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THE STRUCTURE, ENERGY BALANCE, AND WINDS OF COOL STARS

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ABSTRACT

A broad theme emerging from IUE observations of cool stars is that magnetic fields control the structure and energy balance of the outer atmospheres of these stars. I summarize the phenomena associated with magnetic fields in the Sun and show that similar phenomena occur in cool stars. High dispersion spectra are providing unique information concerning densities, atmospheric extension, and emission line widths. A recent unanticipated discovery is that the transition lines are redshifted (an antiwind) in β Dra (G2 Ib) and perhaps other stars, which I interpret as indicating downflows in closed magnetic flux tubes as are seen in the solar flux tubes above sunspots. Finally, I classify the G and K giants and supergiants into three groups — active stars, quiet stars, and hybrid stars — depending on whether their atmospheres are dominated by closed magnetic flux tubes, open field geometries, or a predominately open geometry with a few closed flux tubes embedded.

Keywords: Stellar Chromospheres, Stellar Coronae, Stellar Winds, Magnetic Fields, Ultraviolet Spectra, Binary Stars, Nonradiative Heating

1. INTRODUCTION

Looking back over the accomplishments of the first four years of IUE, I am struck by what we have learned about cool stars compared with how little we knew from ground-based observations and the Copernicus and balloon observations from space. Prior to IUE we were only able to study the chromospheric Mg II and Ca II resonance lines, He I λ10830, and several far ultraviolet lines in only one star, Capella. IUE has truly opened up the ultraviolet for spectroscopic studies of the whole range of cool stars both at low dispersion and increasingly at high dispersion. This field has become too large to be surveyed in a short talk, so I must restrict myself to a limited number of topics. In particular, I will not discuss pre-main sequence stars, many interesting binary systems, and stars with low metal abundances, and I will not say much about theoretical models. For a more complete survey, I suggest the review papers by Ayres (Ref. 1), Dupree (Refs. 2-4), and Linsky (Refs. 5-8).

IUE is providing us with considerable evidence that changing magnetic fields are the cause of most phenomena observed in cool stars. I will therefore concentrate my attention on the consequences of magnetic fields in cool star atmospheres. The importance of magnetic fields should come as no surprise, however, as they lie at the basis of most solar phenomena, and the Sun is the best studied cool star (cf. Refs. 9-11). As a guide, I summarize below a few aspects of the solar magnetic field that should be applicable to a wider range of stars, and also list some factors which may produce magnetic fields in stars:

1.1 General properties of solar magnetic fields

(1) They are inhomogeneously distributed across the solar surface.

(2) They are variable on many time scales.

(3) Strong fields tend to clump into large groups of closed loop structures (active regions) or small groups (chromospheric network) at the edge of supergranule cells.

(4) Large regions of predominately weak fields with open topologies (coronal holes) exist at the poles and often at low latitudes.

1.2 Influence of closed magnetic loops on atmospheric structure

(1) Closed flux tubes are the dominant geometrical structures in the solar outer atmosphere.

(2) The nonradiative quasi-steady state heating rate, perhaps due to slow mode MHD waves, is enhanced in closed flux tubes. Rapid conversion of magnetic to thermal energy and energetic particles occurs during flares.

(3) Since strong, closed magnetic fields prevent flows across field lines, winds may occur only in open field geometries (coronal holes).

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(4) Closed magnetic fields also restrict heat conduction across field lines, so that heat conduction to space is unimportant but heat conduction down to the chromosphere can be an important energy loss mechanism.

(5) The enhanced nonradiative heating rate and restricted loss of energy to space by outflow and thermal conduction together are responsible for the bright ultraviolet emission line spectra of typical magnetic flux tubes.

(6) Variability of the emission line flux from the Sun viewed as a point source is due to the rotational modulation of the few active regions present on the solar disk and to secular changes in the flux tubes.

(7) On the basis of the above properties, it is likely that the reason for the two orders of magnitude spread in the ultraviolet emission line flux detected in stars lying in similar regions of the H-R diagram (Refs. 12, 13), is in the number of magnetic flux tubes present in the outer atmospheres of different stars.

(8) Downflows with velocities of 10-20 km s^{-1} in the C IV and Si IV lines (Refs. 14, 15) are commonly seen in magnetic flux tubes, especially above sunspots.

1.3 Influence of open magnetic fields on atmospheric structure

(1) Since energy loss by outward thermal conduction and wind expansion is permitted in magnetically open regions, these regions tend to be cooler, of lower density, and be characterized by weaker ultraviolet emission lines than active regions. Coronal holes are the origins of high speed wind streams and perhaps most of the solar mass loss.

(2) Momentum deposition by MHD waves may be responsible for the acceleration of the solar wind in addition to the Parker-type thermal pressure gradient mechanism.

1.4 Origin of magnetic fields in stars

(1) In relatively young stars, remnant fields may exist from an earlier stage of evolution.

(2) Magnetic fields can be strengthened by dynamo processes from the interaction of convection and differential rotation. It is commonly assumed that dynamo processes are enhanced by rapid rotation and deep convection zones, but self-consistent calculations of internal rotation and field amplification are still in a primative state.

(3) Rapid rotation in cool stars could be a consequence either of youth, when the loss of angular momentum by the stellar wind has not yet slowed the rotation of the stellar envelope appreciably, or of tidally-induced synchronism for close binary systems such as the RS CVn, Algol, and W UMa systems.

2. GROSS ATMOSPHERIC STRUCTURE

In the Sun nonradiative heating processes produce a region called the chromosphere, extending typically over 6 pressure scale heights, where the temperature rises gradually from roughly 4200 K to 10,000 K. This region is easily detected by bright emission in the resonance lines of Ca II, Mg II, H I, C I, O I, and Si II. Chromospheric emission lines are detected in nearly all stars cooler than spectral type early F. Solar emission lines formed at temperatures above 10^4 K and below the corona ($T \gtrsim 10^6$ K) generally arise in an inhomogeneous yet geometrically narrow region, called the transition region (TR), where the temperature gradients are very steep. TR emission lines are typically seen in all dwarf stars cooler than spectral type early F, but the appearance or absence of these lines is a more complex phenomenon among the luminous stars.

