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Stellar Coronae with *XMM-Newton* RGS
I. Coronal Structure

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Abstract. First results from high-resolution coronal spectroscopy with the *XMM-Newton* Reflection Grating Spectrometers (RGS) are reviewed. Five stellar systems (HR 1099, Capella, Procyon, YY Gem, AB Dor) have been observed. The emphasis of the present paper is on overall coronal structure. Elemental abundances in *active stars* are found to be 'anomalous' in the sense that they tend to increase with increasing First Ionization Potential (FIP - i.e., signifying an inverse FIP effect). Coronal densities are measured at levels of a few times 10^{10} cm^{-3} for cooler plasma, although there are indications for very high densities in the hotter plasma components.

1. Introduction

High-resolution X-ray spectroscopy now available from *Chandra* and *XMM-Newton* has opened new access to coronal diagnostics. For the first time, densities, elemental abundances, the thermal structure, and mass motions can be measured explicitly based on atomic X-ray line diagnostics for a large number of

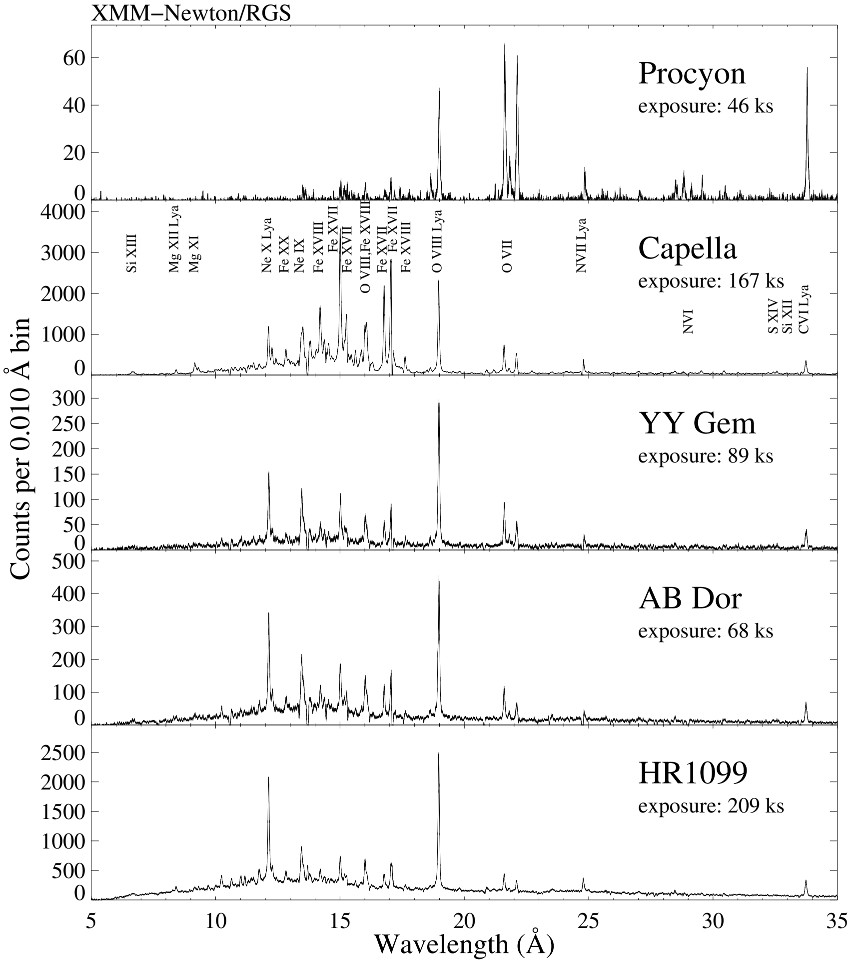

Figure 1. Five spectra observed with RGS, smoothed to 30 mÅ effective resolution. The average coronal temperature increases from Procyon (top), to Capella (2nd panel), YY Gem (3rd panel), AB Dor (4th panel) and HR 1099 (bottom).

sources. Such measurements are pivotal for our understanding of coronal structure, coronal heating, and mass transfer from the lower layers into the corona.

The two Reflection Grating Spectrometers (Brinkman et al., this volume) onboard *XMM-Newton* (Jansen et al., this volume) have started their mission with the First-Light target HR 1099 and later continued to obtain deep X-ray spectra of various coronal sources for an extended survey of coronal activity. We report here a first summary of results (see also Audard et al., this volume).

