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Winds from Cool Stars

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Abstract.
Recent spectroscopic results from the far ultraviolet and X-ray region coupled with infrared observations demonstrate that winds from luminous stars can be warm (300000K) and fast (speeds of several hundred km s^{-1}) linking the hot solar wind to the cool, massive winds of luminous M-type supergiant stars. Hot coronal material (T $\sim 10^7$ K) appears to be confined near the star, and not expanding in the wind. These new spectra enable a comprehensive picture to be constructed of the presence and character of winds in cool stars.

1. Introduction

Stellar winds affect stellar evolution through the reduction of the stellar mass itself and the decrease of stellar angular momentum due to the torque of the wind. Observational constraints on mass loss from cool stars derive from the comparison between the color-magnitude diagram of star clusters and theoretical tracks of stellar evolution. Such comparisons suggest that low mass stars, in evolving from the main sequence to the tip of the red giant branch must lose about 0.2 $M_\odot$. The distribution of stars in the color-magnitude diagram of globular clusters is mainly determined by metallicity but a yet-unknown second parameter is still required to match observations. Candidates for this second parameter include the mass loss rate of stars. It has been conjectured that the rotation of the star, and even perhaps its local environment can effect the mass loss rate of cool stars. Mass loss is currently taken as a theoretical assumption, since no direct measurements exist of cluster stars losing mass. In fact there is a long history of attempts to detect the material presumed lost in the cluster by this process (Smith et al. 1990). While observations of surrogate stars – the metal deficient field giants – suggest that fast winds may be present with sufficient velocity to escape the cluster, detection of the putative winds is currently missing in cluster stars themselves.

In our local neighborhood, the history of winds, mass loss, and associated high energy phenomena in the early Sun carries implications for the environment of the planets in our solar system or others. Young stars, still accreting material from a circumstellar disk, are thought to expend a fraction of the accretion mass flux in a collimated outflow signaled by jets of cool material.

In addition to the significant astrophysical implications of mass loss, the physics of the process itself is challenging. Advances have occurred in our un-

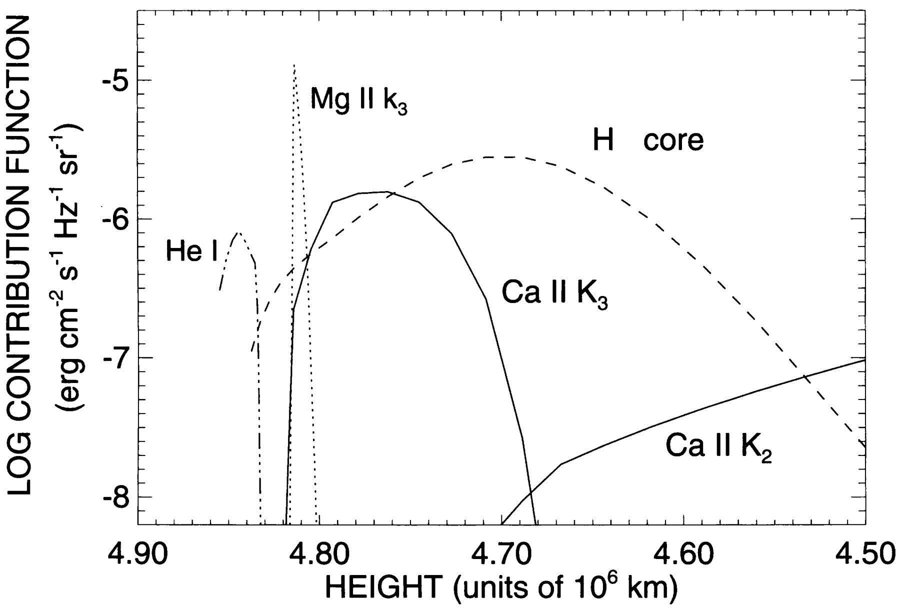

Figure 1. Contribution functions for some of the well known chromospheric emission features in the spectrum of a late-type giant star. Note that height in the atmosphere increases to the left. Whereas the optical transitions (Hα and Ca II) may be sensitive to stellar outflows, the higher regions of the atmosphere as sampled by Mg II and He I are better situated to identify outflows.

