ULTRAVIOLET SPECTROSCOPIC MEASUREMENTS OF COOL STARS

A.K. Dupree
Harvard-Smithsonian Center for Astrophysics
Cambridge, MA 02138 U.S.A.

1. INTRODUCTION

A vast increase in the amount of information on cool stars has occurred during the past 3 years starting with the spectroscopy of the brightest objects from the Princeton experiment on Copernicus, the near ultraviolet balloon measurements from BUSS, low dispersion observations in the far ultraviolet from rocket instruments, and most recently, spectra from the International Ultraviolet Explorer satellite (IUE). IUE now gives access to a wide variety of cool stars and stellar systems enabling systematic studies to be made.

Drawing on the most recent material from IUE, we discuss the presence and structure of chromospheres and coronae in single stars of varying gravities, surface temperatures, and activity. Evidence of mass loss and the concurrent presence of a corona are also noted. Binary systems of late-type stars (the RS CVn and W UMa type) are briefly discussed since they display extremes of surface activity. A binary system such as VV Cep containing a late-type star and an early-type companion provides a unique probe of cool extended stellar atmospheres.

Many of these early observations place constraints on existing theory, and also demonstrate the close analogy between solar and stellar phenomena. The stars we are concerned with show emission features characteristic of a chromosphere and corona. Typically these transitions include Mg II (λ2800), O I (λ1302), C II (λ1335), C IV (λ1550), and N V (λ1240). It is expected that most of these lines are formed under collisionally dominated conditions and hence reflect the electron temperature in the atmosphere. Emission in O I and He II (λ1640) can be influenced by the Ly-β and EUV radiation field, and so may not directly indicate local conditions. Bohm-Vitense and Dettmann (1979) have surveyed the presence of emission features to determine the regions where stellar chromospheres occur. From this, one can infer the presence of convective envelopes. They find the boundary for main sequence stars and giants (luminosity classes III and V) to occur at spectral type F2 and later. For supergiant stars, characteristic emission occurs redward of the

Patrick A. Wayman (ed.), Highlights of Astronomy, Vol. 5, 263–276.

https://doi.org/10.1017/S1539299600003993 Published online by Cambridge University Press

Cepheid instability strip. A-type stars including Am or Ap types did not show emission features. Appearance of emission towards later spectral types is believed to confirm the theoretical conclusion that convection determines the presence and onset of stellar chromospheres.

2. SPECTRA OF SINGLE STARS

2.1 Dwarf stars

Selected spectra of dwarf stars taken with IUE are shown in Figure 1. They display the characteristic emission features found in a solar spectrum. Lines from C II, C IV and N V are typically present giving evidence for plasma at T $\sim$ 2 x 10^5 K. These stars can be called "quiet dwarfs" as estimated by weak or absent Ca II emission cores in optical spectra. By contrast, spectra of 2 active dwarfs (Xi Boo A and EQ Peg) are shown in Figure 2 (Hartmann _et al_. 1979). Here high temperature species are present, as well as a strong line of He II (λ1640).

