X-ray spectra did not have the power to measure individual lines, the new gratings aboard Chandra and XMM-Newton allow individual line fluxes to be measured for the first time. This requires new analytical approaches. In principle, a complete model spectrum can be synthesized from tables containing all our knowledge of the atomic physics (atomic databases) and be compared with measured spectra of any spectral resolution. This method (global fitting) will be limited by the quality of the spectrum (when applied to low-resolution spectra) or by the quality of the atomic database in use (when applied to high-resolution spectra). I will first describe how low-resolution spectra have been analyzed and what could be learnt and then address a number of aspects which have been deduced from the analysis of individual lines.

2 Analysis of low-resolution spectra

While the earliest X-ray missions allowed only the detection of the X-ray intensity in a broad energy band, more refined missions had some spectral resolution based on the energy-sensitivity of the detectors (CCDs, proportional counters). Although individual spectral features could not directly be seen a lot of useful information could still be obtained by convolving model spectra to the instrumental spectral resolution. These model spectra basically contain the relevant atomic physics and within a surprisingly good range the physical parameters could be optimized in order to find good agreement with the measured spectra.

In order to construct a model spectrum an atomic database is needed, which contains the information on the formation of lines induced by atomic transitions under the assumption of an optically thin plasma (i.e., only the production of photons is described, but no absorption; see also Sect. 3.1). Since the coronal plasma is in principle dominated by collisional ionizations and exci-
tations, it is sufficient for the modelling of stellar coronal spectra to assume the 'coronal' approximation. Going beyond this assumption would need more refined efforts.

The parameters put into a model are temperatures, emission measures, and elemental abundances. The temperature is the main parameter entering a spectral model. It will affect the ionization fraction and (along with the density) the population of the excited levels. Also the contribution of a continuum, which consists of bremsstrahlung, recombination, and two-photon continuum, depends on the temperature. Since nature does not provide isothermal plasma, a temperature distribution has to be assumed. This can be approximated by using, e.g., three isothermal components, which each carry a weighting factor in terms of an emission measure value (specifying the amount of emitting material in the corona at the given temperature). Three spectral models are then constructed and will be co-added for the final model. The number of temperature components can be chosen arbitrarily high, but including additional temperature components makes only sense when an improvement in agreement with the measurements can be accomplished. In contrast to a (generally low) number of isothermal components, a smooth temperature distribution can be assumed and optimized (e.g., Schmitt et al., 1990). The next physical parameter is a set of elemental abundances. All lines originating from ions of the same element are linearly scaled by the value of its abundance. In the models the elemental abundances and the temperature components are modelled simultaneously, but a sufficient number of lines must lie in the spectral region for sensible constraints on the abundance. Note, however, that changes in the elemental abundances will also affect the bremsstrahlung continuum, because in hot plasma, highly ionized metals will insert a considerable number of additional electrons. Within the ranges of abundances now typically found in stellar coronae the bremsstrahlung continuum changes only by a few percent for typical hot coronal temperatures.

With these spectral models it was possible to establish a temperature-activity relation (Jordan and Montesinos, 1991; Schmitt et al., 1990). Also, it was found that the hotter average temperatures in more active stars are mainly caused by an additional hotter temperature component, while only a slight shift of the cooler temperature component was noticed (Güdel et al., 1997). This can be explained by an increasing number of active regions with increasing activity as in the solar activity cycle.

The methods applied to model low-resolution spectra can in principle also be applied to high-resolution spectra (which show individual emission lines). However, the accuracy of the available atomic databases then imposes the major limitations, while the same method applied to low-resolution spectra was limited by the quality of the spectra. The improvement of the quality of the results has thus been pushed to the limits of the databases and further progress can only be made by improving the atomic data.

An alternative approach is to measure the line fluxes of strategically chosen individual lines and compute line fluxes reflecting specific physical aspects.
In the next section I will discuss some aspects which can be addressed by measurement of line fluxes and line flux ratios.

3 Analysis of high-resolution spectra

A high-resolution spectrum in the present context is defined as a spectrum which allows one to resolve a minimum number (at least five to ten) of individual emission lines. Taking the present X-ray missions this implies that the CCD spectra (ACIS-S, ACIS-I, EPIC-PN, and EPIC-MOS) are considered low-resolution spectra, while the grating spectra (LETGS, HETGS, and RGS) are considered high-resolution spectra.

