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X-Ray and Radio Emission from Stellar Coronae

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Abstract. Stellar coronae are sources of intense radio and X-ray emission. This radiation contains valuable diagnostics for the structure of coronal magnetic fields, although model bias and simplifications often ignore the complexity of real coronae. This article discusses selected open problems and controversies in stellar coronal research.

Key words. Stars: coronae – Stars: flares – Stars: radio emission – Stars: X-ray emission

1. Introduction

Recent stellar coronal research has focused on X-ray emitting hot plasma, and justifiably so. *XMM-Newton* and *Chandra* offer unprecedented access to coronal physics through *X-ray spectroscopy*. Yet, X-ray diagnostics probes plasma that is no more than the end product of a chain of processes starting with the elusive mechanism of coronal energy release, itself a consequence of the dynamics in the stellar interior and on the magnetized surface.

I will not aim at reviewing recent stellar coronal research but intend to emphasize selected but significant gaps in our understanding of stellar coronae, challenges owing to coronal complexity, and the danger of simplifications. For more general reviews, I refer to Güdel (2002) and Güdel (2004). I use the expression "stellar corona" in a comprehensive sense, meaning the ensemble of magnetic structures in the low plasma-beta portion of the outer stellar atmosphere that may or may not be filled with various kinds of static or non-static, thermal or non-thermal plasma.

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2. Coronal Structure

The extent and predominant locations of closed magnetic structures currently hold the key to our understanding of the internal magnetic dynamo. I discuss examples and briefly illuminate problems for various methods.

2.1. Eclipse and Rotational Modulation

Rotational modulation has been successfully used to estimate limits on (mostly X-ray) coronal extent, although subject to caveats:

1. Rotationally modulated light curves may be strongly distorted by emission that evolves on shorter timescales than a rotation period, such as flares or evolving active regions (e.g., Kürster et al. 1997).
2. Very little information is available for i) volumes in constant view, and ii) for ensembles of structures that are uniformly distributed in stellar longitude.

While point (2) precludes unique conclusions from the absence of rotational modulation, the presence of deep modulation in some active stars (Güdel et al. 1995; Audard et al. 2001;

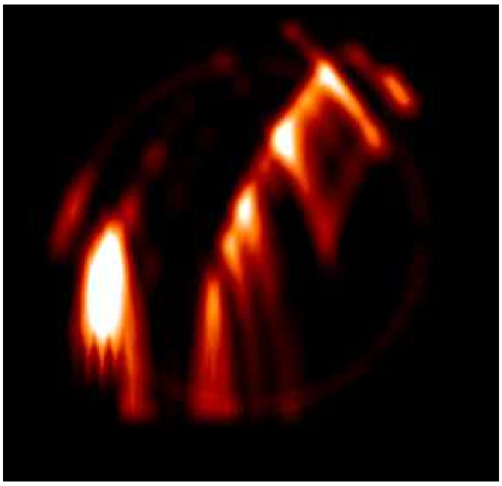

Fig. 1. X-ray eclipse map of α CrB (after Güdel et al. 2003a).

Marino et al. 2003; Huenemoerder et al. 2006) challenges the view that X-ray saturation (i.e., $L_X/L_{bol} \le 10^{-3}$) is due to *full coverage of the stellar surface with solar-like active regions*. It also sets stringent upper limits to the extent of the *X-ray modulating*, active regions and lower limits to their densities (Güdel et al. 1995), often suggesting compact active regions with heights less than R_*.

Eclipse monitoring offers the advantage that potentially all of the emitting volume is eclipsed, often on time scales short enough to avoid distortions by flares. On the other hand, eclipse mapping is usually non-unique (Siarkowski et al. 1996; Güdel et al. 2003a).

For α CrB (A0 V + G V), self-rotation of the stars can be neglected, and the eclipsing A star is entirely X-ray dark. Eclipse mapping of the active G star shows solar-like active regions with enhanced densities (of at least several times 10^{10} cm^{-3}), but also large X-ray dark areas; no emission is found significantly beyond one pressure scale height of the limb (Fig. 1, after Güdel et al. 2003a).

