Mg II h AND k PROFILES IN HIGH-LUMINOSITY, LATE-TYPE STARS

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ABSTRACT

Using high-resolution spectroscopic data taken with the Goddard High Resolution Spectrograph aboard the Hubble Space Telescope and with the International Ultraviolet Explorer satellite, we compare the profiles of the Mg II h and k lines seen in stars with spectral types ranging from early K through mid-M and luminosities from giants to supergiants. For all of these stars the lines are broad emission features with a central absorption. When plotted on a velocity scale the absorption features of the h and k lines agree very well in both shape and position, as do the blue wings of the emission component. The red wings of the emission, however, show a pronounced difference, with the k line wing consistently shifted to the red of the h line wing. At present the reason for this discrepancy is unknown, but we suggest several possibilities, including radiative transfer effects and high-speed stellar winds.

Subject headings: stars: late-type — supergiants — ultraviolet: stars

1. INTRODUCTION

The Mg II resonance lines at 2795.5 Å (k line) and 2802.7 Å (h line) are among the most important chromospheric diagnostics in the spectra of high-luminosity, late-type stars, where they appear as centrally reversed emission features. The strength of the emission is a direct measure of chromospheric activity, while asymmetries and blueshifted absorption features are generally interpreted as indicating the presence of winds (e.g., Stencel & Mullan 1980a, b).

The two resonance lines differ in opacity by a factor of 2 and are both known to have extremely large optical depths in the stellar chromosphere. It is generally assumed, therefore, that the two lines come from the same portion of the atmosphere and should have the same profile shape. In general, this seems to be the case, with most published Mg II spectra having similar shapes in the two lines (Stencel et al. 1980). Occasionally, however, there is a pronounced difference. One of the most extreme cases is α Ori, where the k line shows a pronounced enhancement of the red peak, while the h line shows either an enhanced blue peak or a symmetric profile (see Fig. 1).

With the launch of the Hubble Space Telescope (HST) we obtained the ability to acquire extremely high quality UV spectra by using the Goddard High Resolution Spectrograph (GHRS). This spectrograph has good photometric precision and the capability of obtaining spectra with both a high signal-to-noise ratio (S/N) and a highly reliable wavelength calibration. Using spectra taken with this instrument we have been able to very accurately compare the profile characteristics of the two Mg II resonance lines. Also, by using the GHRS spectra as reference we are able to assess the accuracy of International Ultraviolet Explorer (IUE) observations, thereby extending the range of stars for which the comparisons can be made.

In this paper, we present the results of a detailed comparison of the Mg II h and k line profiles for a wide variety of stars, ranging in spectral type from early K through mid-M and in luminosity from dwarf to supergiant.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. GHRS Data

High-resolution GHRS observations of the Mg II resonance lines have been obtained for three late-type giant or supergiant stars for which the secondary, if present, contributes a negligible amount of flux. These stars are α Ori (M1.5 Lab), γ Cru (M3.4 III), and γ Dra (K5 III). The spectra were obtained through the 0.25 aperture with the echelle B grating, using detector 2 and are located in the STScI archives under file names Z0YLO20HM, Z0W10119T, and Z0J7010GT, respectively. In all cases these spectra had a resolution (R = λ/Δλ) of 85,000 and a S/N ratio in excess of 30:1 throughout most of the line profile. The data were reduced at the Goddard Space Flight Center using the CALHRS routine, which combined the individual data samples, eliminated or reduced the effects of weak or inoperative diodes, subtracted the background and echelle scattered light, corrected for instrumental vignetting and the echelle "ripple" function, and applied absolute flux and wavelength calibrations. Each observation was tied to a special calibration exposure which allowed the absolute wavelength scale to be determined to an accuracy of better than 0.3 km s⁻¹.