The same methods applied to low-resolution spectra, especially the global fit approaches can just as well be applied to high-resolution spectra and the results gain accuracy from the improved spectral resolution, but not beyond the quality of the atomic databases. At the moment, the limitations of the results are determined by the quality of the databases alone. However, the quality of global fits can be improved further by excluding wavelength regions where there are high degrees of uncertainties in the databases by calculating the fit goodness parameter as demonstrated by Audard et al. (2003). With this approach one can avoid to a large extent misidentifications of measured line features belonging to lines not listed in the databases. In the latter case a global fit would seek physical conditions pulling up other line fluxes listed at nearby wavelengths, while line-based approaches would leave these features as unidentified, ignoring them for further interpretation.

The three X-ray gratings cover the wavelength ranges 1–40 Å (the LETGS goes up to 175 Å) with different spectral resolution and sensitivity. The strategic lines in this wavelength region are the H-like and He-like lines of Si, Mg, Ne, O, N, and C (altogether 24 lines). Also, a number of Fe L-shell and K-shell lines are measurable with these instruments. It is possible to obtain a large amount of information from these few lines without the use of global models, which use thousands of lines simultaneously.

For the interpretation of line fluxes and line ratios the same atomic databases must be used. The line-based analysis uses the strongest lines with the smallest uncertainties (constrained by both theoretical calculations and laboratory measurements), but these strong lines might also be blended with fainter lines from complicated ions, e.g., lines of Fe. The blending can be significant, e.g., for the Ne He-like lines (Ness et al., 2003a) and in these cases the limitations are essentially the same as in global models. Accounting for the blending lines is intrinsically implemented in the global fit approach, while a line-based approach has to carefully predict the blending lines.

3.1 Measurement of opacities

Before any analyses based on the information obtained from the atomic databases can be carried out, one has to assure that any measured photon rate
actually represents the photon production rates. In principle, photons produced in lower layers might be absorbed in higher layers and re-emitted into other directions (scattering). The solar corona is commonly assumed to be optically thin, however, the strongest resonance lines with high radiative excitation probabilities might place considerable absorption cross sections into the line of sight. Absorbed photons will be re-emitted, but not necessarily back into the line of sight and some photons will be re-emitted back to the stellar surface and are thus effectively lost. In all cases, with no balance of scattering out of the line of sight and into the line of sight (called "effectively optically thin"), these "resonant scattering" effects would significantly distort the measured line fluxes compared to those produced. This distortion can be modelled, but the modelling requires assumptions about the structure of the absorbing layers (e.g., spherical geometries) but coronal plasma can have extreme geometries (especially when active regions are involved), so the modelling would become extremely complicated. It is therefore common practice to neglect resonant scattering effects, but this can be tested. In principle one could easily see resonant scattering effects when comparing measured (affected) resonance lines with measured forbidden lines, which can be considered to be 100% thin. The ratio of a resonance line and a forbidden line can be compared with a corresponding theoretical ratio from the databases predicting optically thin fluxes. In order to eliminate any temperature- and abundance effects, the choice of lines should focus on lines of the same element and the same ionization stage. A prominent example is the ratio of two Fe xvii lines at 15Å and 15.27Å. The latter is a forbidden line (oscillator strength $f = 0.6$ in contrast to $f = 2.6$ for the 15Å line) and the ratio $\lambda 15.27/\lambda 15$ will increase with increasing opacity effects. Ness et al. (2003b) have compared a large number of stellar $\lambda 15.27/\lambda 15$ (and other) ratios with each other and found the measured ratios all higher than theoretical predictions for an optical thin plasma (suggestive of significant opacity effects). However, they found no systematic trend with activity yielding similar ratios for all stars in their sample. This means that the amount of emitting plasma has no effect on the line ratios, and so Ness et al. (2003b) concluded that the higher measured ratios rather imply erroneous theoretical ratios than identical optical depths for all kinds of stellar coronae. Testa et al. (2004b) analyzed the ratio Ly$_{\beta}$/Ly$_{\alpha}$ for the ions of oxygen and neon for a sample of stars, but found only two exceptions from the zero-optical depth scenario. However, their claims of unique first-time findings of resonant scattering effects in stellar coronae are confirmed by both ions only for one corona (IM Peg).

