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A stellar perspective on chromospheres

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Abstract. The Sun is not alone in hosting a *chromosphere*: virtually all convective stars (F-types and later) possess them. Properties can vary wildly from object to object. Historically, three key systemic behaviors were recognized. First is the strong preference of chromospheres for the cool half of the H–R diagram. Second is the so-called rotation-age-activity connection ("Skumanich law"). Third is the Ca II H & K emission width–luminosity relation ("Wilson-Bappu effect"). In the modern era of ultraviolet and X-ray telescopes in space, additional phenomenology has been recognized; mainly concerning energetic relationships between chromosphere and corona, importance of atmospheric dynamics, and the curious "buried coronae" of red giant stars. Collectively, these pieces of evidence hint that "relentlessly dynamic" stellar chromospheres are the rule, not the exception.

Key words. Stars: activity – Stars: chromospheres – Ultraviolet: stars – X-rays: stars

1. Introduction

The *chromosphere* is a prominent layer of the solar atmosphere, a critical transition zone where the classical cool radiation dominated photosphere gives way to the highly non-classical, mechanically heated, extremely hot corona. Although the solar chromosphere has been known since ancient times, thanks to solar eclipses, the stellar analogs received virtually no attention until relatively recently. This is because the main spectral signature of chromospheric activity – the Ca II H & K doublet near 3950 Å – is relatively subtle: faint emission cores at the bottoms of deep absorption troughs. These could not be recognized in stars until development of astronomical spectroscopy. It was not until the early 20th century, in fact, that the first reports concerning chromospheres on other stars appeared. For example, Deslandres & Burson (1921) described prismatic spectra of Ca II H & K in several yellow and red giants, calling attention especially to the very bright emission in Capella (α Aurigae: G6 III + G1 III) compared with the Sun. And, just as the solar chromosphere was fundamental inspiration for the development of non-LTE spectral line formation theory, by Thomas, Athay, and others in the 1960's, and the extensive numerical modeling embodied in the important series of semi-empirical studies published by Vernazza, Avrett, & Loeser beginning in the early 1970's, so too did the stellar counterparts inspire a parallel series of numerical efforts in the 1970's that dealt with key issues such as hydrogen ionization, partial frequency redistribution, and multi-level interlocking effects (see the so-called "Stellar Model Chromospheres" series in ApJ by J. Linsky, R. Shine, T. Ayres and collaborators).

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The advantages of studying chromospheric processes on the resolved face of the Sun are obvious. There is the danger, however, that one becomes mired in the details. Stars, on the other hand, probably have equally complex chromospheric atmospheres, but these cannot be resolved, and what one sees is a blending of many kinds of phenomena that average to some extent, leaving behind a more top-level view.

The phenomenology of stellar chromospheres is diverse, covering the gamut of starspots, flares, winds, stellar cycles, and so forth. An excellent review, mainly from an observer's perspective, has been given recently by Hall (2008). For the sake of conciseness, I will focus here on only a few key aspects that I believe are directly relevant to the Sun.

Historically, three main types of systemic behavior were recognized. First, chromospheres are found almost exclusively in the cool half of the Hertzsprung–Russell diagram, strongly associated with surface convection. Second is the so-called rotation-age-activity connection (or Skumanich law): the Ca II H & K emission cores are brighter in fast spinning stars of young galactic clusters compared with older, slower rotating field stars like the Sun (Skumanich 1972). Third is the "Wilson-Bappu (W–B) effect," a steady broadening of the chromospheric Ca II emission cores with increasing absolute visual luminosity, extending over a remarkable 15 stellar magnitudes (Wilson & Vainu Bappu 1957).

I will discuss especially how the W–B effect relates to basic structural properties of the chromospheric layers, but will bring in, as well, more recent satellite UV and X-ray perspectives on the "relentless dynamics" (De Pontieu et al. 2007) that seems to be a characteristic of this break-away zone of the stellar outer atmosphere.

2. H–R diagram

Figure 1 is a schematic view of the cool-half of the H–R diagram. This is the domain of surface convection, defining the so-called "late-type" stars. This is where chromospheres are found ubiquitously, and nearly exclusively. The upper right shaded area, the realm of red giants and supergiants, is where cool ($T \sim$ few $\times\ 10^4$ K) low-speed (tens of km s^{-1}) winds of significant mass loss rate ($\dot{M} > 10^{-9}\ M_\odot$ yr^{-1}) become prominent. Chromospheres still are prevalent in the wind zone, although the more enigmatic super-hot coronae tend to avoid this region (Linsky & Haisch 1979, Ayres et al. 1981; more on this later [§6]). The middle and lower left hand portion of the diagram is where multi-MK coronae usually are found. The boundary at the bottom of the wind zone labeled "Hybrids" encompasses a class of yellow supergiants that display mixed corona plus wind behavior, running counter to the normal mutual avoidance of these phenomena (Hartmann et al. 1981). Note that stellar evolution carries all the massive, hot, early-type main sequence stars into the cool half of the H–R diagram toward the end of their lives, so that virtually all stars will pass through a chromospheric phase at some point.