2.2. Coronal Spectroscopy

Under coronal conditions, transitions of He-like C V, N VI, O VII, Ne IX, Mg XI, and Si XIII provide useful density diagnostics (Gabriel & Jordan 1969), with some caveats. First, the density-sensitive range for the latter two ions exceeds $n_e \approx 10^{12}$ cm^{-3}, densities that are unlikely to be found in most stellar coronae. Second, the density-sensitive range shifts to higher values for increasing ion formation temperature, T_{ion}. Low densities cannot be explicitly measured in very hot plasmas. And third, T_{ion} of all above ions is in the range of 1–10 MK, while the bulk of the plasma in very active stars reaches several tens of MK (e.g., Audard et al. 2004). Some Fe lines are also sensitive to n_e (e.g., prominent lines of Fe XVII and Fe XXI; Mewe et al. 1985), but similar caveats apply.

Comprehensive surveys of stellar coronal n_e measurements were presented by Ness et al. (2004) and Testa et al. (2004). These studies concluded that the surface filling factor (derived from the emission measure, the measured n_e, and a realistic coronal scale height) of magnetic loops containing *cool* X-ray emitting material increases from inactive to moderately active stars but then "saturates" at levels of about ten percent. In the most active stars, hot coronal loops are added, with a sharply increasing filling factor. This trend may be a consequence of increasing magnetic interaction in the corona. As one moves from low to intermediate activity levels, magnetic flux bundles become more densely packed, leading to more frequent interactions between magnetic features (Güdel et al. 1997). More frequent flaring may be the consequence, implying increased X-ray luminosity, higher temperatures and higher densities, as observed. *This view would require non-static coronal models.*

Bias is introduced because the often-quoted simplest assumption of constant source density is clearly the least plausible one. Realistic coronae reveal a distribution of electron densities, with infinitely many distributions resulting in the same line flux ratios. Further, ratio-derived densities are not linear averages across the emitting volume owing to the n_e^2 dependence of the line fluxes. The flux ratios therefore provide information on distributions of volume in density rather than on "electron densities" (Güdel 2004). *Complex* *coronal models building on distributions of realistic but widely varying magnetic structures are needed in the future* - see the interesting work to this end by Schrijver & Aschwanden (2002) and Jardine et al. (2002).

A rather surprising - and to the present day controversial - result have been indications for *very high* n_e (10^{12} – 10^{13} cm^{-3}) derived from ions forming in *hot* plasma (e.g., Mg XI, Si XIII, and Fe XXI; see, e.g., Mewe et al. 2001; Argiroffi et al. 2003, and the work referring to EUVE summarized in Bowyer et al. 2000). The controversies are the following:

- Some lines forming in high-density plasmas are not present in high-resolution spectra, indicating low n_e (Ayres et al. 2001a; Phillips et al. 2001; Ness et al. 2004).
- Most high-density measurements straddle the low-density limit of the respective transition. Slight uncertainties in the atomic physics tabulations or ill-recognized line blends then affect the implied n_e dramatically (Phillips et al. 2001). The similar density values just slightly above the low-density limits found for a *wide variety of stars* indeed suggest that they all represent the low-density limit (Ness et al. 2004).
- Densities inferred from different ions with similar T_{ion} can differ largely. For example, Osten et al. (2003) found n_e up to a few times 10^{12} cm^{-3} from He-like triplets, Fe XXI and Fe XXII, but lower n_e from Mg XI.

Even if the density trend suggested from some observations is real ("hotter plasma is denser"), then a multitude of different, mutually isolated coronal structures must be present as pressure equilibrium does not apply; the denser, hotter regions are much more efficient radiators and potentially dominate (i.e., bias) our spectra, *once again emphasizing the need to study models of complex coronal structure.*

2.3. X-Ray Spectroscopy and Dynamics

X-ray spectroscopic Doppler information may open up new ways to mapping stellar coronae. Ayres et al. (2001b) reported Doppler shifts with amplitudes of $\approx$ 50 km s^{-1} in X-ray lines of HR 1099. Amplitudes and phases locate the bulk of the X-ray emitting plasma on the K star rather than in the intrabinary region. Periodic line *broadening* in YY Gem (Güdel et al. 2001) confines the emitting plasma to rather compact regions with a radial density profile compatible with a barometric atmosphere. Periodic X-ray line shifts also suggest compact active regions on the contact binary 44i Boo (Brickhouse et al. 2001).

Likewise, line-shift periodicities relate the X-rays from the Algol system to the active K subgiant (Chung et al. 2004), although the source may be slightly displaced toward the companion B star, perhaps owing to tidal distortions. But excess line broadening (above thermal broadening) limits the coronal scale height to about one stellar radius, consistent with the pressure scale height of the hot coronal plasma. Similar results have been reported for the active K star AB Dor, with no indications of very extended ($> 1R_*$) coronal features (Hussain et al. 2005).