derstanding of the solar wind (Habbal 2004, Poletto 2004), but the heating and acceleration of winds in a low gravity environment, and where magnetic processes may be weak or absent, introduces new physical phenomena in these extreme conditions. A star such as the supergiant Alpha Ori (Betelgeuse, M2 Iab) has a mass loss rate 10^8 times higher than the solar rate, in an environment where gravity is 10^4 times less than the solar value. The solar paradigm is frequently invoked in which the magnetic field configuration - whether closed or open – determines the confinement or escape of atmospheric material. Just how well this model can be transferred to luminous cool stars has been questioned ever since the first spectroscopic observations of cool star coronas became available about 25 years ago. The Sun has a hot (10^6K) corona, with a hot (10^6 K), fast (700 km s^{-1}) wind, of low mass loss rate (2×10^{-14} M$_\odot$ yr^{-1}). A supergiant, such as Betelgeuse possesses a cool (10^4 K) atmosphere, a cool (10^4 K), slow ($\sim$20 km s^{-1}) wind of high mass loss rate (10^{-6} M$_\odot$ yr^{-1}). Is such a simple bifurcation of atmospheric and dynamical structure real? Can coronal material persist in the presence of a massive wind? Do X-rays and winds coexist? Spectroscopy in the ultraviolet and X-ray region, as well as new infrared capabilities can help to answer these questions as we begin to construct a comprehensive picture of coronal evolution and mass loss.

2. Detection of Winds

Winds from cool stars are difficult to detect directly. Even for the Sun, the inference of a solar wind first came from observing the motion of comet tails. Much later, *in situ* measurements gave direct confirmation of plasma escaping the Sun. There is no such luxury with stars. The first detection of a wind from a star also came indirectly. Adams and MacCormack (1935) noted Doppler-shifted absorption lines in the spectrum of the supergiant star α Her. Because the velocities were less than the escape velocity from the stellar surface, Spitzer (1939) conjectured that the outflowing material became ionized and then returned to the star. About 20 years later, Deutch (1956) noted stationary lines in the spectroscopic binary that is a companion to the supergiant. These resonance lines from low ionization species defined the extended nature of the wind from the supergiant (at least 1000 au to reach the companion binary); their velocities confirmed that indeed the material was escaping. This is the first documented observation of mass loss from a star other than the Sun.

Even today, no direct detection exists of mass loss from a 'normal' dwarf star like the Sun. An active dwarf binary may have emitted the equivalent of a coronal mass ejection (Bond et al. 2001). Pre-main sequence stars exhibit jets of material (Calvet 2004; Shang 2004); recent He I measures show great promise for detecting winds in these sources as discussed below. The only inference of a wind from solar-like stars has been made by Wood & Linsky (1998). They estimated wind parameters in 2 dwarf stars (61 Cyg A and 40 Eri A) from modelling the subtle interstellar absorption that may arise from the region where the stellar wind forms a shock in the interstellar medium. But a direct detection of winds remains elusive.

Luminous stars with extensive atmospheres, lower gravity, and massive winds offer a better opportunity for detection. It is important to identify spectroscopic features that can do this. Since the scale heights for line formation are large in these luminous stars, spectral diagnostic lines are formed in physically well-separated regions (Fig. 1). While optical (H-α and Ca II) and ultraviolet (Mg II) features have been studied in the past (Stencel & Mullan 1981, Dupree & Reimers 1989, Robinson & Carpenter 1995, Dupree & Smith 1995) , advances in detector technology have allowed access to the He I line at λ10830 which is proving insightful.

2.1. The He I λ10830 transition

The He I transition at λ10830 ($1s2s\ ^3$S - $1s2p\ ^3$P) is formed in the high chromosphere of a cool star. The lower level of the transition is metastable, and is populated by recombination following photoionization of He I by the extreme ultraviolet flux of a star. Thus it is decoupled from local conditions and is a sensitive marker of mass flow. Early spectra of a few stars obtained by Lambert (1987) noted that the line appeared in absorption and emission, and that the absorption could be broad in cool giants. Scattering of photospheric infrared radiation causes the absorption at a temperature of formation $\sim 10^4$K. Emission