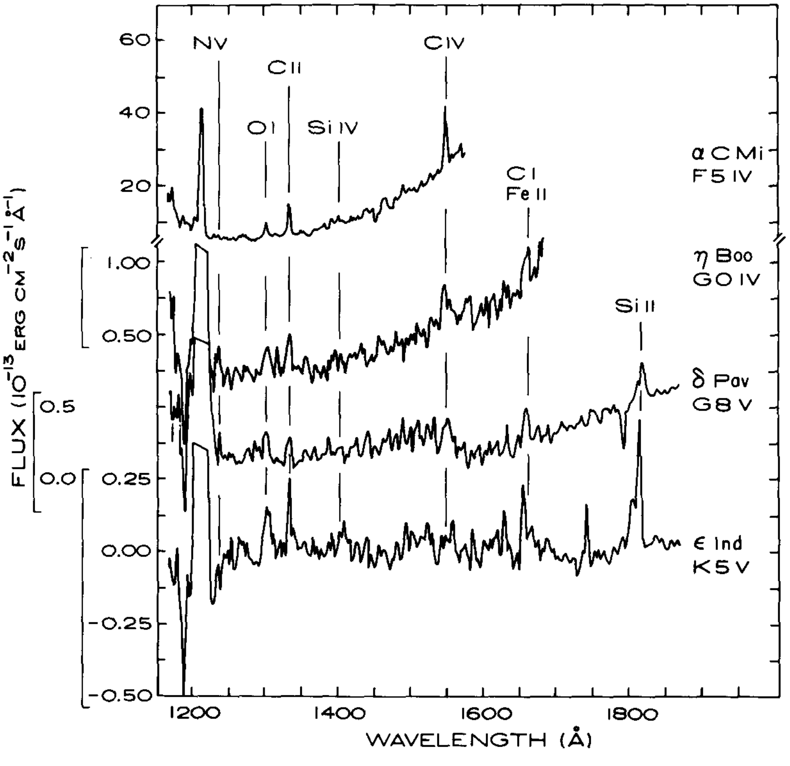

Figure 1. IUE short wavelength spectra of dwarf stars. Note the presence of high temperature species, N V and C IV. Geocoronal Lyman-α emission occurs at λ1216 and has been truncated.

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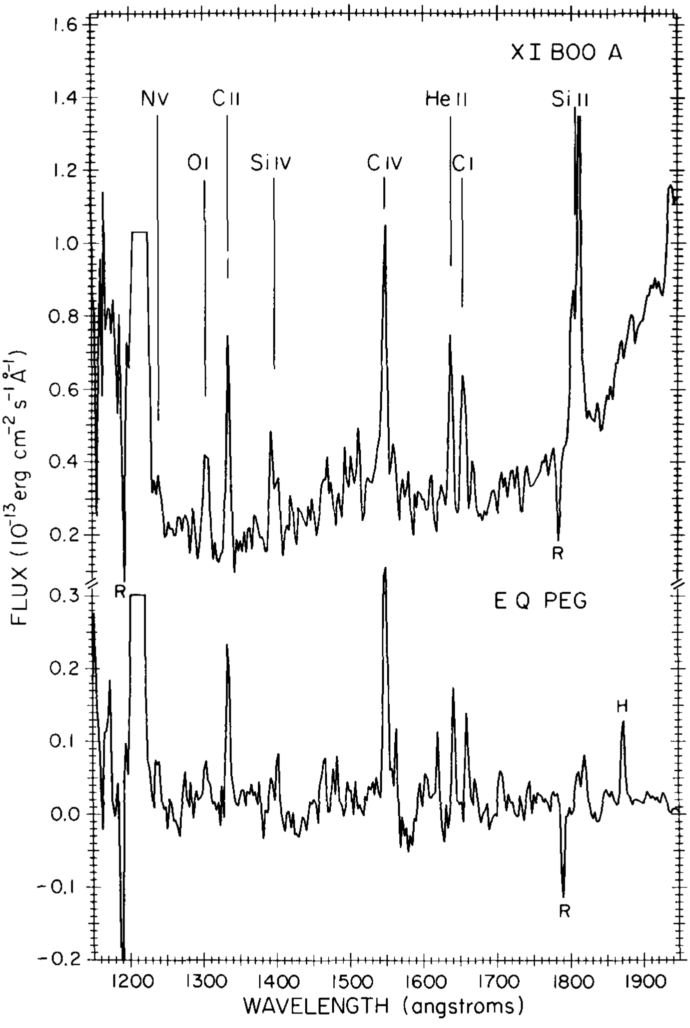

Figure 2. IUE short wavelength spectra of two active dwarf stars Xi Boo A (G8 V) and EQ Peg (dM4) from Hartmann et al. (1979). R denotes a reseau mark; H marks a particle "hit".

This transition is of particular interest for in solar active regions it can be formed by recombination following photoionization of He II (Raymond, Noyes and Stopa 1979) and in these stars appears to confirm the presence of hot coronal plasma ($T \sim 2 \times 10^6$ K) (Hartmann et al. 1979). Spectra of active dwarfs are similar to those of the quiet dwarfs, indicating the presence of an atmosphere of at least $T \sim 2 - 3 \times 10^5$ K, although, as noted later, the surface fluxes of active dwarfs are higher and the strong He II λ1640 line can signal the presence of a still hotter corona. An indication of the distribution of material at high temperatures can be observed also in the C IV/C II ratio which is ∿ 2 in the active dwarfs and is ∿ 1 in the quiet dwarfs (Brown, Jordan, and Wilson 1979). It is remarkable how similar the spectra of the two active dwarfs are to each other considering the change in effective temperature between G8 and M4. The surface fluxes confirm this as noted later. The independence of atmospheric characteristics on temperature as emphasized by Hartmann et al. (1979) provides an important constraint on any theory of coronal heating. The few T Tauri stars (Gahm et al. 1979; Gondhalekar, Penston, and Wilson 1979) that have been observed show spectra similar to that of the active dwarfs, but with a noteworthy weakness or absence of the He II line in all but one star - GW Ori.