2.4. Radio Methods

Radio interferometry with a spatial resolution below one milliarcsec is the only means to directly image stellar coronae. The pioneering study by Mutel et al. (1985) identified compact, evolving "cores" and extended "haloes" possibly surrounding the entire binary systems. Polarization gradients suggest large-scale ordering of the extended, perhaps dipolar or intrabinary, magnetic fields (Beasley & Güdel 2000). Massi et al. (2006) suggested very extended helmet-streamer structures in the T Tau binary V773 Tau, based on radio VLBI and millimeter observations. Some structures defy any explanation in terms of solar analogy. Both Algol (Mutel et al. 1998) and the active M dwarf UV Cet (Benz et al. 1998; Fig. 2) reveal very large radio-emitting sources aligned with the (putative) rotation axis. Large-scale, dipole-like magnetospheres may be the answer.

2.5. Summary on Coronal Structure

What does the available evidence tell us about magnetic coronal structure?

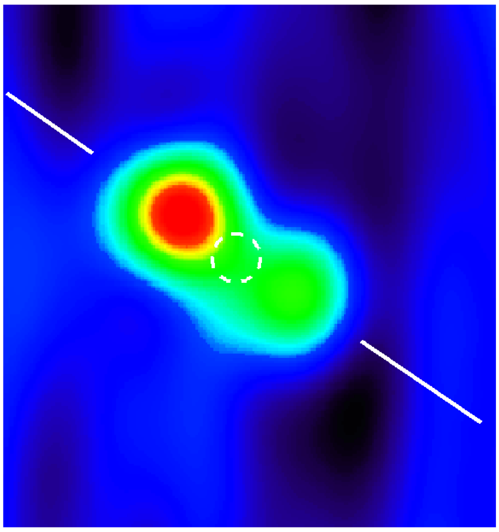

Fig. 2. Radio interferometric image of UV Cet (after Benz et al. 1998).

• Clearly, there is *compact coronal structure* ($R < R_*$) reminiscent of solar active regions, suggested by X-ray eclipses and rotational modulation, and electron density estimates ($n_e > 10^{10}$ cm^{-3}).
• Equally clearly, there is large-scale *extended structure* ($> R_*$), perhaps subject to some global ordering, for which radio interferometry provides direct evidence.
The apparent contradiction disappears when we recall the n_e^2 dependence of X-ray intensity, biasing X-ray detections very strongly to within one pressure scale height above the stellar surface, while large-scale magnetic structure may contribute little. In contrast, energetic electrons avoid compact regions because of strong collisional losses but can easily be trapped in extended, closed magnetic fields. *A comprehensive description of stellar coronae requires a large range of size scales.*

3. Flares

As suggested above, flares may be important contributors to the coronal energy budget. The standard flare scenario assumes that non-potential fields (distorted by the photospheric magnetic-footpoint motions) interact in regions containing antiparallel magnetic-field components. The reconnection process heats plasma and accelerates electrons. The latter, usually visible by their radio gyrosynchrotron emission, stream down along the field lines to collide in denser layers where they heat and explosively evaporate cooler material. The hot plasma streams into the corona, increasing its density.

Observations of the "Neupert effect" have supported this scenario. This effect results from radio emission being roughly proportional to the instantaneous rate of electron injection, while X-ray emission is related to the total amount of X-ray emission measure accumulating in the corona. The light curve of radio emission (and similarly, of short-wavelength optical/UV radiation and hard X-rays emitted from the impulsively heated chromosphere) should therefore roughly follow the time derivative of the increasing X-ray light curve.

This effect is well known on the Sun (e.g., Dennis & Zarro 1993) and has also been found in active stars. A strong flare on Proxima Cen (Fig. 3, Güdel et al. 2002) showed a nearly perfect Neupert relation for X-rays and U-band emission, and furthermore revealed strongly increased electron densities around the two flare peaks ($n_e \approx 4 \times 10^{11}$ cm^{-3}). Recently, in what is a very significant discovery in this field, Osten et al. (2007) recorded hard X-rays (10–100 keV) that also precede the soft X-ray peak of a giant flare and that seem to be the analog of non-thermal hard X-rays in solar flares.

Complications arise from flares that appear to reject this model entirely. Osten et al. (2005) reported coordinated observations of strong flares on the M dwarf EV Lac (Fig. 4). Most notably, evidence for non-thermal electrons is seen in a giant radio burst and a precisely coincident U-band burst, but no trace can be seen in X-rays. This is remarkable given that the optical emission should come from the magnetic footpoints, the radio emission from the extended corona, while the soft X-rays should originate from somewhere in between. More complex coronal-flare models are required.