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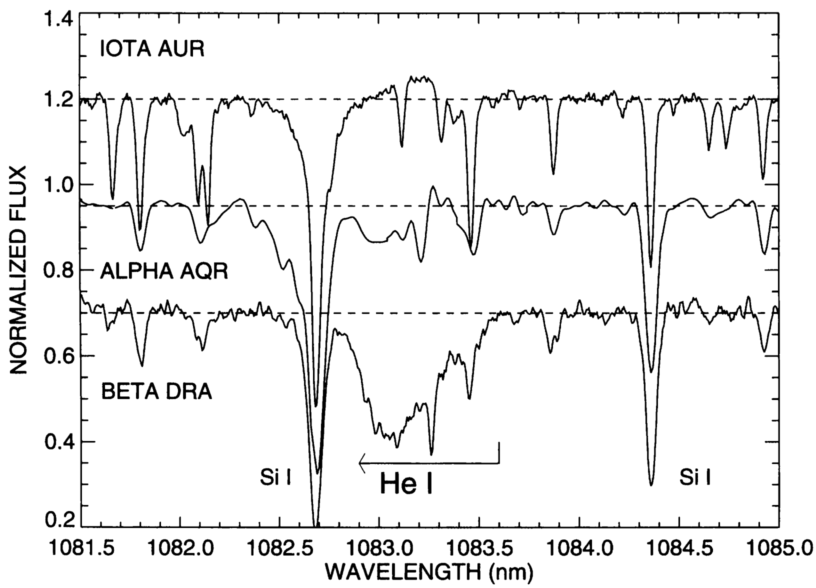

Figure 2. Three luminous stars: Iota Aur (HD 31398), Alpha Aqr (HD 209750) , and Beta Dra (HD 159181) showing the extent of He I absorption from its rest wavelength (λ10830.3). In all cases, it extends to shorter wavelengths beyond the Si I line (λ10827.1) some 90 km/s away. Spectra obtained at the CFHT/FTS and the Nordic Optical Telescope/SOFIN.

requires collisional excitation from the lower level and is likely to require higher temperatures, $\sim$ 30,0000K.

It has long been known (Harvey et al. 1975) that absorption in the λ10830 transition can delineate the presence and extent of coronal holes in the Sun because of the sensitivity of the level population to the euv flux. The line becomes much weaker over coronal holes – which are cooler and produce less euv flux to ionize He I. In addition, and of importance for atmospheric dynamics, the profile of the λ10830 line in the sun appears to mark the onset of mass flow in coronal holes (Dupree, Penn, & Jones 1996). An extended absorption wing to short wavelengths, signifying outflow is found in the centers of supergranulation cells in coronal holes. The amount of this shift depends on the angle of observation suggesting that a radial outflow of 8 km s^{-1} has been initiated in the chromosphere.

In luminous stars the extension of the He I line to short wavelengths can be dramatic, (Fig. 2) and modeling of such an extended profile suggested that supersonic acceleration is present in the chromosphere in many of these stars (Dupree, Whitney, & Averett 1992). Infrared spectra indicate that speeds