2.1.1. α Ori

The GHRS echelle spectrum of α Ori in the region of the Mg II resonance lines is shown in Figure 1. The Mg II lines are the strong, broad, double-peaked emission features, while all other structure in the region is in absorption. This spectrum shows that the h and k line profiles have remarkably different shapes. Here the k line (2795.5 Å) has a pronounced red wing
enhancement, which is compatible with other cool, high-luminosity stars (Stencel & Mullan 1980a) and is thought to indicate the presence of a wind. The H line (2802.7 Å) on the other hand, has a weak blue wing enhancement, which is characteristic of stars with earlier spectral types. The Fe I (UV 3) line at 2795.006 Å is known to be involved in the fluorescent process which is responsible for Fe I (42) emission at 4391 Å in the visual. For many years it has been assumed that at least some of the differences in the Mg II lines are caused by the absorption of Fe I (UV 3) as well as Mn I (UV 1) in the blue wing of the k line (Bernat & Lambert 1976). The GHR5 data, however, suggest that both sources of opacity are much too narrow to account for the asymmetry.

A simple way of visualizing the Mg II asymmetry is to assume a symmetric emission feature on which is superimposed an absorption component formed at higher altitudes (see, e.g., Hummer & Rybicki 1968). Different motions within the two formation regions then result in the asymmetry. To help quantify the asymmetry of the α Ori profiles we adopted this idea and attempted to fit the profiles with a simple two-component model consisting of a Gaussian emission feature with an overlying absorption component caused by a simple isothermal slab. The results of the fit are presented in Figure 2, which shows a rough agreement between the model fit and the observations. In the figure we indicate the radial velocity (RV) of each of the components. Note that while the absorption features have nearly identical RVs (16 km s\(^{-1}\)) the emission component for the k line is redshifted with respect to that of the h line by 23 km s\(^{-1}\).

By converting the wavelength scale to a velocity scale it is possible to compare the profile shapes directly. This is done in Figure 3, which confirms the close agreement between the absorption features, as well as the discrepancy in both the red and blue wings of the lines. When the h line is scaled so that the peak intensities of the red wings match (see Fig. 3), the red wing discrepancy appears as a simple redshift of the k line emission by about 20 km s\(^{-1}\) with respect to the h line wing.

The Mn I and Fe I absorption features overlying the Mg II profiles are most probably formed in the circumstellar shell. Analysis shows that these lines can be adequately modeled as absorption features from a simple overlying slab which has a Gaussian absorption coefficient. The best fits for the absorption yield a FWHM of 120 mÅ, a radial velocity of 13.0 km s\(^{-1}\), and an optical depth of about 3 for the three Mn I lines. The Fe I line is much weaker, with an optical depth of less than 1, a FWHM of 60 mÅ, and an RV of 13.1 km s\(^{-1}\). The measured RV of the lines is consistent with a wind of about 10 km s\(^{-1}\), since the RV of the stellar photosphere is about 22 km s\(^{-1}\) (Carpenter et al. 1992). The width of the Fe I (UV 3) line indicates an upper limit of only 6 km s\(^{-1}\) for the turbulent velocity in the shell. This is substantially smaller than the turbulence occurring in the chromosphere, which has been measured from the FWHM of the C II intercombination lines near 2325 Å as 37 km s\(^{-1}\) (Carpenter et al. 1992).

2.1.2. γ Dra and γ Cru

High-resolution GHR5 spectra for γ Cru and γ Cru are presented in Figures 4 and 5. These stars represent a partial...
s spectral sequence for giants and also represent differences in chromospheric activity. While \( \gamma \) Cru is a standard, quiet star, \( \gamma \) Dra is a known hybrid, having detectable emission lines formed at both transition region and coronal temperatures (Linsky, Andrilis, & Brown 1992) as well as a high-speed wind, which is manifested in the Mg II h and k profiles as an absorption feature at \(-85 \) km s\(^{-1}\).

In both stars the h line is weaker than the k line. When the h line is scaled to match the k line intensity we see a very good agreement in the shape of the absorption core as well as a displacement of the red wing of the k line with respect to that of the h line, as was the case for \( \alpha \) Ori.