The hatched area in the middle of the figure is the so-called "Hertzsprung gap" where moderate-mass ($M \sim 3M_\odot$) early-type stars first cross into the convective part of the H–R diagram during their post-MS evolution. This phase is brief, less than 1% of the stellar lifetime, consequently few stars are found there in color-magnitude diagrams (hence the "gap"). Thanks to the nearly horizontal evolution in luminosity, the stellar expansion is only modest. Given that many of the early-type progenitors were fast rotators on the MS, the modest expansion guarantees that these stars still will be spinning rapidly (up to 100 km s^{-1}) as they enter the yellow giant region, at early-F spectral types. There, they experience first a burst of coronal activity through the early G's, followed by strong braking and diminishing coronal activity as they cross into the later G's (Ayres et al. 1998).

In contrast, the post-MS tracks of lower mass stars like the Sun are more vertical in luminosity. Such stars are very slow rotators at the conclusion of the long, multi-Gyr MS phase. So, by the time they bloat into red giants, a few dozen times the MS size, their spins should have faded away, and their activity as well, to the extent that the rotation-activity connection applies (Ayres et al. 1981).

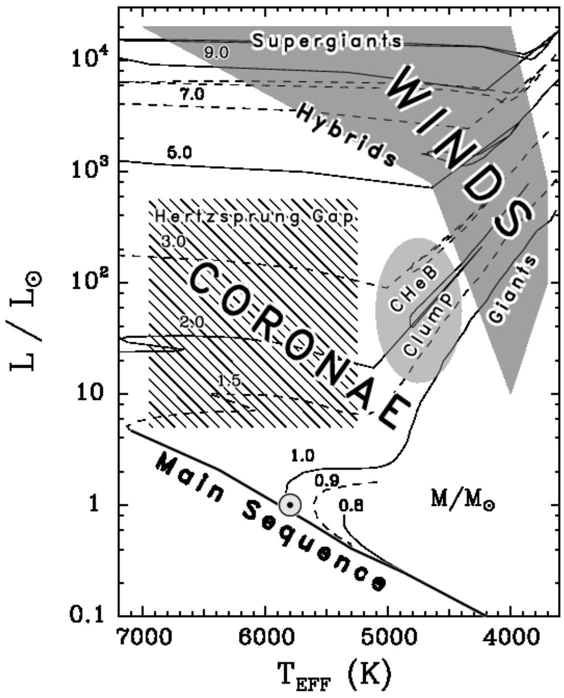

Fig. 1. Chromospheres are found throughout convective half of H–R diagram ($T < 7000$ K) at all luminosity classes, although related phenomena like cool winds and hot coronae occupy distinct zones. ($\odot$ = Sun)

Both the low- and intermediate-mass stars find themselves returning to the core helium burning (CHeB) "clump" (oval in figure) following the rise to the red giant tip and subsequent helium flash. CHeB is a long-lived phase of evolution, 10–20% of the lifetime. Accordingly, the clump is well populated in color-magnitude diagrams. At the same time, the clump contains objects of very mixed heritage. Thus, a diversity of chromospheric (and coronal) behavior appears in this region.

The close association of chromospheres with surface convection zones inspired early ideas that the nonclassical layers were powered by deposition of acoustic energy propagating upward from the noisy, turbulent convection cells in the deep photosphere (e.g., Biermann 1946; Schwarzschild 1948). While this is partly true, convection also is strongly associated with intermittent surface magnetism, and it has long been recognized that part of the chromospheric power is derived from magnetic processes (e.g., Osterbrock 1961).

3. Skumanich law

Skumanich's rotation-age-activity relation tells us that chromospheric emission strengthens in fast rotating stars, almost certainly thanks to intensifying "dynamo" action. The dynamo is a mechanism that manufactures magnetic flux in stars, drawing on the power of turbulent convection, but relying as well on the catalyzing influence of differential rotation (Parker 1977). On the Sun, areas of enhanced chromospheric brightness, say in H & K or Hα, are closely associated with magnetic regions (so-called Ca II "plage") on the large scale; and as well on the small scale with the fibril fields found ubiquitously in the lacy pattern of the supergranulation network. Age enters the Skumanich law, because single stars spin down over time owing to magnetospheric braking by their coronal winds. Wind braking represents a negative feedback on the dynamo.