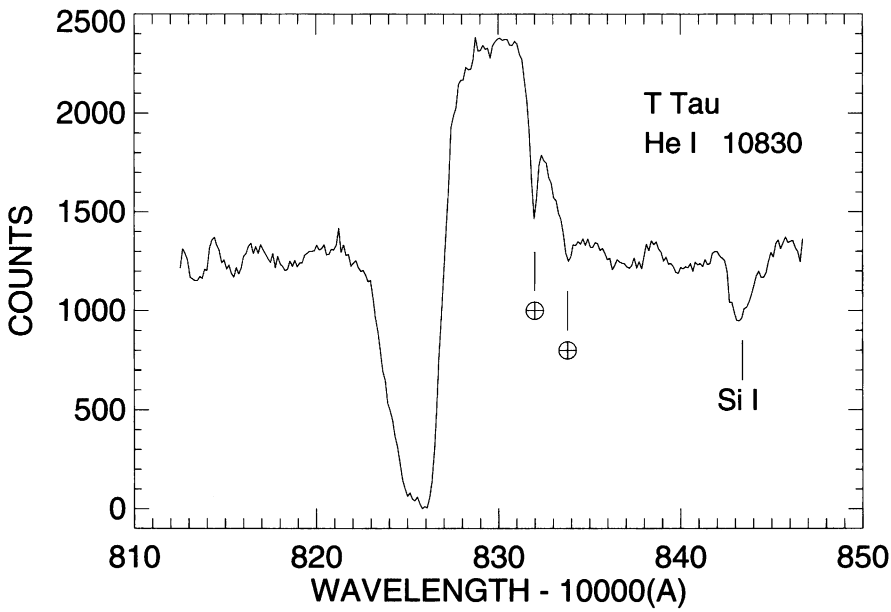

Figure 3. A spectrum of T Tauri obtained at the IRTF with CSHELL in 1992 showing the presence of a fast continuous wind that reaches the high chromosphere (~30,000K) where the He I is formed.

of several hundred km s^{-1} are common and that the He I line absorption is variable. Only a few telescopes have had capability to measure He I spectroscopically, and were mostly confined to brighter objects. Notable among these were CSHELL/IRTF, FTS/CFHT and SOFIN/NOT, but recently with NIRSPEC/KECK, PHOENIX/GEMINI, and ICS/SUBURU, we can anticipate many more spectra in the future.

Young stars also reveal broad absorption in the helium profile. A variety of low mass stars that have high disk accretion rates also have warm helium winds (Edwards et al. 2003; Takami et al. 2002). This is typified by T Tauri (Fig. 3) where absorption is continuous from the photospheric velocity and extends to -200 km s^{-1}, faster than indicated by other diagnostics from low ionization species. These wind features trace the acceleration region of the inner wind and the depth of the absorption (down to complete absorption) in the case of T Tauri, suggests that much of the stellar disk is occulted by the expanding wind. The strong emission suggests that an additional source of excitation may be present. Observation of these lines, gives a more complete tracing of the wind outflow than the traditional optical signatures (such as reported in Najita et al. 2000).

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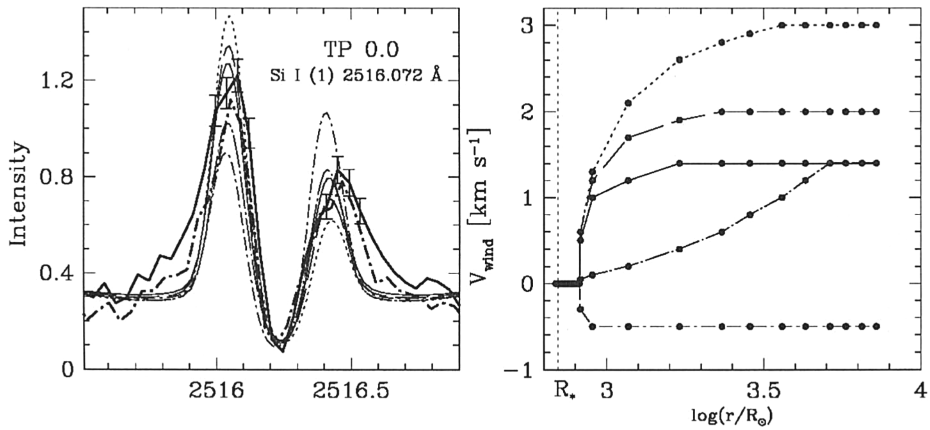

Figure 4. The Si I line at λ2516 as observed in the center of the disk of Alpha Ori (*left panel*) in 1998 Sept (*bold solid line*) and in 1998 April (*bold dash-dotted line*). The best NLTE fits to the lines computed in spherical geometry are shown using semiempirical dynamic models (*right panel*). Note the changes in the line asymmetries: inflow produces a short wavelength peak stronger than the long wavelength peak; outflow produces the opposite asymmetry (Lobel & Dupree 2001).

2.2. Transition Region and Coronal Emissions

Regions of high temperature can be probed with high resolution far ultraviolet spectra, such as those recently available with *FUSE*. The *FUSE* survey (Dupree et al. 2004) of cool luminous stars reveals that emission from C III and O VI, characteristic of temperatures to 3×10^5 K is present across the cool half of the HR diagram with the exception of the supergiant α Ori (M2 Iab). This material is warm, and the profiles can indicate the dynamics in the line-forming region.