Various methods have been designed to derive physical information from X-ray light

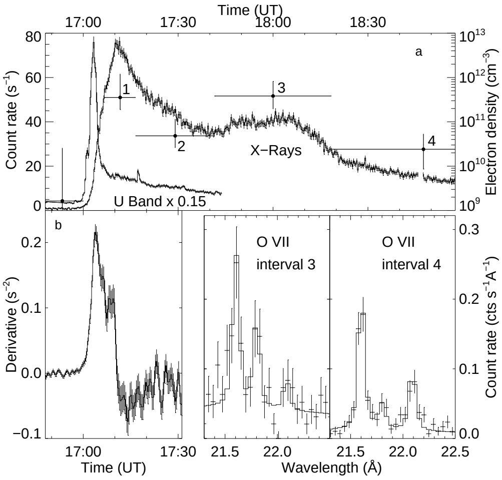

Fig. 3. *Top:* X-ray and U band light curves of a large flare on Proxima Cen; large crosses give electron densities. *Lower left:* Time derivative of X-ray light curve. *Lower right:* O VII triplet during intervals 3 and 4 (after Güdel et al. 2002).

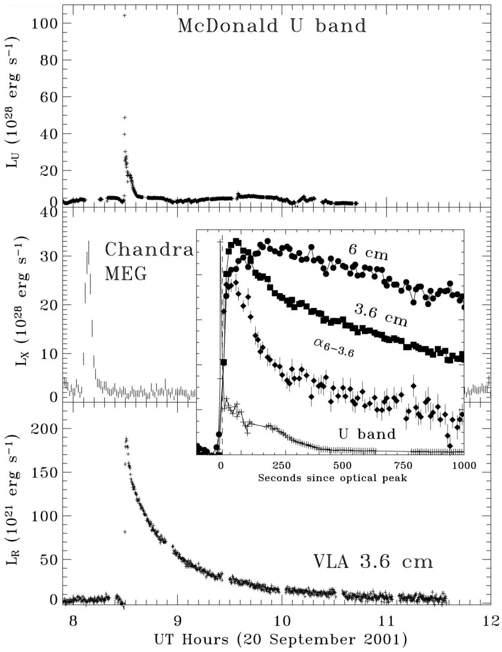

Fig. 4. U-band, X-ray, and radio observation of giant flares on EV Lac (from Osten et al. 2005).

curves. They are based either on cooling physics in plasma loops, or on the energy release behavior of pre-defined magnetic structures - see Güdel (2004) for a summary. Fig. 5 contrasts the enormously rich magnetic structure of a solar X-class flare (the flare type most reminiscent of flares detected in active stars), with its simple, featureless soft X-ray light curve. While a multitude of substructures and hundreds of individually ignited "magnetic loops" of different size heat and cool on time scales *shorter than the time scale of the X-ray light curve* (Aschwanden & Alexander 2001), the substructure information is completely lost in the total X-ray light curve. In such cases, implications from light curves on coronal structure may be questionable.

4. Stochastic Coronal Heating

Stellar flares have been detected down to the (solar) "low M-class" level (Güdel et al. 2002). Like in the solar corona, the flare rate follows approximately a (decreasing) power-law distribution in emitted energy, indicating that the large number of small flares may be energetically important. This question has been addressed based on long and sensitive monitoring observations by Osten & Brown (1999) for RS CVn binaries, Audard et al. (2000) for main-sequence stars, and Wolk et al. (2005), Arzner et al. (2007), and Stelzer et al. (2007) for T Tauri stars. New statistical methodology was introduced by Kashyap et al. (2002) and Güdel et al. (2003b) (Monte-Carlo simulations), and Arzner & Güdel (2004) (analytic light-curve inversion).