2.1 Solar-type dwarfs

The spectra of the Sun and two representative dwarf stars are compared in Figure 1 in terms of apparent line flux divided by the apparent bolometric luminosity. These spectra contain emission lines of C I, O I, Si II, Fe II, and other chromospheric species formed at temperatures cooler than 10^4 K, and lines of He II, C II, C III, C IV, N V, Si III, and Si IV formed at temperatures of 2×10^4 - 2×10^5 K. On the basis of the presence of all these lines and the similar relative strengths compared to the Sun, we conclude that these stars and stars with similar spectra contain chromospheres and TRs, although the parameters characterizing these atmospheric regions may differ from those values for the Sun. There is an important difference, however, between the ultraviolet spectra of ξ Boo A and ε Eri compared to the Sun: the

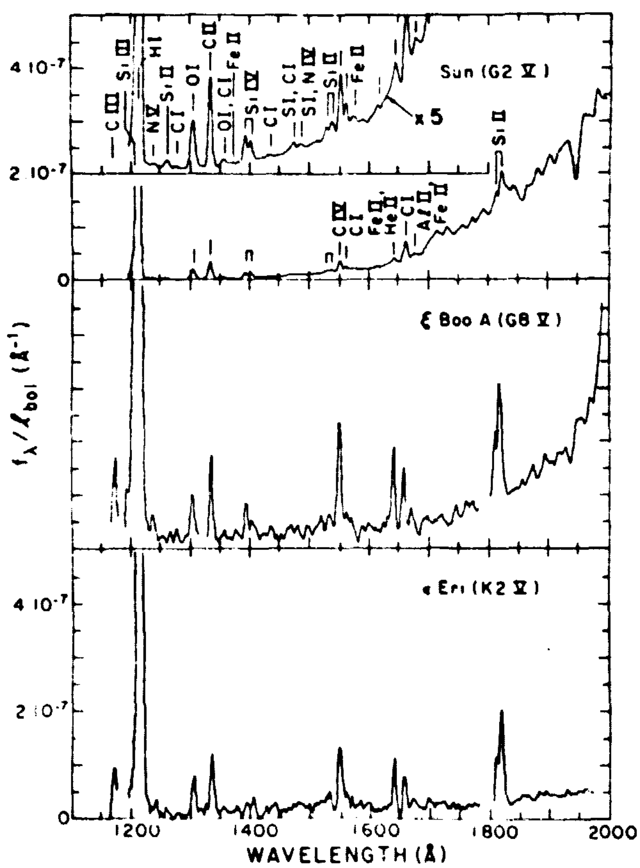

Fig. 1. SWP low dispersion spectra of ξ Boo A and ε Eri and the solar spectrum degraded to the IUE resolution (Ref. 16).

emission line fluxes (f_L/ℓ_{bol}) are roughly an order of magnitude large. (cf. Ref. 16). All three stars have measured magnetic fields of several thousand gauss, but for the Sun these fields cover less than 1% of the photosphere whereas for ξ Boo A (cf. Ref. 17) and presumably also ε Eri these fields cover roughly 30% of the stellar surface. These data suggest that the wide range in ultraviolet emission line surface flux and soft X-ray flux detected in cool stars of similar spectral-luminosity class (Refs. 13, 18, 19) is due to different fractional surface areas covered by strong magnetic fields. That is, stars with similar photospheres have bright chromospheres and TRs due to larger coverage by regions analogous to solar active regions (plages).

2.2 A and F stars

Böhm-Vitense and Dettmann (Ref. 20), and Linsky and Marstad (Ref. 21), among others, have noted the disappearance of chromospheric and TR emission lines as one goes to stars hotter than about spectral type F0. A careful search for these emission lines in A-type stars by Crivellari and Praderie (Ref. 22) using both low and high dispersion IUE spectra has resulted in no detections. While this could be due to the absence of these regions in the hotter stars as a consequence of weak convection, a more likely explanation is that the rapid increase in the photospheric ultraviolet continuum with increasing T_{eff} makes it difficult to measure the emission lines for lack of contrast (see discussion in Ref. 6). I believe this to be correct because some A stars like Vega (A0 V) and two A stars in the young Hyades cluster (Ref. 23) exhibit coronal X-ray emission, and there must be layers with temperatures intermediate between the photosphere and corona in these stars. Since young A stars presumably have the largest magnetic fields, they should be searched carefully for ultraviolet emission lines (cf. Dravins, Ref. 24). Dwarf stars later than about spectral type F2 V exhibit spectra with relative emission line strengths similar to the cooler stars (e.g. Refs. 25, 26).

2.3 Cool dwarfs

As one proceeds down the main sequence, ultraviolet emission lines indicative of chromospheres and TRs are readily detected by IUE in stars as cool as UV Cet (M5.5e V) since the background continuum is very weak (Refs. 27, 28). There are several dM dwarfs observed that do not show C IV emission at upper limits of 0.3 that of the quiet Sun, but weak TRs may exist on these stars as well. However, those stars that show indirect evidence of strong magnetic fields such as flares and photometric variability indicative of rotational modulation of dark star spots, invariably exhibit emission lines with surface fluxes 10-100 times that of the quiet Sun.

2.4 Cool giants and supergiants

Near the beginning of IUE operations, Linsky and Haisch (Ref. 29) noted a trend in the ultraviolet spectra of cool giants and supergiants in which the warmer stars with V-R < 0.80 (the yellow giants) show emission lines formed at all temperatures up to 10^5 K, whereas the cooler stars with V-R > 0.80 (the red giants) show only chromospheric emission lines. On this basis they proposed a nearly vertical dividing line in the H-R diagram near V-R = 0.80 (see Fig. 2) separating the yellow giants that typically have TRs from the red giants that do not. Subsequently, Ayres et al. (Ref. 19) showed that the Einstein soft X-ray observations are consistent with the typical presence of hot coronae in stars to the left of a similar boundary and the absence of coronae in single stars to the right (see Fig. 2). Also Stencel (Ref. 30), and Stencel and Mullan (Refs. 31, 32) presented evidence for the onset of massive cool winds in stars lying to the right of a similar boundary.