Although the Skumanich law overall emphasizes the importance of the magnetic connection to chromospheric activity, it also is known from detailed studies of the Sun that an important component of the chromospheric mechanical heating in quiet areas, especially supergranulation cell interiors, is due to hydrodynamical processes: shocks arising from outward running acoustic disturbances associated with the spatially intermittent convective wave field. The intricate spectral morphology of these Ca II transient bright points was beautifully captured in pioneering 1D radiation-hydrodynamic simulations by Carlsson & Stein (1995). The quiet solar chromosphere probably is powered about equally by transient shocks and the steadier heating in the network magnetic fibrils, but the contribution from active region plage becomes progressively more important as the Sun's 11-year sunspot cycle swings into higher gear.

4. Wilson-Bappu effect

The W–B effect tells us something about the structural properties of a chromosphere, as I will outline below. I will spend some time on this issue, because first of all the W–B effect probably is not familiar to many solar physicists, who might regard it in any event mainly of historical interest. Secondly, the early explanations for the strong positive correlation between the Ca II core emission widths and increasing stellar visual luminosity were based on the idea that the broadening was by the Doppler effect, and that the connection was a product of a dramatic increase in chromospheric turbulence from dwarfs to supergiants (Hoyle & Wilson 1958). Although I mentioned earlier the important role for atmospheric dynamics in the chromospheric energetics, and will emphasize this point again later in a somewhat different context, a kinematic origin for the W–B effect itself seems rather unlikely, for a variety of reasons described below. Thus, ironically, while the classical W–B effect seemed to be pointing toward a highly dynamic chromosphere, the true signatures of chromospheric kinematics are more subtle. An excellent review of the extensive literature on the W–B effect has been given by Linsky (1999), in a special issue of the Astrophysical Journal on the occasion of its 100th anniversary.

Figure 2 sets a spectral context for the discussion, utilizing the ultraviolet Mg II h & k lines, rather than the more familiar classical Ca II H & K features. The tracings are from Space Telescope Imaging Spectrograph (STIS), from the UV stellar spectral catalog "StarCAT"[1]. Because of the increasing Plankian contrast in the UV compared with the visible, and the fact that magnesium is fifteen times more abundant cosmically than calcium, the h & k features are a much better indicator for the presence of a chromosphere than H & K. The emission cores of h & k fall close to each other at 2800 Å, and the partially blended absorption wings can be seen on either side rising into the heavily blanketed continuum. Also in this region is the Mg I λ2852 resonance line. It too is a prominent feature in cool stars, although much weaker than h & k thanks to the ionization equilibrium, which strongly favors Mg^+. The deep narrow absorptions in the Mg I and Mg II cores are interstellar.

Figure 3 compares average Mg II k profiles of quiet solar-like stars (dark shading) and more active counterparts (light shading). Again, the spectral material is from StarCAT. The ordinate is a normalized flux density that depicts the fraction of the stellar luminosity emitted per Å. The normalization compensates for the different stellar distances and sizes. Note that the Mg II cores are about 1 Å wide so that the combined flux of h & k is somewhat more than 1×10^{-5} of the bolometric luminosity for the quiet stars, and almost ten times that for the active ones. The h & k lines together account for a large percentage of the chromospheric radiative cooling (Linsky & Ayres 1978), so the total chromospheric *heating* probably is only a few times the Mg II value. Thus, we remind ourselves that the chromospheric energy budget is around 0.01% of the total luminosity in

[1] See: http://arlsrv.colorado.edu/~ayres/StarCAT/

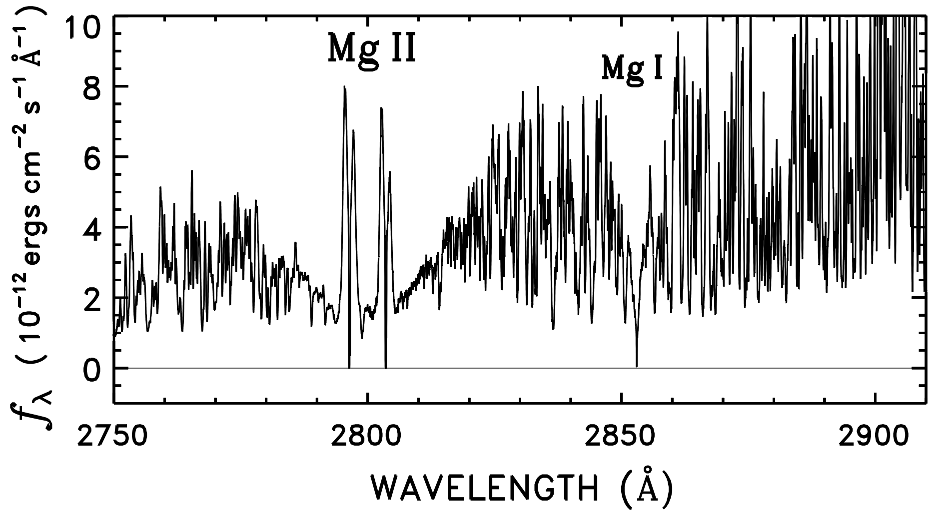

Fig. 2. Broad view of Mg II region in yellow supergiant β Camelopardalis (G1 Ib-II).