For a simple power-law distribution, the total energy release rate is given by the integral $\int_{E_0}^{E_1} E(dN/dE)dE$ where dN/dE is the measured differential distribution of the flare rate in emitted energy, and E_0 and E_1 are the integration limits, signifying the lowest and the highest flare energies to be considered. If $dN/dE \propto E^{-\alpha}$ and $\alpha \geq 2$, then the integral diverges as $E_0 \rightarrow 0$, i.e., a lower limit for the flare energy is required because the small flares dominate the energy budget ("microflare hypothesis"). The upper limit is of less importance because the largest flares occur rarely, with recur-

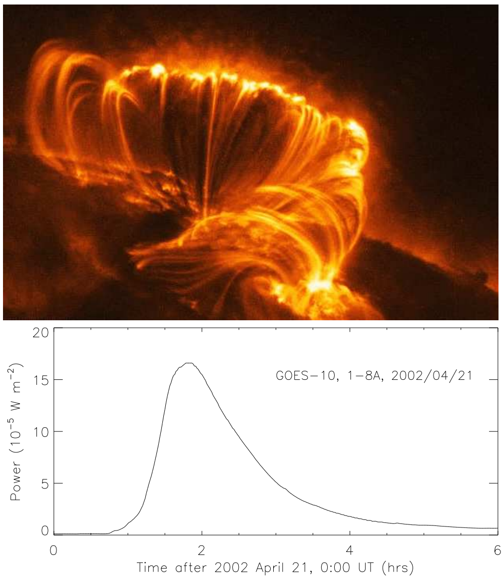

Fig. 5. TRACE 195 Å Fe XII+XXIV image and GOES 1-8 Å light curve of the X-class solar flare on 21 April 2002.

rence time scales much longer than their decay time scales.

Most of the studies mentioned above found $\alpha > 2$ or at least compatible with such values. It is thus conceivable that the coronal X-ray output is dominated by emission from stochastic flares. Despite a number of caveats (see Güdel et al. 2003b), further evidence suggests an important role of stochastic flares: i) the nearly persistent, non-thermal radio emission in active stars requires frequent replenishment of accelerated electrons, for which flares are the most obvious sources; ii) the extremely hot plasma in active stars attains temperatures similar to solar flares; flare-evaporated plasma may then also increase the electron density sufficiently to explain the high levels of X-ray output. iii) The shape of the differential emission measure distribution of active stars can be modeled by the time-averaged emission measure distribution of a stochastically flaring corona (Güdel et al. 2003b).

If flares do dominate the coronal energy release, interpreting magnetically active coronae might require stochastic flare models rather than hydrostatic coronal loop models.

5. Exotic Coronae

Some recent developments promise new momentum in the field of coronal research. I address two features that might, at this time, best be described as "exotic coronae".

5.1. A "Soft Excess" in T Tauri Stars?

TW Hya was the first accreting, classical T Tauri star (CTTS) studied in spectroscopic detail in X-rays; its spectrum showed, first, an emission line pattern dominated by very cool (≈3 MK) plasma; second, Ne IX and O VII triplets that require unusually high densities of order 10^{12}–10^{13} cm^{-3}, the forbidden line of the O VII line essentially being absent; and third, an unusually high Ne/Fe abundance ratio of about 10 relative to the solar photospheric ratio (Kastner et al. 2002; Stelzer & Schmitt 2004).

The model proposed by Kastner et al. (2002) and Stelzer & Schmitt (2004) relies on magnetically guided accretion streams from the disk to the star. Material falling toward the star reaches near-free fall velocities, $v_{\rm ff} = (2GM/R)^{1/2}$, i.e., a few hundred km s^{-1} for CTTS. Strong shocks at the photospheric impact site heat material to $T = 3\mu m_{\rm H}v_{\rm ff}^2/16k$ (μ is the mean molecular weight of the infalling gas, and $m_{\rm H}$ is the mass of the hydrogen atom). Shock densities and temperatures agree with observations if moderate accretion filling factors are assumed ($f = 0.1 - 10\%$, Calvet & Gulbring 1998).

The anomalous Ne/Fe (also N/Fe, Ne/O) abundance ratios have been suggested (Stelzer & Schmitt 2004; Drake et al. 2005) to reflect depletion of Fe and O in a relatively evolved accretion disk where almost all elements condense into grains except for N (Savage & Sembach 1996; Charnley 1997) and Ne (Frisch & Slavin 2003) that remain in the gas phase which is accreted onto the star.

