THE SOHO-STEellar RE-CONNECTION

Thomas R. Ayres

Center for Astrophysics & Space Astronomy, University of Colorado,
389 UCB, Boulder, Colorado, 80309, USA

ABSTRACT

Ultraviolet and X-rays studies of stars can provide a valuable perspective on coronal heating, beyond the exquisitely detailed—but singular—case of the Sun itself. One can access the wide range of stellar properties relevant to the coronal heating problem, especially rotation rates, convection zone depths, and age. And, by observing the entire star all at once, instead of the tiny fields of view of contemporary solar imaging spectrometers, one can record in a collective way widespread global dynamical phenomena, which might be glossed over in the narrow view. Here, I will provide a few examples to illustrate these points; each one is accompanied by cautionary notes for solar observers based on the stellar experience.

Key words: stars, ultraviolet, X-rays, spectroscopy.

1. INTRODUCTION

In 1999, during the Monterey workshop on the solar corona, I presented a paper “The SOHO-Steellar Connection” (Ayers 2000), which described some of the then recent insights on coronal physics originating from studies of other stars, some Sun-like, others radically different. This was shortly after the launches of NASA’s Chandra X-ray observatory and the Far-Ultraviolet Spectroscopic Explorer; just before the orbiting of ESA’s X-ray Multi-mirror Mission (now known as XMM–Newton); and only two years after the installation of the superb Space Telescope Imaging Spectrograph in Hubble.

The five years since Monterey has witnessed a surge of progress in understanding the breadth and depth of coronal processes in the cool half of the Hertzsprung–Russell diagram. We now know that coronal phenomena extend to even the most pathic examples of stars, the L and T “brown dwarfs” (Neuhäuser 2000; Preibisch 2003); have discovered “buried coronae” on the old, spun-down non-coronal red giants (Aires, Brown, & Harper 2003); and increasingly have recognized the importance of flares in the coronal energy budgets of many types of objects: at the extreme top end of the activity scale—short-period tidally locked binaries (Osten & Brown 1999); at the bottom, among the fully convective red dwarfs (Linsky et al. 1995); and in the middle for age-diverse stars (Güdel et al. 2003).

To be sure, every recent insight on the stellar side has been accompanied by its fair share of new puzzles. Thus, it now is even more imperative than ever to bring together the two perspectives on coronal processes: the broad but detail-lite views of the myriad distant suns, with the narrow but information-rich probes of our nearby star. Here, I will attempt to make that reconnection from the stellar side, focussing on recent UV and X-ray results. This update admittedly will be highly biased, drawing mainly on my own recent work, and that of my collaborators; and concentrating on a few areas of potential importance to the coronal heating problem; while slighting the vast, rich literature on high-energy stellar processes not connected with solar coronal phenomena.

Figure 1. Coronal H–R “bubblegram.”

2. THE CONVENTIONAL WISDOM

The broad outlines of our understanding of coronal behavior in the cool half of the H–R diagram can be summarized in the following three charts. Although it will be obvious that the main controlling factor in stellar activity is rotation, through the well-known hydromagnetic dynamo (Parker 1977), the true power source is, of course, turbulent convection. That is why coronal activity is most conspicuous among cool convecting stars, those of spectral types later than about early-F (Vaiana & Rosner 1978).

Figure 1 illustrates the general behavior of coronal activity in an X-ray H–R diagram. Each bubble represents...
the location of an X-ray star in surface temperature and bolometric luminosity; the size of the bubble is proportional to $R_X \equiv L_X/\dot{L}_{\text{bol}}$ according to the legend (the activity ratio removes any bias associated with unknown stellar distances or sizes). The soft X-ray measurements come from the all-sky survey, and selected pointed observations, of the German ROSAT satellite, which was a prolific source of coronal data for cool stars over its nearly decade-long mission in the 1990’s (see Ayres et al. 1995). Red shaded bubbles represent main sequence (“dwarf”) stars; yellow bubbles are for evolved giants and supergiants. The curves are evolutionary tracks (enumerated later in Fig. 2, below), ranging from just below 1 $M_\odot$ at lower right, to 9 $M_\odot$ at upper left. Three features of the diagram are worth noting.

First, there is a broad range of activity levels on the main sequence, exhibited by the age-diverse sample of stars obtained in flux-limited surveys of the solar neighborhood.

Second, among the ordinary (class III) giant stars, there is a region in the middle of the H–R diagram where most of the stars appear to be X-ray active, while to the right of that region (where the evolutionary tracks take a turn upward into the giant branch), coronal sources are very faint or absent entirely. The region of high stellar activity corresponds to the “Hertzsprung gap” (described in more detail later), while the coronal void to the right is the so-called “noncoronal” zone identified originally by Linsky & Haisch (1978) on the basis of early surveys of the coronal proxy C IV, and later confirmed with direct X-ray measurements (Ayres et al. 1981). This region also is known as the “coronal graveyard” (Ayres, Fleming, & Schmitt 1991) for reasons that will be clear in a minute.

Third, the whole upper part of the diagram, the realm of the supergiants, is generally lacking in strong X-ray detections: although legitimate sources certainly are present, the overall scale of activity as measured by $L_X/\dot{L}_{\text{bol}}$ is significantly depressed compared to MS stars or Hertzsprung gap giants.