The idea of a boundary as proposed by Linsky and Haisch has been criticized on the basis of the few stars in the original data sample, the absence of detected TR emission lines in some yellow giants (cf. Ref. 33), and the existence of some red giants, the so-called hybrid stars, that show evidence for massive winds and C IV emission lines (Refs. 34-36). The hybrid stars were proposed to have winds that are cool far from the star, on the basis of blue-shifted absorption features in the Mg II lines, and 10^5 K winds closer to the star, on the basis of the broad C IV emission lines. These valid criticisms led to a reexamination of the existence of a boundary by Simon, Linsky and Stencel (Ref. 37) on the basis of a much larger sample of 39 single stars and a smaller reverse bias sample. They found (see Fig. 2) that the yellow giants show a wide range of C IV fluxes (i.e. $f_{C\ IV}/\ell_{bol}$), including stars with small upper limits, that they ascribed to a mixed evolutionary status of these stars. Some stars have just recently evolved from the upper main sequence and could be relatively rapid rotators with strong magnetic fields and bright emission lines, whereas some may be post-helium flash stars that are slow rotators. Among the 18 red giants in their sample, only three stars have detected C IV emission but two of these three show ultraviolet continuum emission indicative of previously unknown companions (56 Peg and α UMa) and the third is the hybrid star α TrA (Hartmann et al., Ref. 35). In a separate IUE study of 15 red giants, Stickland and Sanner (Ref. 38) also found no evidence for C IV emission. Simon et al. (Ref. 37) therefore concluded that the boundary originally proposed by Linsky and Haisch is a real phenomenon in the sense that single stars to the right, with the exception of one hybrid star, contain significantly less 10^5 K plasma than typical single stars to the left of the boundary.

The question of a boundary remains open, however, for the following reasons. First, in the red giants, fluorescence in the fourth positive system of CO can produce emission features near the C IV 1550 Å and C II 1335 Å lines (Ref. 39). Thus, high dispersion spectra are needed to reliably estimate upper limits for these TR emission line strengths. Second, the C IV emission lines detected in such hybrid stars as ι Aur (K3 II) and θ Her (K2 II) (cf. Ref. 36) are so weak as to be at the level of some noise features. T. Simon recently reobserved θ Her with a 175 min SWP low-dispersion exposure (see Fig. 3), and saw no evidence for C IV emission. Thus C IV emission in some of the hybrids is variable or not definitively detected. Third, the existence of a boundary demands a physically self-consistent explanation. I will return to these questions when I discuss high dispersion spectra at the end of this talk.

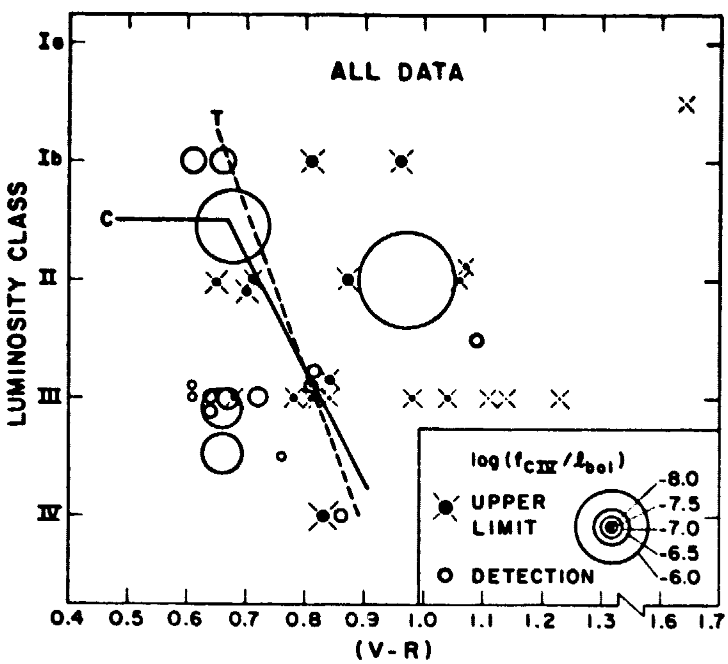

Fig. 2. Measured ratios of the C IV λ1550 flux to the apparent stellar bolometric luminosity from Simon, Linsky and Stencel (Ref. 37). Open circles are detections and filled circles are upper limits. The line marked T is that originally proposed by Linsky and Haisch (Ref. 29) to separate stars with (to the left) and without (to the right) 10^5 K plasma. The line marked C was proposed by Ayres et al. (Ref. 19) to separate stars that generally show soft X-ray emission (to the left) from stars that generally do not (to the right). Two of the three detections to the right of the line marked T are previously unknown binary systems.

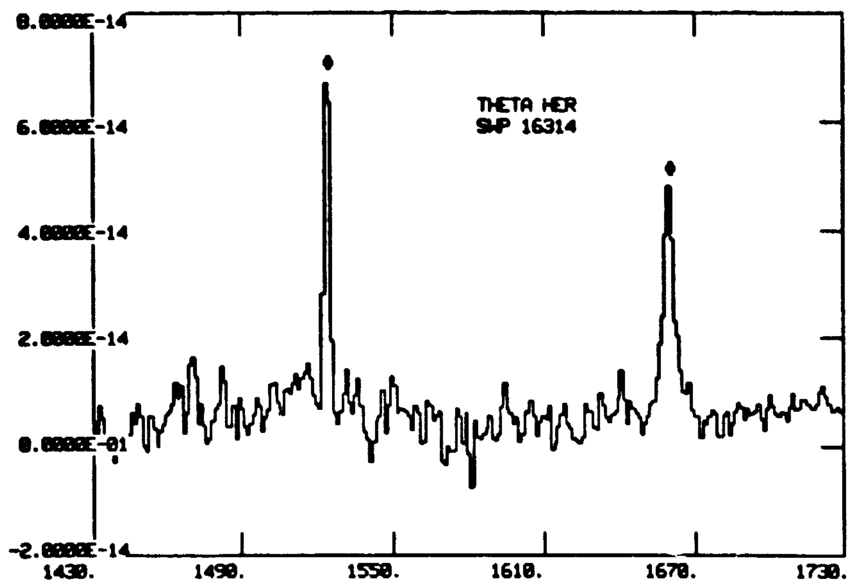

Fig. 3. A 175 minute SWP low dispersion spectrum of the hybrid star θ Her (K2 II) obtained by T. Simon. This long exposure shows no evidence of emission at the location of the C IV λ1550 feature. The two indicated features are radiation hits.

3. ATMOSPHERIC INHOMOGENEITY AND VARIABILITY

3.1 Spatial inhomogeneity

As mentioned in §1, magnetic fields produce inhomogeneity in the solar outer atmosphere by controlling the geometry and energy balance of closed flux tubes. A number of observing programs with IUE have confirmed that the outer atmospheres of cool stars are similarly inhomogeneous. Hallam and Wolff (Ref. 40), for example, have monitored the chromospheric emission line fluxes in three dwarf stars — 111 Tau (F8 V), ε Eri (K2 V), and 61 Cyg A (K5 V). They found that these fluxes vary sinusoidally with periods that are the likely rotational periods of the stars. These data provide evidence for the rotational modulation of an inhomogeneous distribution of bright emitting regions, presumably analogous to solar plages, across the surfaces of these stars. Several groups will be continuing such monitoring programs during the fifth year of IUE, in some cases with coordinated magnetic field observations to confirm the hypothesis that the plage regions have strong magnetic fields.

