STEEL CORONAL STRUCTURES

J. L. LINSKY\textsuperscript{1,2}

\textsuperscript{1} Joint Institute for Laboratory Astrophysics
University of Colorado and NIST
Boulder CO 80309-0440, U. S. A.

\textsuperscript{2} Staff Member, Quantum Physics Division
National Institute of Standards and Technology

Abstract. Large magnetic structures in the corona of stars containing gas at a wide variety of temperatures are now being studied in X-rays, radio wavelengths, and H\alpha. Here I will summarize what we are learning about coronal structures in three types of stellar systems: the magnetic chemically peculiar stars, the RS CVn binary systems containing G- and K-type subgiants, and active solar-type dwarfs like V471 Tauri and AB Doradus.

Key words: Stars: Coronae – Magnetic Fields – Stars: Binary – Stars: Winds

1. A Very Brief Introduction to Stellar Coronae

The proximity of the Sun permits us to obtain beautiful high-resolution images at X-ray to radio wavelengths that reveal the phenomena and physical processes occurring in the corona of this relatively inactive, slowly rotating G-type dwarf. Stars will never be studied in such detail, but new observing techniques allow us to begin studying the structures and physical properties of some stellar coronae. We are now finding stars that have coronal structures analogous to those observed on the Sun but with dimensions and energies that are often orders of magnitude larger.

The solar corona plasma is inhomogeneous with observable structures because locally strong magnetic fields separate plasmas with different heating and mass loss rates, which in turn are controlled by the local fields. The same physical principles that require that the Sun have a hot, inhomogeneous corona must also require qualitatively similar coronae on other stars that have strong magnetic fields and are otherwise similar to the Sun. However, stars with observed X-ray emission indicative of hot coronal plasmas display a variety of basic properties (e.g., effective temperature, gravity, radius, magnetic field structures, age, abundances, and rotation rate) that differ considerably from those of the Sun. Thus we should expect to observe stellar coronae with diverse properties that may even have qualitatively different structures. In this brief survey of stellar coronal structures I will concentrate on three classes of stars that differ from the Sun in one or more of their fundamental properties.

\textsuperscript{IAU Colloq. 144 “Solar Coronal Structures”, V. Ru\texthinspace\textsuperscript{š}in, P. Heinzel, \\& J.-C. Vial (eds.), 641–650
\textcopyright1994 VEDA Publishing Company, Bratislava – Printed in Slovakia}

© The Astronomical Institute, Slovak Academy of Sciences • Provided by the NASA Astrophysics Data System
The parameter $\beta = 8\pi P_{\text{gas}}/B^2 \leq 1$ describes magnetic fields that are sufficiently strong locally to channel the plasma flows and thus separate dissimilar ionized plasmas. This criterion is typically valid in the solar corona. Photospheric magnetic fields have now been measured in many late-type stars, mostly dwarfs, using line broadening techniques (e.g., Saar, 1988). Two important results are that the nonspot photospheric fields increase from 1500 Gauss for G dwarfs to more than 5000 Gauss for M dwarfs. The magnetic filling factors for active dwarfs can be as large as $f = 0.5$, whereas for the Sun $f_\odot \approx 0.01$. Thus we anticipate that stellar coronal magnetic fields can be much larger than are found in the solar corona.

I will first summarize very briefly the properties of unresolved stellar coronae deduced from X-ray observations with the *Einstein* and ROSAT satellites (see Linsky, 1990). Observed X-ray emission indicates the presence of hot coronae in dwarf stars between spectral type A7 (e.g., Altair) and the coolest M dwarfs, and the existence of coronae in giant stars as late as about spectral type K2 III. X-ray luminosities ($\log L_x$) for rapidly rotating, young stars can be orders of magnitude larger than for the quiet Sun ($\log L_x \approx 27.7$). The observed values of $\log L_x$ extend up to 30.1 for the young dMe stars, up to 30.4 for the G and K stars in the young ($10^{7.8}$ yr) Pleiades cluster, and up to 31.8 (cf. Dempsey et al., 1993) for the tidally synchronous RS CVn binary systems. During flares these stars can have even larger X-ray luminosities. X-ray surface flux ratios appear to saturate near $F_x/F_{\text{bol}} \approx 10^{-3}$ (Vilhu, 1987) for the most active stars compared to the mean solar ratio of $10^{-6.5}$. The low resolution X-ray spectra are usually interpreted in terms of coronae with two thermal components with $\log T$ near 6.4 and 7.2, but EUVE spectra now provide evidence that coronal emission measure distributions are continuous over a broad range of temperatures (e.g., Dupree et al., 1993). Higher resolution X-ray spectra from ASCA, XMM, and AXAF will provide additional information on stellar coronal temperatures and abundances.

