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A Systematic Spectroscopic X-Ray Study of Stellar Coronae with XMM-Newton: Early Results

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Abstract. We have been conducting a comprehensive survey of stellar coronae with the *XMM-Newton* Reflection Grating Spectrometers during the commissioning, calibration, verification, and guaranteed time phases of the mission, accompanied by simultaneous observations with the EPIC cameras and, for several targets, with the radio VLA and/or the VLBA. The principal aim of this project is threefold: i) To understand stellar coronal structure and composition by studying systematics in the coronae of stars with widely different levels of magnetic activity; ii) to investigate heating and particle acceleration physics during flares, their role in the overall coronal energy budget, and their possible role in the quiescent stellar emission; iii) to probe stellar coronal evolution by studying solar analogs of different ages. We report early results from this project.

1. Introduction

With the advent of *XMM-Newton* and *Chandra*, it has become possible for the first time to routinely investigate high-resolution stellar X-ray spectra. The *XMM-Newton* Reflection Grating Spectrometer (RGS) team is conducting a comprehensive survey of coronae of cool stars, in particular to investigate i) stellar structure and composition, ii) coronal energy release and heating, and iii) long-term evolution of stellar coronae. Complemented by targets from the calibration and performance verification phase and some guest observer targets, the survey comprises 26 targets. We present here selected and preliminary results related to various issues.

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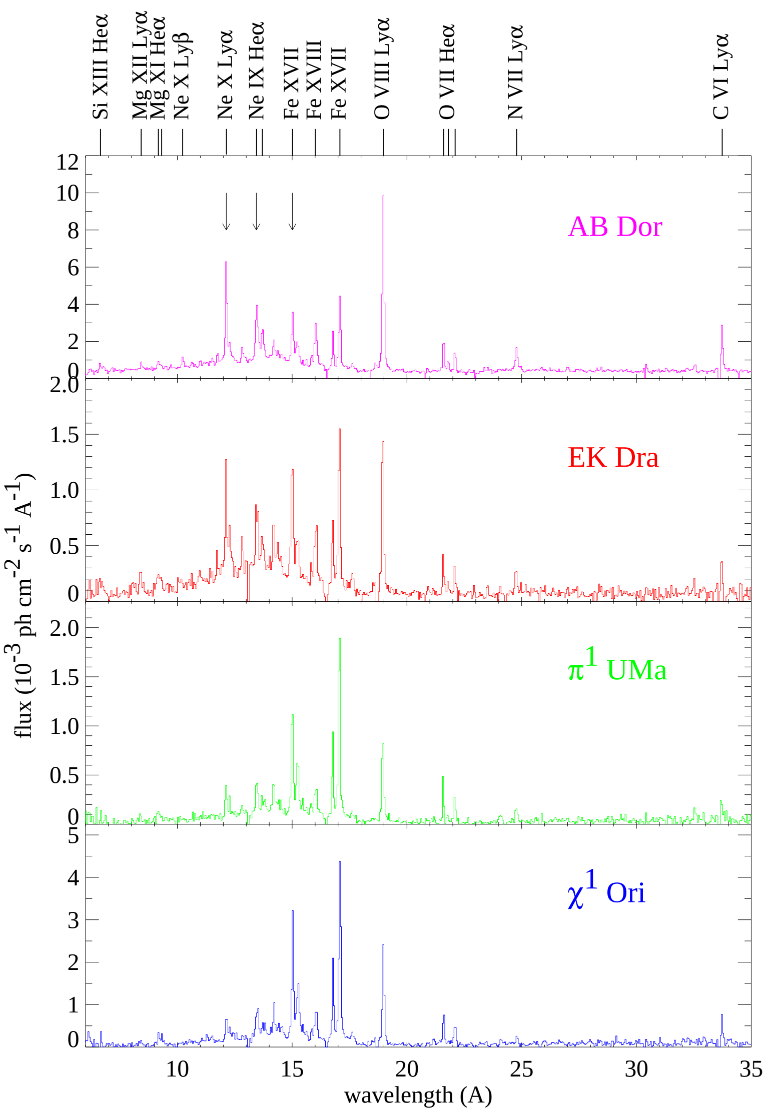

Figure 1. Fluxed RGS X-ray spectra of four solar analogs. The overall coronal activity decreases from top to bottom, while age increases. The arrows point at Ne X, Ne IX, and Fe XVII lines that have similar maximum line formation temperatures.