The extended blue wing in the \( \gamma \) Dra spectrum is caused by a dense high-speed wind and is characteristic of hybrid stars (e.g., Hartmann et al. 1985). There is some indication of an extended blue wing in \( \gamma \) Cru as well and a slight suppression of flux near \(-45 \) km s\(^{-1}\) which may result from a weaker high-speed wind. However, this feature is very close to that expected from the Fe i (UV 3) line, so an alternative explanation may involve fluorescent processes in the chromosphere. There are no indications of absorption from the Mn i (UV 1) lines so it is unlikely that a substantial circumstellar shell exists around either star. Note that the blue wings of the h and k lines agree reasonably well in both objects, with the scaled h line flux exceeding the k line flux slightly except in the very far blue wing, where the k line dominates. The strong asymmetry in the Mg II absorption cores in \( \gamma \) Cru also shows up in the self-reversed Fe II profiles and is probably caused by strong flows in the chromosphere of the star (see Carpenter, Robinson, & Gessner 1993; Carpenter, Robinson, & Judge 1995) as well as absorption by the interstellar medium.

2.2. IUE Observations

While the GRS observations provide exceptional data, they are limited in the range of spectral types which are covered. To more fully understand the behavior of the Mg II resonance lines we searched the IUE archives for single or single-line binary stars with spectral types from late G through mid-M and luminosities ranging from giants to supergiants. A list of the program stars is presented in Table 1, where we have specifically excluded known hybrid stars.

When more than one IUE spectrum was available we improved the S/N value by combining them using a technique similar to that described by Ayres et al. (1986) and Robinson et al. (1994). Briefly, this technique involves cross-correlating each spectrum against the highest quality spectrum in the group and then doing a weighted mean at each wavelength, with the weight at each point being determined by the value of the data quality flag. When three or more spectra were available we also compared the calibrated intensity of each point with the mean value and assigned smaller weight to those points deviating from the mean by more than 5 standard deviations. This helps eliminate the effects of particle hits.

Of particular concern in the analysis is the fact that the Mg II h and k lines are observed in different echelle orders with the IUE. Thus, in the reduction each order was extracted separately and the individual spectra were combined for the h and k lines independently. To check on the reliability of the differential wavelength scales we compared co-added IUE spectra from \( \alpha \) Ori, \( \gamma \) Cru, and \( \gamma \) Dra with the GRS spectra described in § 2.1. When the IUE spectra of these stars are put on the GRS wavelength scale by aligning the IUE and GRS k line profiles, a systematic displacement of the IUE h line by 2–3 km s\(^{-1}\) to the red of the GRS reference is found. A systematic correction of \(-2 \) km s\(^{-1}\) is thus applied to the order containing the h line in all the IUE spectra used in this study.

In Figure 6, we plot the h and k line profiles for the program stars, arranged roughly in order of spectral type and luminosity. The general properties of the profiles agree with those already listed for the GRS observations, e.g., a close positional overlap between the cores, moderate agreement in the blue wing of the lines, and a substantial redshift of the red wing of the k line with respect to the h line. Several dwarf and subgiant stars (e.g., \( \epsilon \) Eri, \( \eta \) Cep, and AT Mic) were examined for comparison. They do not show this effect and have a nearly identical profile for both lines.

3. DISCUSSION

To quantify the behavior of the line profiles we have parameterized the lines using three variables: width, asymmetry, and \( \Delta V \), as shown in Figure 7. Here width is the average width of the h and k lines as measured at 10% maximum intensity and was used to assign an absolute magnitude (given in Table 1) to the stars using the Mg II equivalent of the Wilson-Bappu effect (Weiler & Oegerle 1979). The asymmetry is the ratio of the maximum flux in the blue (B) to the red (R) emission peaks, and \( \Delta V \) is the offset of the k line wing from the h line wing (in km s\(^{-1}\)) as measured over a small range of intensities near the 50% intensity level after normalizing the h and k line profiles to the same maximum intensity. Before measuring, the two profiles

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were aligned so that the centers of the central absorption features coincided, as suggested by the GHRs observations. Typically, this required an adjustment of only 1–2 km s\(^{-1}\) after the IUE \(h\) line profile is adjusted by the 2 km s\(^{-1}\) systematic shift mentioned in § 2.2. The results of the analysis are presented in Table 1 and Figures 8 and 9.