Recent development has led to a more ambiguous view. First, there are now two examples of accreting stars (AB Aur, Telleschi et al. 2007a, and T Tau, Güdel et al. 2007) showing no indications of high densities. Second, high abundance ratios of Ne/Fe or O/Fe have been found in larger samples of T Tauri stars, but

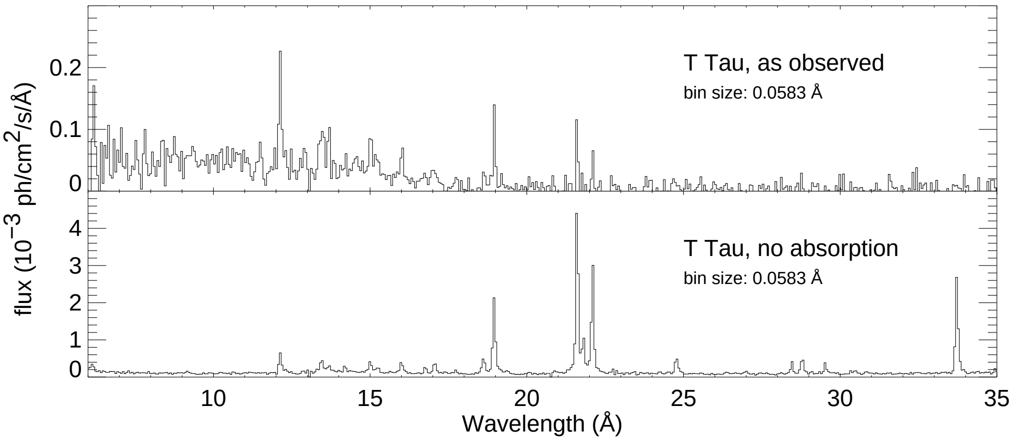

Fig. 6. Absorbed (top) and modeled unabsorbed (bottom) X-ray spectrum of T Tau (after Güdel et al. 2007).

these include CTTS and non-accreting weak-line T Tauri stars (WTTS) alike; the ratios agree with the inverse First Ionization Potential Effect also seen in zero-age main sequence (ZAMS) stars; the ratios vary as a function of spectral type or stellar effective temperature rather than accretion signatures. And third, the analysis of the O VII and O VIII lines reveal a *thermal anomaly* in that the O VII/O VIII flux ratio is unusually high for accretors when compared to WTTS or ZAMS stars (Telleschi et al. 2007b). In the intrinsic X-ray spectrum of T Tau, the O VII λ21.6 line is the strongest line regardless of the otherwise very hot corona of T Tau (Güdel et al. 2007, Fig. 6).

The latter observations suggest the presence of a *soft excess* due to anomalous amounts of cool plasma in the coronae of accreting stars. For cases where accretion shocks are unlikely, a suggestive source of the soft excess are coronal active regions that are pervaded by cool, infalling accretion streams that *cool* coronal material to low temperatures (Telleschi et al. 2007b).

5.2. X-Ray Dark Coronae?

While X-ray studies of low-mass stars initially provided little indications of a breakdown of coronal heating toward later spectral types, recent searches for (evolved) brown dwarfs (BD) have met with very modest success. The observations suggest a significantly lower heating efficiency for L-type BDs than for late-M stars (Berger et al. 2005), perhaps due to the lower ionization degree of the photospheres that lead to a decoupling of magnetic fields from surface convection (Mohanty et al. 2002).

However, radio observations of BDs have been a rather puzzling surprise. Field BDs emit steady and flaring radio radiation that reveals essentially no difference to late-M dwarfs (Berger et al. 2002, 2005). The radio luminosity shows, if anything, even a slight increase toward later spectral types when normalized with $L_{\rm bol}$ (Berger et al. 2002). A correlation between radio and X-ray luminosity reported earlier for M dwarfs and other active stars (Güdel & Benz 1993) breaks down entirely, the radio emission exceeding “expected levels” by several orders of magnitude.

The particle acceleration efficiency in BD coronae does not not seem to diminish, indicating that magnetic interactions do not cease even at low photospheric ionization degrees. For some reason, however, these particles do not evaporate cool gas into the corona, perhaps because the magnetic-field topology in BDs is different from compact, solar-like active regions (Berger et al. 2006). Unusual magnetic-field structure has indeed been mapped by radio-interferometric means around the low-mass M dwarf UV Cet (Benz et al. 1998).

6. Conclusions

The field of stellar coronal physics is advancing rapidly, particularly owing to fantastic observing capabilities provided by *XMM-Newton* and *Chandra*. However, simplified, analytic models devised a long time ago must be confronted with complexities that are particularly evident in modern solar coronal observations. The stellar coronal complexity projects onto simple, degenerate light curves and spectra whose inversion cannot recover more than a few simple parameters. One out of a very large number of stellar coronal models applies in each case, and it is surely *not* the simplest model that approaches the truth, as solar experience has now amply shown. Devising complex stellar coronal models is a difficult but rewarding task for the future.

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