These general features of the X-ray H–R diagram can be explained in at least a superficial way by simple consideration of stellar evolution principles, as illustrated in Figure 2.

This diagram plots the locations of selected cool stars for which high-quality UV spectra are available from Hubble Space Telescope’s first-generation spectrometer GHRS (red-outlined symbols) or second-generation STIS (blue-outlined). Here, the evolutionary tracks are marked with the corresponding stellar masses. The red hatched region indicates the Hertzsprung gap, allude to above, the orange oval is the post-helium flash “clump,” and the green polygonal area is where strong, cool stellar winds ($T \approx 10^4$ K vs. $10^6$ K for the Sun) are found. The latter partly coincides with the noncoronal zone, leading early workers to conclude that the outflows were perhaps draining away energy that otherwise would power hot coronae: Linsky & Haisch (1979).

Let’s consider the main sequence first. At the birth of low-mass stars like the Sun, accretion from the protostellar envelope injects an impulse of angular momentum, bringing about a brief period of strong dynamo action and intense coronal activity. While the star ages, however, the activity fades as the stellar spin is persistently braked by the magnetized coronal wind. I find this negative feedback to be a fascinating aspect of the dynamo, as well as the major controlling force in its evolution, at least among single stars and wide binaries. Thus, age inversely equates to rotation rate among single low-mass MS stars, and random samples of such objects generally will show a broad spread in activity.

Eventually, the old slowly rotating dwarf evolves into a red giant, climbing up to helium flash: evolutionary expansion guarantees even slower rotation, thus accounting for the dearth of dynamo/coronal activity in the zone where the low-mass evolutionary tracks turn steeply upward. This is the magnetically inactive (although not quite dead, as we’ll see below) coronal graveyard mentioned previously.

Next, consider the moderate-mass giants ($\approx 3 M_\odot$) in the Hertzsprung gap, which follow an entirely different path in their coronal evolution than lower-mass stars like the Sun. As fast spinning A and B dwarfs, they lose little angular momentum during their MS lives. When such stars develop into post-MS giants, and first become convective as they cross rapidly through the F spectral
types, they begin to display symptoms of strong magnetic activity: intense C IV emission in the FUV, and kilovolt soft X-rays. (The rapidity with which these stars cross into the cool half of the H–R diagram, and the relatively small population of MS progenitors compared with the much more common low-mass dwarfs, makes the “first-crossers” relatively rare, thus creating a conspicuous “gap” in color–magnitude diagrams.) However, the Hertzsprung gap stars exhibit a puzzling “X-ray deficiency”—their X-ray/C IV flux ratios are only about 10% of those of later-type giants (Simon & Drake 1989; Fig. 3 below)—and “super-rotational broadening” of their hot UV features (like C IV), with line widths up to 2× expected from their photospheric $v \sin i$ (Ayres et al. 1998).

On the red side of the gap, in the mid-G spectral types, stellar rotation rates suddenly plummet (Gray 1981), in a narrow region called the Rapid Braking Zone (RBZ). Ironically enough, it likely comes about by the strengthening of dynamo action as the evolving convection zone deepens—although the corona intensifies temporarily, magnetic wind braking is highly effective in giant stars (owing both to large surface areas to enhance the overall mass loss, and large Alfven moment arms, beyond which the entrained flow breaks free of the stellar field), and very soon the stellar spin, the dynamo, and its associated activity are quenched (much like what happens to the low-mass stars by middle age).

The mid-G first-crossing gap giants display much reduced coronal activity compared with their predecessors at the brink of the RBZ, but typically much higher levels than at the subsequent stages of evolution. In particular, these stars next ascend the giant branch, ignite helium in their partially degenerate cores (a stage called helium flash), and then return to the base of the giant branch as core-helium burners. This “second-crossing” phase is much longer lived than the first crossing, and stars from a range of masses tend to congregate there, creating a “clump” in color–magnitude diagrams. One would think, after all of the trauma of helium flash and prolonged mass loss in the clump phase, that these giants would be as coronally inactive as their middle-aged hydrogen MS dwarf counterparts, like the Sun. That expectation is met by most of the clump denizens, but there is a puzzling small percentage of these giants that are anomalously X-ray active: $\beta$ Ceti (K0 III) and the G8 III primary of the $\alpha$ Aurigae binary are good examples in the solar neighborhood (Ayres, Schiffer, & Linsky 1983).

The final region to consider is that occupied by the supergiants. These should evolve in a way roughly similar to the moderate-mass giants in the Hertzsprung gap, except that here we are dealing with more massive stars that have correspondingly shorter lives, with much more centrally condensed interiors. These objects stray so far from the solar paradigm that I don’t wish to say much about them, except to note that there are examples of coronally inactive G supergiants that possess strong low-temperature winds sitting right beside (in an H–R diagram sense) X-ray active G supergiants lacking any circumstellar signa-

tures of cool winds; but otherwise ostensibly identical to their “quiet” neighbors in mass, luminosity, age, and surface temperature.

