CORONAL DICHOTOMIES

Tom Ayres
Joint Institute for Laboratory Astrophysics
University of Colorado and National Bureau of Standards
Boulder, Colorado

I. INTRODUCTION

Recent studies of cool-star outer atmospheres with the International Ultraviolet Explorer have revealed two remarkable dichotomies.

The first dichotomy is the apparent division of the cool half of the HR diagram into two distinct regions; one occupied by prominent, solar-like coronae, and the other where coronae are weak or absent entirely (Linsky and Haisch 1979). The second dichotomy is the existence in the bright spectroscopic binary Capella (G6 III + F9 III) of two ostensibly very similar giant stars that exhibit extraordinarily different levels of chromosphere-corona activity (Ayres and Linsky 1980a). The Capella situation is in sharp contrast to the solar-type dwarfs of α Centauri (G2 V + K1 V) that are rather solar-like in their outer-atmosphere properties (Ayres and Linsky 1980b).

The existence of the first dichotomy suggests that coronae must discriminate in some essential way among different kinds of stars. The second dichotomy provides an important clue to the basis for that discrimination.

II. THE CORONA-WIND BOUNDARY

In the course of a low dispersion ultraviolet survey of cool stars with IUE, Linsky and Haisch (1979) recognized an abrupt division in the HR diagram between stars that exhibit solar-like emission in the 1150-2000 Å short wavelength region, and stars with a decidedly nonsolar spectrum. In the solar-type spectra, emission lines formed at temperatures up to $2 \times 10^5$ K (N V 1240 Å), such as are found in the solar transition region (TR), are prominent, while in the nonsolar spectra only the cooler, chromospheric (T < $2 \times 10^4$ K) lines are apparent. Linsky and Haisch argued that the presence of "hot" TR-type emission was proxy evidence for the existence of a solar-type, multi-million degree corona. If so, the solar/nonsolar division is a boundary between the presence and absence of coronae.
The solar/nonsolar dividing line falls in the middle of the red giant branch, between G and K spectral types. The line stops short of the main sequence, because virtually all cool dwarfs observed with IUE show evidence for hot outer atmospheres. The extension of the boundary toward the supergiants has been hindered by a lack of data, partly because supergiants are comparatively rare in the galaxy.

The Linsky-Haisch boundary falls somewhat to the left of another characteristic division in the HR diagram, namely that segregating strong stellar winds ($\dot{M} \geq 10^{-8} \, M_\odot \, yr^{-1}$) from the mild, solar-type coronal "breezes" ($\dot{M} < 10^{-10} \, M_\odot \, yr^{-1}$). Because the stars with hot emission spectra seem to lack strong winds, while the purely chromospheric stars often exhibit massive winds, Linsky and Haisch characterized their dividing line as a corona-wind boundary. In fact, the energy drain required to power the enormous mass loss rates of the red giants and supergiants is roughly the same fraction of the stellar bolometric luminosity needed to heat a solar-type corona. One is tempted to argue that the heating which would under other circumstances power a hot outer atmosphere, is instead channeled into the strong, chromospheric wind (Haisch, Linsky and Basri 1980).

1) The binary dilemma

There is some question whether the Linsky-Haisch boundary line is "sharp" or "fuzzy" (Dupree 1980, Dupree and Hartmann 1980). Indeed, Dupree, Hartmann, and Raymond (1980) have identified two cases of "hybrid" emission spectra; solar-type emission from a windy supergiant. However, none of the studies to date has considered carefully a vexing, but fundamental, problem that confronts low resolution ultraviolet or soft X-ray surveys, namely the binary dilemma. The dilemma is as follows. Many stars, particularly giants and supergiants, that are thought to be single on the basis of long-standing optical studies, are in reality unrecognized double or multiple systems. This is of little practical concern in optical or infrared work, where source size is the deciding factor for visibility, but is of critical importance in ultraviolet and soft X-ray surveys, where source temperature controls visibility, but source identification must rely primarily on classical optical astronomy. In short, a lowly dwarf star likely will be unrecognized against the bright optical emission of a companion giant, yet the dwarf can easily outshine the giant at C IV 1550 Å or in soft X-rays if the giant has little material at TR or coronal temperatures. Nevertheless, if the source identification is based on the optical spectrum, and none of the conventional spectroscopic symptoms of duplicity are present, the hot emission from the "unseen" dwarf companion will be misattributed to the bright primary.

Figure 1 demonstrates a practical encounter with the binary dilemma. I have plotted on an HR diagram a small sample of stars that were observed at low resolution with IUE. Details concerning the acquisition, reduction and calibration of the ultraviolet spectra used to construct the figure are given by Marstad, Ayres and Linsky (1980).
Figure 1. The corona-wind boundary and the binary dilemma.