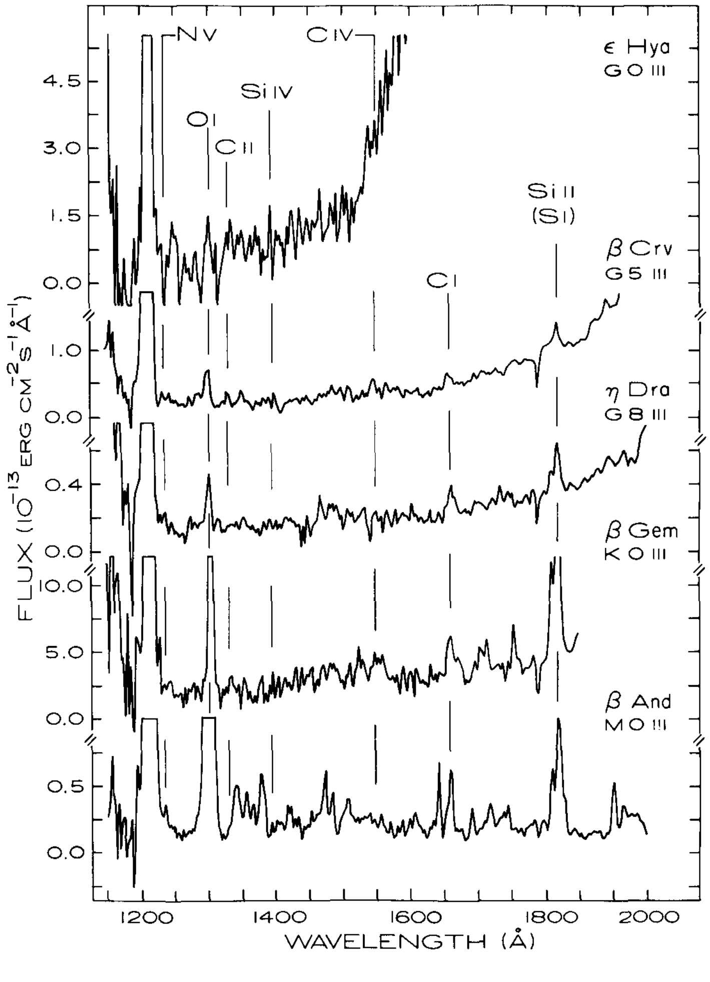

Figure 3. IUE short wavelength spectra of single giant stars. Note the dominance of O I towards later spectral types. C IV is present in multiple exposures of β Gem yet weak or absent in several exposures of η Dra.

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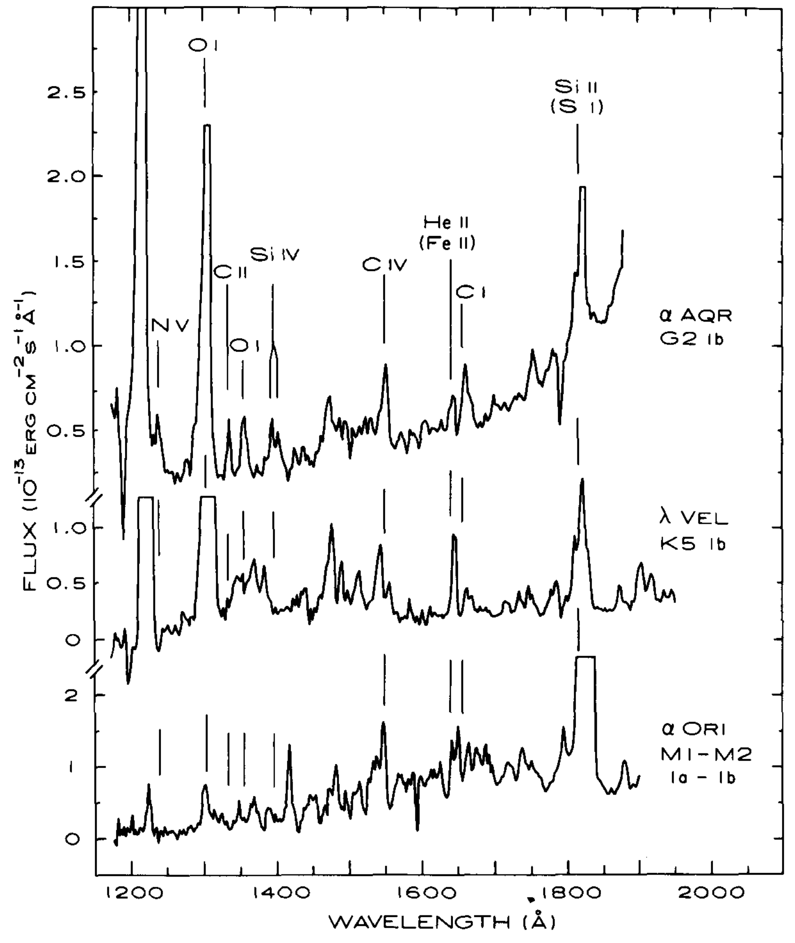