Close binary systems with cool components typically show bright ultraviolet emission lines and photometric variability indicative of rotational modulation of dark star spots (cf. Refs. 41-42). One therefore expects that the ultraviolet emission line flux should vary with rotational phase such that emission line maximum corresponds to photometric minimum. Baliunas and Dupree (Ref. 43) have done this experiment on the long-period RS CVn system λ And (G8 III-IV + ?), confirming that the emission lines are strong at photometric minimum and weak at photometric maximum. Marstad et al. (Ref. 44) have monitored three RS CVn systems (HR 1099, II Peg, AR Lac) and the prototype BY Dra system over at least one period for each system. They found clear variability in II Peg that is consistent with the presence of a relatively small plage region that is centered on the visible hemisphere at photometric minimum. They found that the plage and quiescent spectra differ, not only in the increased flux when the plage is on the disk, but also in the relative enhancement of high temperature lines in the plage spectrum, similar to what is seen in solar plage spectra.

3.2 Stellar flares

Flares have also been detected in IUE spectra of the RS CVn system UX Ari (Ref. 45) and in dMe flare stars (Refs. 28, 46). Such flares are probably also magnetic in character with the dMe star flares similar to solar flares and the RS CVn flares perhaps involving reconnection between flux tubes of the two stars. In addition to the expected enhancement of the emission lines, Butler et al. (Ref. 28) found continuous ultraviolet emission during a flare on GL 867A, which is presumably analogous to solar white light flares. One property seen in both the dMe and RS CVn flares is the relative enhancement of the high temperature (TR) lines compared to the chromospheric emission lines. This important property will be discussed next.

4. ENERGY BALANCE AND NONRADIATIVE HEATING RATES

4.1 Empirical studies

Since theoretical calculations of the nonradiative heating rates in stellar chromospheres and TRs have not proved useful in predicting the observed properties of cool star atmospheres, it is essential that empirical studies provide guidance for the theoreticians. IUE observations have provided four important pieces of information concerning nonradiative heating processes:

(1) Linsky and Ayres (Ref. 12) showed, on the basis of Mg II fluxes measured prior to IUE, that the chromospheric radiative loss rate per unit surface area of a star shows no dependence on stellar gravity. This implies that the heating rate is also independent of gravity, contrary to prior computations of heating due to the dissipation of shocks produced by purely acoustic waves in a nonmagnetic atmosphere, which imply a g^{-1} dependence and a T_{eff} dependence different than observed. This result was modified slightly by Stencel et al. (Ref. 47), who showed that IUE observations of cool supergiants are consistent with a small increase in the heating rate as the gravity decreases. Subsequently, Stein (Ref. 48) and Ulmschneider and Bohn (Ref. 49) have proposed that slow mode MHD waves in magnetic flux tubes are a likely heating mechanism because they match the observed dependence of heating on g and T_{eff}, and these waves can produce the large heating rates observed in some young stars.

(2) Also using IUE observations of fluxes in the Mg II resonance lines, Basri and Linsky (Ref. 13) showed that there is a wide range in the chromospheric radiative loss rates and thus nonradiative heating rates in cool stars of similar effective temperature and luminosity (and thus gravity). Vaiana et al. (Ref. 18) and Ayres et al. (Ref. 19) found a similar result for coronal X-ray emission. Thus the heating rate must depend on some parameter other than the values of T_{eff} and g that together determine where a star lies in the H-R diagram. The tight correlation of local nonradiative heating with magnetic field strength across the solar surface implies that the fractional coverage of a stellar surface by strong magnetic fields is the important missing parameter.

(3) Using SWP low dispersion observations of 28 cool stars, Ayres, Marstad and Linsky (Ref. 16) showed that the emission line fluxes of chromospheric and TR lines are not linearly correlated (see Fig. 4). Instead, as one goes to stars with brighter chromospheric emission (i.e. $f_{Mg\ II}/\ell_{bol}$), the TR lines brighten even faster such that $(f_{C\ IV}/\ell_{bol}) \sim (f_{Mg\ II}/\ell_{bol})^{1.5}$. Walter, Basri and Laurent (Ref. 50) and Oranje, Zwaan and Middlekoop (Ref. 51) find similar results but with slightly smaller power law dependences using different data samples. This phenomenon was previously noted in the comparison of the II Peg plage to quiescent spectra and the flare to quiescent spectra. It is also seen by comparing solar plage to quiescent spectra and thus must be a general property of stellar atmospheres. Hammer, Linsky and Endler (Ref. 52) have proposed an explanation for this phenomenon. They pointed out that the radiative loss rate in TR emission lines for realistic magnetic flux tube models (e.g. Ref. 53) depends on pressure to a higher power than the corresponding radiative loss rate in chromospheric emission lines (e.g. models in Ref. 54). Thus with an increase in available mechanical energy flux, the location of the base of the TR (intersection point of the curves in Fig. 5) moves to larger pressures and the TR lines brighten by a larger factor than the chromospheric lines.

(4) A general increase in chromospheric Ca II emission line flux with increasing stellar rotation rate and decreasing stellar age have been known since the 1950s from the work of Kraft, Wilson, Skumanich, and others, and had been explained as due to enhanced magnetic fields in the young rapidly rotating stars by dynamo processes. IUE and Einstein have extended this rotation-age-activity connection to TRs and coronae. For example, the large enhancement of chromospheric and TR line fluxes in young cluster and field stars is shown in the work of Zolcinski et al. (Ref. 55), Barry and Schoolman (Ref. 56), and Boesgaard and Simon (Ref. 57). Stern et al. (Ref. 23) showed that the young Hyades stars have very large X-ray