![Figure 3. Flux–flux diagram for F–K giants.](image)

Figure 3 is a “flux–flux” diagram comparing X-ray (in the energy band 0.2–2 keV) and C IV (1548+1550 Å) fluxes normalized to $L_{bol}$ (i.e., the fraction of the stellar luminosity emitted in these species). In this rendition, the drawn symbols represent luminosity class III giants, separated into three spectral type groups according to the legend in the lower right hand corner. The shaded zones in the diagram represent schematically the locations of other classes of stars, as described in more detail below.

As demonstrated in large-scale surveys such as Ayres et al. (1995), flux–flux diagrams usually display power-law correlations between coronal and subcoronal tracers, $R_X \sim R^\alpha_q$, with $R \equiv L/L_{bol}$, particularly among F–K MS stars where the relations are tight, although the power law exponents $\alpha$ vary slightly with spectral type (reflected by the wedge-shaped region 1 in the figure). Moderately active mid-G–K0 giants (as gauged by $L_X/L_{bol}$) to the left of the Linsky-Haisch noncoronal boundary fall into region 4, while low-activity K0–1 clump giants at the L–H dividing line tend to fall in region 5, which lies somewhat below a simple extrapolation of the active-giant behavior. Zones 2 and 6 are notable in this regard. The former contains the G supergiants, while the latter is where most of the fast-rotating, fast-evolving F–G0 Hertzsprung gap giants are found. Both of these regions are “X-ray deficient” with respect to MS stars of

© European Space Agency • Provided by the NASA Astrophysics Data System
the same $L_{CV}/L_{bol}$ (e.g., Simon & Drake 1989), signaling perhaps a systematic dramatic change in coronal properties. The Hertzsprung gap stars jump to zone 4 as they cool off through the mid- and late-G spectral types, on their way to the base of the red giant branch.

Zone 3 is where the hyperactive short-period binaries are found. Unlike single stars, the close binaries are tidally spun up so that the rotation periods are slaved to the orbital period. And, as they age, angular momentum lost by the two stars in their coronal winds is replenished from the large reservoir in the orbit. However, the stars nevertheless are drawn closer to one another as the orbit gradually collapses, and the components thus spin ever more rapidly as they grow older; in contrast to single coronal stars, the close binaries exhibit positive dynamo feedback. Ultimately, these systems will form something like a W Ursae Majoris-type contact binary, which subsequently will coalesce, with perhaps catastrophic evolutionary consequences.

The most famous of the short-period binaries is the RS Canum Venaticorum class, consisting usually of a mildly evolved early-K subgiant, a few times larger than the Sun but only slightly more massive, and a main sequence companion typically of solar-type (Hall 1978). There are cases of RS CVn systems, however, where both components are dwarf stars with about equal—and very extreme—levels of activity: a good example is $\sigma^2$ Coronae Borealis ($F9 V + G0 V, P = 1.2 d$, Strassmeier & Rice 2003). Solar-type stars in RS CVns can have quiescent X-ray luminosities a thousand times larger than the Sun’s, a rather extreme level of coronal activity to be sure, raising important questions of how coronal heating can be sustained at values near 0.1% of the total bolometric flux. The situation worsens considerably during flares, where over the course of a few hours the X-ray luminosity brightens to several times the pre-flare level (e.g., Osten et al. 2003; their Fig. 4 for a Chandra grating observation of $\delta^2$ CrB). The fast radiative cooling timescales indicate that the flare area is a small fraction of the stellar disk, yet that tiny region is capable of—at least temporarily—outshining by several times the entire already extremely active corona of the system. A proper discussion of the short-period binaries is beyond the scope of this review, but I mention them here because they represent the extreme top end of stellar coronal activity.

The final zone to be mentioned is number 7, in the lower left corner of the figure. This is the coronal graveyard, inhabited by evolved single red giants of near-solar mass; the very bottom end of the coronal activity scale. These objects are extremely faint in coronal X-rays, and to date only the optically brightest (Arcturus: a Boo; K1.5 III) has been positively detected in X-rays, and then just barely. These old, spun-down stars meet our expectations of extremely weak dynamo activity, yet the full—surprising—story on these objects has become clear only recently, as we will see later.

The X-ray/C IV flux—flux diagram is rich in diagnostic detail, particularly in informing our understanding of the dramatic changes in the global structure of the stellar corona that accompanies stellar evolution. Again, however, much of that discussion is beyond the scope of the stellar-solar connection, so I will focus on three key aspects.

First, the Sun follows a trajectory in the flux—flux diagram over its activity cycle that fully parallels the $\alpha = \frac{3}{2}$ power law that is defined by the age- (and cycle-) diverse samples of early-G field and open cluster stars (Ayres et al. 1995; Ayres 1999). At the same time, the stellar samples religiously follow equally tight power laws between their coronal emissions and equatorial rotational velocities. This means that at the peak of its activity cycle, the Sun is behaving as if it were rotating somewhat faster than normal, while at minimum it behaves as if it were rotating somewhat more slowly. Although this might seem to be a trivial point, one could imagine, on the contrary, that the Sun (and other G stars) might have obeyed a different behavior over its cycle, say an $\alpha = 1$ linear relation; and that the $\alpha = \frac{3}{2}$ emerges only when one compares a broad range of rotationally-diverse stars at random phases of their cycles. The importance of this point will be addressed further below.