Figure 4. IUE short wavelength spectra of three supergiant stars. High temperature species (N V, C IV, Si IV) are apparent in the spectra of α Aqr, yet weak or absent in λ Vel and α Ori.

2.2 Giant and supergiant stars

In stars of luminosity class III (Figure 3), the spectra are dominated by the Si II (λ1808) doublet and the O I (λ1302) multiplet. The O I transition increases in strength relative to C II towards lower temperatures and may reflect a transition to an extended cool atmosphere where Ly-β pumping is effective. C IV (λ1550) is present in some single giants as, for instance, multiple exposures of Beta Crv and Beta Gem have shown, yet is absent in repeated observations of Eta Dra. The coolest giants (as exemplified by λ And) apparently lack substantial hot material as evidenced by the weakness of high temperature species (C II, Si IV, C IV).

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Early-type supergiant stars exhibit a complex spectrum (Figure 4) consisting of high temperature (C IV) species and low temperature emission lines (C II, C I, Fe II, S I). The Si II lines are especially strong relative to other ions; the O I dominates in the earlier stars α Aqr (G2 Ib) and λ Vel (K5 Ib), and is weaker relative to Si II in the coolest atmospheres, typified by α Ori. Of great interest is the presence of hot species - N V, C IV - found in the spectrum of α Aqr and other early G supergiants (Hartmann et al. 1979, Dupree et al. 1979). Such stars have hybrid atmospheres exhibiting both the characteristic lines of low excitation species simultaneously with lines formed at temperatures typically found in the solar transition region.

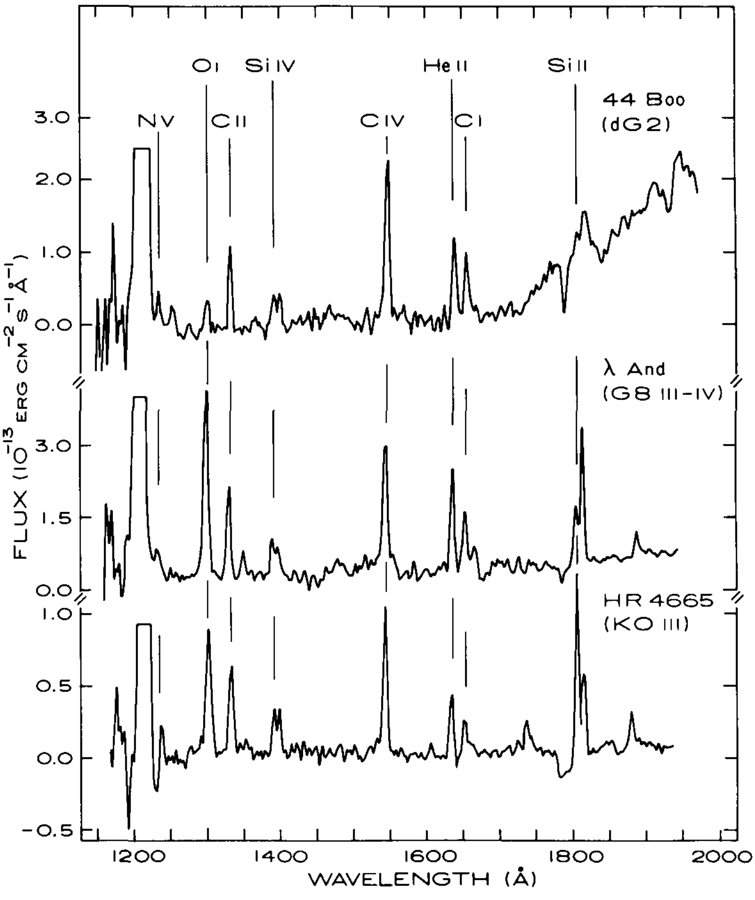

Figure 5. IUE short wavelength spectra of a W UMa-type star (44 Boo) and 2 stars of the RS CVn class: λ And and HR 4665. High temperature species and a strong He II λ1640 line are present in all spectra.

