*Proceedings of "X-ray Astronomy 2000", Palermo, Sep. 2000*
*ASP Conference Series, Vol. TBD (in press), 2001*
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# Stellar Coronae with *XMM-Newton* RGS II. X-ray Variability

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**Abstract.** First results from high-resolution coronal spectroscopy of flares with the Reflection Grating Spectrometers on board the *XMM-Newton* satellite are reviewed. Rotational modulation in the X-ray light curve of HR 1099 is discussed. Results from time-dependent spectroscopy of flares in the active stars HR 1099, AB Dor, YY Gem are also presented. Variations in the shape of the emission measure distributions, in the abundances and in the average density of the cool plasma are discussed.

## 1. Introduction

Stellar coronae often display variability in their X-ray emission. Energetic explosive events (flares), eclipses, and rotational modulation are among the most interesting features found in X-ray light curves of coronal stars. Flares are at the center of a scenario that assumes an ensemble of flares as agents of heating of stellar coronae ("microflare hypothesis"; e.g., Parker 1988). Recent results suggest that flares can contribute significantly to the coronal heating of active stars (Audard et al. 2000). In a standard model, magnetic energy is released

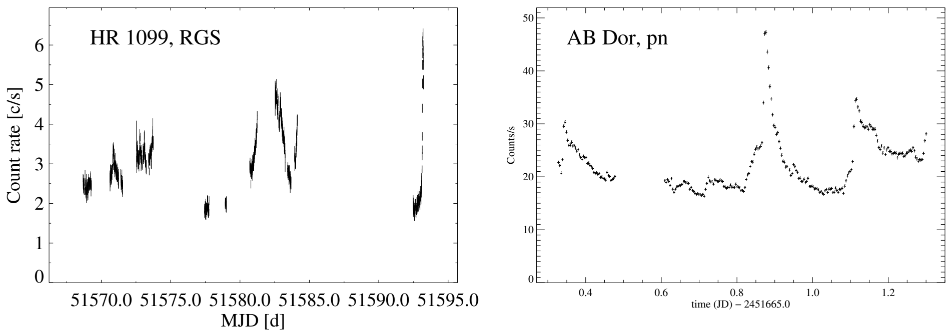


Figure 1. *Left*: Total 1st and 2nd order RGS light curve of HR 1099. *Right*: EPIC pn light curve of AB Dor (April 30/May 1).

during a flare, heating the dense layers of chromospheric material. Hot ionized material is then driven into the corona by the pressure increase and fills the coronal loops (chromospheric evaporation; see Antonucci et al. 1994). Optically thin X-ray radiation occurs through continuum processes and electronic transitions. Flares are therefore important agents that bring "fresh" material from the chromospheric layers to the corona.

In the non-flaring Sun, a First Ionization Potential (FIP) effect is observed, with enhanced coronal abundances for elements with low FIP ($<$ 10 eV), while high-FIP elements show solar photospheric values. In the stellar case, evidence for the presence of the FIP effect is less clear, but has been found in some stars (e.g., Drake et al. 1995; 1997). Recently, Brinkman et al. (2001) has found in HR 1099 evidence for an *inverse* FIP effect and a strong enhancement of Ne relative to O. Stellar coronal flares often show enhanced metal abundances (e.g., Ottmann & Schmitt 1996). Also, some classes of solar flares can be Ca-rich (Ca is a low-FIP element; Sylwester et al. 1984) or Ne and S-rich (Ne and S are high-FIP elements; Schmelz 1993).

In this paper, we report a summary of first results (see also Güdel et al., this volume) from studies of stellar flares with the *XMM-Newton* Reflection Grating Spectrometers (RGS). Recent observations include HR 1099, AB Dor, YY Gem/Castor (see Audard, Güdel, & Mewe 2001 and Güdel et al. 2001ab for more details).

