Plasma Thermal Structure and Metallicity of Stellar Coronae Observed with XMM/EPIC

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ABSTRACT

We present the results of extensive sets of simulations, performed to evaluate the diagnostic potential of the analysis of EPIC spectra.

1. Introduction

X-ray spectroscopy of "normal" (i.e. relatively quiet) late-type stars, like our Sun, is crucial to understand the basic processes in coronal plasmas, like magnetic heating and energy balance, the spatial scales of emerging magnetic fields (and hence of X-ray emitting coronal structures), the metal abundance anomalies and their role on radiative losses and hence on "equilibrium" plasma temperatures. On the other hand, the most intense (X-ray bright) coronal sources belong to the class of the "active binaries" (RS CVn-like, or Algol-like systems): while X-ray spectroscopy of these sources can be performed more easily, it is unclear whether the coronae of these extremely active stars can be interpreted extrapolating the solar paradigm.

XMM will provide simultaneous medium- and high-resolution X-ray spectra: in particular, EPIC CCD-based detectors will provide deep observations of the X-ray sky, over the 0.1-10 keV band, while the RGS will achieve much higher spectral resolution, but it will allow to obtain reasonably high S/N spectra only for a few "normal" coronal sources, because of its lower sensitivity and higher dispersion. Hence, the vast majority of the "normal" late-type stars will be studied only through EPIC spectra. We have estimated that EPIC spectra with 10^4 counts or more will be available for tens of stellar sources in young open clusters and associations and for nearby solar-type dwarfs, with typical exposure times of 50 ks.

2. Our approach: Spectral fitting simulations for XMM/EPIC

Parametric spectral fitting, already commonly adopted for the analysis of X-ray spectra taken with non-dispersive detectors, will be probably still appropriate for the analysis of EPIC spectra. However, a blind application of this approach may lead to biased results due to inappropriate source emission models, sometimes including more free parameters than required, and to cross-correlation among parameters of the model.

Since X-ray spectra of "normal" coronal sources may indeed be quite different, depending on the activity level (age) of the star, the plasma metallicity, and the complex distribution of magnetic coronal structures, simulations may help to understand which photon counting statistics are needed to discriminate between different emission models, and what improvement in diagnostics is to be expected with respect to previous missions.

We have performed several simulations assuming different input source spectra. Each simulation set is composed of 200 realizations, i.e. randomizations of the same parent (input) spectrum, and for each realization we have performed a χ^2 fitting of the simulated spectrum with one or more fitting models. Finally, we have computed median values of the best-fit model parameters, and the central 68% interquartile range, for each simulation set, as an estimate of the uncertainty at the 68% confidence level that would be derived from the analysis of real data.

2.1. Two-component isothermal source model

This is the simplest emission model, adopted in most cases for spectral fitting of ROSAT/PSPC, ASCA, and SAX spectra. The simulations allow us to investigate in the most simple, controlled way the issue of cross-correlation among model component parameters. The major drawback of using this fitting model is that it is difficult to interpret the model parameters in a physically sound way.

The simulation results show "intrinsic" uncertainties on best-fit parameters which increase for decreasing metallicity (Fig. 1). These uncertainties are due not only to photon counting statistics, but also to cross-correlation among different model components, e.g. the emission measure ratio vs. the metallicity (Fig. 2).

2.2. Two-component coronal loop model

This is a class of physically sound models, matured and tested in the solar context, which allow to interpret fitting results naturally in terms of coronal structures. Coronal loop models, like the one in Fig. 3), have been already adopted to fit ROSAT/PSPC spectra of solar-type stars (Ventura et al. 1998), and SAX spectra of dMe flare stars (Sciortino et al. 1998). It is worth to stress that coronal loop models do not always work, but when they work, the physical insight is certainly superior than that provided by multi-T models.