Second, at the relatively low level of coronal activity exhibited by the Sun, the FUV C IV $\lambda 1548,50$ doublet radiates nearly as much luminosity as the entire 0.2–2 keV corona. This is a rather curious fact, with regard to the traditional picture of coronal loops in which the X-ray radiation from the bulk of the $\sim 10^6$ K magnetically confined plasma is comparable to the conductive flux down through the loop footpoints (e.g., Rosner, Tucker, & Vaiana 1978), which ultimately is degraded into FUV transition zone emission (i.e., near $10^6$ K). In particular, C IV is only one of several important TZ emissions (including the bright O V $\lambda 630$ and C III $\lambda 977$ lines), so $L_{C IV}$ is a lower limit to the true radiative loss from the subcoronal layers. Including hydrogen and helium lines makes the disparity even worse. Thus, either the collection of magnetic structures that makes up the solar corona does not globally obey the rough equipartition—between the high-energy radiative losses and the downward conductive flux—predicted by classical quasi-static coronal loop models, or there is a large population of purely subcoronal structures lacking plasma (or at least detectable emission) at coronal temperatures. Another implication is that even among the highest luminosity coronal X-ray sources, the total FUV line emission probably still is comparable to the high-energy kilovolt flux. This can be important for understanding the photochemistry of accretion disks around protostars, as well as the radiative erosion of primitive planetary atmospheres in young solar systems (including our own: see, e.g., Ayres 1997; Guinan, Ribas, & Harper 2003).

Third, the fact that the power law between the coronal and subcoronal diagnostics is nonlinear suggests that there is not some fundamental “quantum” of activity, that simply becomes spatially more pervasive as the overall activity level increases; otherwise, an $\alpha = 1$ relation would be found. In fact, when one examines the X-
ray temperatures of stellar coronae—say using line ratios in resolved Chandra or XMM–Newton grating spectra—one finds that coronae become systematically hotter (and denser) with increasing X-ray activity level (e.g., Ness et al. 2003). This is another indication that the nature of coronal heating changes systematically with the level of magnetic activity, much as the relatively bland coronal appearance of the Sun at cycle minimum gives way to a more highly structured, active-region dominated situation at maximum.

That concludes the overview of coronal behavior among more-or-less normal dwarfs and giants of near-solar spectral class. I now will move on to a few specific applications, to draw the stellar-solar connection a bit tighter.

Figure 4. X-ray bubblegram for solar-like stars.

3. THE SOLAR X-RAY CYCLE

A central dilemma in comparing the Sun to the stars is that in some cases the instruments used to observe the one are vastly different in concept and design from those pointed at the other. An obvious difference is that solar observations typically exploit spatial resolution: over a small field of view, perhaps, in spectroscopic observations with SUMER; or the full disk in the case of, say, an EIT or Yohkoh frame. Stars, in contrast, must be observed as unresolved point sources. The lack of spatial resolution on the stellar side is both a curse and a blessing. A curse, because we know from the Sun that the corona is highly structured on a hierarchy of scales extending from enormous coronal streamers down to below even the grasp of contemporary solar instruments. A blessing (of sorts, to be sure) because we can devote the extra real estate on our stellar detectors to pack in, say, broader spectral coverage than is achieved in typical solar work. In addition, as we will see later, there might be relatively subtle global phenomena that can be recovered easily when a star is observed as a point source, all at once; which might be much more elusive in a typical long-slit observation of the solar surface, which captures only a very narrow field of view in each exposure.

A good example of the potential effects of instrumental bias is embodied in a recent study by Judge, Solomon, & Ayres (2003). The authors addressed the practical question of the strength of the solar corona, and its cycle variations, as it would have been seen in soft X-rays by ROSAT; the instrument responsible for the most detailed and extensive stellar coronal surveys to date. Previously, there had been a disconnect between the solar view of the Sun in coronal X-rays, which reported enormous variations over the solar cycle (e.g., Orlando et al. 2001; almost a factor of $10^2$ in the 0.1–2.4 keV band), and surveys of solar-type stars in clusters like the Hyades which saw hardly any differences between the X-ray levels of individual members despite the fact that the stars must be in random phases of their cycles (Stern, Alexander, & Acton 2003). The resolution of the dichotomy was the recognition that oftentimes the solar cycle results were derived from instruments that favored the more energetic (“harder”) coronal radiations, such as Yohkoh and the GOES flare monitors, which can strongly skew the interpretation compared with what the relatively soft response of ROSAT would record.

Judge et al. exploited an array of ultra-soft X-ray photometers on the Student Nitric-Oxide Explorer satellite to reconstruct what ROSAT might have seen if it had been equipped to observe the Sun. Fig. 4 depicts the range in solar X-ray activity over a portion of the present cycle observed by SNOE, and extrapolations to a full average cycle using historical measurements of the coronal proxy C IV and a scaling law between X-rays and C IV deduced from the SNOE epoch. The Sun falls near the bottom of the ROSAT coronal activity scale, and the FWHM variation over a full solar cycle is about a factor of six, substantially smaller than many of the earlier estimates. The latter point is emphasized in Fig. 5 in histogram form.