Stellar coronae are also observed at radio wavelengths by the VLA and other synthesis arrays. The radio flux from active stars is thought to be gyrosynchrotron emission from relativistic electrons or coherent emission during flares. The Sun is a very weak radio source at 6 cm with $\log L_6 = 10.5-12.0$. The only detected solar-like star is Procyon (F5 IV-V) with $\log L_{3.6} = 11.7-12.2$ (Drake et al., 1993). By comparison, active stars including dMe stars and RS CVn binaries are very luminous with $\log L_6$ as large as 17.5 (Drake et al., 1989). An important question is why the luminosity of thermal X-ray emission should be well correlated with nonthermal radio emission over six orders of magnitude (Güdel and Benz, 1993).

2. Coronal Structure of the Magnetic Chemically Peculiar (Bp and Ap) Stars

Some A- and B-type stars have pronounced chemical peculiarities and strong surface magnetic fields. These magnetic chemically peculiar (MCP) stars have relatively
simple dipolar or quadrupolar magnetic fields with surface field strengths as large as 17 kG (cf. Borra et al., 1982). Their high effective temperatures (typically above 15,000 K) and very narrow photospheric line widths indicate that these stars do not have deep convective zones, a stellar property which previously had been thought to be required for the heating of coronae. Nevertheless, Linsky et al. (1992) detected 16 of these stars (including members of both the helium-strong and the helium-weak, silicon-strong subclasses of MCP stars) as sources with radio luminosities in the range \( \log L_\alpha = 15.7-17.9 \), a factor of \( 10^6 \) larger than the active solar corona and more luminous than either the dMe stars or the RS CVn binaries (see below). The properties of this radio radiation are consistent with gyrosynchrotron emission from mildly relativistic electrons. The cooler MCP stars (including the classical Ap(SrCrEu) stars) are not detected as radio sources with \( \log L_\alpha < 15.0 \). Another surprise was the detection of X-ray emission from several of the hotter MCP stars during the ROSAT all-sky survey (Drake et al., 1994). The X-ray luminosities are also large (\( \log L_x \approx 30.0 \)) with typical values of \( \log L_x / L_{bol} \sim -6.0 \), intermediate between typical values for the O-type stars and the active late-type stars.

Linsky et al. (1992) proposed a magnetospheric model to explain the radio emission properties of these stars. Radiation pressure in the B-type MCP stars accelerates a wind with mass loss rates that are far smaller than those of O-type stars and which decrease rapidly with decreasing effective temperature. These rates as calculated with standard radiatively driven wind theory decrease from \( \dot{M} = 10^{-7.5} M_\odot \text{ yr}^{-1} \) for spectral type B1 V to \( \dot{M} = 10^{-12.5} M_\odot \text{ yr}^{-1} \) for spectral type A2 V. The radio luminosities are consistent with the empirical relation \( L_\alpha \sim B_{rms}^2 M^{0.5} \), where \( B_{rms} \) is the rms value of the photospheric magnetic field strength. This relation indicates that the MCP stars are unlike the O-type stars, for which the free-free radio emission from the wind apparently does not depend on the stellar magnetic field, and are unlike the late-type stars, for which the radio emission does not depend on the mass loss rate. Thus the MCP stars form a new class of stellar radio sources.