Our simulations show that correlations among model parameters are also present, but weaker than in the case of the 2-T models. Spectra with at least 10^4 total counts allow to discriminate easily 2-loop models and 2-T models, unless the "true" plasma metallicity is very low ($Z < 0.5$ solar). 3-T models may provide acceptable fits to 2-loop spectra, but the plasma metallicity would be underestimated (Fig. 4). However, 2-loop spectra with 3×10^4 total counts or more, from plasmas with solar abundances ($Z = 1$) can be easily discriminated from 3-T model spectra even if metallicity is a free parameter.

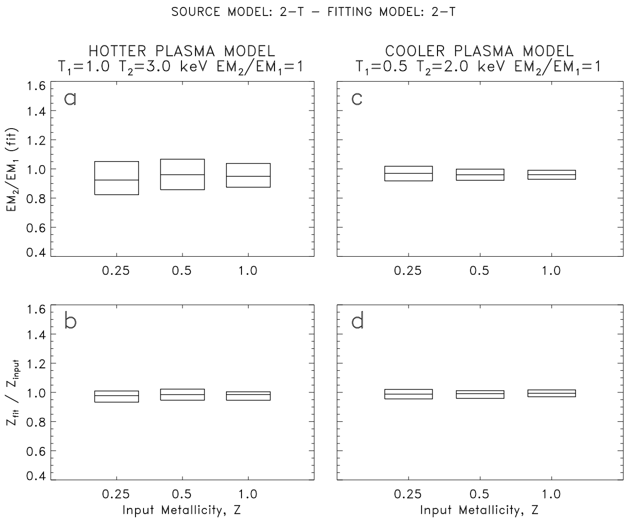

Fig. 1.— Results of simulations of 2-T EPIC/pn spectra with 3×10^4 total counts, assuming three different plasma metallicities (as indicated in the abscissae). Panels **a-b** refer to a source model having $T_1 = 1.0$ keV and $T_2 = 3.0$ keV ("hotter" model); panels **c-d** refer to a model having $T_1 = 0.5$ keV and $T_2 = 2.0$ keV ("cooler" model). In both cases the emission measure ratio is $EM_2/EM_1 = 1$. The fitting model is also a 2-T MEKAL model. The panels show boxplots of the fitted emission measure ratio (**a,c**), and of the ratio between the fitted metallicity and the input value, Z_{fit}/Z_{input} (**b,d**). In each box, the central horizontal line marks the median value of the parameter distribution, while the upper and lower edges indicate the central 68% interquartile range. **Note how this range, related to the 1σ uncertainty, increases for decreasing input metallicity and in going from the "cooler" to the "hotter" model.** We stress that the photon counting statistics is the same for all simulations. The uncertainties on the fitted metallicity and EM ratio are correlated (see Fig. 2).

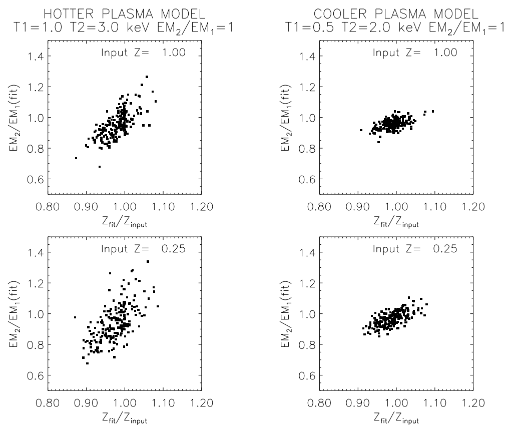

Fig. 2.— Scatter plots of the best-fit emission measure ratio vs. fitted metallicity, normalized to the input value. Four different simulations, selected among those in Fig. 1, are considered: The two panels on the left refer to the "hotter" source model, and the ones on the right to the "cooler" source model; two input metallicities have been assumed in turn, as indicated in each panel. **Note the correlation among the plotted parameters, and its dependence on the input source model: the spread is larger for decreasing input metallicity and in going from the "cooler" to the "hotter" model** (cf. Fig. 1).