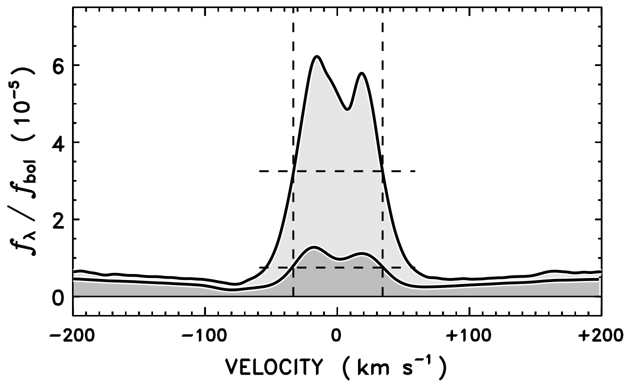

Fig. 3. Mg II k in quiet and active G dwarfs (interstellar absorptions suppressed).

quiet stars, but perhaps 0.1% in active ones; small fluxes to be sure, but orders of magnitude larger than the coronal power, and a profound impact on the plasma state of the stellar outer atmosphere.

The Mg II cores, even in a relatively quiet star like the Sun, show large contrast, very similar to Ca II in spatially resolved plage (Shine & Linsky 1972). The Mg II cores of the active stars are correspondingly more enhanced. Surprisingly, the full width between the half power points ($\frac{1}{2}\,[f_{\rm max} - f_{\rm min}]$) is the same for the quiet and active profiles, despite their manifestly different emission levels. This is a somewhat counter-intuitive property of the W–B effect: emission width does not depend strongly on activity level. Already this is persuasive evidence that the core width

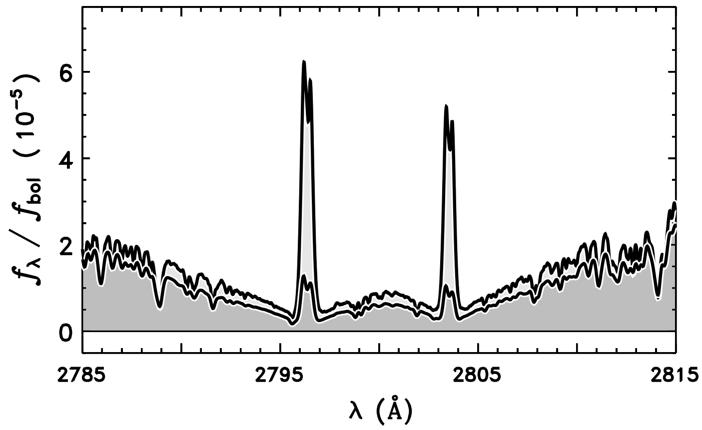

Fig. 4. G dwarf average Mg II h & k cores and wings: quiet (lower, darker); active (upper, lighter).

is not dominated by any velocity fields responsible for the chromospheric heating, otherwise enhanced broadening would accompany increased activity.

Figure 4 provides a more panoramic view of the quiet and active G-dwarf Mg II features. Notice that not only is the core intensity higher in the active stars, but the broad photospheric *wings* are brighter as well. The same separation is seen between the Ca II wings of solar plage and quiet areas (Shine & Linsky 1972), and indicates that substantial mechanical heating occurs throughout the upper photosphere (Ayres 1975). The impact of the heating is much more dramatic at the higher altitudes, however, because suppressed radiative cooling (at low densities) leads to a thermal instability and consequent sharp temperature rise that is the trademark of a chromosphere.