If outflows were present, optically thin emission profiles might be expected to be shifted to shorter wavelengths. However, it is more frequently the case, for resonance lines, that asymmetries indicate the presence of mass flow. Hummer & Rybicki (1968) first noted that a differential expansion (or contraction) can cause red (or blue) asymmetries of a line profile. A calculation of the effect of mass flows on a line profile such as Si I (Fig. 4), in a luminous star has been calculated for α Ori. The detailed modeling of this line (in a non-LTE spherical atmosphere) clearly demonstrates the linkage between line asymmetry and mass flow. Even modest velocities ($\sim$1–2 km s^{-1}) cause asymmetries as this figure demonstrates. Larger velocities cause greater asymmetry.

Strong resonance lines are good places to detect winds because they are likely to show wind opacity. The opacity at line center for a thermally broadened line is proportional to the elemental abundance, the wavelength and oscillator strength of the line, the mass of the atom and temperature of formation and the column density of material in the line-forming region. Atomic physics alone makes C III a better diagnostic of opacity than O VI. And C III is also more sensitive than C IV by this criterion. Ions formed at lower temperatures,

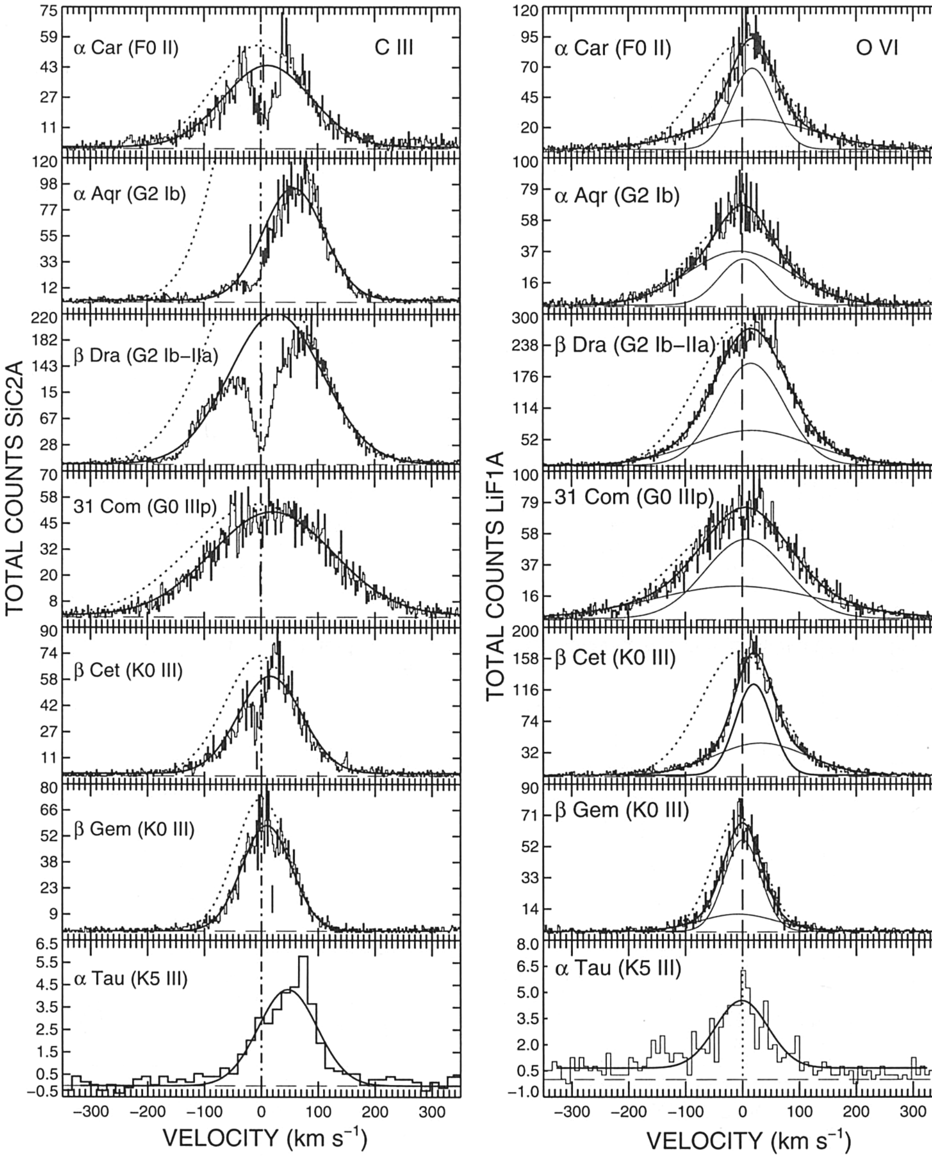

Figure 5. Profiles of the C III (λ977) and O VI (λ1032) emission in cool luminous stars taken from the *FUSE* Cool Star Survey. Single Gaussian fits are made for C III and 2-Gaussian fits are derived for O VI. The dashed line fit in both instances results when only the long wavelength side of the emission profile is considered, in order to assess the presence of absorption on the short wavelength side of the emission. The C III profiles are asymmetric and in all cases have excess opacity on the short wavelength side of the line. O VI is more narrow, and appears to have less line asymmetry, although the core of the emission, particularly in β Dra and 31 Com indicates an asymmetric profile.

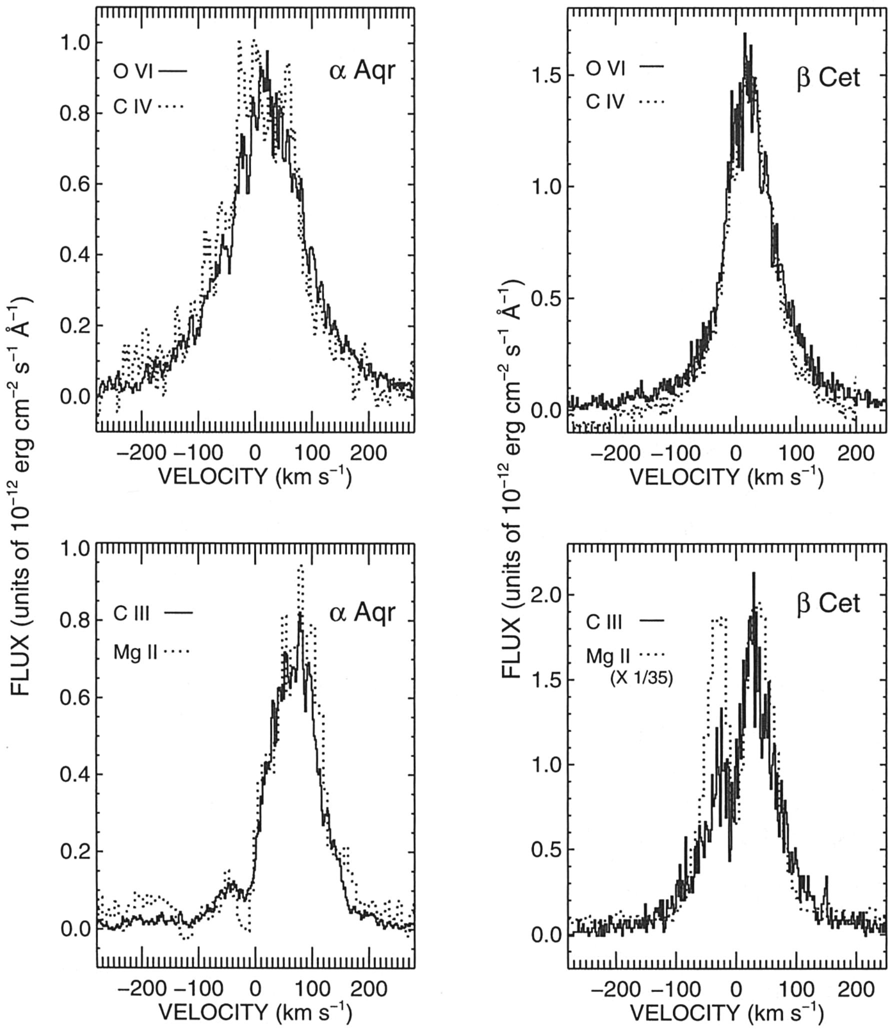

Figure 6. Profiles of chromospheric and transition region lines from *FUSE* (C III and O VI) and *HST* and *IUE*. In α Aqr (G2 Iab), the massive wind causes similar profiles in Mg II and C III indicating a continuous outflow to plasma with temperatures of 80000K. While β Ceti (K0 III) exhibits asymmetries in the chromospheric C III suggesting outflow, it does not appear as substantial a chromospheric wind as in the supergiant star as indicated by the Mg II line which does not exhibit extreme asymmetry.