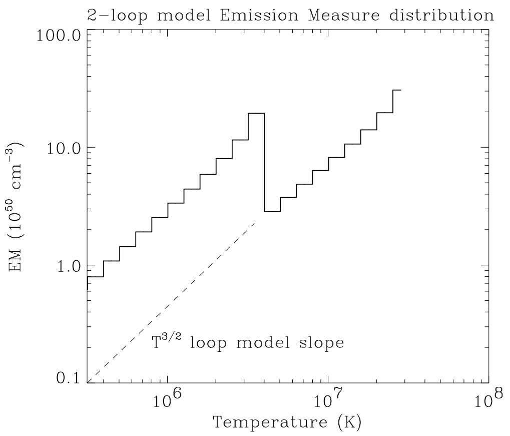

Fig. 3.— Emission measure distribution vs. temperature, EM(T), described by a coronal 2-loop model, whose components have maximum plasma temperature $T_{1max} = 0.36$ keV and $T_{2max} = 3.4$ keV, respectively, loop semi-lengths $L_1 = L_2 = 10^{-2} R_{\odot}$ cm, and the ratio of surface filling factors is $f_2/f_1 = 2.2 \times 10^{-4}$. This model has provided the best fit to the ROSAT/PSPC spectrum of the G9 IV star GJ 732.1 (Ventura et al. 1998), one of the most X-ray luminous ($L_{\rm x} = 5 \times 10^{29}$ erg s^{-1}) G-type stars within 25 pc from the Sun. **Note the characteristic slope, common to any static coronal loop with constant cross-section,** determined by the energy balance and by the hydrostatic equilibrium.

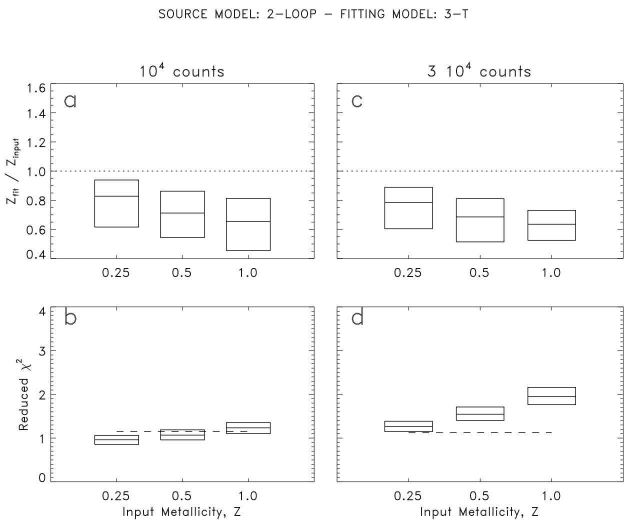

Fig. 4.— Results of simulations of 2-loop EPIC/pn spectra, assuming different plasma metallicities (as indicated in the abscissae). The two panels on the left refer to simulated source spectra having 10^4 total counts, while the panels on the right refer to simulations with 3×10^4 total counts. The same 2-loop model parameters (as in Fig. 3) have been assumed. The two panels in each column show boxplots of the ratio between the fitted metallicity and the input value, Z_{fit}/Z_{input} (**a**,**c**), and the reduced χ^2 values obtained adopting a three-component isothermal (3-T) fitting model. The dashed horizontal segments indicate the reduced χ^2 values at the 90% confidence level, with the number of degrees of freedom appropriate to each simulation. **Note how the fit quality becomes worse and worse for increasing input metallicity and/or total number of counts in the simulated spectrum. Note also that the fitted metallicity underestimate the "true" (input) value, systematically**. The latter effect is due to having adopted an inappropriate model for the fitting.

2.3. Source model spectra derived from emission measure distributions

EM distributions, e.g. derived from EUV emission line strengths, provide a more realistic description of the thermal structure of stellar coronae. Therefore they are a better starting point to simulate realistic X-ray spectra. We have performed two sets of simulations:

AR Lac, an example of a very active coronal source: Double-peaked EM distributions vs. temperature, are very common among very active coronal sources (Dupree 1996; Griffiths & Jordan, 1998). The EM distribution of AR Lac (Fig. 5) may not be typical of the less active “normal” stars, but steep rises and sharp peaks have been derived also in the EM distributions for young G-type stars.