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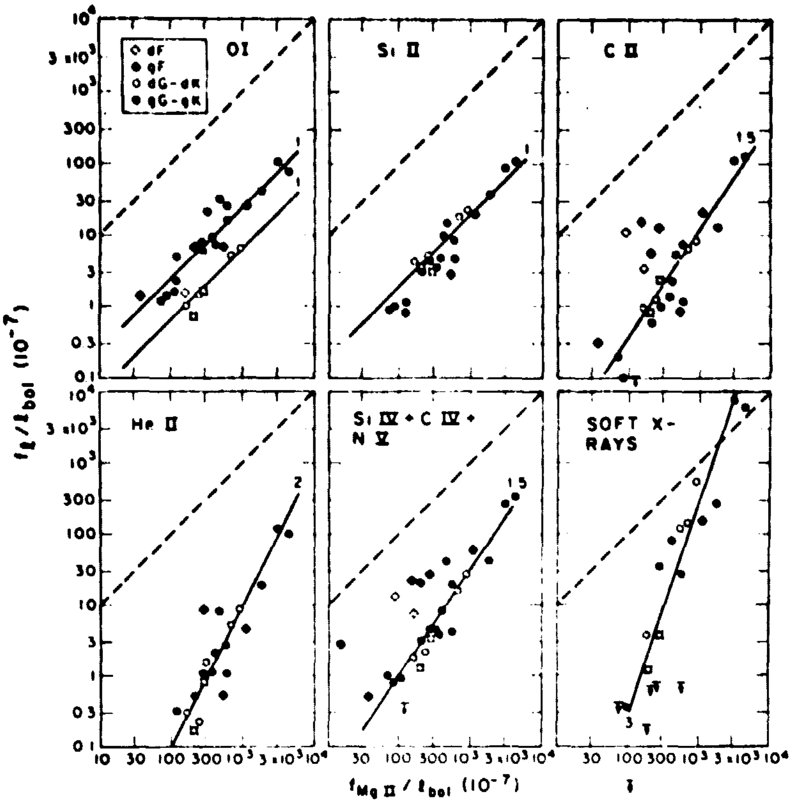

Fig. 4. Correlation plots of chromospheric, transition region, and coronal fluxes compared to the Mg II line relative flux (Ayres, Marstad and Linsky (Ref. 16)). The slope of 1.5 in the correlation plot for transition region lines (Si IV + C IV + N V) is an important result concerning the energy balance in stellar atmospheres.

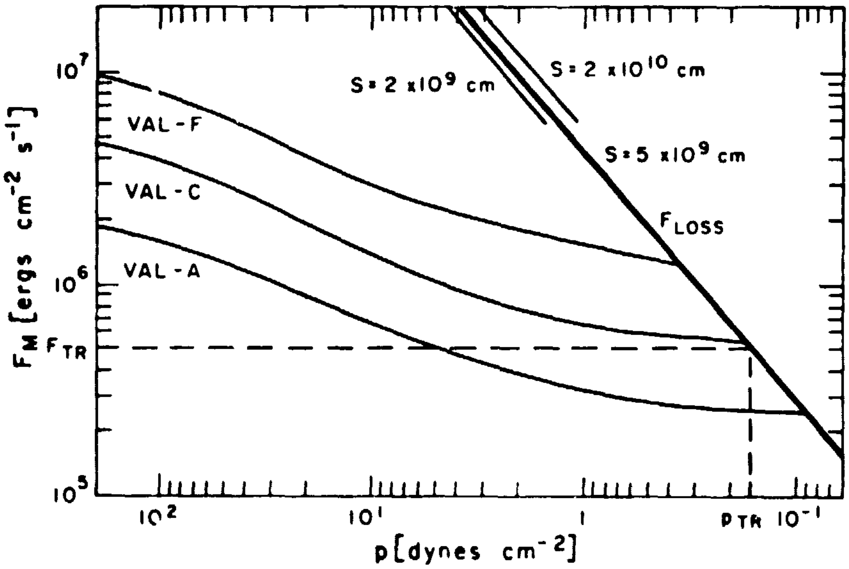

Fig. 5. Total mechanical energy flux F_M as a function of the pressure p for the chromospheric models A, C, and F of Vernazza, Avrett and Loeser (Ref. 54). The transition region lies at the intersection point with a curve (drawn heavy) that gives the total energy losses F_{Loss} of the transition region and corona as a function of the base pressure and the semilength S of the coronal loops (cf. Ref. 53). From Hammer, Linsky and Endler (Ref. 52).

surface fluxes, and Walter (Ref. 58), Walter and Bowyer (Ref. 59), and Walter, Basri and Laurent (Ref. 50) proposed functional relations between X-ray or ultraviolet emission line fluxes and stellar angular velocity. The development of a fully self consistent theory of dynamo field creatic and stellar internal rotation is still in th ture, but the comparison of stellar X-ray servations with approximate theories (e.g. 60, 61) is encouraging.

4.2 Semiempirical model atmospheres

IUE measurements of chromospheric and TR line fluxes have been used to construct semiempirical atmospheres for a range of stars including F, G, and K-type dwarfs (Refs. 25, 26, 62, 63), cool giants and supergiants (Refs. 64, 65), and RS CVn-type systems (Refs. 66, 67). The aim of this approach is to derive the temperature and density structure of the outer atmosphere of individual stars by matching the empirical line surface fluxes and, where feasible, by using density-sensitive ratios of lines observable by IUE. As such models become more reliable, they can be used to evaluate the local energy balance and to identify the heating mechanisms and their dependence on height. In their study of Procyon, for example, Brown and Jordan (Ref. 26) concluded that in the TR of this F5 IV-V star the radiative losses exceed the net conductive flux and that local heating by shock waves in a magnetic plasma is needed.

Important as these studies are, they must be viewed as provisional, because they ignore the essential inhomogeneity of stellar atmospheres and they use only a few spectral lines. Also, the outer atmospheres of stars are most likely dynamic rather than static as these models assume, so that nonequilibrium ionization and even nonequilibrium electron energy distributions are possible. It is especially important to not presume the nature of the TR energy balance, such as assuming the equality of radiative losses and conductive heating, but rather to determine which terms in the energy balance are important for different types of stars.

5. NEW RESULTS ON COOL STAR ATMOSPHERES PROVIDED BY HIGH DISPERSION SPECTRA

Until now I have summarized some of the important results concerning cool stars that have been obtained by analyzing low dispersion SWP spectra, and high dispersion LWR spectra in the region of the Mg II resonance lines. High dispersion spectra, especially with the SWP camera, contain important new information that is only now beginning to be exploited. The reason for the few high dispersion SWP spectra of cool stars is that 16 hour observations are usually required even for second magnitude stars. Nevertheless, good exposures of several stars have been obtained with some unexpected results.