The bottom line is that the Sun’s corona is perfectly normal in its strength and variation over the sunspot cycle; a comforting fact, no doubt, to those who would seek to model dynamos and coronal heating under the assumption that the Sun is an ordinary example of a star, not an oddball.
4. UV SPECTROSCOPY OF STARS

Another example of a fundamental difference between solar and stellar observational capabilities can be found in the UV. Figure 6 illustrates a full UV atlas, 1150-3000 Å in 50 Å segments, of the nearby solar twin α Centauri A (G2 V), obtained at high spectral resolution ($R \equiv \lambda/\Delta \lambda = 110,000$) using HST STIS (Pagano et al. 2004). The broad, strong H I λ1215 Lyα feature, with central ISM absorption, can be seen at about 0.4 Å, while the important mid-chromospheric 2800 Å doublet of Mg II can be seen near the top of the figure (note the twin self-reversed emission cores—at left and right, four and five traces down—at the bottom of the broad blended absorption profiles). This is the highest quality—in spectral resolution and S/N—ultraviolet tracing of any solar-type star, including the Sun itself. In contemporary solar work, spectral resolution, spectral coverage, and even S/N are sacrificed to some extent to push the domains of spatial coverage and time resolution; both essential to record the highly dynamic corona and subcoronal layers.

One might ask whether these sacrifices are worthwhile. One should be especially concerned about the spectral resolution part, because high dispersion guards against accidental blends and allows one to record subtle—but dynamically significant—line Doppler shifts and asymmetries. Figure 7 depicts what happens to the innate profiles of the C IV doublet (as recorded at 110,000 resolution: black curve) as one degrades the resolution to 20,000 (red) and 10,000 (blue). The profiles are shown on a linear scale in the upper panel, and logarithmic in the lower; the green curves are 1σ photometric noise levels. Note the weak emission blends in both C IV components, particularly λ1550. Modern solar UV spectrometers, such as SOHO SUMER, utilize resolutions of around 15,000; which by the comparison in Fig. 7 must be considered perfectly adequate. Again, the stars have provided some comfort to solar observers. At the same time, there is a woeful, unconscionable lack of wavelength calibration lamps on solar UV spectrometers, which enormously hinders the proper assessment of subtle Doppler shifts associated with TZ downdrafts, and outflows in coronal plume regions. All of the HST UV spectrometers, on the other hand, have been exquisitely calibrated by such lamps, to the great benefit of the stellar science.

4.1 Dynamics

Many late-type stars have been observed with STIS, with good enough S/N to accurately measure line shapes and Doppler shifts. Figure 8 illustrates C IV line profiles of several solar-like dwarfs (upper panels) and dM flare stars (lower panels). The two components of the C IV doublet were scaled to the same peak flux and overlaid. If optically thin, they should have identical line shapes, aside from any disturbing blends. The thin blue curves (smooth and dashed) are Gaussians fitted (sparely) to the cores of the features. In the active solar-type dwarf ξ Bootis A (G8 V) there is evidence for a second line component of lower amplitude, but much broader. These so-called
“broad components” (e.g., Wood, Linsky, & Ayres 1997) are particularly conspicuous in the red dwarf flare stars, and are though to arise from global averaging over pervasive “explosive events” like those seen commonly in the solar network and attributed to X-point reconnection jets (e.g., Innes et al. 1997).

Figure 9 compares dynamical properties of TZ lines in five solar-type dwarfs. Alpha Cen A and τ Ceti are low-activity objects; the other three are highly active. The line Doppler shifts are arrayed in order of increasing formation temperature. The high-excitation doublets of Si IV, C IV, and N V are marked with vertical lines: orange, green, and blue, respectively. Features in the range $T < 10^4$ K are narrow optically thin chromospheric lines: the red line is their average. The photospheric radial velocity has been subtracted from all the measurements of a given star. Several points can be made here.

First, the low-excitation chromospheric lines fall close to the photospheric velocity, in fact typically within the uncertainties of published values of the latter. This is potentially comforting news for those solar spectroscopists who use narrow chromospheric emissions, say in a SUMER spectrum, to calibrate the drifting zero point of the wavelength scale. Secondly, all the dwarfs exhibit redshifted TZ lines at about the same amplitude, with no obvious differences between active and quiet stars. Finally, there appears to be a trend of decreasing redshift going from the warmer (F-type) to cooler (late-G) stars. That trend is emphasized when one considers also the dM stars (Table 1, below).

The STIS wavelength scales are so precisely tied together, by the internal lamp calibrations, that one can straightforwardly combine profiles of similar-excitation species from widely differing wavelengths; coadding them to improve S/N and compensate for hidden blends. Figures 10 and 11 depict this procedure for two representative stars: familiar α Cen A and active yellow giant μ Velorum (G5 III). The right hand upper panels show the superposition of the scaled components of the Si IV, C IV, and N V doublets; the right lower panels show the “hot-line” average ±1 σ and an analogous coaddition for narrow chromospheric emissions of O I and C I (smaller profile). The left panels illustrate double-Gaussian fits on linear and logarithmic scales. Note that the hot lines in both objects are nearly isomorphic, so that the coaddition will succeed in emphasizing properties that are common to all three doublets. Note also the extended blue wing of the μ Vel profile: some flare activity occurred during the STIS observations, and apparently a substantial amount of $10^9$ K material was ejected at speeds up to 400 km s$^{-1}$, much faster than the photospheric escape velocity.