2. Coronal Abundances

Brinkman et al. (2001) reported an *inverse First Ionization Potential* (IFIP) effect in the active corona of HR 1099, i.e., an increase of the elemental abundances with increasing FIP of the element, relative to solar photospheric abundances. Similar results were found for other very active stars (Güdel et al. 2001ab) but not for less active objects like Capella (Audard et al. 2001a). One of the fundamental problems relates to the mostly unknown *photospheric* abundances of the

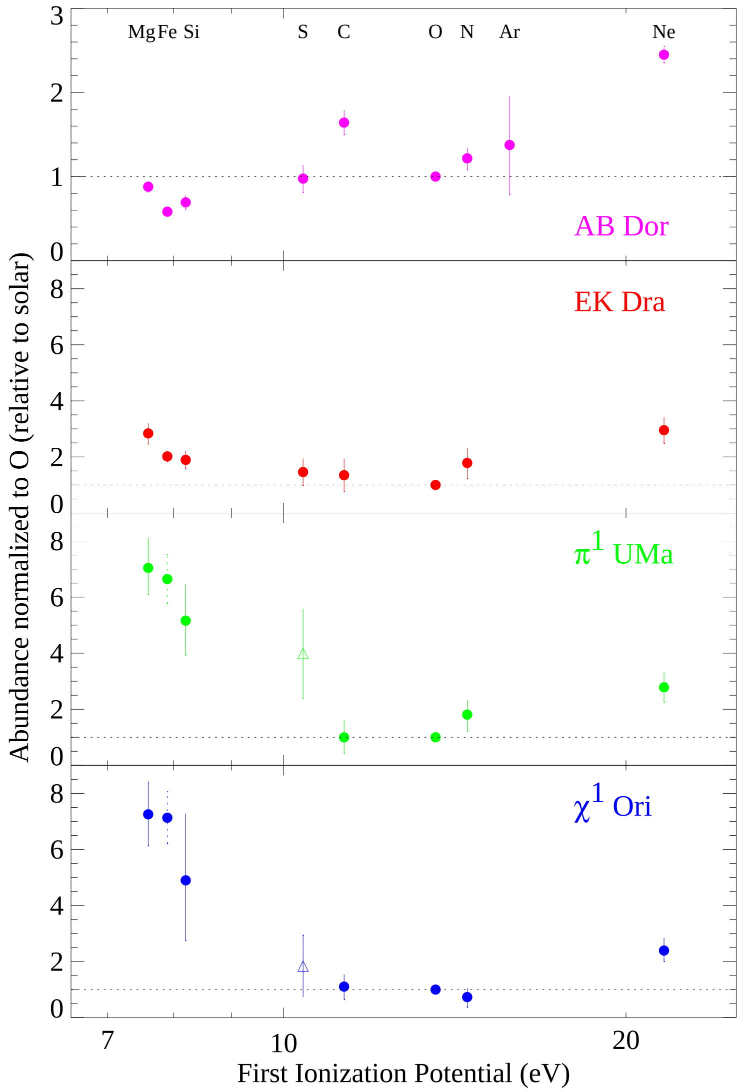

Figure 2. Coronal elemental abundances of the same four solar analogs, relative to the oxygen abundance and normalized with the respective solar photospheric ratios, as a function of FIP. Note the change from an IFIP effect (top) to a normal FIP effect (bottom) in the course of stellar evolution.

respective stars (Audard et al. 2001b). Since the coronal material ultimately derives from the photosphere, a physically interesting result should relate coronal to *stellar* photospheric abundances.