The simulation results indicate that X-ray spectra simulated from plasma EM(T) distributions with a steep rise and a sharp peak may be fitted with 2-T or 3-T models, but not with models of coronal loops having constant cross-section (Fig. 8). Plasma metallicity can be underestimated if a 2-T model is adopted (Fig. 6).

The Sun, a prototype of a quiet coronal source: The solar corona near the maximum of solar cycle can be taken as the best example of a “normal” G-type coronal source in the solar neighborhood. EM(T) distributions over the temperature range $10^{5.5} - 10^{7}$ K (Fig. 7), recently derived from Yohkoh data (Peres et al. 1998), have been used to synthesize the X-ray spectrum as it would be observed by EPIC.

We found that the Sun-as-a-star X-ray spectrum can be best-fitted with 3-T models, but also 2-loop models provide an acceptable description (Fig. 8). In spite of the better fitting, the 3-T model allows no insight on the real nature of the coronal plasma emission, originating from a complex distribution of closed magnetic structures. Instead, the coronal loop model fitting yields loop characteristics similar to typical large-scale structures and active regions, observed in the solar corona.

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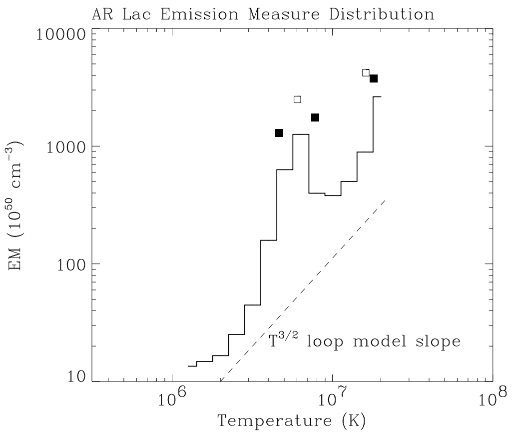

Fig. 5.— Emission measure distribution vs. temperature, EM(T), in the corona of the active binary AR Lac, derived from EUV emission line fluxes (Griffiths & Jordan 1998). Note the slope, steeper than predicted by static coronal loop models with constant cross-section, and the sharp peak. The empty squares are located at the temperatures and emission measure values derived from the best-fit 2-T model. The filled squares indicate analogous parameters obtained with a 3-T model.

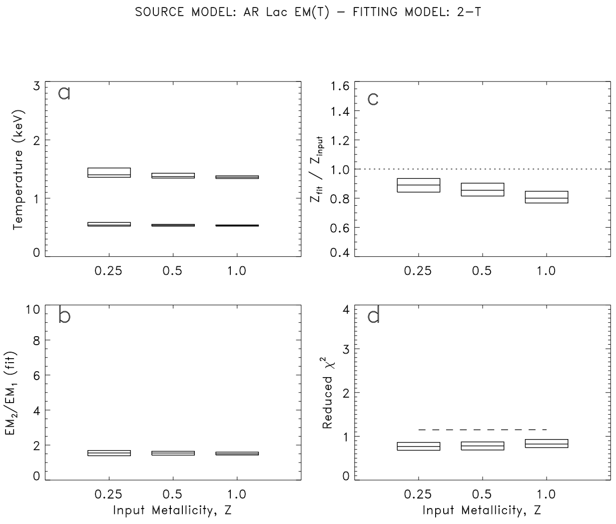

Fig. 6.— Results of simulations of EPIC/pn spectra with 10^4 total counts, synthesized from the EM(T) distribution of AR Lac, assuming different plasma metallicities (as indicated in the abscissae). The fitting model is a 2-T MEKAL model, in all cases. The four panels show boxplots of the fitted temperatures (**a**), the emission measure ratio (**b**), the ratio between the fitted metallicity and the input value (**c**), and the reduced χ^2 (**d**). In each box, the central horizontal line marks the median value of the parameter distribution, while the upper and lower edges indicate the central 68% interquartile range. **Note that the source metallicity is systematically underestimated as result of the fitting, in spite of its good quality (low χ^2 values), and this bias is more severe for higher values of the "true" (input) source metallicity.**