In the Linsky et al. (1992) model the stellar wind plasma can leave the star near the poles where the field lines are open, but outflowing plasma is confined by the closed field lines near the equator. The wind pressure of this gas exceeds the local magnetic pressure at 10-20 stellar radii, drawing out the dipolar magnetosphere into a current sheet configuration similar to that found in the terrestrial magnetotail. Instabilities in this current sheet, especially for stars with misaligned magnetic and rotation axes, can lead to particle heating and acceleration. Nonthermal electrons spiralling back towards the star along the field lines produce optically thick gyrosynchrotron radio emission and the thermal electrons may be responsible for the observed X-ray emission. This emission mechanism is consistent with the radio angular diameters for two of these stars measured with VLBI techniques (Phillips and Lestrade, 1988). A schematic of this model is shown in Fig. 1. The magnetic structures in this model are similar to solar helmet streamers but with larger geometric scales. Also like the Sun the heating and acceleration of electrons is a consequence of the stressing of magnetic fields, but
for the MCP stars the stressing agent is the wind, whereas for the Sun the convection-driven motions of the footpoints of magnetic loops below the photosphere stress the field lines in the corona.

**Figure 1.** A schematic of the magnetospheric model for a magnetic chemically peculiar star proposed by Linsky et al. (1992). For simplicity an aligned rotator is shown. Electrons are accelerated in the current sheet and spiral back towards the star into regions of larger magnetic field. Higher frequency radio radiation originates in the higher field regions (darker stipple) closer to the star.

### 3. Coronal Structure of the RS Canum Venaticorum Binaries

Stars of roughly one solar mass evolve off the main sequence into the giant branch as slow rotators without detectable X-ray, radio, or even UV emission lines formed at $10^5$ K such as C IV 1550 Å. Those stars that are cooler than spectral type K2 III lie to the right of a dividing line in the H-R diagram (Linsky and Haisch, 1979) separating stars with and without evidence of stellar activity, but the presence of a close binary companion totally changes the behavior of these stars. The RS CVn systems, named after the prototype system RS Canum Venaticorum, are detached binaries (neither star fills its Roche lobe) in which one or both stars have evolved into subgiants or giants of spectral type G or K. Typically these binaries are close enough to have orbital periods less than about 20 days, in which case tidal forces can synchronize the orbital and rotational periods within evolutionary timescales. Thus one or both stars in RS CVn systems have deep convective zones characteristic of K-type subgiants and giants and rotational periods that are far more rapid than single stars of the same spectral type. This combination of deep convection and rapid rotation is conducive to an efficient magnetic dynamo, which is believed to be the underlying cause of stellar activity in late type stars.

There are no conclusive direct measurements of magnetic fields on these stars, presumably because rapid rotation makes it difficult to measure Zeeman line broadening.
for stars with photospheric magnetic field strengths predicted to be smaller than for the Sun on the basis of equipartition of magnetic pressure and the photospheric gas pressure, which is smaller for giants than for the Sun. Nevertheless, these stars must have magnetic fluxes that are far larger than those of the Sun on the basis of the large dark starspots covering up to 40% of the visible hemisphere (as inferred from their periodic optical light curves which have amplitudes as large as 0.3 magnitudes and Doppler imaging measurements of photospheric absorption lines, e.g., Vogt and Penrod, 1983). Doppler imaging analysis of Mg II h and k line spectra obtained at many phases during an orbit by the IUE satellite, permitted Neff et al. (1989) to locate three large plages in the chromosphere of the AR Lac system. The largest plage covered 9% of the surface of the cooler (K0 IV) star in the AR Lac binary and extended 0.5 $R_\star$ $\approx$ 1.5 $R_\odot$ above the stellar photosphere. This result is inferred from Doppler shifts that exceed the equatorial rotational velocity of the K0 IV star at certain phases, implying that the emitting structure extends above the limb if it is rigidly rotating (as expected for a magnetic structure) and the plasma is not flowing along the loop. The cool plasma ($T \approx$ 7, 000 K) in this large structure is almost certainly confined by magnetic loops that are very large compared to those seen on the Sun.