2. RGS Spectra and Thermal Structure

Stars of higher activity level reveal coronae of higher average temperature. This simple correlation (see, e.g., Güdel, Guinan, & Skinner 1997) has defied a con-

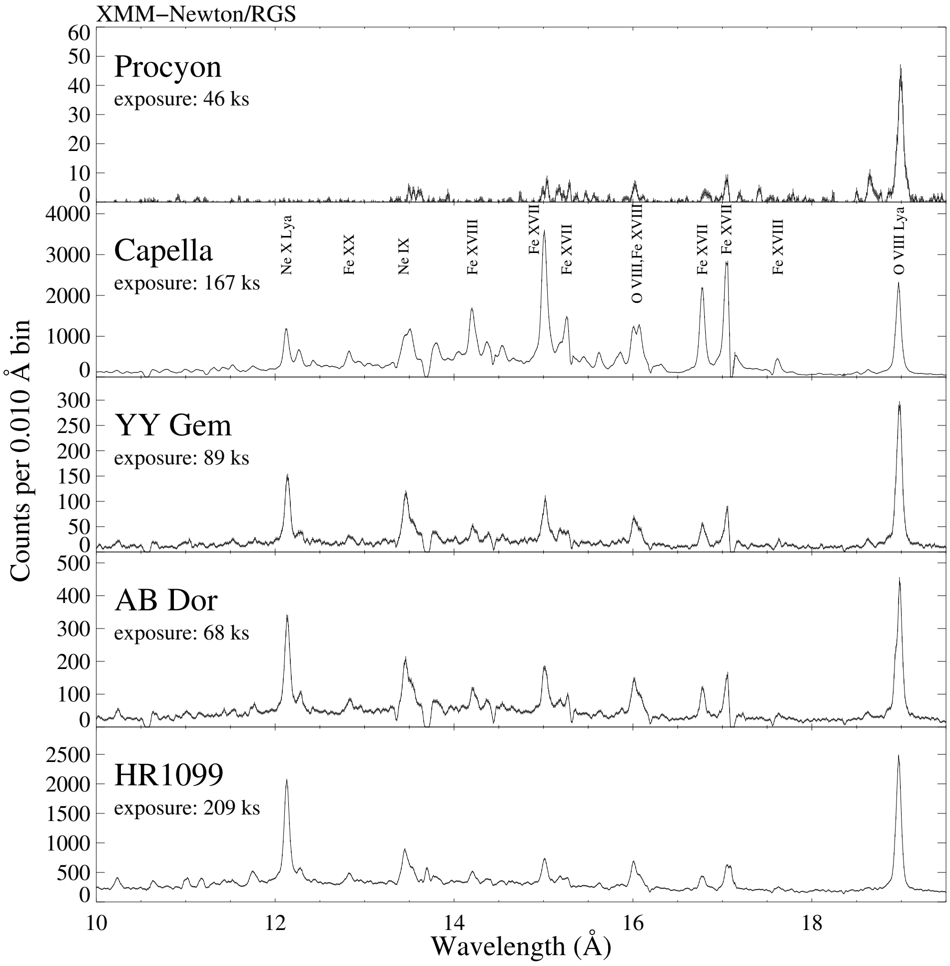

Figure 2. Extract from Fig. 1, showing the Fe L-shell region, together with lines of Ne and O.

clusive physical explanation, although models involving higher average but quiescent heating rate (Schrijver, Mewe, & Walter 1984) or higher "micro"-flare rate (Güdel et al. 1997) have been discussed in the literature.

RGS spectroscopy explicitly reveals differences in the thermal structure through atomic lines. Figures 1 and 2 show spectra of five sources (Procyon, Capella, YY Gem, AB Dor, and HR 1099 in order of increasing 'activity' or average temperature). The increasing relative importance of the continuum toward higher activity is evident (note that much of Capella's 'pseudo-continuum' around 15 Å is due to overlapping scattering line wings). The rather cool 'solar-like' corona of Procyon reveals only weak Fe lines, while the spectrum is dominated by lines of C V, N VI, N VII, and O VII, formed around 1–2 MK. A further evident temperature diagnostic is given by the flux ratio between the O VIII Lyα line at 18.97 Å and the O VII resonance line at 21.6 Å; clearly, this ratio systematically increases from Procyon to HR 1099.