We have studied a rather select sample of targets, namely young solar analogs with known photospheric metallicities - all of them are indistinguishable from solar photospheric. The stars vary essentially by their rotation periods (from 0.5 to 5 days) and therefore activity levels (from $L_X \approx 10^{30}$ to

$\approx 10^{29}$ erg s^{-1}). The combined RGS1&2 spectra are shown in Figure 1. Comparing the most active (AB Dor - with a slightly later spectral type of K0 V) with the least active (π^1 UMa and χ^1 Ori) targets, one sees that the continuum level is much lower in the latter, and the O VIII/O VII flux ratios are smaller, indicating a lower coronal temperature for lower activity. However, the maximum line formation temperatures of the Ne X and the Ne IX lines narrowly bracket the formation temperature of Fe XVII, the latter two ions being formed at very similar temperatures. These lines are marked by arrows in Figure 1. It is evident, however, that the line ratios grossly change from the most active to the least active star, indicating that the relative *Fe abundance increases.* Figure 2 shows the abundance ratios of different elements to oxygen from a full spectral analysis (in XSPEC), normalized to the photospheric ratios. We find clear evidence for the inverse FIP effect in AB Dor, but a continuous change to a normal, solar-like FIP effect in the less active stars.

What is the cause for this transition? It is interesting to note that the non-thermal coronal radio emission, attributed to gyrosynchrotron radiation from accelerated, high-energy electrons, rapidly drops from AB Dor to π^1 UMa, by a factor of at least 300 (Lim et al. 1992, Gaidos, Güdel, & Blake 2000). One suspicion is that high-energy electrons penetrating into the stellar chromosphere build up a (downward-pointing) electric field that pulls the chromospheric ions (mostly from low-FIP elements) downward, thus preventing them from reaching the corona, leaving a high-FIP enriched upper layer in the chromosphere that can access the corona. As the non-thermal particle density decreases, this effect becomes less important, and a solar-like FIP effect can develop. For this mechanism to work, a number of delicate conditions must be fulfilled. Most importantly, the downward electron flux must not exceed the limit above which explosive chromospheric evaporation develops as the energy cannot be radiated away sufficiently rapidly. If evaporation does occur (e.g., during a flare) a larger part of the chromosphere will be transported into the corona and the material will be mixed, so that a near-photospheric composition is recovered. This quenching of the IFIP effect has in fact been suggested from observations of large X-ray flares (e.g., Güdel et al. 1999, Audard, Güdel, & Mewe 2001c).

3. The Neupert Effect in Stellar Flares - Evidence for Chromospheric Evaporation?

A standard flare scenario devised from many solar observations proposes that accelerated coronal electrons precipitate into the chromosphere where they lose their kinetic energy by collisions, thereby heating the cool plasma to coronal flare temperatures. The subsequent overpressure drives the hot material into the coronal loops, giving rise to a soft X-ray flare. The radio gyrosynchrotron emission (with a luminosity $L_{\rm R}$) from the accelerated electrons is roughly proportional to the instantaneous number of particles and therefore to the power injected into the system. On the other hand, the X-ray luminosity $L_{\rm X}$ is roughly proportional to the total energy accumulated in the hot plasma. One thus expects, to first order,