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3. BINARY SYSTEMS

Binary systems of the RS CVn and W UMa-type have been studied with IUE. Spectra of two RS CVn systems, λ And and HR 1099 were obtained during the early work of the IUE Commissioning Team (Linsky et al. 1978). Spectra of 3 binaries: 44 Boo (W UMa-type); λ And and HR 4665 (RS CVn-type) are shown in Figure 5. As in the active dwarfs, high temperature species are clearly found including the He II λ1640 line that is consistent with the detection of 44 Boo (Cruddace and Dupree 1979) and other RS CVn stars as X-ray sources. The enhanced O I is similar to that found in giant stars.

4. ULTRAVIOLET SURFACE FLUXES

The surface fluxes of these emission lines show behavior that is partially dependent on stellar luminosity (see Figure 6). Quiet dwarf stars of the type shown in Figure 1 have flux ratios very similar to that found for the integrated solar spectrum. Active dwarfs show enhancements typical of solar active regions - averaging about 10 times the integrated solar flux. The more luminous giant and supergiant star show greater variations in surface flux among them, ranging over severa orders of magnitude. For the cool supergiants, lines formed at tempera tures of $\sim 10^5$ K are substantially less than 0.1 of the solar surface flux; the hot supergiants show enhancements comparable to active regions. Binary systems, not shown in Figure 6, exhibit fluxes that vary from 10 to 100 times the solar surface flux, the enhancement increases with increasing temperature of formation and there appears to be a correlation with orbital period (Dupree et al. 1979). The shortest period binaries - those of the W UMa class and the RS CVn type of short period-approach the higher values of 100 times the solar surface flux. Rotation appears to be a dominant factor in causing enhancement of the ultraviolet emission lines to a greater extent even than the Mg II and Ca II transitions.

5. THE Mg II TRANSITION

This chromospheric transition has proved useful for it can generally be studied at high resolution with ultraviolet spectrometers and give evidence for mass motions and radiative losses at the base of a stellar chromosphere. Pagel and Wilkens (1979) have surveyed the line parameters in a variety of cool stars and have extended the luminosity - width correlation (Wilson-Bappu effect) to many more objects than contained in the original surveys of Dupree (1976), Weiler and Oegerle (1979), Kondo, Morgan, and Modisette (1976), McClintock et al. (1975). The reason for this correlation is still not clear.

Asymmetries of the ultraviolet line profiles may give some information on the occurrence of mass flow at chromospheric levels. Line asymmetries can occur in optically thick resonance lines (Mg II, Ly-α) in

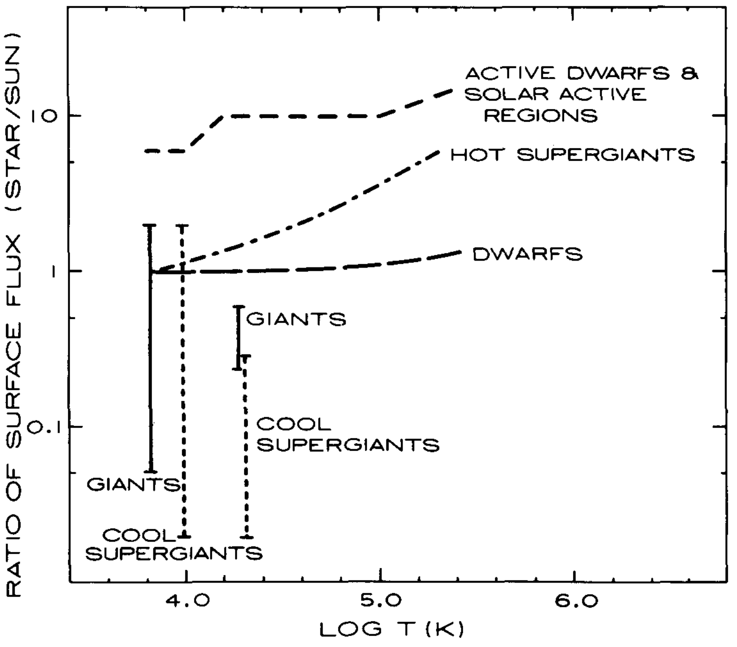

Figure 6. The ratio of stellar surface flux to the corresponding solar value for emission lines formed at various temperatures. Giant and cool supergiant stars show a wider range of values than found in other single stars.