The corona of AR Lac has been studied extensively using the Einstein, Exosat, and ROSAT satellites. AR Lac is a particularly interesting member of the RS CVn class because this 2.0 day period system is bright in X-rays and the two stars (spectral types K0 IV and G2 IV) eclipse each other, providing useful probes of the coronal geometry of both stars. Einstein observations obtained in June 1980 near primary and secondary eclipse led Walter et al. (1983) to propose a model in which coronae with small scale heights ($\sim$ 0.02 $R_\star$) and high densities (about $5 \times 10^{10}$ cm$^{-3}$) similar to small solar flares surround both stars. They also found evidence for extended, asymmetric coronal plasma with a large scale height ($\sim$ 1 $R_\star$) and lower density (about $3 \times 10^9$ cm$^{-3}$) around the equator of the K0 IV star. They concluded that hot plasma, presumably confined by closed magnetic structures, may fill a volume comparable to the binary system with a stellar separation of 9.1 $R_\odot$. Simon et al. (1980) and Uchida and Sakurai (1983) have proposed that some field lines connect the two stars in RS CVn systems and that these field lines are continually stressed by differential rotation of the two stars.

White et al. (1990) used Exosat in July 1984 to observe AR Lac continuously for a full orbit. Their detection of a factor of 2 dip in the soft X-ray flux ($E < 1$ keV) centered on primary eclipse (total eclipse of the G2 IV star by the K0 IV star) and a shallow dip before secondary eclipse (annular eclipse of the K0 IV star by the smaller G2 IV star) indicated that cooler plasma ($T \sim 7 \times 10^6$ K) lies close to the two stars. On the other hand, the absence of any dips in the higher energy X-ray flux at the time of both eclipses indicated that hotter plasma ($T \sim 3 \times 10^7$ K) occupies a volume much larger than either star. This is additional evidence that hot plasma is likely confined by magnetic loops with lengths comparable to the binary separation. A very similar picture emerges from the Exosat observations of the 3.2 day system TY Pyx...
(G5 IV + G5 IV). Culhane et al. (1990) model the dips seen in soft X-rays in terms of a cooler coronal plasma in a compact active region near the surface of each star and hotter plasma that pervades the entire binary system.

A somewhat different picture appears in the June 1990 ROSAT observations of AR Lac analyzed by Ottmann et al. (1993). They find a deep primary eclipse at all X-ray energies, including the 1.1–2.4 keV band, and a shallow dip before secondary eclipse, indicating that both hotter and cooler coronal plasma is being eclipsed. Unlike Walter et al. and White et al., they find no compelling evidence that hot coronal plasma pervades the whole binary system. Instead, they fit the X-ray light curve with a model in which most of the emitting plasma lies in a small structure on the G2 IV star (scale height \( \sim 0.03R_\odot \)) and in a more extended structure near the K0 IV star (scale height \( \sim 1-2R_\odot \)). This model is similar to that proposed by Walter et al. (1983) based on data obtained 10 years earlier.

Probably a more accurate picture of the coronae of AR Lac and TY Pyx emerges from the reanalysis of the same Exosat data by Siarkowski (1992) and by Siarkowski et al. (this issue) using an iterative method to infer three-dimensional coronal models. They find extended coronal structures near and between the stars in the AR Lac system (see Fig. 2) and for TY Pyx a large active region on one star and bright emission located between the two stars. These models strengthen the case for large, presumably magnetic, loop structures extending to the inner Lagrangian point and perhaps connecting the two stars.

4. Coronal Structure of Active Solar-Type Dwarfs

4.1. Cool Loops above Starspots on V471 Tauri

Binary star eclipses also provide unique information concerning structures located within the coronae of solar-type stars, which otherwise would have to be modelled either as spherically symmetric sources or with the addition of an active region located in longitude when the X-ray light curve is periodic. There has been little work so far on identifying coronal active regions on G and K dwarf stars from x-ray light curve variations, but studies of the eclipsing V471 Tauri system have yielded important insights concerning the presence of large cool loops within the coronae of active solar-type dwarfs. V471 Tau is a 12.5 hour period eclipsing system consisting of a K2 V star and a hot \( (T_{\text{eff}} = 35,000 \, \text{K}) \) white dwarf. Since the white dwarf is small \( (R_\star = 0.0095R_\odot) \) and emits a bright, featureless UV continuum, one can measure the column densities of different ions in the K2 V star’s atmosphere from absorption features in the white dwarf spectrum when the star is above the limb of the much larger K2 V star before and after total eclipse. Periodic variations in the optical light curve of the dominant K2 V star indicate the presence of large starspots, which are expected for a star which is young (it is a member of the \( 6 \times 10^8 \) yr old Hyades cluster) and very rapidly rotating due to tidal synchronism.
Figure 2. A model for the coronal 0.05–2.0 keV X-ray emission in the AR Lac system obtained by Siarkowski (1992). The gray-scale is in units of $10^{-6}$ counts s$^{-1}$ looking down on the orbital plane.