In Figure 8 we summarize the relative shifts found in the red and blue wings of the lines. In all cases the red wing of the \(k\) line was redshifted with respect to the \(h\) line. The shifts in the blue wing are consistently smaller than those observed in the red wing, with the supergiants having the \(k\) line wing blueshifted with respect to the \(h\) line, while the giants typically show a redward shift in the scaled plots. An obvious trend is the increase in the magnitude of the red wing shift with increasing luminosity. There may also be a slight tendency of increasing shift with decreasing effective temperature, but this is much less pronounced.

Figure 9 summarizes the line asymmetries. A red asymmetry (e.g., \(B/R < 1\)) is typically taken as an indication of the presence of a massive, slow wind, while a blue asymmetry marks stars with magnetically confined active regions, similar to those seen on the Sun. Stencel & Mullan (1980a, b) showed the existence of a relatively sharp boundary between these two classes of stars, indicated in the figure by a dotted line.

While the asymmetry in the \(h\) and \(k\) lines is normally in the same sense, the characteristics of the stars on either side of the boundary are substantially different. Stars with a red asymmetry (e.g., winds) typically have a pronounced asymmetry in the \(k\) line and a smaller asymmetry in the \(h\) line. In only a few cases (such as \(\beta\) Uma) does the \(h\) line asymmetry exceed that in the \(k\), and this may be the result of absorption in the interstellar medium. In stars with a blue asymmetry (e.g., “coronal”) the situation reverses and the \(h\) line asymmetry dominates. The magnitude of the average asymmetry in these stars also tends to be much smaller than that in the stars on the right-hand side of the H-R diagram. Near the boundary some giant stars exist where the asymmetry in the two lines has opposite senses (e.g., \(\beta\) Oph and \(\eta\) Pup), with a red asymmetry of symmetric \(k\) line and a blue asymmetry for the \(h\) line.

Absorption of Mg II by the interstellar medium can seriously affect the observed Mg II profiles, especially the asymmetry (see, e.g., Bohm-Vitense 1981). In Figures 3, 4, and 5 we have indicated the estimated RV of the interstellar medium, using the relations presented by Crutcher (1982). In the case of \(\alpha\) Ori (Fig. 3), the interstellar absorption is completely masked by the deep intrinsic absorption feature of the star, most probably arising from non-LTE effects in the stellar chromosphere and wind (see Drake & Linsky 1983). For \(\gamma\) Cru, the interstellar absorption is shifted out of this range and produces a strong cutoff on the blue side of the central absorption. To determine the effect of this absorption we did some simple line-fitting experiments similar to those mentioned in § 2.2.1. This indicated that the asymmetry of the line was primarily caused by the strong central reversal, as is the case for \(\alpha\) Ori. The interstellar absorption simply removed light from the blue portion of the core without significantly affecting the peak flux. At most, the asymmetry of the \(k\) line would be expected to change from the observed value of \(B/R = 0.55\) to about 0.65 if the interstellar absorption were removed, with similar effects for the \(h\) line. Finally, the low velocity absorption feature for \(\gamma\) Dra appears to be caused mainly by the interstellar medium, as suggested by Drake, Brown, & Linsky (1984). From a profile-fitting analysis similar to that described in § 2.1.1, this feature was found to have an RV of \(-14\) km s\(^{-1}\) in both the \(h\) and \(k\) lines, very close to the predicted value of \(-16.5\) km s\(^{-1}\). Both lines showed the same EW of \(180 \pm 20\) mA, with the errors caused primarily by uncertainties in normalizing the strongly varying emission line background. The lines were found to be slightly saturated, with a central optical depth of about 2.5 and a Doppler width of 15 km s\(^{-1}\), which is much larger than the

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Fig. 6.—Comparing the Mg ii h (dotted) and k (solid) profiles for a variety of cool, high-luminosity stars observed by JUE. In most cases the spectra represent a coaddition of three or more individual exposures, as explained in the text. Profiles have been shifted so that the absorption components of both profiles are at zero velocity.
Fig. 6—Continued
Fig. 6—Continued
thermal width of a gas at $5 \times 10^3 \text{ K}$. As point out by Bohm-Vitense (1981), the Mg II absorption in cool stars is important since most of the nearby stars are cool and the strong absorption strength of Mg II allows us to study the characteristics of the interstellar medium in the close vicinity of the Earth.