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such as Fe II and O I (Carpenter et al. 1999) have been used to identify outward motions in the low chromosphere of stars, but spectra from *FUSE* are the first to clearly display asymmetries caused by winds at high temperatures.

Emission from a sample of luminous stars (Fig. 5) shows the prevalence of asymmetric profiles. The C III (λ977) transition suffers from cool interstellar C III absorption, but the gross asymmetries (see α Aqr) reveal a substantial opacity due to wind. The profiles of C III have been fit to one Gaussian (which in several cases is a demonstrably bad approximation), and also to one Gaussian that is fit only to the long wavelength wing of the line. This latter procedure makes absorption more visible on the short wavelength side of the profile. The O VI line can be 'better fit' by 2 Gaussians, although the physical significance of such a fit is not clear. [See another paper in this volume by Peter (2004), that addresses this procedure for the sun.] Again a Gaussian approximation to the long wavelength wing only reveals that absorption on the blue wing appears to be present. Bisection of these profiles also confirms their asymmetry.

What is the cause of such asymmetry? Restricted regions of the sun frequently show red-shifted lines that are interpreted as downflows in the magnetically restricted regions. To apply such an interpretation to luminous stars which are not spatially resolved, and whose radii can be an order of magnitude or more larger than the sun, appears unlikely. Moreover, chromospheric line profiles as observed in other ions (see Fig. 6) show asymmetries and absorption at similar velocities. Thus, the *FUSE* spectra give the first documentation of warm winds in these luminous stars.

3. Coronal Species and Winds

Atmospheres of many cool stars reach coronal temperatures and emit X-rays. Whereas the current generation of X-ray satellites lacks the spectral resolution to measure the wavelengths of coronal emission directly, some coronal transitions occur in the ultraviolet and far ultraviolet spectral regions where echelle spectra make measurement possible. Transitions that are frequently used arise from Fe XXI (λ1354) (Linsky et al. 1998; Johnson et al. 2002), Fe XII (λ1242) (Jordan et al. 2001) Fe XVIII(λ974) and Fe XIX (λ1118) (Young et al. 2001; Redfield et al. 2003; Dupree et al. 2004). Of these, the Fe XVIII transition is preferable because it is free of blending by nearby lines. Detection of Fe XVIII in several cool stars with the *FUSE* satellite (see Fig. 7) shows that it has the stellar photospheric velocity (Redfield et al. 2003), and confirms that the hottest plasma ($\sim 6 \times 10^6$K) is confined. Of course, since the identification of Fe XVIII in many cool stars and stellar systems with the *EUVE* satellite and the determination that such high temperatures were a constant feature in luminous cool star spectra (cf. Sanz-Forcada et al. 2003), confinement by magnetic fields is obvious. High temperature coronae would easily escape the low gravity environments of giant and supergiant stars.

There are early indications of coronal evolution from XMM-NEWTON spectra of β Dra and α TrA. The latter star is a hybrid star, with both hot plasma and a massive wind. The temperature of its corona, as measured from the XMM-NEWTON RGS spectra is cooler than the temperature of the supergiant, β Dra

(Dupree & Brickhouse 2002), suggesting that, by analogy to solar coronal holes, the massive wind does not coexist with the highest temperatures.

4. Conclusions

Winds appear to vary smoothly in their character across the cool half of the HR diagram (Fig. 8). There is no sharp dividing line between the appearance of hot, warm, or cool winds. It must be remembered that at present we are only observing the whole star in each case. Indications of the complexities of atmospheric dynamics and opportunities for the future are found in the studies of Betelgeuse (α Ori). Because this star has such a large apparent size, spectra can be obtained with *HST* with spatial resolution on and off the optical disk (Gilliland & Dupree 1996; Lobel & Dupree 2000, 2001). The dynamics revealed in this way are complicated, as Betelgeuse is pulsating asymmetrically.

