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# The coronae of bright late-type stars observed with EPIC and RGS

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**Abstract.** X-ray bright late-type stars have been selected as targets of *XMM-Newton* observations, with the aim to study in detail the plasma thermal distributions and chemical abundances of their coronae, and the characteristics of their X-ray emission variability. Both high-resolution spectra with RGS and high signal-to-noise medium-resolution EPIC spectra have been employed to this aim. I present some representative cases of such studies.

**Key words.** Stellar Coronae – X-Ray Activity – Coronal Abundances

## 1. Why bother with stellar coronae

Stellar coronae are interesting not only per se, but also in the broader context of stellar astrophysics, including the physics of star formation and evolution, as well as the physics of young planetary systems. Observations of the solar corona show that the X-ray emission arises from magnetically-confined structures where the trapped plasma is heated to temperatures of few million degrees; sometimes these structures undergo impulsive heating events which trigger X-ray flares of characteristic duration of $\sim$ 1 h. Observations of stellar coronae tell us that the integrated X-ray luminosity can be up to four orders of magnitude larger than in the solar case; a question still open is how coronal magnetic structures in active stars compare with the solar one, and what are the differences (if any) in the heating mechanisms. The spatial scales of the coronal magnetic structures and the fraction of surface they cover are determined by the characteristic sizes and strength of emerging magnetic fields, which are likely produced by shear motion of the plasma in the stellar interior. These same fields may influence the stellar structure (the convective efficiency, in particular) and hence the stellar evolution. Finally, young late-type stars emit X-rays copiously: this high-energy radiation may influence the ionization of the interstellar medium and hence the processes of star and planetary formation; ones the planets are formed, the same emission likely affects the chemistry of the young planetary atmospheres.

## 2. Relevance of EPIC observations

The high sensitivity of EPIC allows us to study the coronal emission of stars having different activity levels, including normal low-activity solar-type stars. EPIC is the right tool to fill the observational gap between the solar corona and the coronae of the most active late-type stars, which we were able to study already with

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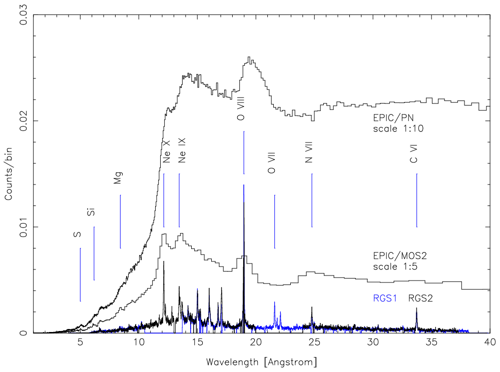


**Fig. 1.** EPIC and RGS spectra of AB Dor, observed in Jan 2001 for ∼ 50 ks. The PN spectrum was scaled by a factor 10, and the MOS spectrum by a factor 5.

past generation instruments. High sensitivity also means the possibility to perform time-resolved spectroscopy and variability analyses of dynamic events, like flares, with an unprecedented detail. Finally, the possibility to get long and/or repeated observations allows us to monitor stellar activity on a wide range of time scales, from minutes to years, and these observations allow us to study different phenomena such as the flare heating or the occurence of magnetic cycles.

In order to achieve the above goals some fundamental methodological issues need to be addressed. In particular, while high-resolution grating spectra allow us to detect and identify emission lines of different elements, and to make a detailed reconstruction of the plasma emission measure distribution and abundances, EPIC spectra are usually fitted using simple models with few isothermal components. In order to understand the limits of this modeling approach, we studyed in detail selected X-ray bright coronal sources, with the aim to compare results based on the analysis of EPIC and RGS spectra, and obtained independently. This check is crucial to interpret the results of our analysis for all the low-activity stars for which only EPIC spectra are available, i.e. for the vast majority of stars we can reach with *XMM-Newton* observations.