$$L_R(t) \propto \frac{d}{dt} L_{\rm X}(t) \tag{1}$$

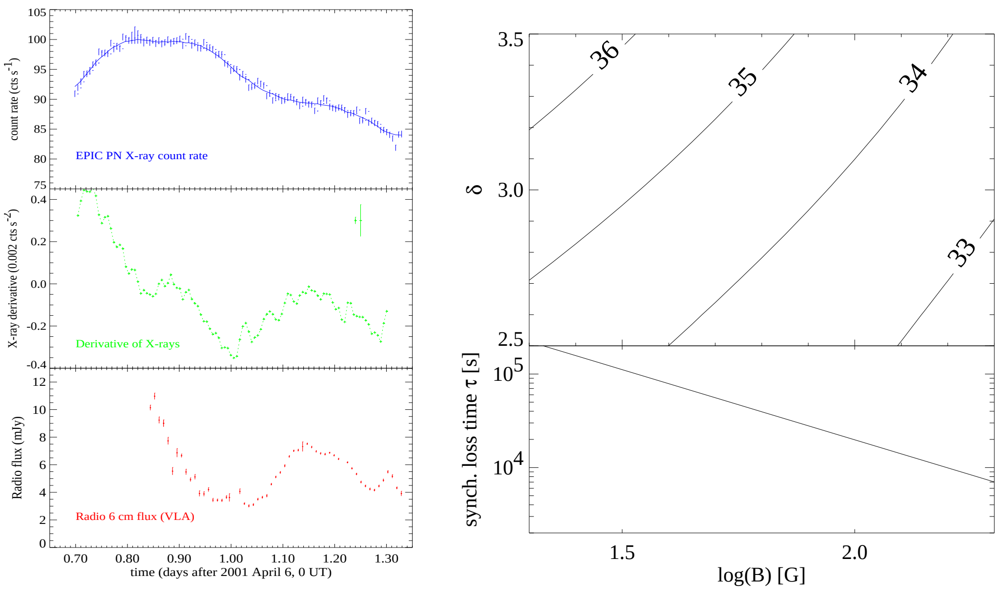

Figure 3. **Left:** Example of the Neupert effect in the RS CVn binary σ Gem. The top panel shows the X-ray light curve, the middle panel presents the time derivative of the X-ray curve, and the lower panel shows the radio light curve. **Right:** Corresponding energy content in accelerated electrons for different values of the magnetic field and the electron energy power-law index δ (the contour labels give the logarithms of the energy content in ergs). The bottom panel illustrates the synchrotron loss time for different magnetic field strengths B (after Güdel et al. 2001c).

which is known as the "Neupert Effect" (Neupert 1968) and has been well observed on the Sun in most impulsive and many gradual flares (Dennis & Zarro 1993). Only one radio+X-ray observation of a *stellar* Neupert effect was obtained previously (Güdel et al. 1996), additional to one observation for which optical and EUV emissions were observed as the respective proxies (Hawley et al. 1995). Both referred to M dwarfs. RS CVn binaries are known to be surrounded by very large, binary-sized magnetospheres (Mutel et al. 1985) - are these coronal systems operating the same way as a more compact solar-like corona?

A recent observation with *XMM-Newton* and the VLA does support a solar-like picture of energy release. Figure 3a shows, from top to bottom, the X-ray light curve, its time derivative, and the radio light curve during a large flare on the RS CVn binary σ Gem. We consider only the second flare episode that is completely covered at radio waves, i.e., the interval [1.02,1.32] d. The radio curve and the X-ray time derivative correlate very well in time, with no significant time delay. Evidently, the release of high-energy particles is closely coupled with the heating mechanism. For chromospheric evaporation to work, however, a necessary condition is that the accelerated particles carry enough kinetic energy

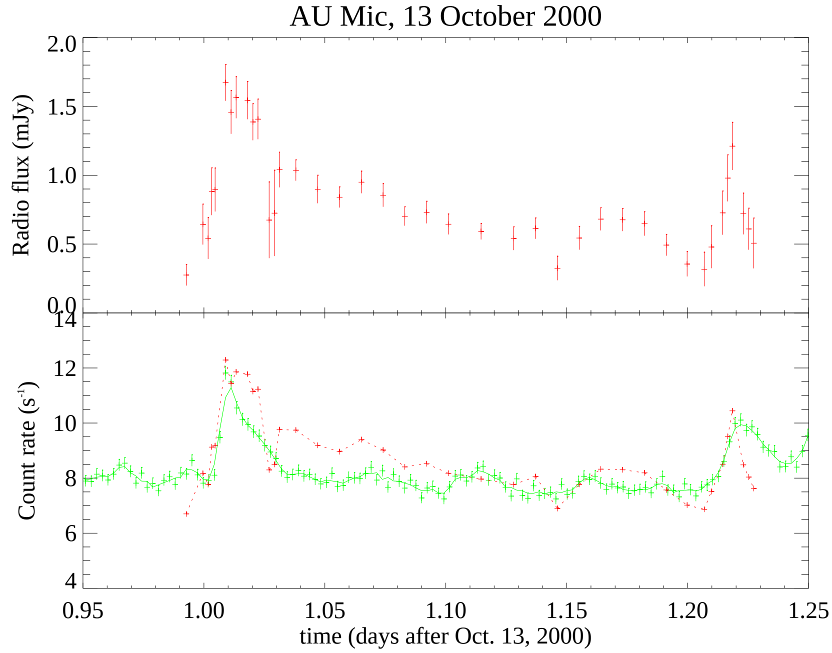

Figure 4. Two flares on AU Mic, observed at radio wavelengths (top, and arbitrarily scaled dashed overplot at bottom) and in X-rays (bottom, error bars). The flare at 1.02 d does not show a Neupert-effect like dependence, while the flare at 1.22 d does.