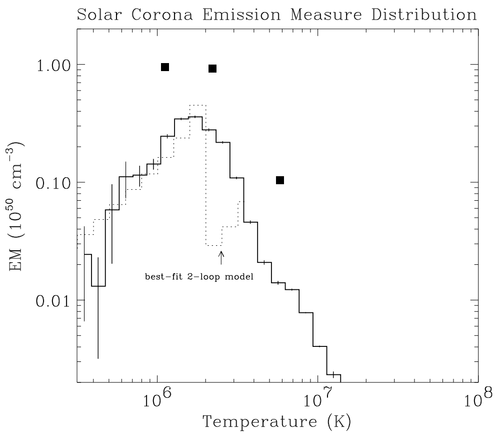

Fig. 7.— Emission measure distribution vs. temperature, EM(T), of the solar corona, derived from full-disk Yohkoh/SXT X–ray observations (Peres et al. 1998), taken on 6 Jan 1992, i.e. near the last maximum of the solar cycle. The filled squares are located at the temperatures and emission measure values derived from the best-fit 3-T model. A dot-line histogram shows the EM(T) distribution predicted by the best-fit 2-loop model, having maximum plasma temperatures $T_{1max} = 0.16$ keV and $T_{2max} = 0.38$ keV, loop semi-lengths $L_1 = 3 \times 10^8$ cm and $L_2 = 7 \times 10^8$ cm, and ratio of surface filling factors $f_2/f_1 = 2.1 \times 10^{-2}$. The resulting reduced χ^2 is 0.99 with 85 d.o.f.

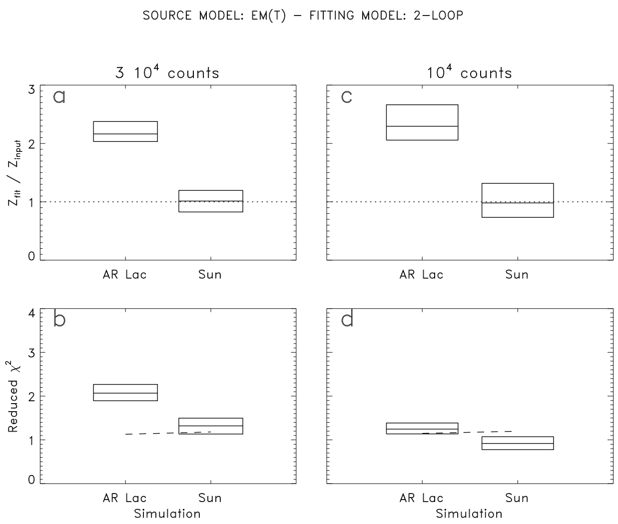

Fig. 8.— Comparison of the simulation results obtained for AR Lac and the Sun-as-a-Star. In both cases, the simulated EPIC/pn spectra have been synthesized from the observed EM(T) distributions, and fitted with 2-loop coronal models. Panels **a-b** refer to simulated spectra having 3×10^4 total counts, while panels **c-d** refer to simulations with 10^4 total counts. The panels show boxplots of the ratio between the fitted metallicity and the input value, Z_{fit}/Z_{input} (**a**,**c**), and of the reduced χ^2 values (**b**,**d**). The dashed horizontal segments indicate the reduced χ^2 values at the 90% confidence level, with the number of degrees of freedom appropriate to each simulation. **Note that 2-loop models provide acceptable fits to the Sun-as-a-star spectrum with 10^4 counts, and marginally also at 3×10^4 counts, while they are unable to provide satisfactory fits to the AR Lac spectrum: in fact, even in the case at 10^4 counts, where the fit quality is marginally acceptable, the source metallicity is largely overestimated.**