## 2. X-ray rotational modulation in HR 1099

The RGS observed the RS CVn binary star HR 1099 (V711 Tau) for a time span of about 25 days (Fig. 1, left). The light curve shows variability on short and long time scales. Similar to previous results (Agrawal & Vaidya 1988; Drake et al. 1994), rotational modulation is suggested, with maximum flux when the more active star (K1 IV) is in front. Recently, Ayres et al. (2001) found consistency between line wavelength shifts and the orbital motion of the K component of HR 1099. Taken together, these observations suggest that one or several active regions are present on the hemisphere of the K star that is facing away from its companion (Audard et al. 2001).

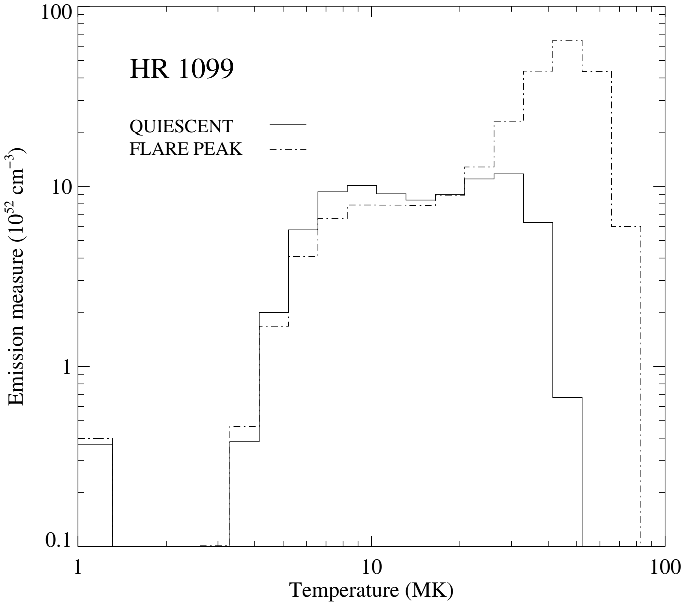


Figure 2. Realisations of the quiescent (solid) and flare peak (dot-dash) EM distributions for HR 1099 using Chebychev polynomials.

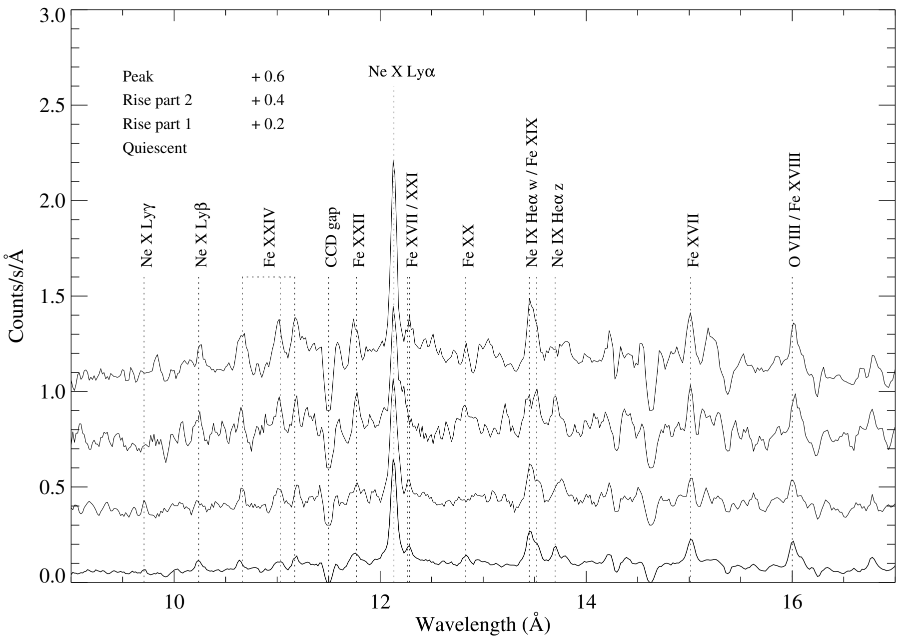


Figure 3. Extract from smoothed RGS spectra of the four time segments (lowest: quiescent; uppermost: flare peak). Note relative shifts of the spectra along the vertical axis.