to explain the released soft X-ray energy. Under simplified assumptions such as an electron power-law distribution in energy, a reasonable lower energy cutoff around 10 keV, and the absence of strong changes in the radio optical depth, an order of magnitude estimate of the total energy in the electrons results in a range of $E_{\rm tot} = 10^{33} - 10^{36}$ erg (Fig. 3b; Güdel et al. 2001c). This estimate holds for a magnetic field strength B between 20−200 G and a power-law index $\delta = 2.5-3.5$, values that have previously been found from magnetospheric modeling (e.g., Mutel et al. 1985), and an electron lifetime of ∼1500 s as inferred from the steepest parts of the light curve (shorter lifetimes result in larger energies). The total released energy in the superimposed X-ray event is estimated to be 4×10^{34} erg. The kinetic particle energy is therefore sufficient to explain the heating for a broad range of parameters B, δ.

There is thus good evidence for the flare energetics in this RS CVn binary to operate in a similar way as in solar flares, and for high-energy particles to play a fundamental role in the energy release and perhaps in the plasma heating. In retrospect, we find a similar timing between radio and X-ray flare events in some previously published light curves, although the Neupert effect was not discussed. Most evidently, radio emission peaking before the soft X-rays, thus suggesting the presence of a Neupert effect, can be seen in the examples presented by Vilhu et al. (1988), Stern et al. (1992), and Brown et al. (1998).

It is important to recognize that the Neupert effect is not a universal property of coronal flares, neither in the Sun (Dennis & Zarro 1993) nor in stars.

Figure 4 shows a coordinated *XMM-Newton* + VLA observation of the dMe star AU Mic. While the second larger flare suggests a Neupert-effect dependence between the emissions, the first flare clearly does not. The time correlation between the two emissions is notable, however, testifying to concurrent particle acceleration and coronal heating.

4. Coronal Structure - A Total Stellar X-Ray Eclipse

Eclipsing binaries are interesting for the study of coronal structure. If the eclipsing component is dark and the eclipse is total, there is hope to derive information on the location and sizes of coronal active regions on the eclipsed star. The optically bright star α CrB is such a fortunate example. The geometry is sketched in Figure 5 (upper right panel). The eclipsing star is an A star, completely dark in X-rays, while the eclipsed object is an intermediately-active mid G-star. Eclipses occur every $\sim$17.3 days and are total. Since the eclipse is not central, the moving limb of the A star cuts out differently oriented slices during ingress and egress, which should allow for a quasi-2-D (but non-unique) reconstruction of coronal features. The first *XMM-Newton* observation on January 13, 2001, partly failed due to a guide star-acquisition problem so that most of the ingress was missed. The experiment will be repeated in summer 2001. The light curve at hand, however, already contains rather interesting information (Figure 5). A model assuming a homogeneous or a spherically symmetric, radially decaying optically thin corona does not produce an acceptable fit to the observation (Fig. 5, top panels). We therefore calculated a pseudo-1-D map simply from the gradients in the smoothed light curve. The location of the emission measure corresponding to a change in flux within a given time interval is unspecified within circular slices cut out by the A star (the projected corona is further confined to $<1.2R_{\rm G}$ in this example). The short segment obtained from the ingress enhances the emission at the lower right limb, indicating that there is an active region in that area. We thus find evidence that the coronal material in this star is highly structured. A full light curve will be useful to further constrain the sizes of the active regions.