The general conclusion is that it appears to be reasonable to neglect resonant scattering effects in coronal plasma, but one has to check individual spectra.

3.2 Abundance anomalies

For coronae resembling the solar corona an abundance anomaly called The FIP effect was discovered with EUVE, Chandra, and XMM-Newton. This effect has
long been known from the solar corona and all elements with a first ionization potential (FIP) lower than 10 eV (∼ 1216 Å, which is the wavelength of the hydrogen Lyα line) are overabundant compared to photospheric abundances. The heating or transport mechanisms obviously prefer to deal with species, which are ionized (possibly by photoionization from Lyα line photons) which can then couple to magnetic fields. For many more active stars an inverse FIP effect has been found with XMM-Newton (e.g., Audard et al. 2003), which is puzzling. The detailed background to the FIP and inverse FIP effects are complicated, but a recent approach by Laming (2004) explains the fractionation quite naturally by ponderomotive forces arising as upward propagating Alfvén waves from the chromosphere transmit or reflect upon reaching the chromosphere-corona boundary.

While about half of these results have been determined by the use of global fits to high-resolution spectra, some methods have been developed to obtain elemental abundances using the specific advantages of measuring individual line fluxes (see summary in Güdel 2004). Schmitt and Ness (2004) developed a method using the H-like to He-like line ratios (see Sect. 3.3) to construct the temperature distribution independently of elemental abundances. All remaining discrepancies from a spectrum constructed from this temperature distribution then reflect abundance effects. Telleschi et al. (2005) compared global methods applied to limited spectral ranges containing bright lines (Audard et al. 2003) with a line-based approach, and found good agreement between these methods.

An interesting effect was discovered by Schmitt and Ness (2002). The lack of any carbon line in the Chandra LETGS spectrum of Algol raised suspicion of an abundance effect, since the nitrogen lines were well detected. Fig. 1 demonstrates that N v/nvi flux ratios greater than one cannot be explained by a temperature effect, but must be explained by abundance anomalies. This effect is well in line with expectations from stellar evolution. Since Algol is evolved, the anomalous abundance pattern reflects dredged-up CNO cycled material. All stars for which an enhanced N v/nvi ratio was detected are evolved stars, while the other stars show normal abundances, with α Cen and Procyon showing low ratios, probably due to low coronal temperatures.

3.3 Plasma temperatures

While the global fits allow one to obtain immediately a complete temperature distribution, individual lines can probe temperatures for specific regions of the temperature distribution. Again, a smart choice of line ratios allows one to eliminate other effects besides temperatures, e.g., elemental abundances. From the available strong lines the ratio of the H-like to one of the He-like triplet (r, i, f) lines (usually the resonance line r or the sum of all three lines) of the same element is temperature-sensitive due to the ionization balance. In hotter plasma the H-like line will be stronger while in cooler plasma the He-like lines dominate. The ratios can then be compared to theoretical predic-
Fig. 1. Predicted ratio of NVII/CVI at solar abundances as a function of temperature. Clearly, some extremely high measured ratios require increased nitrogen abundances.

Fig. 2 shows the theoretical predictions of H-like to He-like line ratios for different elements (see Schmitt and Ness, 2004). A steep increase of the ratios can be recognized indicating a very sensitive temperature diagnostic. In addition I include measured line flux ratios for different stars, and it can be seen that the stars selected have quite different temperature distributions. While Algol has systematically higher line ratios (indicative of higher temperatures), Procyon has only a high carbon H-like to He-like line ratio, while the Si lines are produced at higher temperatures than found in Procyon’s corona. These ratios provide a good starting point for constructing temperature distributions, where the ratios can be used as interpolation points. The shape of the emission measure distribution has to reproduce the measured line ratios, and no abundance effects interfere, because all line ratios are independent of the elemental abundances.

3.4 Densities

Density measurements are not possible with low-resolution spectra, because the effects from densities are too subtle to significantly affect a low-resolution spectrum. Therefore, no density analyses have been carried out for stellar X-ray coronae and structural information was only available from eclipsing sys-
tems, where one component is X-ray dark (e.g., for α CrB or Algol Güdel et al., 2003; Schmitt et al., 2003, estimated densities from the spatial distribution of intensity). From measurements of the emission measure EM, the total emitting volume $V$ can be inferred if densities $n_e$ are known by simply applying the relation $EM = 0.85n_e^2V$, which defines the volume emission measure; here, a homogeneous geometry is assumed. Densities are also needed in order to apply loop scaling laws (developed for the Sun) in order to investigate whether stellar coronae can be considered as scaled-up versions of solar active regions or whether new concepts have to be developed. Again, a geometry has to be assumed, e.g., a set of identical loop-like structures.