## 3. AB Doradus: a case study

Fig. 1 shows the EPIC and RGS spectra of AB Dor, a young active K dwarf which has been observed many times with *XMM-Newton* as a calibration target (Sanz-Forcada et al. 2003). This figure emphasizes some characteristics of EPIC spectra of coronal sources: they have high S/N ratio at long wavelengths, because the emission (thermal continuum + emission lines from an optically-thin plasma) suffers little interstellar absorption, in many cases; hence, the instrument calibration at $E <$ 0.6 keV is crucial to get reliable results from the spectral fitting. These kind of spectra are usually fitted with multi-component isothermal models including a number of element abundances as free parameters. Fig. 1 shows that most of the strongest emission lines, clearly visible in the RGS spectrum, are buried in the continuum when we consider the EPIC spectra. This is the case of the C VI and N VII Ly$\alpha$ lines, and of the O VII resonance line, while more evident features correspond to the O VIII and Ne X Ly$\alpha$ lines: in any case, these spectral features carry the information required to measure the CNO and Ne abundances, but a good calibration is necessary to this aim. At shorter wavelengths we also have the H-like and He-like complexes from heavier elements (Mg, Si, S, Ar) but the signal is relatively lower. By a detailed study of cases like the one of AB Dor we learned that some care must be exercised in the determination of C and N abundances, because of residual uncertainties in the EPIC calibration; other problematic abundances are those of minor elements like Al, Ca, Ni, and more in general elements having only weak lines in the spectrum. In spite of these limitations, we are now able to get consistent results from different instruments for the most abundant elements in stellar coronae, as shown in the following.

## 4. Selected results

### 4.1. Coronal abundances

Fig. 2 shows the element abundances in the coronae of two stars of similar mass but different evolutionary phases: the Hertzsprung gap

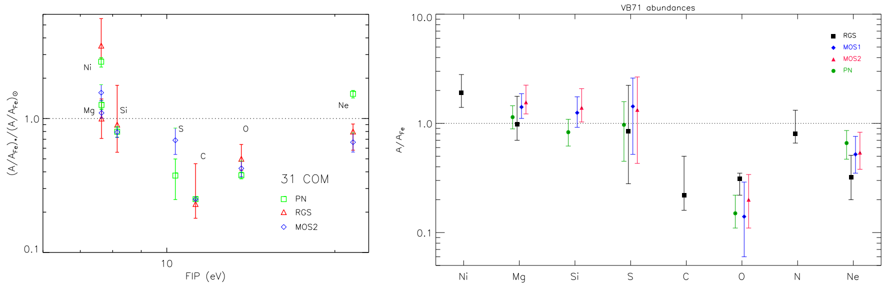


**Fig. 2.** Left panel: Abundances (relative to solar values) of 31 Com (G5 III) vs. First Ionization Potential, obtained from MOS2, PN, and RGS spectra (Scelsi et al. 2003). Right panel: Abundances vs. element (sorted by FIP) for $\theta^1$ Tau (K0 III); different symbols for RGS, MOS1, MOS2, and PN determinations (Franciosini et al., in preparation).

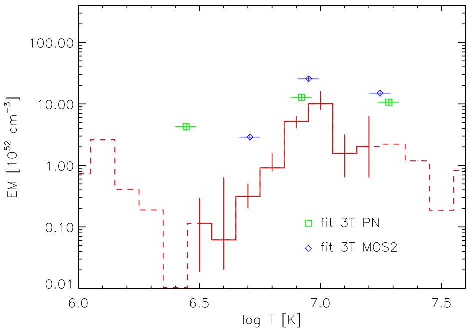


**Fig. 3.** Emission measure distribution vs. temperature (not constrained where dashed) for 31 Com, derived from the RGS spectra, compared with 3-temperature models best-fitting the MOS2 and PN spectra (Scelsi et al. 2003).

giant 31 Com (Scelsi et al. 2003), and the clump giant $\theta^1$ Tau in the Hyades open cluster (Franciosini et al. 2003). The abundances are sorted by First Ionization Potential (FIP) of the element, because in the solar corona the abundances of low-FIP (< 10 eV) elements are (on average) overabundant by about a factor 4 with respect to the photospheric values, due to a fractionation mechanism still poorly understood. Stellar coronae show abundance vs. FIP patterns very different one from the other, but some similarities also exist: at variance with the solar case, many active stars show a dip in the abundance pattern for mid-FIP elements (C and O for 31 Com and $\theta^1$ Tau, respectively) and they usually have relatively higher abundances of both low-FIP and high-FIP (Ne in particular) elements. $\theta^1$ Tau also shows evidence of relatively higher N abundance with respect to C and O, which appears consistent with the expected photospheric composition of a clump giant, due to deep convective mixing during the first ascent on the red giant branch. In conclusion, the observational evidences gathered up to date point toward the existence of several effects which concur to determine coronal abundances: the photospheric composition, the activity level, and a FIP-related fractionation mechanism in some (low-activity ?) cases.