Figure 5 illustrates the core, as it were, of the classical W–B effect: the central k-line emission features of a yellow dwarf, a giant, and a supergiant, scaled to roughly the same peak intensity (after subtracting the inner wing minimum flux, ignoring absorptions unrelated to Mg II). The dashed curve is for the nearby solar twin α^1 Cen. The deep, slightly offset core absorption is interstellar, although a genuine chromospheric central reversal also is present (viz., the inflection points in the upper part of the absorption feature). The broad, dot-dashed profile is that of the yellow supergiant β Cam, illustrated earlier in Fig. 2. Now, a shallow chromospheric central reversal is clearly seen, together with a deep, doubled ISM feature. The intermediate, solid curve is for the active yellow giant HR 9024. The central absorption again is interstellar. Notice the dramatic widening of the Mg II cores with increasing stellar luminosity, reaching a remarkable 300 km s^{-1} FWHM in the supergiant. Notice also that all the profiles display a blue asymmetry – blue peak brighter than red – a key dynamical marker in spatially average solar Ca II profiles, devolving from the transient "K_{2V}" bright points (Rutten & Uitenbroek 1991). Incidentally, the Mg II widths are systematically several times the corresponding Ca II values (in Å), whereas they would be only 70% as wide if they were responding to similar Doppler broadening.

Figure 6 illustrates the *wings* of the h & k lines, back on an absolute $f_\lambda/f_{\rm bol}$ scale. Just like the chromospheric cores, the photospheric wings of the Mg II lines broaden (become shallower) with increasing luminosity. This is an important clue to the origin of the W–B effect.

Figure 7 depicts average Mg I λ2852 profiles of quiet and active G dwarfs, analogous to Fig. 3 for Mg II. Although Mg I shows much

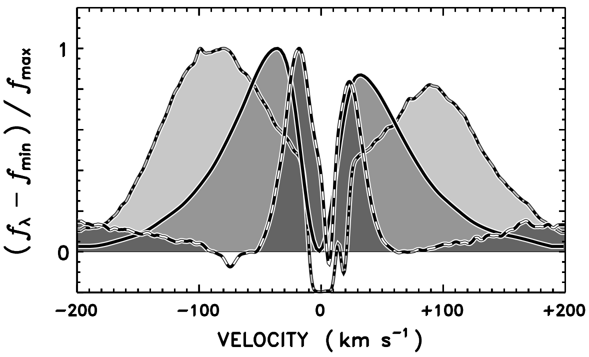

Fig. 5. Mg II λ2796 k-line cores in G stars of luminosity classes V (narrowest), III, and I (broadest).

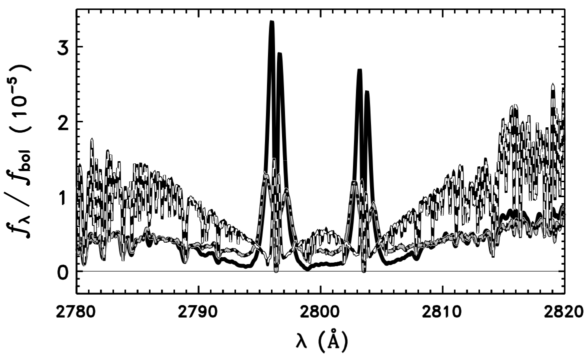

Fig. 6. Mg II wings of G stars of luminosity classes V (dashed), III (solid), I (dot-dashed).

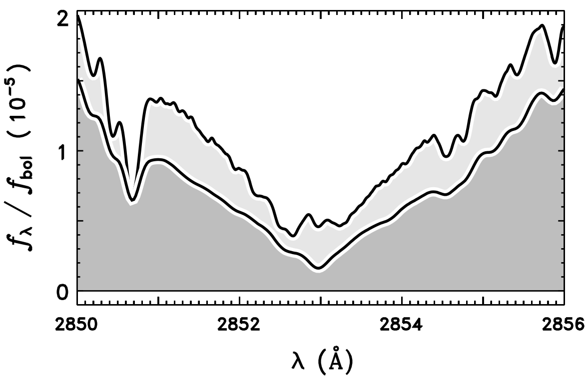

Fig. 7. Average Mg I λ2852 resonance line of G dwarfs: quiet (lower) and active (upper).

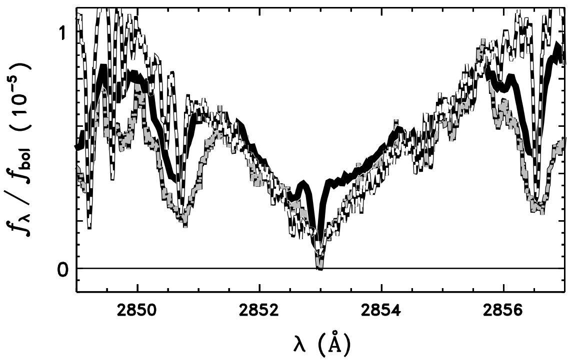

Fig. 8. Mg I cores and wings of luminosity-diverse G stars.

reduced contrast compared with Mg II, there still is a clear distinction between the quiet and active cores, and the line wings also display the same separation in flux density seen in Mg II. In fact, the Mg I lineshapes bear a striking resemblance to solar Ca II H & K profiles of quiet and moderately active areas.