© European Space Agency • Provided by the NASA Astrophysics Data System
Figure 10. Coadded hot-line profiles $\alpha$ Cen A.

Figure 11. Same, for yellow giant $\mu$ Velorum.

Table 1 summarizes properties of the decomposed average hot-line profiles of four separate groups of stars. The average standard deviations within each sample are as follows: column $\#3$, $\sim$ 1 km s$^{-1}$; column $\#4$, $\sim$ 5 km s$^{-1}$; column $\#5$, $\sim$ 4 km s$^{-1}$; column $\#6$, 3–30 km s$^{-1}$. Note that the narrow components are dominantly redshifted in all the stars, but the velocity amplitude decreases with increasing surface gravity (G$\rightarrow$M, III$\rightarrow$V). The broad components, too, are dominantly redshifted, with an amplitude typically twice that of the corresponding narrow component. The broad component flux ranges from about 20% up to 60% of the total, well correlated with the $R_{CIV}$ activity index. The lowest value is from solar-like $\alpha$ Cen, but even the 22% contribution is much larger than the $\sim$ 5% deduced from spectral imaging of the solar TZ (see Wood, Linsky, & Ayres 1997). Finally, in both the dwarfs and giants, the broad components are about 2.7$\times$ wider than the narrow components, while the narrow components of the giants are about 1.6$\times$ wider than the narrow components of the dwarfs. Measurements like these will provide important input into future discussions of coronal dynamics and heating mechanisms.

Table 1. Broad and Narrow Components.

<table>
<thead>
<tr>
<th>Group</th>
<th>$N_*$</th>
<th>$v_{\text{narrow}}$</th>
<th>$W_n$</th>
<th>$v_{\text{broad}}$</th>
<th>$W_b$</th>
<th>$f_b/f_{\text{tot}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>G V</td>
<td>5</td>
<td>+4.3</td>
<td>+5.9</td>
<td>+103</td>
<td>0.22</td>
<td>0.54</td>
</tr>
<tr>
<td>K V</td>
<td>3</td>
<td>+2.2</td>
<td>+6.8</td>
<td>78</td>
<td>0.46</td>
<td>0.56</td>
</tr>
<tr>
<td>M V</td>
<td>4</td>
<td>+1.6</td>
<td>+8.0</td>
<td>105</td>
<td>0.35</td>
<td>0.42</td>
</tr>
<tr>
<td>G III</td>
<td>4</td>
<td>+6.5</td>
<td>+12.2</td>
<td>156</td>
<td>0.49</td>
<td>0.61</td>
</tr>
</tbody>
</table>

Notes: $W$ is FWHM, $v$ is Doppler shift; both in km s$^{-1}$

4.2 Coronal Forbidden Lines

In addition to the chromospheric and TZ temperature range amply covered by resonance lines in the FUV, there are a number of forbidden lines of highly ionized species—primarily iron—that probe coronal temperatures. The most prominent are Fe XIII $\lambda\lambda 1242,1349$ ($\sim 2 \times 10^{6}$ K) and Fe XXI $\lambda 1534$ ($\sim 1 \times 10^{7}$ K) in the STIS range, and Fe XVIII $\lambda 974$ in the FUSE bandpass. Figure 12 illustrates Fe XXI profiles from HST STIS observations of several late-type stars (Ayres et al. 2003). (Note the blend with a weak C I line: it is easily corrected.) Additional candidate coronal forbidden lines in the 920–1180 Å region were reported in a companion FUSE study by Redfield et al. (2003).

The significance of the FUV coronal features is twofold. First, although these features are faint, they are observed with spectrometers that have resolutions some twenty times, or more, better than the best contemporary cosmic X-ray spectrometers (of Chandra and XMM–Newton). This is a crucial advantage for studies of gas kinematics associated with flare activity, or separating the coronal contributions of the components of a spectroscopic binary system (see Ayres et al. 2003). Second, the FUV region is longward of the major opacity barrier presented by atomic hydrogen below 912 Å, and as well by neutral and singly ionized helium at shorter wavelengths. The presence of these photoionization continua means that the chromosphere is extremely opaque to radiation below 300 Å, in the extreme ultraviolet where important solar coronal spectrometers, like SOHO CDS, operate. From a practical point of view, then, the large chromospheric volume is invisible in the EUV; and it is not possible to probe any coronal processes that might be occurring in those layers, at least with EUV spectroscopy. However, the FUV coronal forbidden lines fall in the opacity window longward of the Lyman edge, and thus could be used to focus on coronal phenomena that might be hiding deep in the cooler chromosphere.
I could go on at length concerning this subject, but instead I point the interested reader to the excellent recent review, “X-rays from Stars,” by Manuel Güdel (2004).