The measurement of densities from high-resolution spectra exploits the increasing number of collisions with increasing electron densities. In a low-density plasma transitions with low de-excitation probabilities (forbidden lines) will still show up. With increasing electron densities the upper levels of these transitions are increasingly subject to collisionally induced further excitations into higher levels with higher radiative de-excitation probabilities and those lines will show up instead. All density analyses are based on either measuring the appearance of the latter lines (e.g., Fe\textsuperscript{xxi} lines in EUVE spectra: Mason et al., 1979) or the disappearance of the former; or both (He-like triplets: Gabriel and Jordan, 1969).

The density measurements are carried out from line flux ratios in order to eliminate abundance and temperature effects. A number of Fe\textsuperscript{xxi} lines which are expected to show up in high-density plasma and an Fe\textsuperscript{xxi} resonance line
(at 128.73 Å) were measured with EUVE. The ratios of the fluxes in the former lines with those in the latter were analysed by Dupree et al. (1993), who reported extremely high densities for Capella, while, e.g., Schmitt et al. (1994) found no evidence at all for deviations from the low-density limits for Procyon. The difficulty with these diagnostics has been described by Ness et al. (2004). One can never say whether an emission feature at the expected wavelength of a density-sensitive line actually corresponds exactly to this line, or whether it comes from (an) unidentified line(s). Ness et al. (2004) investigated several Fe XXI line ratios for several stellar coronae using the LETGS (Chandra) and found not a single star with consistently high densities from all line ratios. Some ratios suggested higher densities (when believing the measured line fluxes to belong to the expected lines), but they were ruled out again by other line ratios, measured at the same time from the same ion (therefore formed in exactly the same environments).

Analyses of the He-like triplets measure the ratio of a forbidden line, f ($^3S_1$–$^1S_0$), versus an intercombination line, i ($^3P_1$–$^1S_0$), (f/i Gabriel and Jordan, 1969; Ness et al., 2004), where the f line will put its photons into the i line with increasing densities. The principle is the same for all He-like ions from different species, formed in different plasma regions with different temperatures. The Chandra and XMM-Newton gratings can measure the He-like triplet lines from Si XIII ($Z = 14$) down to C V ($Z = 6$) and plasma regions with temperatures ranging from 15 MK down to 1 MK can be probed, measuring densities in the range $10^9$–$10^{14}$ cm$^{-3}$. Those He-like triplets formed at high temperatures probe only high densities (above $10^{12}$ cm$^{-3}$), while low-temperature ions measure only lower densities ($\sim 10^{10}$ cm$^{-3}$); this leaves two cases unexplored: low densities in hot plasma and high densities in cool plasma. From the O VII measurements of stellar coronae the case of high densities at low temperature can be excluded, but the case of low densities at high temperatures remains unexplored.

4 Conclusions

The analysis of emission line fluxes from grating X-ray spectra is a powerful tool complementing global fit approaches. It is possible to survey the temperatures in different regions of the temperature distribution, identify abundance anomalies, recognize effects from resonant scattering, and measure densities. Some of these issues can only be addressed with emission line measurements, especially the densities. Ness et al. (2004) measured O VII and Ne IX densities and Testa et al. (2004a) measured the Mg XI densities, and the combined results suggest that all three ions originate from different pressure regions. Since the coronal structures implied (generally believed to be loop-like arches) usually do not extend higher than the pressure scale heights of the individual stars, each loop must have constant pressure, and the different pressures from the different density diagnostics thus imply that different classes of loops ex-
ist. The O\text{vii} loops are characterized by low pressures and low temperatures (thus small scale heights), and these loops are found to occur in stellar coronae in all stages of activity. In contrast to this, the Ne\text{ix} and the Mg\text{xi} loops have higher pressures (higher temperatures and higher densities) and occur with increasing number in more active stars (characterized by higher X-ray surface fluxes). It appears reasonable to conclude that a standard cool temperature corona always exists, while active regions containing hotter plasma are a privilege of the more active stars.

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