Figure 8 compares the average Mg I λ2852 profiles of the three representative G stars illustrated in analogous Figs. 5 and 6, with the same coding. Now, the Mg I cores have about the same width, regardless of luminosity class. (Note: the sharp central dips are interstellar.) So do the line wings, even though other absorption features in this interval display dramatic broadening with increasing luminosity. This could be called an "anti-W–B effect."

All these peculiarities can be understood very simply in terms of systematic behavior of chromospheric thickness and mean electron density as a function of surface gravity (Ayres 1979). Namely, the gas radiative cooling depends on two powers of the density, because the emission is from electron collisional excitation (one power of density) of majority ionization stages of abundant elements like Mg, Ca, H, and so forth (the other power of density). The radiative heating also goes roughly as density squared because the main source of opacity, H^-, depends on $n_e\, n_H$. Thus, a stellar photosphere can maintain radiative equilibrium with slowly falling temperatures, even as the density declines sharply outward following the barometric law. At low temperatures ($T < 5000$ K), hydrogen mainly is neutral, and the electron density is directly proportional to the hydrogen density owing to the first ionizations of low-FIP Fe, Mg, and Si (with proportionality constant 10^{-4}, the collective abundance of the metals relative to hydrogen). All would be well and good, except for the presence of mechanical energy dissipation on top of the radiative heating. At some altitude the mechanical source becomes more important than the local radiation, and the steep outward decline of the radiative cooling ($\sim n_H^2$) cannot keep up with the energy input at low temperatures. At this point, the gas heats up above 5 000 K, where now additional electrons are freed, by partial ionization of hydrogen, to fuel the radiative cooling. In fact, over the narrow temperature range 5 000–8 000 K, n_e/n_H increases *four orders of magnitude*, from the metal ionization lower limit of 10^{-4} to the upper limit of 1 where hydrogen is fully ionized. Thus, the atmosphere can respond to mechanical heating, say constant per gram of material, over a wide range of altitudes with only slowly rising temperatures and *nearly constant* n_e, even in the face of the outward barometric drop of the hydrogen density. One ends up with a thick (many pressure scale heights), warm (5 000–8 000 K) layer: voila, a chromosphere!

The stable cooling region is terminated, however, when temperatures rise above 8 000 K. Now, hydrogen is fully ionized, and again the cooling will fall off rapidly with decreasing density, forcing a second thermal instability (the "transition zone"). By this token, the "ionization valve" that regulates the chromospheric thickness in late-type stars cannot operate in the hotter, early-type objects, because their atmospheres already have a high degree of hydrogen ionization, so there is little latitude to free n_e from the outwardly falling hydrogen density. Even if there is a source of mechanical heating, a many scale-height thick *chromosphere* would not be possible, although one still could have a TZ-analog (next step in the thermal instability sequence). Of course, early-type stars have negligible surface convection zones, so not only would the ionization valve be broken, but there probably also is not a ready source of mechanical energy to power a chromosphere or TZ in the first place. Supporting this idea, Simon et al. (2002) have reported a very sharp boundary in the middle A stars ($T_{\rm eff} \sim 8200$ K) where emission from chromospheric H I, and higher temperature species like O VI, abruptly vanishes.

When one folds in the effect of surface gravity on the density squared radiative heating and cooling functions, one can develop scaling laws (Ayres 1979) for the thickness and mean electron density of chromospheres with decreasing g (increasing luminosity). One finds that *both* photosphere and chromosphere thicken dramatically in column density as surface gravity decreases. This leads directly to broader cores and wings in majority ion species (like Ca^+ and Mg^+) whose opacities scale linearly with n_H in contrast to the density squared dependence of H^- (i.e., G stars of all luminosity classes would have very similar $T(\tau_{H^-})$ profiles, but the corresponding hydrogen column densities [and $\tau_{\rm MgII} \sim N_H$] would increase rapidly with decreasing g). A key assumption is that the outer edges of the Ca II and Mg II emission features are formed by radiation damping broadening, rather than the Doppler effect (see Ayres 1979). On the other hand, a density-squared species such as atomic Ca or Mg (minority ion stage) will scale the same way with surface gravity as τ_{H^-}, and should display minimal profile width changes, in either core or wings, with increasing luminosity (e.g., Fig. 8).

Thus, the W–B effect tells us something about the gross structural properties of chromospheres that devolve from simple considerations of the density dependence of gas heating and cooling. An important consequence is that a red giant chromosphere can be a large fraction of its radius, perhaps 10–15%, or more. For a dwarf star like the Sun, on the other hand, the chromosphere is a very thin layer (perhaps only 0.2% R). This has important implications, as will be described later (§6).