It would not be surprising to find that such complexity lurks in the whole-star profiles discussed here! Interferometers are needed in the future, especially for the ultraviolet (and X-ray regions) to probe the hot outer atmospheres of cool stars.

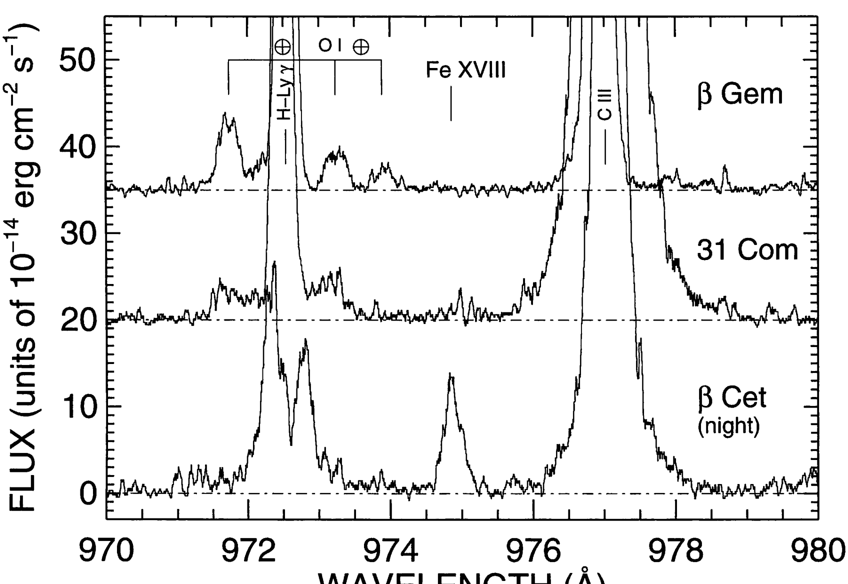

Figure 7. The Fe XVIII region as measured by *FUSE*. This high temperature ion is not seen in β Gem (K0 III), but is weakly present in 31 Com (G0 IIIp) and clearly in β Cet (K0 III). This high temperature feature is consistent with the photospheric velocity of the star. the giant, β Ceti does exhibit expansion in C III (80000K), and demonstrates the anchoring of the high temperature material where present.

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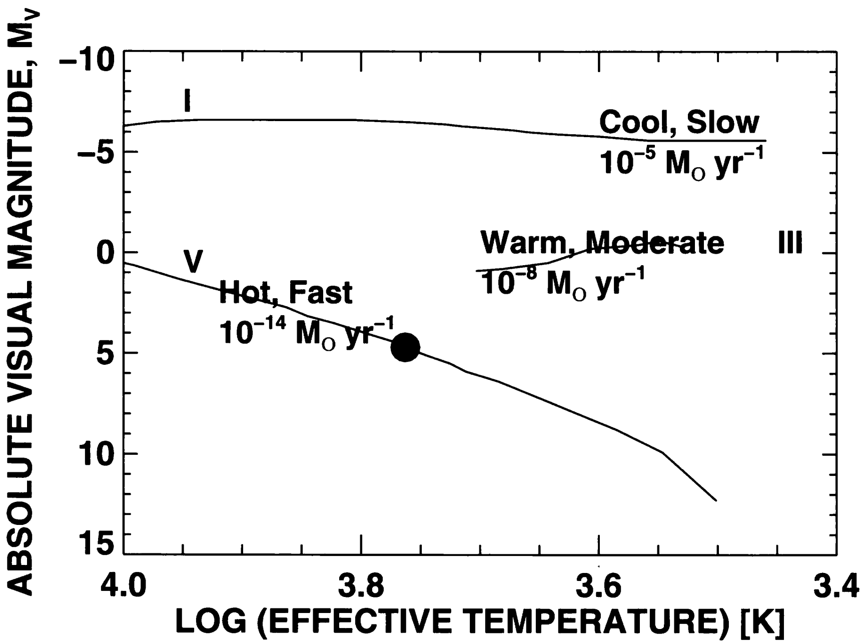

Figure 8. Wind temperatures, speeds, and approximate mass loss rates of stars on the cool side of the HR diagram. A smoothly varying pattern of temperature, velocity, and mass loss rate appears as the stellar luminosity increases.

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