the presence of a differentially expanding atmosphere. There may also be additional conflicting effects resulting from energy deposition in the atmosphere. However, among the stars of luminosity classes I to III asymmetries show a pattern with decreasing effective temperature (see Dupree 1976; Dupree and Hartmann 1979; Mullan and Stencel 1979). Asymmetries appear first in the Lyman-α line, then the Mg II doublet, followed by Ca II, and the appearance of circumstellar features as defined by Reimers (1977). If these asymmetries represent the onset of outward mass motion in the atmosphere they may reflect the penetration of motion to lower levels of the atmosphere in cooler stars. Alternately, since this progression represents an opacity sequence there may simply be a continuously increasing flow with lower effective temperature. It remains to be seen whether there is a sharp "turn-on" in mass loss as Mullan (1978) has proposed.

A particularly interesting example is found in the spectrum of β Aqr shown in Figure 7. The clear correlation between absorption features in Ca II and Mg II indicates the presence of an extended region of mass outflow and a supersonic wind. This supergiant is notable because it is one of the hybrid variety (Hartmann, Dupree, and Raymond 1979) containing C IV emission, implying a hot corona, in the presence of a massive stellar wind.

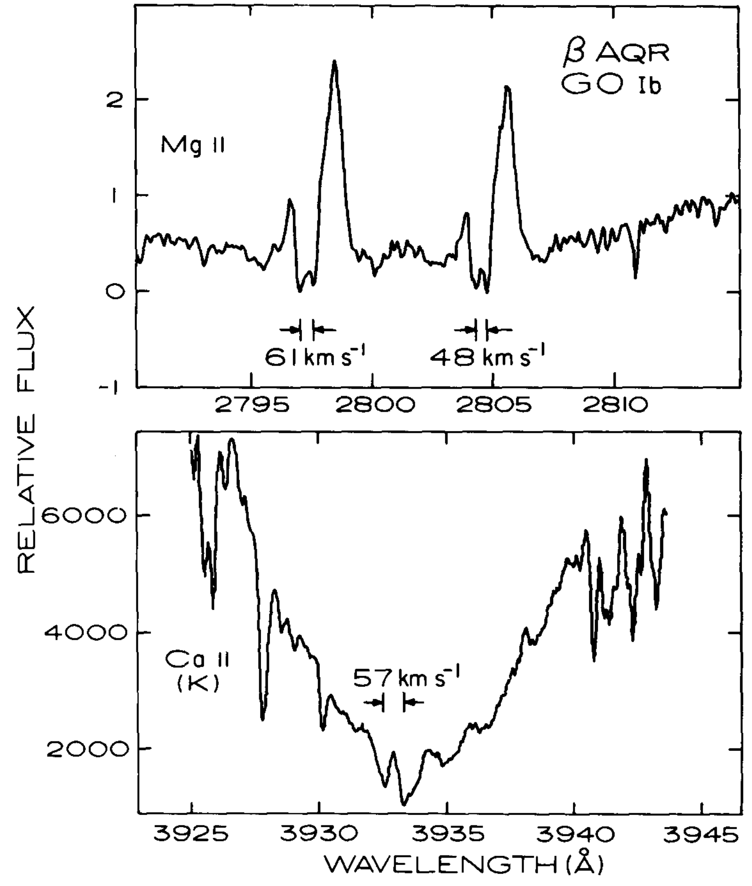

Figure 7. Profiles of Mg II and Ca II lines in β Aqr showing the presence of strong absorption features. Mg II spectra were obtained with IUE; the Ca II spectra were taken with the echelle spectrograph and Reticon detector system at the Mt. Hopkins Observatory.

The radiative losses in the Mg II lines place a minimum value on the energy necessary to heat a stellar chromosphere and corona and may constrain theoretical models of the temperature minimum. Basri and Linsky (1979) have summarized these losses and find no clear dependence on temperature or luminosity; variations of about a factor of ten occur among stars of a given type. Moreover, the generally enhanced values found in RS CVn systems are similar to the behavior of surface fluxes from the high temperature species.