5. Do X-Rays Reveal Magnetic Activity Cycles?

We have been observing the very active, near-ZAMS solar analog EK Dra since 1990 using ROSAT, ASCA and EUVE. The most recent observation was obtained by *XMM-Newton*. Active stars usually show irregular quasi-cycles of magnetic activity, although EK Dra is a clear example revealing a long-term behavior in magnetic spot coverage, with a cycle period around 11-12 years as measured in optical photometry (Figure 6, top panel, Guinan et al. 2002). Does the activity cycle reflect in the average X-ray luminosity? Combining snapshot data from various instruments is not without problems and poses challenges to cross-calibration and data interpretation. Our best-effort result is shown in Fig. 6. A notable anticorrelation - high X-ray luminosity during low photometric brightness or large spot coverage - is indicated. Although no proof for an X-ray cycle, the data are very suggestive, and a coherent continuation of this monitoring program would be helpful to confirm a long-term trend.

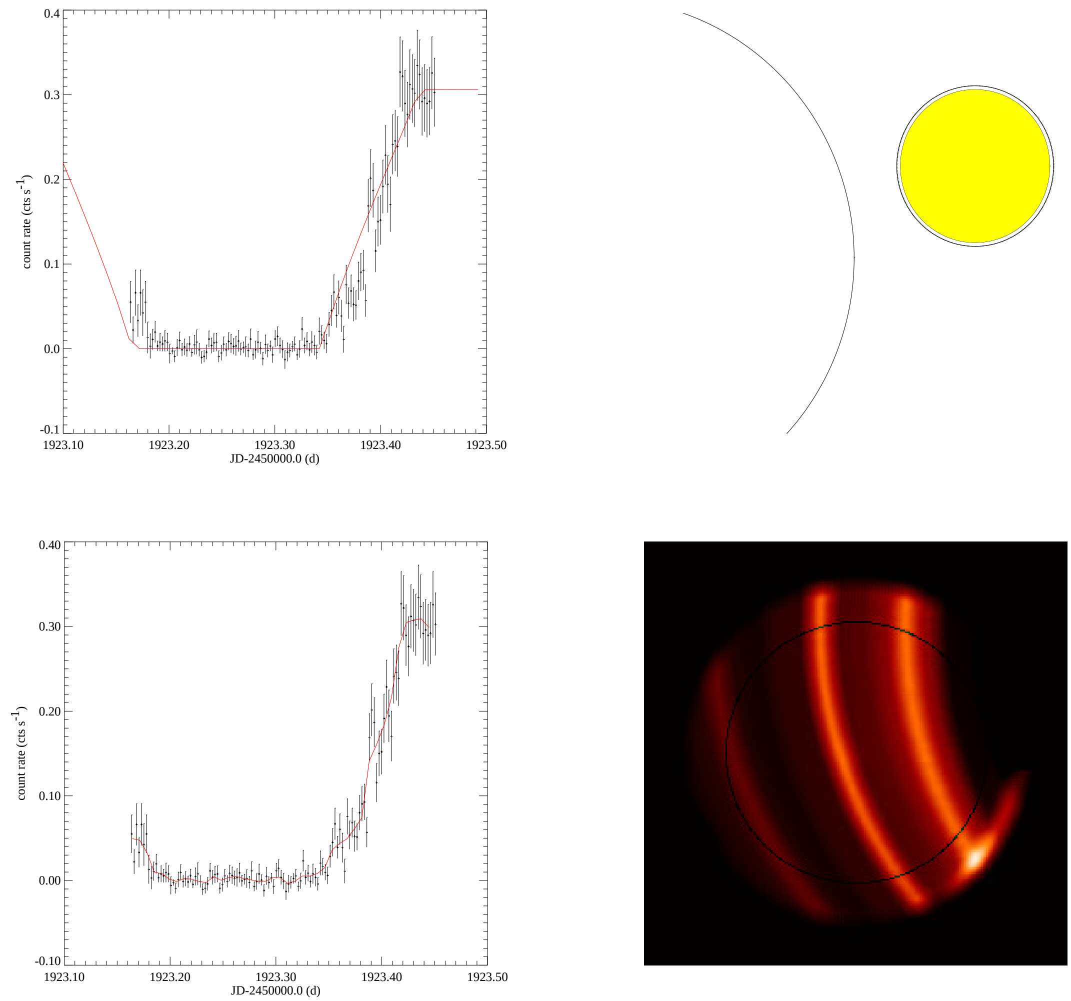

Figure 5. Total X-ray eclipse of the secondary in the α CrB system. **Top left:** Observed light curve and model light curve assuming a uniform, optically thin corona extending to $1.05R_*$, as illustrated in the **top right** figure. **Bottom left:** Observed light curve and smoothed boxcar average that results in a pseudo-1-D model shown at **bottom right**.