5. Chromospheric dynamics

Now, I turn to the issue of atmospheric dynamics. Figure 9 illustrates average FUV (1200–1700 Å) lineshapes of $T \sim 10^5$ K species (larger, light shaded) and $T < 10^4$ K chromospheric lines (smaller, darker) of several representative yellow giants and solar twin α^1 Cen (Ayres et al. 2007). The "hot-line" tracings – again from STIS – are averages of the Si IV, C IV, and N V doublets. The chromospheric average is based on narrow atomic lines. Scales are linear on the left, logarithmic on the right.

The pair of smooth solid curves in each panel are a double-Gaussian decomposition, analogous to the "broad" and "narrow" components identified in solar TZ profiles (e.g., Wood et al. 1997, and references therein). The solar broad components, in particular, are identified with TZ explosive events (Dere et al. 1989), which appear to occur mainly in the supergranulation network (Porter & Dere 1991). Note, also, that the narrow components often are slightly *redshifted,* perhaps mirroring the TZ downdrafts seen ubiquitously on the Sun (Doschek et al. 1976).

All the yellow giants show a similar bifurcation of their hot-line profiles, with similar narrow components (except for 31 Com, a rapid rotator: the flat-topped chromospheric profile is a signature of large $\upsilon \sin i$), but more diverse broad components. Note the blueshifted tail of the μ Vel profile, extending beyond -400 km s^{-1}, due to a small flare. Also, the broad component of the α^1 Cen profile accounts for about 20% of the total line flux,

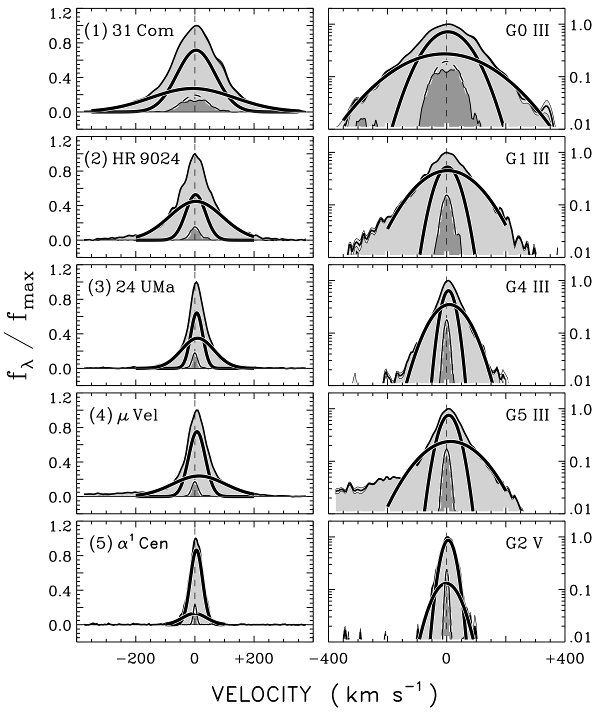

Fig. 9. Composite FUV hot-line profiles from representative G giants, and solar twin α^1 Cen.

compared with an estimated 5% for the solar explosive events. Ironically, the stellar value might be more representative of the true solar situation, since the explosive event fraction is tricky to extract from spatially and temporally resolved solar spectra, whereas the long exposures of the unresolved star naturally capture more legitimate spatial/temporal averages. Incidentally, α^1 Cen is very similar to the Sun in coronal properties (Ayres 2009).

Although the hot lines conventionally are thought to form in layers distinct from the cooler chromosphere, flux–flux diagrams (Ayres et al. 1995) show that the TZ emission is much better correlated with chromospheric Mg II than either are with coronal X-rays (which display a "deficiency" in fast-spinning Hertzsprung gap giants like 31 Com). Further, the total TZ energy losses usually well exceed those of the corona, except in the most active objects. So, it is proper to view the "TZ" as an integral player in the heating/cooling picture, not just a minor thermal interface. Indeed, the extreme dynamics revealed by broad components of the hot lines might result from explosive energy releases *within* the "relentlessly dynamic" chromosphere, such as are thought responsible for the spectacular hypersonic jets ("Type II spicules") discovered by *Hinode* (De Pontieu et al. 2007).