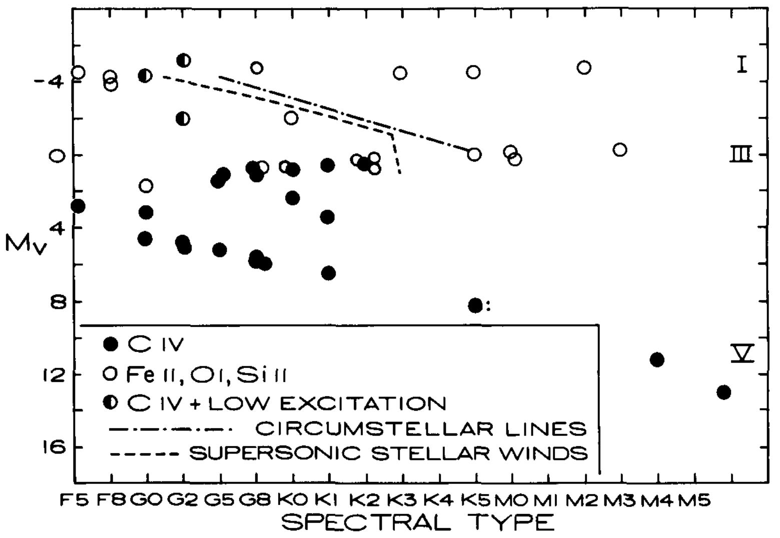

Figure 8. The presence of various spectral features in stars of different spectral types and luminosities. The broken line indicates the locus proposed by Mullan (1978) for the onset of strong stellar winds; the dot-dash line denotes the high temperature boundary of the appearance of circumstellar lines in optical spectra (Reimers 1977).

6. PRESENCE OF HOT PLASMA

It is instructive to examine the overall pattern of the presence of ultraviolet emission features associated with high temperatures, taking C IV as the principal ionic species characteristic of $T \sim 10^5$ K. By analogy with the sun, these atmospheres would be expected to contain higher temperature material although the stellar transition region and corona may well be at different temperatures from the solar case. In Figure 8, results from various authors have been summarized, namely Bohm-Vitense and Dettmann 1979; Brown, Jordan, and Wilson, 1979; Dupree et al. 1979; Hartmann, Dupree, and Raymond 1979; Linsky and Haisch 1979; Linsky et al. 1978; Carpenter and Wing 1978.

Inspection of the figure shows that dwarf stars uniformly show C IV and C IV is absent or extremely weak in the coolest, more luminous giant and supergiant stars. These extremes were noted as well by Wing (1978) and Linsky and Haisch (1979). There is also a substantial region in the HR diagram, from G0 to G2 supergiants and extending down to the giant branch between spectral types G5 to $\sim$ K3, in which the spectra are not easily predictable. Either the hybrid structure of the early supergiants occurs or else giant stars may have either of two characteristic spectra. The coolest extremes of this region are roughly bounded by the appearance of circumstellar absorption lines (Reimers 1977), and near the locus of increased mass flow (Mullan 1978) constructed from the minimum flux corona models of Hearn (1975). This coincidence requires further investigation.

7. WIDELY SEPARATED BINARY SYSTEMS

Several binary systems containing a cool supergiant with a hot companion offer a unique probe of the atmospheric structure of an extended stellar atmosphere. Several systems of this type have been studied: α Sco (van der Hucht *et al.* 1979); KQ Pupp (Wing 1979); ε Aur (Hack and Selvelli 1979); and 32 Cyg (Stencel et al. 1979). A fortuitous occurrence near the time of the launch of IUE was the egress of the secondary of VV Cephei from eclipse - an event that occurs every 20.3 years. This system has been studied in the ultraviolet by Faraggiana and Selvelli (1979) and Hagen et al. (1980). At short wavelengths, the changing character of the spectrum is remarkable (see Figure 9). Hagen et al. (1980) note that egress as observed in the ultraviolet lagged the optical egress by two to three months due to the higher ultraviolet opacity of the atmosphere of the M supergiant. The ultraviolet spectrum λλ1200-1900 was first dominated by fluorescent emission lines from the M supergiant that are excited by the continuum of the hot companion. As the companion emerges through the extended atmosphere of the supergiant, the continuous spectrum becomes stronger and is blanketed by absorption features. High dispersion spectra show many species of low excitation that vary progressively in strength. These are used to determine the ionization structure, density distribution and mass motions in the system. The primary star classified as M2 Iabep has surface fluxes in Fe II and Mg II emission lines in excess of those for a single M supergiant, perhaps resulting from the influence of a hot companion upon the atmosphere.