6. Summary

A comprehensive coronal survey is underway with the instruments onboard *XMM-Newton*. New standards of sensitivity and spectral resolution provide an entirely new approach to problems in coronal physics. A summary of early results follows:

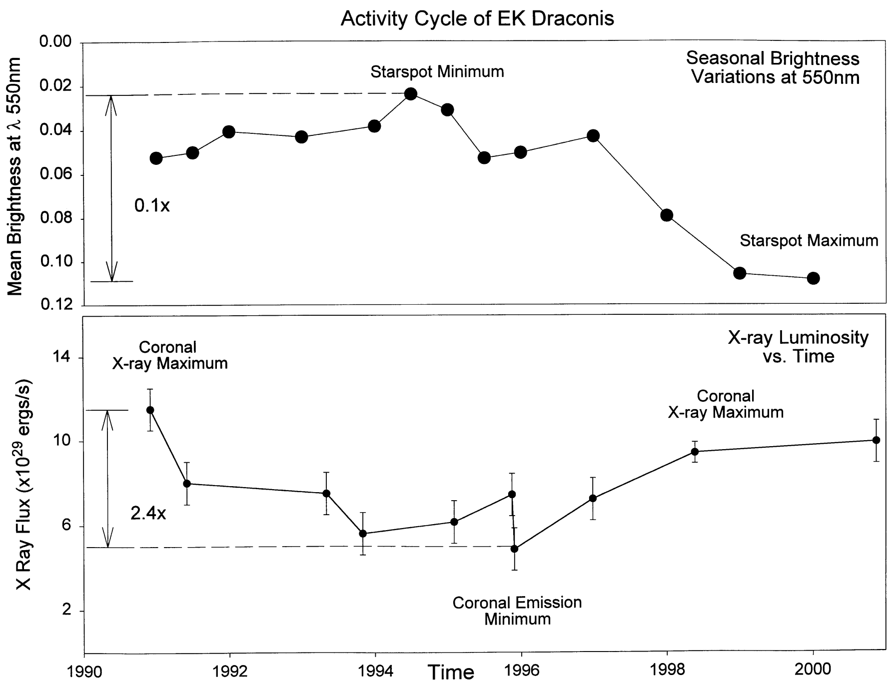

Figure 6. Photometric (top) and X-ray snapshot "light curves" of the young solar analog EK Dra between 1990 and 2001. There is evidence that the starspot minimum coincides with the lowest X-ray flux levels (Guinan et al. 2002).

- There is evidence that coronal abundances follow some systematics related to the overall coronal activity and hence the overall coronal temperature. Since coronal activity is controlled by rotation, the coronal composition changes during main-sequence evolution. We speculate that high-energy processes, revealed at radio wavelengths and indicating high-energy electrons, could be responsible for a bias in the elemental composition of coronae of active stars.

- We find indirect evidence for flare chromospheric evaporation on an RS CVn binary by identifying the Neupert effect in simultaneous radio and X-ray light curves. Energy estimates suggest that accelerated particles play an important role in the energy release process, and perhaps in coronal heating in general.

- Eclipsing binaries are ideal objects to study coronal structure. The example of α CrB, a totally eclipsing system, provides clear evidence for inhomogeneity in the G star corona.

- There is tentative evidence for a magnetic quasi-cycle in the active, young solar analog EK Dra both in optical photometry and in X-rays. If confirmed, it shows that a corona near the saturation level still sensitively responds to changes in the photospheric activity level. A longer monitoring program is clearly warranted.

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