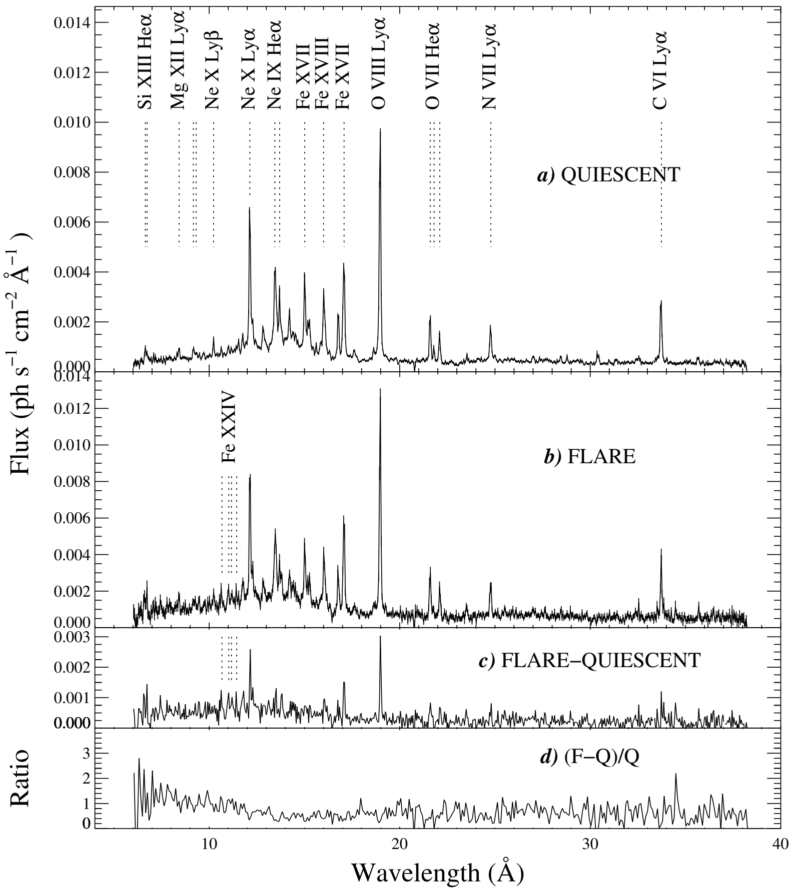


Figure 4. RGS fluxed spectrum of the **(a)** quiescent and **(b)** flaring AB Dor, **(c)** the difference spectrum, and **(d)** the ratio "(flare−quiescent)/quiescent". Data are binned to a resolution of 0.04375 Å for (a-c) and to 0.0875 Å for (d). Note different flux scales. The Fe XXIV lines and an excess continuum shortward of 10 Å are evident in (c) and (d).

## 3. RGS spectra of flares

Time-dependent spectroscopy has been performed on the flare data sets (HR 1099, AB Dor, YY Gem). We have first studied the quiescent emission measure (EM) distributions and found them to be continuous over a wide range of temperatures (e.g., Fig. 2). The EM of HR 1099, for example, drops to very low values below ≈5 MK. A small but significant EM is needed around 1–3 MK in order to explain "cool" lines such as the bright C VI Ly$\alpha$ line and the O VII triplet around 22 Å. Audard et al. (2001) further constrain the EM of Capella at the coolest temperatures using dielectronic recombination satellite lines of O VI. During the flare on HR 1099, the EM changes considerably but only at high temperatures, while the cooler plasma remains essentially unchanged,

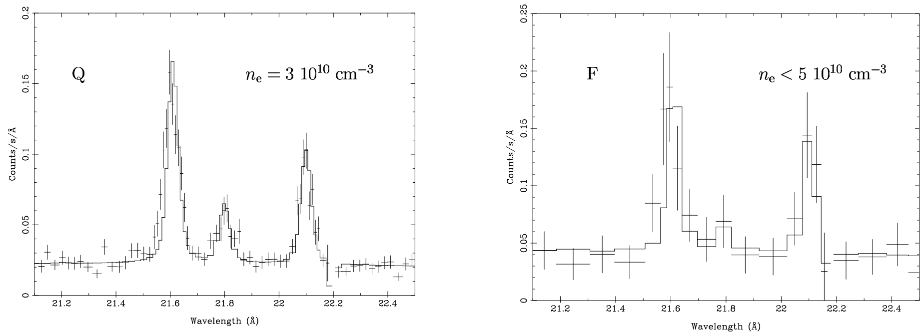


Figure 5. Density-sensitive line triplet of He-like O VII (resonance, intercombination, and forbidden line for increasing wavelength). Left panel shows best-fit (histogram) to RGS data (error bars) during AB Dor's quiescence, while right panel shows the triplet for data selected during flares.