I have indicated with Sun-symbols those stars that have solar-type hot outer atmospheres, and which we have reason to believe are genuinely single (or at least are individually observed in well-separated binaries). Two of the K giants in the sample show no compelling evidence for hot lines (e.g. C IV 1550 Å), and also seem to be single (or if double, both components lack the hot lines). These are indicated by filled circles. The remaining stars (split circles) are cool giants that exhibit solar-type spectra, but also show anomalously bright continuum emission at and longward of 1800 Å. The ultraviolet continuum signature suggests that the cool giants have unrecognized hot companions, probably main-sequence stars. Clearly, such systems cannot be treated on the same footing as single stars for the purpose of delineating boundary lines.

I have sketched in Figure 1 the corona-wind boundary originally proposed by Linsky and Haisch, and schematic evolutionary tracks for 1-3 $M_\odot$ stars (Iben 1967). Note that the questionable stars straddle the boundary line. Therefore it is premature to say whether the corona-wind boundary is sharp or fuzzy until the binary dilemma is resolved. (A similar caution can be applied to the detection of "hybrid" winds.)

Nevertheless, I for one would be very surprised if the corona-wind boundary is extremely sharp, simply because the HR diagram itself is such a superficial characterization of stellar properties.
III. A TALE OF TWO SYSTEMS

The existence of the corona-wind boundary, whether sharp or fuzzy, suggests that the presence or absence of coronae is governed by what is very likely a simple mechanism. One might anticipate that clues to the nature of such a mechanism would be uncovered through detailed investigations of individual stars. I describe, below, studies of two binary systems, α Centauri (G2 V + K1 V) and Capella (α Aurigae A: G6 III + F9 III), which have confirmed that naive expectation.

1) System properties

Figure 2 compares the gross properties of α Centauri and Capella with our own solar system.

The α Centauri binary is widely separated (P ≥ 80$^3$), with orbital dimensions comparable to those of the outer solar system. Capella has a much more compact orbit (P ≥ 0.29$^3$), with dimensions comparable to the inner solar system. Nevertheless, the Capella giants are well-enough separated that mutual tidal influences and mass exchange should be unimportant.

The α Centauri stars are similar to our Sun in terms of physical sizes, masses, surface temperatures and luminosities. In fact, the α Centauri primary is a cosmic twin of the Sun (Flannery and Ayres 1978). On the other hand, the Capella giants are considerably larger, more massive and more luminous than the Sun, although the surface temperature of the Capella secondary (α Aur Ab) is similar to those of the Sun and α Cen A, while the temperature of the Capella primary (Aa) is similar to that of α Cen B.

The two binaries and the Sun are compared on an HR diagram in the right-hand panel of Figure 2. The Sun is a middle-aged star that is burning hydrogen in its core and slowly evolving away from the Zero Age Main Sequence (ZAMS). The solar-mass α Centauri primary also has evolved slightly away from the ZAMS, while the less massive, and consequently more slowly evolving secondary is still firmly rooted in the ZAMS. Flannery and Ayres have proposed an evolutionary scenario for α Centauri. They find that the system is somewhat metal-rich (2 × solar), and consequently sits on an enhanced-metallicity ZAMS (the dashed curve in the right-hand panel of Figure 2) that is displaced slightly above the solar-composition ZAMS (solid curve). Nevertheless, the evolutionary age of the α Centauri stars, 6 × 10$^9$ yr, is virtually identical to that of the solar system (5 × 10$^9$ yr).

In contrast, the Capella system is considerably more evolved than the Sun or α Centauri, yet the Capella giants are only one-tenth the age of the Sun. The seeming contradiction arises, of course, because the Capella stars are more massive than the Sun, and evolve more rapidly as a result. Iben (1965) has proposed an evolutionary scenario for Capella. He argues that both components were early A stars on the ZAMS. The more massive primary exhausted its core supply of hydrogen first. The primary then evolved horizontally in the HR diagram, burning hydrogen in a shell, until reaching the
Figure 2. System properties for α Centauri, Capella, and the Sun.
tip of the G-giant branch, whereupon the helium core ignited (helium flash). Subsequently, the primary evolved leftward and downward in the HR diagram onto the helium core main sequence, where it sits today. At the same time, the less massive secondary has only recently completed its main sequence phase, and initiated shell hydrogen burning on the horizontal branch. Consequently, the Capella siblings are currently evolving toward one another. Iben's scenario explains in a natural way how the two giants of slightly different mass can be found in nearly the same region of the HR diagram, but with vastly different lithium abundances (the secondary is Li-rich [Wallerstein 1966, Boesgaard 1971]) and rotation rates (the secondary is a fast-rotator [e.g. Herbig and Spalding 1955]).