5.1 Spectral Line Identification

Line identification and line flux measurement is often difficult when several lines are likely to be present within a 6 Å spectral resolution element of the low dispersion format. For example, an emission feature in low dispersion at 1640 Å could contain lines of Fe II λ1640, He II λ1640, and O I λ1641 (cf. Ref. 68), among others. High dispersion spectra show that for α Cen A (G2 V) the Fe II and He II lines have about equal flux and O I is absent, whereas for α Boo (K2 III) only the O I line is present (Refs. 69, 70). A determination of what fraction of the low dispersion 1640 Å emission flux is actually He II is important because the He II line may measure the soft X-ray flux (Refs. 34, 71). Also, high dispersion spectra of α Tau (K5 III) and β Gru (M2 II) clearly distinguish important S I lines from other species (Ref. 72). Another problem is to separate the C II λ1335 and C IV λ1550 features from the fluorescent CO bands at adjacent wavelengths (Ref. 39). The high dispersion spectrum of α Boo shows no C II or C IV features present, which allowed Ayres et al. (Ref. 70) to set surface flux upper limits 0.02 times those of the quiet Sun. Thus we can argue that this star has very little if any 10^5 K plasma.

5.2 Identification of emission components in close binary systems

Since a spectral resolution element at high dispersion corresponds to roughly 30 km s^{-1}, IUE can determine from Doppler shift measurements which component in close binary systems is the dominant emitter in different lines, provided the maximum velocity separation is not too much smaller than 30 km s^{-1} and the signal-to-noise is adequate. In perhaps the first application of this technique to cool stars, Ayres and Linsky (Ref. 73) observed Capella (G6 III + F9 III) at conjunction (zero velocity separation) and one quadrature (maximum velocity separation) and found that the secondary star is responsible for essentially all of the TR emission line flux, whereas both stars contribute to the chromospheric emission line flux. Since the primary star had been previously assumed to be the dominant emitter in all lines, this result is important for understanding the system. Subsequently, Ayres and Linsky (Ref. 74) observed the RS CVn system HR 1099 (K0 IV + G5 V) at opposite quadratures. They found that the primary star is the dominant emitter as expected from previous optical studies, but that there are emission features at the G5 V star velocities in the Si II λ1808 and He II λ1640 lines. Another result of this study was evidence for a patchy distribution of emission across the surface of the K0 IV star as indicated by a factor of 1.5 enhancement of the TR line fluxes at phase 0.76 compared to phase 0.21 and a displacement of the emission centroid velocity at phase 0.76 consistent with emission from a plage region near the trailing limb of the K0 IV star, which faces toward the secondary star. Further studies of close binary systems are planned.

5.3 Densities and atmospheric extension

Measurements of integrated line fluxes can be converted to surface fluxes and volume emission measures (EM ~ $\int n_e^2 dV$), provided one can estimate the stellar angular diameter. Emission measures are important (cf. Ref. 75), but to determine the geometrical thickness of the emitting region, and thus whether it is thin or thick compared to the photospheric radius, one must measure the electron density separately. One important technique is to measure line ratios that are density-sensitive over the relevant range of densities. Stencel et al. (Ref. 76) have shown that ratios of lines in the UV 0.01 multiplet of C II at 2325 Å are sensitive to densities in the range 10^7–10^9 cm^{-3}, and that these emission lines are observed in high dispersion LWR spectra of cool giants and supergiants. These data and subsequent observations presented by Stencel and Carpenter (Ref. 77) indicate that the chromospheres of the yellow giants are geometrically thin, but those of the red giants and supergiants are extended with dimensions of several stellar radii. Also, upper limits to the C II λ1335/ C II λ2325 flux ratios in these stars indicate that the extended chromospheres are cool (T<10,000 K). The well-studied M supergiant α Orionis (M2 Iab) provides additional evidence for extended, cool chromospheres on the basis of its radio emission (e.g. Ref. 78) and optical spectra (e.g. Ref. 79). A lunar occultation angular diameter of 119 Tau (M2 Ib) in the Hα line and the continuum confirms this result (Ref. 80).

Densities in stellar TRs at $T \approx 5 \times 10^4$ K can be derived using several line flux ratios available in the SWP data, including C III λ1909/Si IV λ1403, C III λ1909/O III λ1666, C III λ1909/Si III λ1892, C III λ1175/C III λ1909 (cf. Refs. 81,82). Each of these line ratios has potential problems including line blending at low dispersion, but when they lead to consistent density estimates for a given star we should accept the resultant densities. These ratios have been used to estimate densities from low dispersion spectra for such systems as Capella, HR 1099, UX Ari, and β Dra. Recently, Stencel et al. (Refs. 83,84) obtained a 1273 minute SWP high dispersion exposure of β Dra (G2 Ib). The line ratios in this spectrum are consistent with a previous low dispersion spectrum (Ref. 64) and imply $n_e = 2 \times 10^{10}$ cm^{-3} and P = 0.3 dynes cm^{-2} for the emitting structures. This density and the measured TR line emission measures require that the TR in this star be geometrically thin like the Sun's despite the three order of magnitude difference in stellar gravities of the two stars.

5.4 Emission line widths

A comparison of line widths in five stars of similar effective temperature but different luminosity and gravity [α Cen B (K1 V), α Cen A (G2 V), λ And (G8 III-IV+?), α Aur Ab (F9 III), and β Dra (G2 Ib)] led Ayres et al. (Ref. 69) to some interesting conclusions. First, they found that for all the stars the line widths (FWHM) increase with increasing temperature of formation. Second, there is a systematic trend of increasing line width with increasing stellar luminosity. A completely unexpected result, however, was the discovery that the widths of TR resonance lines (e.g. C II λ1336, Si IV λ1394, C IV λ1548) are twice as large as the widths of the TR intersystem lines (e.g. Si III λ1892, C III λ1909) formed at similar temperatures. The recent long exposure of β Dra confirms this result as the FWHM of the TR resonance lines is typically 150 km s^{-1}, whereas the FWHM of the TR intersystem lines is typically 80 km s^{-1} (see Fig. 6). Since none of these stars shows any evidence for winds, Ayres et al. (Ref. 69) proposed that the lines are broadened by turbulence that increases with temperature and luminosity, and that the additional factor of 2 in the line widths of the TR resonance lines in the luminous stars is due to opacity broadening of optically thick lines. Since the three luminous stars have TR line surface fluxes much larger than the quiet Sun, they are presumably covered by many magnetic flux tubes and the turbulent broadening could be due to upflows and downflows of plasma within these many flux tubes.