IUE spectra of V471 Tau contain absorption lines of C III 1175 Å, C II 1335 Å, Si IV 1400 Å, and C IV 1550 Å just before and after those eclipses that occur when starspots are located near the portion of the K2 V star limb that is occulting the white dwarf star. This indicates the presence of $10^4 - 10^5$ K gas extending up to 400,000 km = 0.8$R_\star$ above the stellar surface. Guinan and Carroll (1990) interpret this absorption as due to cool magnetic loops located above the large starspots containing plasma at densities of $10^9 - 10^{11}$ cm$^{-3}$ (see Fig. 3). These absorption lines are not seen before or after other eclipses, indicating that only hot coronal plasma is present above the limb away from starspots. Cool magnetic loops (also called active region plumes) are often seen in the solar corona above sunspots (e.g., Foukal, 1976), but they extend only up to 100,000 km = 0.14$R_\odot$. In addition, the absorption of soft X-rays at certain phases (Jensen et al., 1986) and the presence of Hα emission features at radial velocities not associated with either star (Young et al., 1991) indicate the presence of transient cool material ejected by flares and lying between the stars.
Figure 3. A schematic diagram of the V471 Tauri system showing the presence of cool loops above spots on the K2 V star and a portion of the orbit of the white dwarf star before eclipse. From Guinan and Carroll (1990).

4.2. Large Prominences on AB Doradus and HD 197890

AB Doradus is a Pleiades age \((3 \times 10^7 \text{ yr})\) G8–K0 dwarf star with a periodic optical light curve that indicates the presence of starspots and a very short 0.51 day rotation period. As expected, this star has a very luminous corona with \(\log L_x = 30.4 - 31.4\) (Vilhu and Linsky, 1987). A long series of \(\text{H} \alpha\) spectra obtained by Collier Cameron and Robinson (1989) reveal the presence of transient \(\text{H} \alpha\) absorption and emission features (relative to the mean profile) that drift systematically from the blue to the red portion of the line profile during their 1–2 hour lifetimes (see Fig. 4). The roughly 190 km s\(^{-1}\) amplitude of this radial velocity drift is twice the projected equatorial rotational velocity \(v_{\text{sin} i}\) of the star.

Collier Cameron and Robinson explain these data with a model in which embedded in the hot, extended corona are cool “clouds” that corotate with the star producing absorption at the radial velocity of the portion of the stellar disk covered by the “cloud”. The \(\text{H} \alpha\) features indicate that the clouds are cool \((\sim 10^4 \text{ K})\). Using a skew-mapping technique, they find that the clouds preferentially form at 3–4 \(R_\star\) from the stellar rotation axis, just above the Keplerian corotation radius. The observed
corotation requires that the clouds be confined in very large magnetic loops. These loops initially contain hot x-ray emitting plasma, but as the loops expand the unstable plasma cools. The cool loops, analogous to solar prominences, that have expanded to beyond the corotation radius can leave the star transporting considerable angular momentum. Another Pleiades age K dwarf, HD 197890 also called “Speedy Mic”, displays many of the same properties as AB Dor (cf. R. D. Jeffries, preprint).

5. Some Concluding Thoughts

I hope that this brief summary of stellar coronal structures will encourage people to think of stellar coronae as being at least as complex as the solar example. While stars will never be studied in this much detail, high resolution spectroscopy, eclipses, Doppler imaging, and variability are just beginning to provide the tools needed to reconstruct the geometry of stellar coronae. We have already discovered that the Sun provides useful prototypes for many structures in stellar coronae.

Acknowledgements. This work is supported in part by grants from NASA to the University of Colorado and to the National Institute of Standards and Technology.

References

Figure 4. Models for the time behavior of cool clouds seen in projection against the surface of AB Doradus on 1984 December 11 and the corresponding synthetic Hα line profiles. From Collier Cameron and Robinson (1989).