11) Low Dispersion UV spectra

Figures 3 and 4 compare low dispersion IUE spectra of the 1150-2000 Å regions of α Centauri and Capella (Ayres and Linsky 1980a,b). Included in each frame is the full-disk spectrum of the quiet Sun (Rottman 1978) as it would appear at a distance of 1 p.c. and degraded to the 6 Å FWHM resolution of the low dispersion mode of IUE. (The solid angle subtended by the Sun at 1 p.c. is similar to that of α Cen A or the combined components of Capella, but is twice that of α Cen B.) Note that the α Centauri stars can be resolved spatially (d_AB ~ 20") and separately observed with the low dispersion mode of IUE, while only the composite spectrum of Capella (d_ab ~ 0") can be obtained. (Fortunately, however, the orbital motions of the Capella giants are sufficiently large that the individual components can be isolated spectroscopically using high dispersion measurements at the appropriate orbital phases.)

A comparison of Figures 3 and 4 reveals that the short wavelength ultraviolet spectra of α Centauri A and B are surprisingly similar to each other and to that of the quiet Sun, whereas the composite spectrum of Capella, though solar-type, is far from solar-like. Note in particular, (1) the strength of the hot lines Si IV, C IV and N V, which are twenty times brighter than their solar counterparts; (2) the reversal of the O I/C II emission ratio in Capella compared with α Centauri or the Sun; and (3) the enhancement of C IV 1550 Å relative to C I 1660 Å (the carbon features are more nearly equal in the solar-type dwarfs).

The solar-like TR emission of the α Centauri stars is compatible with the solar-intensity coronal soft X-ray emission detected from that system by HEAO-1 (Nugent and Garmire 1978). Likewise, the enhanced TR emission from Capella is compatible with the intense soft X-ray emission detected by HEAO-1 and earlier experiments (Cash et al. 1978, and references therein).

In fact, Capella shares many optical, ultraviolet and X-ray properties in common with the chromospherically active short-period RS CVn-type binary systems (Walter, Charles and Bowyer 1978), and Capella tentatively has been designated a long-period member of that class (Hall 1976).
Figure 3. Low dispersion, short wavelength IUE spectra of α Centauri (courtesy of The Astrophysical Journal).

To summarize, low dispersion IUE spectra and HEAO-1 soft X-ray detections of α Centauri reveal that the solar-type dwarfs are rather solar-like in their outer-atmosphere properties. However, analogous observations have revealed that the Capella system is enormously more active than the Sun or the α Centauri stars.

The existence of the Capella-Sun emission dichotomy suggests that some fundamental property of the active giant system sets it apart from the quiescent main sequence stars. A rather unexpected clue to the nature of that property was discovered in high dispersion, echelle spectra of Capella with IUE.
iii) Echelle spectra of Capella

The spectroscopic orbit of Capella is 104d (Batten, Fletcher and Mann 1978). At the two velocity crossings in the orbit (phase 0d, 52d), the spectra of the two giant stars are superimposed in velocity. At the two elongations (phase 26d, 78d), the component spectra are separated by about 53 km s^{-1}. The spectral resolution of the short wavelength echelle of IUE is somewhat better than 30 km s^{-1} FWHM. Consequently, line splittings or asymmetries induced by the orbital velocity shifts should be easily detectable. This proved to be the case in the low temperature, chromospheric features such as O I 1305, 06 Å, Si II 1808 Å, He II 1640 Å, and the 2800 Å Mg II h and k resonance doublet (which was observed with the long wavelength echelle). Strangely enough, however, the hot lines, such as Si IV 1394, 1403 Å, C IV 1548, 51 Å and N V 1239, 43 Å, showed no tendency to split or become asymmetric near elongation. Instead, the hot lines bodily shifted toward the red near the phase 78d elongation, following the radial velocity motion of the secondary, exclusively (Ayres and Linsky 1980a).

The curious behavior of the Capella spectrum at high resolution is summarized in Figure 5.