The main point I want to make here is that we currently have nothing on the solar side that is remotely comparable to the broad spectral coverage and high resolution of, say, the Chandra gratings. The crystal spectrometers of Solar Maximum Mission did provide a series of excellent high-resolution X-ray spectra two decades ago, but mainly in limited energy bands and mostly in flares. I believe solar coronal physicists are missing an important opportunity—to diagnose physical conditions in coronal plasmas on the Sun—by not developing and deploying a next generation of high-resolution X-ray spectrometers.

5. STELLAR X-RAY STUDIES

A lot can be said concerning recent X-ray studies of late-type coronal stars, particularly with the spectacularly successful Chandra and XMM–Newton observatories. Chandra has much better imaging capabilities than XMM–Newton (1″ versus ~ 10″), and higher spectral resolution (up to $E/\Delta E \sim 2000$ for Chandra’s Low-Energy Transmission Grating mode versus ~ 300 for XMM–Newton’s Reflection Grating Spectrometer); while XMM–Newton excels in sensitivity, wider fields of view, and better-quality $R \sim 50$ CCD spectral imaging (the Chandra CCD cameras suffered unexpected damage from, ironically enough, low-energy solar protons early in the mission).

Both Chandra and XMM–Newton have recorded excellent coronal X-ray spectra of a few dozen late-type stars each. Many of these objects are much more active than the Sun, a bias of instrumental sensitivity limits, so their relevance for understanding the solar corona is debatable.

Both Chandra and XMM–Newton have recorded excellent coronal X-ray spectra of a few dozen late-type stars each. Many of these objects are much more active than the Sun, a bias of instrumental sensitivity limits, so their relevance for understanding the solar corona is debatable.

Both Chandra and XMM–Newton have recorded excellent coronal X-ray spectra of a few dozen late-type stars each. Many of these objects are much more active than the Sun, a bias of instrumental sensitivity limits, so their relevance for understanding the solar corona is debatable.

5.1 Buried Coronae

I conclude the discussion of recent X-ray work with an example that illustrates the important synergy between X-ray and UV observations, and perhaps conveys an important message for studies of solar coronal activity: the case of the buried coronae.

A recent study of the “noncoronal” giants Arcturus and
Aldebaran (α Tauri: K5 III) using the High Resolution Camera (HRC) of Chandra obtained a mildly significant detection of the former (3 events on a negligible background), but only an upper limit for the latter (Ayres, Brown, & Harper 2003). Figure 13 illustrates in the main panel the new 19 ks Chandra observation (small red points) on top of a previous ROSAT PSPC image of comparable exposure duration (contours). The two small circles show the predicted positions of the red giant in the two different epochs. Selected Chandra sources are shown at higher resolution in the upper panels, as spatial maps of the individual X-ray events. Panel 1 is further magnified in the top frame to show the 3 events detected at the position of Arcturus; a highly significant result, because the expected background (0.2 counts) is negligible, and a fluctuation in the background as large as 3 events is highly unlikely. At the same time, Poisson statistics tells us that our knowledge of the intrinsic source flux is poor.

Figure 14. Flux-flux diagram for red giants.

Despite the tentative HRC detection of Arcturus, Figure 14 shows that the 0.2–2 keV emission still is at a very reduced level compared with low-activity early-K “coronal” giants (zone 5). The chart is a revised X-ray/C IV flux-flux diagram (like Fig. 3) focussing on a sample of noncoronal giants originally surveyed by ROSAT, but now including the new Chandra results, and revisions of several of the earlier ROSAT detections, for which new positional registrations of the PSPC frames revealed that the apparent X-ray source was significantly offset from the predicted stellar location (see Ayres 2005).

Figure 15. Buried corona scenario.

The plot thickened, however, when close examination of HST STIS spectra of Arcturus and Aldebaran revealed that not only were the usual TZ lines—like C IV—present, albeit weak; but also some of the hot lines exhibited absorption features from overlying relatively cool species, like Ni II, suggesting that the C IV-emitting structures are at least partially buried in the thick stellar chromosphere. Thus, any soft X-rays that might be associated with these structures are apt to suffer substantial attenuation.

This effect can occur because atmospheric extension is amplified in giants and supergiants relative to main sequence stars: the pressure scale height is inversely proportional to the surface gravity, g, and thus directly proportional to the radius squared, $R^2$. If the average size of coronal magnetic loops scales only as the radius, $R$, then such structures might be well-exposed above the thin atmosphere of a high-gravity dwarf star, but partially or wholly buried within the thick chromosphere of a giant or supergiant. Under these circumstances, the “noncoronal” character of the red giants might be viewed as a bias of the internal absorption of intrinsic coronal X-rays, rather than an absence of the associated $10^6$ K material. Figure 15 is a cartoon of the buried corona scenario: when scaled to the stellar radius, the thickness of a K giant chromosphere is many times that of a high-gravity dwarf like the Sun; yet, the depth of the red giant’s convection zone—which likely determines the length of magnetic loops—is approximately the same fraction of its radius as the Sun’s ($\sim 30\%$).