6. Buried coronae

The final topic concerns the so-called "noncoronal" red giants. These evolved K-type stars appear to have relatively normal chromospheres, aside from their trademark cool winds, but rarely are detected as coronal X-ray sources, even with deep pointings by sensitive telescopes like *Chandra* (Ayres et al. 2003). The red giant branch is a "coronal graveyard," if you will (Ayres et al. 1991). Early in the *IUE* era, it was thought that the FUV hot lines similarly were absent in noncoronal gi-

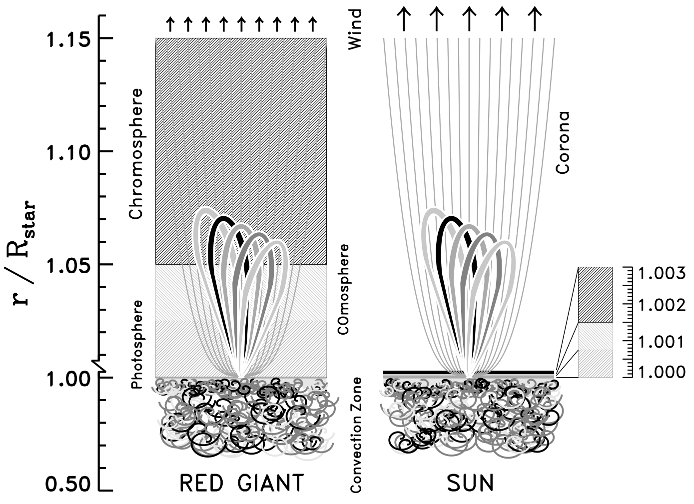

Fig. 10. Buried coronae. "COmosphere" consists of cool molecule-rich 'clouds' above photosphere.

ants (Linsky & Haisch 1979). Later, however, more sensitive space observatories like *HST* and *FUSE* were able to capture the subcoronal emissions, albeit weakly (e.g., Ayres et al. 1997). After accounting for distortions due to superposed fluoresced H_2 emissions (from the stellar equivalent of the solar "COmosphere" [Ayres 2002]), it was found that the hot lines were similar in shape and width to those of coronal yellow giants (which are more solar-like in their FUV and X-ray properties: Ayres et al. 2003). This suggested that the noncoronal giants are experiencing similar explosive heating episodes, although apparently not as pervasive as in the coronal giants. The heating almost certainly is via a magnetic mechanism, because the relatively soft hydrodynamical shocks – which likely also are present and contribute to the chromospheric heating – cannot reach the very high temperatures of the hot lines. Although it was argued earlier that dynamo action probably is weak or absent in the evolved low-mass red giants, it nevertheless is likely that a "distributed dynamo" still operates, much like that which produces the "magnetic carpet" fields in the quiet Sun (Title & Schrijver 1998). The distributed dynamo derives purely from convection, independent of differential rotation. But, if so, one also expects X-ray emission from the same population of magnetic loops, much as is seen in the pervasive, cool ($T < 1$ MK), always present, quiet Sun corona.

A breakthrough occurred when it was recognized that several of the hot lines, specifically N V and Si IV, suffered discrete absorptions by relatively cool species, C I and Ni II respectively (Ayres et al. 2003). This suggested that the hot-line emitting structures were *buried* under cooler material, probably the extended chromospheric layers. This raised the intriguing possibility that the associated, likely magnetic, phenomena might be responsible for the acceleration of the red giants wind (a long-standing astrophysical mystery in its own right); something like unbound spicular ejections, perhaps. In this picture, coronal loops sit *within* the chromosphere, and any X-ray emission would be severely attenuated by H and He photoionization, although the FUV lines longward of the LyC edge at 912 Å could shine through less impeded, aside from the selective absorptions noted earlier. This upside-down corona can happen because, as was described earlier, the chromosphere of a red giant is proportionately much more extended than the very thin counterpart on a dwarf star. Thus, if magnetic loops are imprinted with a size scale that is a fixed, small percentage of the stellar radius (say, from a distributed dynamo operating in the shallow convective layers), such loops would be able to rise above the chromosphere of a dwarf, but would be completely submerged within that of a red giant. Perhaps only an occasional over-long coronal loop would be able to penetrate the red-giant chromosphere and shine X-rays freely to space. Figure 10 is a cartoon of the scenario.

7. Conclusions

The main lessons we draw from the stars are that chromospheres are ubiquitous in the cool, convective half of the H–R diagram, and behave systematically with surface gravity, probably thanks to an "ionization valve" mechanism. There is good evidence in the red giants that coronal heating can occur deep in the chromosphere, and it is not so wild to imagine that similar processes can happen in the solar case. As Aschwanden et al. (2007) have argued, the chromosphere is precisely the layer of the outer atmosphere where the magnetic complexity is highest, and thus the place where impulsive reconnection heating would be favored. Finally, the broad components in FUV hot lines of dwarfs and giants mirror the extreme dynamics that increasingly has been recognized in the Sun's chromosphere and corona, especially in the contemporary, relentless *Hinode* era (De Pontieu et al. 2009).

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