5.5 Properties of stellar winds

High dispersion IUE spectra will likely prove to be increasingly valuable in determining the properties of winds in cool luminous stars. Until now this work has primarily involved searching for blue-shifted circumstellar absorption components in the Mg II resonance lines that indicate cool

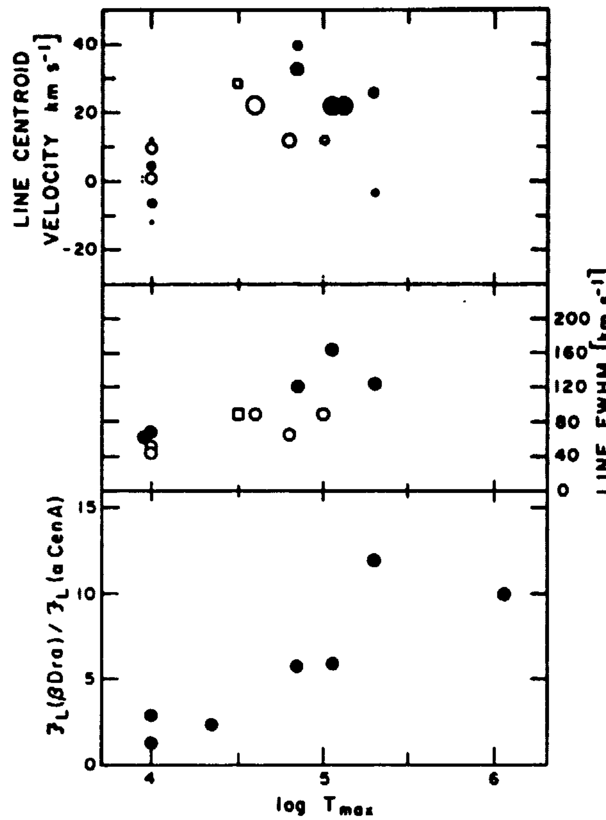

Fig. 6. Plots of the line centroid velocities, line widths, and relative surface fluxes as a function of line formation temperature for β Dra (G2 Ib) (Ref. 83). In the top two panels resonance lines are indicated by filled circles and intersystem lines by open circles. In the top panel the size of the symbol indicates the relative line flux and thus its weight in determining the mean velocity for the low and high excitation lines.

outflowing gas. For example, Hartmann et al. (Refs. 34, 35) and Reimers (Ref. 36) have called attention to the hybrid stars which typically show Mg II absorption components both at low velocity and at roughly -100 km s^{-1}. Hartmann et al. (Ref. 35) also proposed that the 150-200 km s^{-1} FWHM of the C IV λ1548 line in the hybrid star α TrA (K4 II) is due to expansion of 10^5 K plasma from an extended region about the star. Hartmann and MacGregor (Ref. 85) have computed Alfven-wave driven wind models that predict a 10^5 K temperature maximum, ~100 km s^{-1} expansion velocities, and significant cool plasma outside of the 10^5 K material that may be observable as Mg II absorption components at -100 km s^{-1}.

It is important to test this hypothesis of 10^5 K winds in the hybrid stars observationally. One test is to search for stars with similar effective temperature and luminosity that have broad C IV lines yet no evidence of outflow of gas at any temperature. The star β Dra (G2 Ib) is an excellent test case because it is similar spectroscopically to the hybrid stars α Aqr (G2 Ib), β Aqr (G0 Ib), and α TrA (K4 II), yet it has broad lines and no evidence of a wind. On the basis of this test we conclude that broad C IV lines provide no unique evidence for a 10^5 K wind. A more conclusive test would be to directly measure the C IV line centroid velocity in the hybrid stars. Unless the TRs in these stars are extremely extended, the C IV lines should show a measurable blue shift. A 16 hour SWP high dispersion exposure recently obtained of α TrA may answer this question.

5.6 Systematic flows of transition region plasma

Perhaps the most exciting and unexpected discovery by IUE concerning cool stars is the very recent evidence for flows of the TR plasma. Stencel et al. (Refs. 83,84) have measured line centroid velocities for 18 lines in the SWP high dispersion spectrum of β Dra by fitting least-squares Gaussians to the observed profiles. They estimate the velocity at the base of the chromosphere using eight subordinate or intersystem lines of C I, O I, S I, and Cl I. These low excitation lines have a mean velocity $\langle v_{LE} \rangle = 3 \pm 3$ km s^{-1}, where the error is the standard error of the flux-weighted mean. A similar measurement of the mean velocity of ten high excitation lines of He II, C III, C IV, N V, O III, Si III, and Si IV is $\langle v_{HE} \rangle = 23 \pm 3$ km s^{-1}. Thus the motion of the high excitation lines relative to the low excitation lines is $\langle v_{HE} \rangle - \langle v_{LE} \rangle = 20 \pm 4$ km s^{-1}. In other words, the TR plasma is flowing down into the star and we are observing a stellar antiwind. They believe that the possible alternative explanation (that the cool plasma is outflowing) is unlikely because the chromospheric lines chosen are not resonance lines and thus should be formed deep in the atmosphere. Also, the Mg II resonance lines show no evidence for outflow. Subsequently, Ayres et al. (Ref. 86) measured $\langle v_{HE} \rangle - \langle v_{LE} \rangle$ in available spectra of five other cool stars. They found (see Fig. 7) that α Aur Ab, β Cet, λ And, and perhaps several dwarf stars appear to show redshifts, though with smaller amplitudes than β Dra.

At first sight the idea of an antiwind in a supergiant star seems preposterous, but upon reflection it should have been anticipated. At the beginning of this talk, I listed a number of properties of the solar magnetic field including the point that downflows with velocities of 10-20 km s^{-1} are commonly seen in the C IV and Si IV lines in magnetic flux tubes above sunspots. I believe that the observed downflow of TR plasma in β Dra and perhaps other stars is merely one more piece of evidence that the phenomena in cool stars are largely controlled by magnetic fields.

6. A PROPOSED EXPLANATION FOR THE OBSERVED SPECTRA OF COOL GIANTS AND SUPERGIANTS

In lieu of a summary, I would like to make two points. First, I believe that IUE is providing much evidence that magnetic fields play essential roles in determining the structure and energy balance of cool star atmospheres. As a result our explanations, models, and theoretical computations must take this essential physics into account. Second, a clear picture appears to be emerging from the observations concerning the G and K giants and supergiants. I believe that three types of stars are present in this group.