The right-hand panel compares several of the prominent ultraviolet spectral features observed at the phase 52d velocity crossing, when the primary and secondary have identical radial velocities. I have illustrated individual profiles of Si II 1808 Å and He II 1640 Å, and composite profiles of O I 1305, 06 Å and the Si IV + C IV doublets. (By composite profile, I mean that several individual line shapes were coadded on a common velocity scale to improve the signal-to-noise of any systematic velocity patterns.) The radial velocity scale is relative to the system center-of-mass velocity, \( V_0 = 29.5 \text{ km s}^{-1} \) (Batten et al. 1978). Note that there is no large systematic shift of the composite hot line profile relative to the low temperature, chromospheric features at velocity crossing. (The error bars within each profile refer to estimated line bisectors.) I conclude that neither component of the system has a discernable stellar wind near 10^5 K, at least compared with the massive winds of red giants and supergiants (\( \dot{M} \gtrsim 10^{-8} M_\odot \text{ yr}^{-1} \)). I cannot, of course, rule out solar-type "breezes" in either of the Capella giants (i.e. \( \dot{M} \lesssim 10^{-10} M_\odot \text{ yr}^{-1} \)), especially if the mass flows are at the elevated temperatures of the solar wind (10^6 K). The apparent lack of a massive wind near 10^5 K in Capella is contrary to the implications of a previous study by Dupree (1975, 1976) using Copernicus. She found what appeared to be a progression of increasing emission line blueshifts with increasing temperature of formation up to 30 km s^{-1} at O VI 1032 Å (3 \times 10^5 K). I suspect, however, that Dupree's result is an artifact of her use of the broad and asymmetric \( \lambda_{\alpha} \) emission profile to define the rest frame velocity of chromospheric material in the Capella system (see Ayres and Linsky 1980a).
Figure 5. High dispersion, short wavelength IUE echelle spectra of Capella at velocity crossing and near elongation (courtesy of The Astrophysical Journal).
The left-hand panel of Figure 5 depicts the most intriguing result of the Capella study. The chromospheric features -- O I, Si II and He II -- become asymmetric near the phase 78° elongation, while the composite hot-line profile shifts uniformly to the red, following the Capella secondary. The straightforward interpretation is that virtually all of the TR emission is from the secondary star.

One can estimate the gross emission difference between the Capella primary and secondary using the simple profile reflection procedure illustrated in Figure 5. The long wavelength wing of each profile near elongation, which presumably is entirely from the secondary, is reflected about the secondary's velocity at that orbital phase. If the intrinsic emission profile of the secondary is symmetric (as is indicated by the line shapes at velocity crossing), then the difference between the actual fluxes in the short wavelength wing of each profile and the reflected wing should represent emission from the primary star. The primary contributions estimated by this technique are depicted as shaded areas in Figure 5. I find that even in the chromospheric features, the secondary is more prominent than the primary. In terms of surface fluxes (ergs cm$^{-2}$ s$^{-1}$ at the star), the secondary is perhaps fifty times brighter than the primary in the hot lines (Ayres and Linsky 1980a).

The Capella-Sun emission dichotomy has therefore resolved itself into an emission dichotomy between the Capella primary and secondary. This is an encouraging simplification, because the Capella giants are obviously quite different from the chromospherically quiescent dwarf stars in their fundamental stellar properties (Figure 2), but the Capella primary and secondary are virtually identical to each other. One anticipates that the extraordinarily different activity levels on these ostensibly rather similar giant stars can be traced to some property that is very different in the two siblings. Linsky and I have proposed that the critical property is rotation.

iv) The Capella rotation dichotomy

Ironically, the key to the Capella ultraviolet emission dichotomy can be found in the red spectrum, near 6708 Å. Boesgaard (1971) has published a pair of high quality spectrogram tracings of that region, taken at opposite elongations in the orbit and aligned according to the primary's velocity scale at each phase. Her spectra contain a series of narrow (FWHM < 0.2 Å) Fe I absorption features that have the radial velocity of the primary at the opposite orbital phases, and a broad (FWHM > 1 Å) feature that shifts relative to the aligned primary features with the amplitude and direction expected for the secondary spectrum. The broad feature has been attributed to Li I 6708 Å absorption in the secondary (Wallerstein 1966, Boesgaard 1971). The strength of the lithium absorption in the secondary, and its weakness in the primary, implies that the secondary is less evolved (Iben 1965). The diffuse appearance of the Li I line shape, and the absence of identifiable Fe I absorption features in the 6708 Å region of the secondary spectrum, implies that the secondary is a fast rotator. The projected rotational velocity ($V \sin i$) suggested by the FWHMs of Li I 6708 Å and Si II 1808 Å (the narrowest of the chromospheric emission features) is of order 30 km s$^{-1}$ (Ayres and Linsky 1980a). Judging by the sharpness of the Fe I features in the Aa spectrum, the primary must have a $V \sin i$ of order 5 km s$^{-1}$ or less.
The fast rotation of the Capella secondary was likely inherited from its main-sequence progenitor, an early A dwarf. The Capella primary was likely also a fast rotator at the same evolutionary phase as the secondary. However, the primary has had ample opportunity during its extensive post-MS evolution to shed much of its initial rotational velocity by magnetic braking (the so-called coronal spin-down effect; e.g. Kraft 1967) or by mass loss prior to and at helium flash (Iben 1965).