indicating that the flare does not affect a major part of the corona (Fig. 2). Above 30 MK, however, a very significant EM component develops, with contributions from plasma up to about 90 MK (Fig. 2). During this strong heating, Fe XXIV lines become significantly enhanced (Fig. 3). The rapid flares on AB Dor (Fig. 1, right) show similar spectral features: strong Fe XXIV lines become apparent during the flares, and the continuum becomes enhanced shortward of 12 Å (Fig. 4).

## 4. Variable abundances

Elemental abundances vary significantly during the observed flares. The metal abundance during one of AB Dor's flare increases by a factor of $\approx$3 and decays back to its quiescent level (Güdel et al. 2001a). In the HR 1099 flare spectra, the Fe and Si elemental abundances increase by factors of $\approx$3, and 10 (despite large error bars, the latter abundance increases by a factor of 6 at least), respectively, while the Ne (high-FIP) abundance does *not* increase, staying constant at its quiescent level, within the confidence ranges (Audard et al. 2001).

## 5. Densities

The He-like O VII triplet around 22 Å provides insight into the *average* density of the "cool" plasma component (around 1–3 MK). Significant quiescent densities have been found in AB Dor ($n_e = [3 \pm 1.5] \times 10^{10}$ cm$^{-3}$; Güdel et al. 2001a), YY Gem ($n_e = 1.6^{+2.6}_{-1.4} \times 10^{10}$ cm$^{-3}$; Güdel et al. 2001b), while only upper limits can be derived for HR 1099 ($< 1 \times 10^{10}$ cm$^{-3}$; Audard et al. 2001) and Castor ($< 3 \times 10^{10}$ cm$^{-3}$; Güdel et al. 2001b). No appreciable change in the *average* density of the emitting *cooler* material has been found during flares (Fig. 5). Recalling Fig. 2, it implies that the flares predominantly affect hot material and have limited influence on the EM of the relatively cool plasma.

## 6. Summary and Conclusions

Flares are frequent in the stellar coronal sources observed so far by *XMM-Newton*. Large flares occurred on HR 1099, AB Dor, and YY Gem, allowing us to perform time-dependent spectroscopy with the high-resolution RGS in the range 5–35 Å (0.35–2.5 keV). The presence of very hot (up to several tens of MK) material has been inferred, and evidence for elemental abundance enhancements has been found. Low-FIP elements appear to increase significantly during a flare on HR 1099, while the high-FIP element Ne stays at constant abundance. This behaviour contrasts with the *inverse* FIP effect found in these coronae during quiescence. Our *XMM-Newton* observations thus indicate that flares are also important as agents that relate chromospheric/photospheric plasma with coronal plasma.

The flare EM distributions appear to be composed of a very hot plasma (up to 100 MK) that evolves rapidly, and of a stable quiescent plasma. This result is consistent with the absence of a change in the density of the cool material. Stellar flares are important probes for stellar coronal plasma and the coronal heating mechanism. The very high temperatures attained by these flares are unknown to solar flares. Such observations are important to extend solar knowledge to more extreme conditions appropriate for magnetically active stars.

**Acknowledgments.** We thank all XMM teams for their support in the evaluation of the present and related data. The PSI group is supported by the Swiss Academy of Natural Sciences and the Swiss National Science Foundation (grants 2100-049343 and 2000-058827). SRON is financially supported by the Netherlands Organization for Scientific Research (NWO). The Columbia University team acknowledges generous support from the National Aeronautics and Space Administration. MSSL acknowledges support from the Particle Physics and Astronomy Research Council. This work is based on observations obtained with XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA member states and the USA (NASA).

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