The case of the buried coronae not only informs our understanding of high-energy processes in the H–R diagram, but also provides an important caution on the solar side. We now suspect that the red giants, despite their implied lack of any sensible dynamo activity, still manage to produce atmospheric magnetic flux and associated
coronal phenomena. This reinforces the idea from the solar side (e.g., Hagenaa, Schrijver, & Title 2003) that magnetic flux can be generated by direct convective processes without the catalyzing agency of differential rotation, which seems to be so important in the large-scale dynamo. We imagine that a red giant like Arcturus has a solar-like “magnetic carpet” and associated network, but no active regions: a star firmly stuck in an evolutionary Maunier minimum. However, the very presence of magnetic flux in the outer atmosphere of the giant, when previously it was believed that such stars were magnetically defunct, offers the prospect that the fields might play a key role in accelerating the red giant wind: the driving mechanism is a long-standing mystery (cf., Rutmann & Cuntz 1995), not unlike that of coronal heating itself.

The cautionary part of the tale is that buried coronal activity might not be confined solely to the bloated red giants, but might in fact be occurring on dwarf stars as well. As mentioned before, such activity will be entirely hidden from our sight, unless we observe through atmospheric opacity windows that reach to the deepest levels of the chromosphere.

6. TYING IT ALL TOGETHER

The Sun is a very representative coronal star, yet near the bottom of the activity heap, befitting its advanced age and slow rotation. Thus, while there is a great opportunity to learn about the detailed micro- and macrophysics of coronal phenomena on our nearby star, it would be foolish not also to examine the extreme X-ray suns for insights concerning the operation of magnetic plasma processes at the pinnacle of the activity heap.

In this regard, the main lessons we have learned so far from high-resolution ultraviolet spectroscopic studies of active stars are: (1) the central role played by dynamics, manifested in the broad and narrow components of the lithium-like resonance lines at TZ temperatures; and (2) the prevalence and importance of flares. The study of dynamical phenomena on the solar surface, and on unresolved stars, benefits enormously from having a reliable wavelength scale, whose short-term thermal drifts are carefully monitored and compensated. Stellar UV spectrometers, such as on the pioneering International Ultra-violet Explorer and the more contemporary Hubble Space Telescope, utilize Pt-Ne hollow-cathode emission lamps for the purpose, and these calibration sources have proved to be rugged, long-lived, and extremely accurate. Ironically enough, however, I am not aware of any solar UV spectrometer that has utilized this type of metrology, even though accurate measurements of dynamical phenomena in the solar atmosphere clearly are important. The stellar side also is aided by the fact that typical dwarf spectrometers employ several times the spectral resolution of their dayside counterparts, although for most purposes—say TZ dynamics—the typical solar resolution of 15,000 in the FUV should be adequate.

A more subtle lesson has come from the recognition that red giant coronae can be smothered beneath their extended chromospheric envelopes, thus extinguishing the telltale X-ray signature of high-energy magnetic activity. Might not a similar effect be happening in the solar outer atmosphere, whereby short—but X-ray active—loops could be submerged entirely in the chromosphere, and thus be invisible to solar X-ray or EUV imagers owing to the formidable opacity wall presented by chromospheric atomic hydrogen (and helium)? The lesson here is that there are significant benefits to observing in the (solar) atmospheric opacity windows longward of the 912 Å Lyman edge, so that one can probe the full inventory of activity throughout the whole chromosphere, not just above its top. In this regard, the FUV coronal forbidden lines of highly-ionized iron could be used to directly sense the presence of coronal temperature gas within the chromosphere, if any indeed is present. If our UV imaging spectrometers are confined solely to the $\lambda < 300$ Å band—which is rich in coronal diagnostics but limited in altitude accessibility—we potentially will miss a lot of coronal action in the deep chromosphere, as well as failing to record the crucial zone of the atmosphere at the transition between the classical photosphere and the highly nonequilibrium corona, through which the mass and energy responsible for populating coronal structures ultimately must flow.

Finally, the Chandra and XMM–Newton missions have amply demonstrated the diagnostic value of moderate-resolution ($R \sim 10^5$) kilovolt spectroscopy for exploring plasma conditions (temperature and density), coronal composition, and kinematics in late-type X-ray stars. The technology for dispersing and sensing high-energy radiation has improved substantially since even the golden era of solar X-ray spectroscopy during the Solar Maximum Mission. Isn’t it time again for the sensitivity and imaging quality of cosmic X-ray instruments to be returned to the Sun, to examine the full range of coronal gas properties, not just during flare events?

So, in the final analysis, the stars have provided not only a series of new perspectives on high-energy coronal activity, but also a set of cautions concerning how we should go about dissecting the corona of our own Sun. The darkside has as well pushed the limits of spectroscopic technology, which hopefully someday can be applied back to the dayside, that for so long was the birthplace of advanced observing techniques, but now has taken something of a back seat.

ACKNOWLEDGMENTS

This work was supported by HST–AR–09550.01 from STScI, NASA–13058 from NASA, and several FUSE and Chandra Guest Observer programs. Travel to SOHO–15 was supported by a grant from the Southwest Research Institute.
REFERENCES

Ayres, T. R. 1997, JGR, 102, 1641
Ayres, T. R. 2000, SolPhPhys, 193, 273
Parker, E. N. 1977, ARA&A, 15, 45
Preibisch, T. 2003, IAU Symposium, 219, 154