Rotation is the most obvious difference between the Capella giants. There may well be other, more subtle differences that are instead responsible for the remarkable emission dichotomy, but rotation is certainly an appealing culprit. In particular, solar intuition tells us that stellar chromosphere-corona activity must be related to surface concentrations of magnetic fields (Vaiana and Rosner 1978). If destruction of the magnetic flux ultimately is responsible for coronal heating, then continual replenishment of the surface fields is necessary if the hot outer atmosphere is to persist over evolutionary timescales. An obvious candidate for the field replenishment mechanism is hydromagnetic dynamo action (Parker 1970). One expects the dynamo to be more vigorous in rapidly rotating, convective stars such as the Capella secondary, compared with more modest rotators such as the Capella primary, the Sun, and the α Centauri dwarfs. In this picture, a rotation-activity connection among cool stars is inevitable.

In fact, a rotation-activity connection allows one to understand why the long-period Capella system exhibits many of the ultraviolet and soft X-ray peculiarities of the short-period RS CVn-type binaries. In particular, the stars in the short-period systems are rapid, synchronous rotators by virtue of tidal friction (Hall 1978). Furthermore, Bopp and Fekel (1977) have proposed that rotation, instead of binarity per se, is responsible for the BY-Draconis flare star "syndrome" among M dwarfs. Finally, a rotation-Ca II emission correlation is well-known among solar-type dwarfs (e.g. Skumanich 1972).

IV. ROTATION AND THE CORONA-WIND BOUNDARY

Can a rotation-activity connection help us understand the corona-wind boundary? Perhaps.

Figure 6 depicts the corona-wind boundary once again. I have included in the figure schematic evolutionary tracks for 1 and 3 M_⊙ stars, contours of constant stellar radius, and arrows indicating the general flow of evolution in the two regions of the HR diagram on either side of the corona-wind boundary. Spectral types along the main sequence and in the giant branch are also given.
Figure 6. A speculative scenario for the origin of a "corona-wind" boundary.

Most of the solar neighborhood giants are of G or K spectral types. The corona-wind boundary neatly separates the Gs from the Ks. Simple consideration of stellar statistics (Allen 1973) reveals that there are as many K giants as A-type MS stars. Since the giant phase occupies only a small fraction of a star's lifetime, the typical K-giant progenitor therefore must be less massive than the A dwarfs. However, it is unlikely that many of the disk population K giants had initial MS masses less than that of the Sun, otherwise, those giants would be more ancient than the galaxy itself ($10^{10}$ yr). It is probable, then, that most of the K giants were originally F and early G dwarfs on the ZAMS. Consequently, the K giants are typically old (several billion years), and have evolved essentially vertically in the HR diagram from relatively slow-rotating antecedents. (F and G dwarfs are slow rotators compared with A and B dwarfs.) On the other hand, the less numerous G-type giants very likely evolved from A-type MS stars (cf. Capella). Consequently, the G giants are typically young (a few hundred million years), and have evolved horizontally from rapidly-rotating antecedents.

Owing to their comparative youth, and modest evolutionary expansion, the G giants likely retain a significant vestige of their progenitors' rapid rotation. On the other hand, the significant evolutionary expansion, advanced age, and slow-rotating progenitors of the K giants virtually guarantee that they themselves will be slow rotators. Furthermore, the development of strong winds in the coolest giants would rapidly spin down any vestige of rotational velocity that had survived to that evolutionary stage.

In short, I propose the following speculative scenario: The corona-wind boundary separates young, fast-rotating G giants from the older, slow-rotating K giants. In the fast-rotating yellow giants, vigorous dynamo action
continually replenishes surface magnetic fields that, in turn, are responsible for the enhanced activity seen in chromosphere-corona tracers. In the slow-rotating red giants, on the other hand, the dynamo is virtually dead, and the outer atmospheres are dominated by quiescent phenomena, including the mysterious, chromospheric winds that are characteristic of the coolest and most luminous of such stars.

This work is supported by NASA through grants NAS5-23274 and NGL-06-003-057 to the University of Colorado. I also thank Jeff Linsky who participated directly in many of the IUE observations and analyses reviewed here.

References