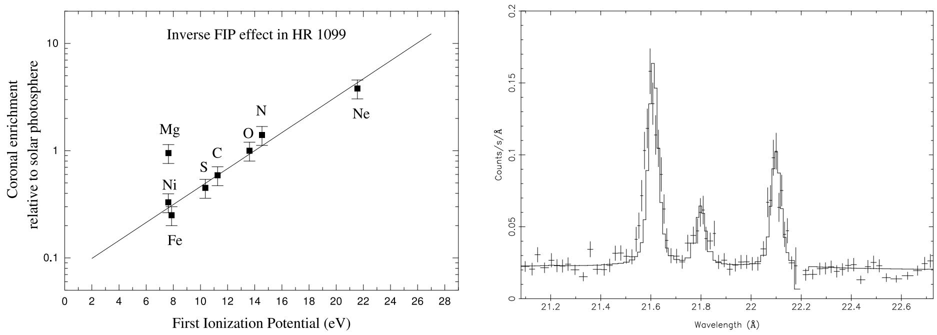

Figure 3. **Left:** Coronal abundances derived for HR 1099 from *XMM-Newton* RGS data, relative to solar photospheric, as a function of FIP and normalized to the oxygen abundance. Note the inverse FIP effect (Brinkman et al. 2001). - **Right:** Density-sensitive He-like line triplet of O VII, measured from the quiescent AB Dor. The three lines are, for increasing wavelength, the resonance, the intercombination, and the forbidden line. The best-fit density is $(3 \pm 1.5) \times 10^{10}$ cm^{-3} (Güdel et al. 2001a).

3. Elemental Abundances

Coronal elemental abundances are known to deviate from photospheric abundances in the Sun (Meyer 1985; Feldman et al. 1992) such that elements with a low First Ionization Potential (FIP, below 10 eV) are overabundant by an average factor of $\sim$4 (Feldman et al. 1992). Various scenarios for the related fractionation process have been proposed, involving magnetic and electric fields (e.g., Hénoux 1995 for a review). It came therefore as a surprise when the coronal abundances of *active* stars did not show evidence for clear FIP dependencies but rather showed that most elements are *depleted* in the corona (Antunes et al. 1994; Drake 1996; White 1996).

Elemental abundances can now unambiguously be determined from separated lines in the X-rays. Fig. 3a shows the surprising result (Brinkman et al. 2001) from the RGS spectrum of HR 1099 (Fig. 1): the relative abundances (normalized to oxygen) *increase* with increasing FIP, in a nearly exponential fashion, with Ne showing an unusually high abundance evident in the very strong Ne X line at 12.1 Å in Fig. 1. There is as of yet no consistent model for this *inverse FIP effect*, but Brinkman et al. (2001) suggest that mechanisms analogous to solar Ne- and S-rich flares may enrich the corona with high-FIP species. Similar results are reported for the other two active sources YY Gem and AB Dor (Güdel et al. 2001ab).

4. Geometric Structure and Densities

X-ray coronal structure is inferred indirectly, based on eclipse mapping, rotational modulation, or density measurements. The latter approach is available in the RGS range based on the He-like density-sensitive triplets of N VI,

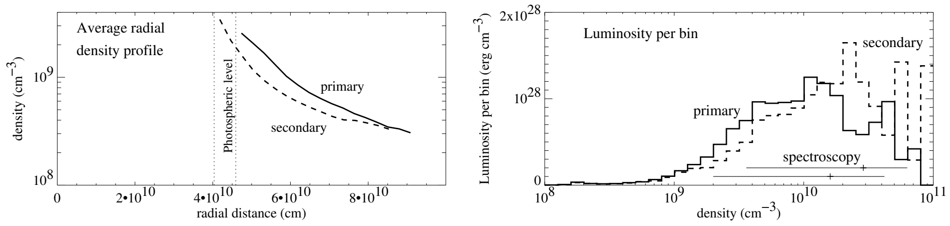

Figure 4. Coronal modeling from light curve inversion of the eclipsing binary YY Gem. **Left:** Average radial density profile for each component. **Right:** Luminosity contribution as a function of density. The bars at the bottom indicate the spectroscopically measured electron densities from RGS data (two methods, see Güdel et al. 2001b).