### *4.2. Coronal thermal stratification*

Fig. 3 shows the plasma emission measure distribution (EMD) vs. temperature in the corona of 31 Com, derived from the analysis of the RGS spectra, compared with the 3-temperature best-fit models of the MOS and PN EPIC spectra (Scelsi et al. 2003). This comparison shows that EPIC multi-component thermal models indicate the correct temperature range of the coronal plasma in this star, but there is some inconsistency between the results obtained from MOS and PN for the low-T components, likely due to cross-calibration problems. Moreover, the spectral resolution of EPIC is simply not sufficient to the aim of deriving detailed EMDs for stellar coronae; in other words, the coronal thermal structure cannot be unambiguously guessed from multi-T models which fit EPIC spectra adequately.

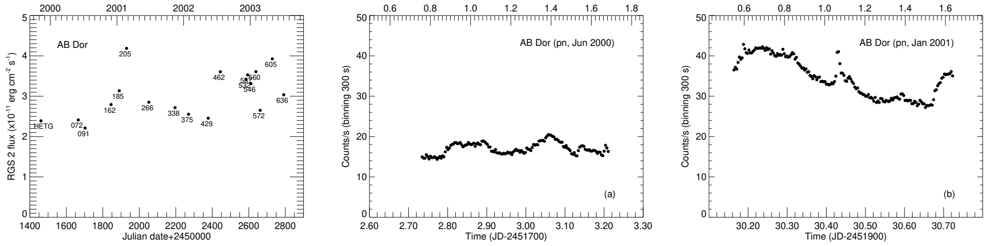


**Fig. 4.** X-ray variability of AB Dor over about 3 years (left panel), and during the observations #91 and #205 (center and right panels, with rotation phase indicated over the top X-axis), corresponding to the lowest and highest state recorded up to date (Sanz-Forcada et al. 2003).

**Fig. 5.** Prox Cen disk and flaring structure (top/right) vs. solar Bastille day flare (inset).

### *4.3. X-ray variability*

Fig. 4 shows the characteristics of short-term and long-term X-ray varibility of AB Dor (with respect to its rotational period $P_{\rm rot} \sim 13\,$h). Coronal sources like our Sun show variability on several time scales, due to different phenomena: flaring activity (minutes – hours), emergence and evolution of magnetic structures (hours - days), rotational modulation due to coronal spatial inhomogeneities ($P_{\rm rot}$), and magnetic cycles (years). We have started a detailed and comprehensive analysis of all the *XMM-Newton* observations of AB Dor (17 in the first 3 years), in order to answer several questions: do stars with coronae in saturated regime (i.e. reaching the treshold emission level $L_{\rm x}/L_{\rm bol} \sim 10^{-3}$) show rotational modulation (inhomogeneous coronae) ? Do they show activity cycles, and on what time scales ? Answering these questions will help to determine the time and spatial scales on which magnetic fields are produced, and it is a crucial step toward understanding the magnetic dynamo mechanism(s) in these stars.

### *4.4. Flares*

Fig. 5 shows schematically the result of one of the best studied flares up to date, occurred in Aug 2001 on Proxima Centauri (dM5.5e). With the help of a detailed hydrodynamic modeling, Reale et al. (2003) show that the observed X-ray light curve provides evidence of a series of triggered impulsive events occuring in sequence in adjacent magnetic structures. In spite of the striking difference in spatial scales and energy budget with respect to solar events, the morphology and time evolution of the flare in Prox Cen are similar to those of the class X6 "Bastille day" flare occured in the solar corona.

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