(1) There are active stars, of which β Dra (G2 Ib) is a prototype, which show bright TR emission lines emitted by a geometrically thin region, bright X-ray emission, no evidence for any outflow of material, and redshifted TR emission lines. These are stars for which closed magnetic flux tubes dominate their outer atmospheres. These stars probably have large magnetic fields either because they have just recently evolved from the upper main sequence (β Dra may be an example) or because they are members of close binary systems that are forced to rotate synchronously (the cool components of RS CVn systems are examples).

(2) There are quiet stars, of which α Boo (K2 III) is a prototype, which show no evidence of TRs or hot coronae to very small upper limits, have cool winds with significant mass loss, and geometrically extended chromospheres. These stars probably have no, or very few, closed magnetic flux tubes but rather have outer atmospheres with magnetically open topologies like coronal holes, and little or no hot plasma. These are probably slow rotators. Precisely how the decay of magnetic fields can lead to a star changing from active to quiet remains to be worked out in detail.

(3) I believe that the hybrid stars, of which α TrA (K4 II) and α Aqr (G2 Ib) are prototypes, are hybrid but in a different sense than originally proposed. These stars show weak and likely variable TR emission lines, no detected X-ray emission, and evidence for a cool wind. I believe that there is no real evidence for 10^5 K winds in these stars, but Doppler shift measurements are needed as previously described to help give a conclusive answer on this point. I would describe these stars as hybrid in the sense that their outer atmospheres contain mostly open field lines along which the cool wind flows, but they do contain a few closed magnetic flux tubes from which the TR lines are emitted. Rotational modulation of these few flux tubes could explain the variability. My guess is that these tubes also contain 10^6 K plasma emitting soft X-rays, but the X-rays are absorbed by the surrounding cool plasma.

Finally, we need to ask why there are apparently no active single stars to the right of the boundary near (V-R) = 0.80 proposed by Linsky and Haisch (Ref. 29). I suspect that the explanation may be very simple. Using a Fourier deconvolution technique, Gray (Ref. 87) measured the rotational velocities of five G5 III stars; four are slow rotators ($v \sin i = 4$ km s^{-1}) and one is a fast rotator ($v \sin i = 24$ km s^{-1}). These data led him to propose that as stars evolve to this location in the H-R diagram from the upper main sequence, the coupling of dynamo-generated magnetic fields and mass loss rapidly decreases the stellar rotation. Since all stars evolve into red giants either from the upper main sequence or from the lower main sequence where the stars are already slow rotators, the absence of active stars among the single red giants is likely due to weak magnetic fields which are a consequence of slow rotation.

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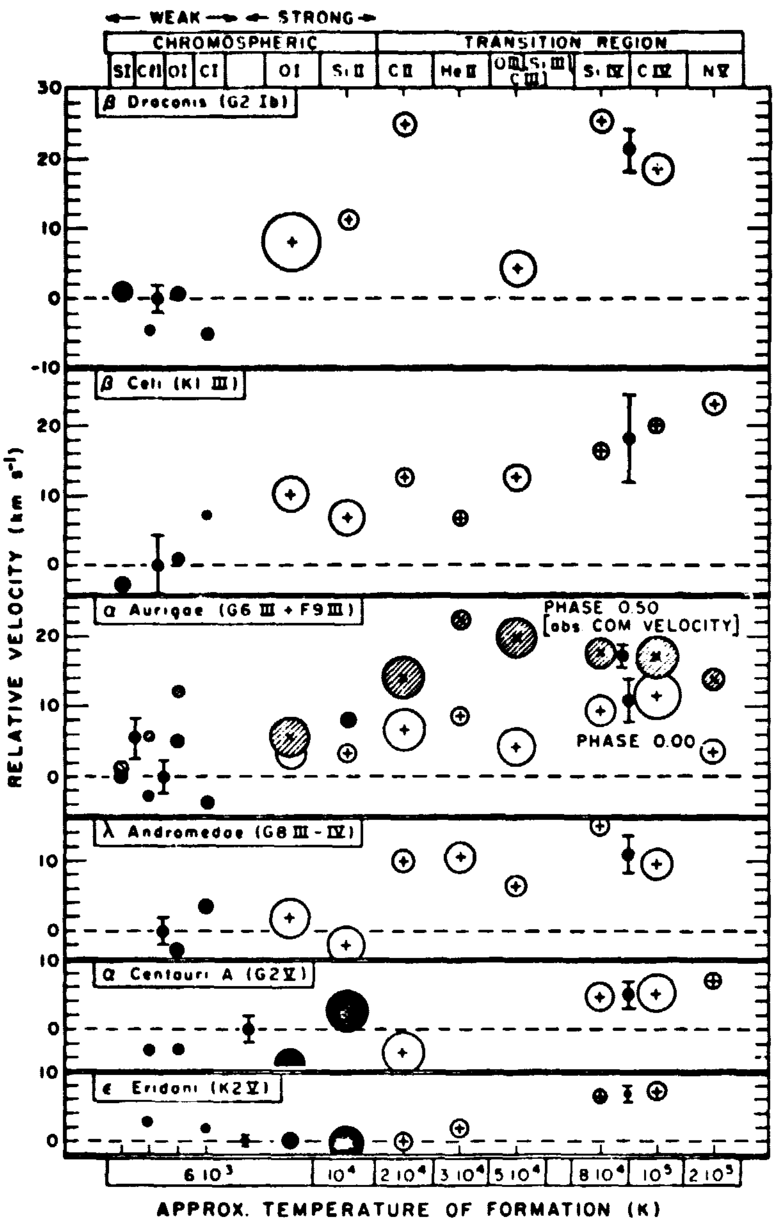

Fig. 7. A comparison of the line of sight velocities of high and low excitation lines obtained by Ayres et al. (Ref. 86). The size of the bubbles indicates the total relative flux of the lines of a given ion. The filled circles are narrow chromospheric lines used in obtaining the flux-weighted mean zero velocity, and the standard error of the mean is indicated by the error bars to the left. The open circles indicate the mean velocities of higher excitation lines, and the error bars to the right indicate the flux-weighted mean velocity of the four C IV and Si IV lines and the error of this mean (including the error of the zero velocity determination). The partially filled bubbles for Capella indicate velocities obtained from a small aperture observation at phase 0.50. These velocities were placed on an absolute center of mass velocity scale by comparison with platinum lamp exposures before and after the Capella exposure. Note that the velocity difference between high and low excitation lines is the same for both Capella data sets, but the small aperture data indicate that the chromospheric lines also appear to exhibit a small red shift.

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