O VII, Ne IX, Mg XI, and Si XIII. Fig. 3b shows an example of the O VII triplet of the quiescent AB Dor. Best-fit measurements indicate a density of $(3 \pm 1.5) \times 10^{10}$ cm^{-3}, quite high by solar standards (but possible in solar active regions). This density value refers to relatively cool material (T of a few MK). However, heavier elements such as Mg tentatively indicate much higher densities for hotter material, up to the order of 10^{12} cm^{-3} (Audard et al. 2001 for Capella). This bi-modal distribution of densities (cool material at low densities, hot material at higher densities) suggests the presence of separate loop structures, with low-lying, compact hot loops on the one hand and larger, cooler loops on the other hand (Mewe et al. 2001).

The luxury of binary stellar eclipses is rarely available, but when it is, the mutual eclipses can be used to infer the geometry of the X-ray corona. The dM1e active binary system YY Gem was extensively observed by *XMM-Newton* (Güdel et al. 2001b), including three deep eclipses. The eclipse light curves were used to reconstruct realisations of fitting geometric coronal models. It was found that the plasma is required to be relatively close to the star, with an average density scale height of $(1-4) \times 10^{10}$ cm (Fig. 4a), which is fully compatible with the spectroscopically measured T of 3$-$10 MK. Most of the detected X-ray light is then emitted from densities around several times 10^9 cm^{-3} to a few times 10^{10} cm^{-3} (Fig. 4b), and these values are again in gratifying agreement with spectroscopic results.

5. Summary and Conclusions

Stellar coronae have been compared with scaled-up versions of the solar corona although this analogy has clearly become doubtful. Not only are the X-ray luminosities of active stars orders of magnitude larger than the Sun's, but the thermal structure is also very different, ranging from cooler solar-like structures of a few MK (probably analogous to the Procyon corona) up to *non-flaring* coronal components at 20$-$30 MK. Spectroscopy clearly provides the necessary information for further study.

The most crucial results from this early *XMM-Newton* RGS stellar coronal survey set active stars apart from the Sun. Coronal elemental abundances, although known before to deviate from solar behavior, are now showing a clear systematic dependence on the FIP value, such that high-FIP elements (O, N, Ne) are largely overabundant compared to low-FIP elements (Fe, Mg, Si, Ni), thus defining an *inverse FIP effect*, contrary to the solar trends. The Sun does occasionally reveal Ne- and S-rich flares (i.e., high-FIP elements are enriched in the flaring plasma), and analogous processes may be responsible for the anomalously high Ne abundance seen in active stars.

Densities found so far for active stars are high for solar standards, even for relatively cool plasma. High densities in hot plasma, although still only marginally detected, have no solar analogy except for flares. Taken together, we speculate that the mechanisms for heating to high temperatures and for inverting the coronal abundance pattern are related, but unknown on the *non-flaring* Sun.

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References

Antunes, A., Nagase, F., & White, N. E. 1994, ApJ, 436, L83

Audard, M., Behar, E., Güdel, M., et al. 2001, A&A, 365, in press

Brinkman, A. C., Behar E., Güdel M., et al. 2001, A&A, 365, in press

Drake, S. A. 1996, in 6th Annual Astrophysics Conference, ed. S. S. Holt & G. Sonneborn (San Francisco: ASP) 215

Feldman, U., Mandelbaum, P., Seely, J.F., Doschek, G.A., & Gursky, H. 1992, ApJS, 81, 387

Güdel, M., Guinan, E. F., & Skinner, S. L. 1997, ApJ, 483, 947

Güdel, M., Audard, M., Briggs, K., et al. 2001a, A&A, 365, in press

Güdel, M., Audard, M., Magee, H., et al. 2001b, A&A, 365, in press

Hénoux, J.-C. 1995, Adv. Space Res., 15, 23

Mewe, R., Raassen, A. J. J., Drake, J. J., et al. 2001, A&A, submitted

Meyer, J.-P. 1985, ApJS, 57, 173

Schmelz, J. T. 1993, ApJ, 408, 373

Schrijver, C. J., Mewe, R., & Walter, F. M. 1984, A&A, 138, 258

White, N. E. 1996, in 9th Workshop on Cool Stars, Stellar Systems, and the Sun, eds. R. Pallavicini and A. K. Dupree (San Francisco: ASP), 193