8. CONCLUSIONS

The early ultraviolet results clearly show the great variety, character, and extent of cool stellar atmospheres. In stars with high gravities, hot plasma is present. In the coolest, most luminous stars, there is little high temperature material. There does not appear to be a sharp division between these types. A large intermediate region of effective temperature and luminosity also exists that may show characteristics of both extremes. The wide variation of radiative losses at a given T_e and log g presents a concern for theory. Such a diversity suggests a similar range in the required nonradiative heating. In active dwarf stars, the losses are independent of effective temperature (Hartmann et al. 1979).

In the coolest stars of low gravity, massive winds occur that apparently suppress the formation of a corona (Linsky and Haisch 1979; Wing 1978); however, the presence of high temperature species and a massive wind in the hotter supergiants demonstrates that both can coexist under appropriate circumstances. These latter hybrid stars having cool winds and

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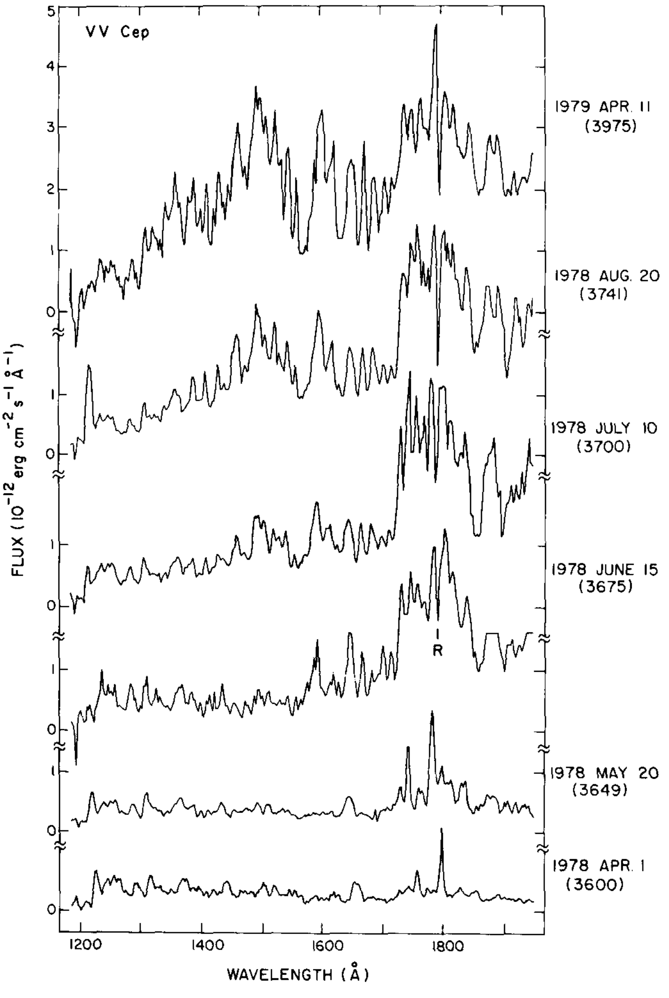

Figure 9. A sequence of short wavelength spectra of VV Cephei showing the emergence of the hot companion from eclipse (Hagen et al. 1980). The Julian Day (2440000+) is indicated in parentheses. In the optical, third contact occurred ∿ 3570 and 4th contact ∿ 3650.

moderate terminal velocities are particularly interesting because they may provide the link between the high velocity coronal wind of dwarfs and the cool, low velocity wind of the late-type supergiants (Hartmann, Dupree and Raymond 1979).

Rotation is clearly a factor in enhancing the radiative losses from an atmosphere (Dupree et al. 1979). It is not hard to believe that synchronous rotation in a binary system can enhance the magnetic field strength which, in the sun at least, is strongly correlated with increased emission. The striking similarity of the behavior of surface flux with that found in a solar active region may be due to localized regions of activity on the stellar surface in an atmosphere dominated by conductive energy losses.

ACKNOWLEDGEMENTS

I am grateful to many scientists, among them E. Bohm-Vitense, C. Jordan, L. Hartmann, J. Linsky, B. Pagel, R. Stencel, and R. Wing who provided results in the form of preprints to be included in this review.

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