To assess the impact of the interstellar absorption on the asymmetries measured in the IUE spectra, we tabulated the RV of the star ($V_\text{star}$) and the estimated velocity of the interstellar medium ($V_\text{int}$) in Table 1. Typically, the interstellar absorption is expected to influence a region of the profile covering between 10 and 40 km s$^{-1}$, depending on the degree of saturation. If the absorption falls near the center of a deep central absorption feature, similar to that seen in α Ori or γ Cru, then only marginal effects will be seen. As the absorption encroaches into one of the wings, the asymmetry will change, as pointed out by Bohm-Vitense (1981). Interstellar absorption in the dominant portion of the observed profile can only decrease the asymmetry from the intrinsic value. Absorption in the subordinate portion of the profile can increase the magnitude or may reverse the sense of the asymmetry. These are the cases to treat with extreme caution in interpreting Figure 9. If we assume that the interstellar absorption should be shifted by at least 10 km s$^{-1}$ from the line minimum to have an appreciable effect on the profile, then a questionable situation occurs when $V_\text{int} - V_\text{star} > 10$ for $B/R > 1$ and $V_\text{int} - V_\text{star} < -10$ for $B/R < 1$. If the RV of the star is sufficiently large, then the interstellar absorption is shifted away from the emission features and has no effect.

Reviewing the numbers in Table 1 shows the existence of nine questionable stars, marked with crosses in Figure 9. For six of the stars the sense of asymmetry was the same for both the $h$ and $k$ lines. The only star in this group with a blue asymmetry ($\eta$ Cep) had the interstellar absorption shifted into the red wing, while the remaining stars, all of which have a red asymmetry, had the interstellar absorption in the blue wing. The effects of removing the interstellar absorption in these stars would be to reduce the degree of the observed asymmetry, thereby emphasizing the trend toward increasing asymmetry with increasing stellar luminosity. In three of the stars the $h$ and $k$ lines had opposite senses of asymmetry, with the $k$ line having a red asymmetry and the $h$ line a blue asymmetry. The effect of removing the interstellar absorption in these spectra would be to increase the asymmetry in one line and decrease it in the other, depending on the location of the absorption. In one case ($\zeta$ Pup) the interstellar absorption is in the red wing, so removing it would increase the $k$ line asymmetry and decrease or possibly reverse the $h$ line asymmetry. This would make the star more compatible with stars of similar color and luminosity. The other two stars ($\iota$ Cet and $\beta$ Oph) both have the absorption in the blue wings. Removing it decreases the $k$ line asymmetry and increases the $h$ line asymmetry, again making the spectra more compatible with those of similar type.
stars. The results allow us to add several stars to the sample used by Stencel & Mullan (1980a, b), and we therefore suggest a second possible dividing line between the wind and nonwind stars, which is shown in Figure 9 as a dashed line. This line is still somewhat questionable due to the small number of stars near the line.

4. CONCLUSIONS

We have compared the Mg h and k resonance line profiles over a wide region of the H-R diagram using data from both the HST and the IUE satellites. When plotted in velocity space it is found that the Mg h and k line profiles for dwarfs agree very well with one another. While the absorption cores in the more luminous stars agree in both shape and position, there appear to be systematic differences in the line wings: (1) The blue emission wing of the k line is typically shifted from that of the h line by a small amount, normally to the red. (2) The red wing of the k line is redshifted from that of the h line by up to 20 km s\(^{-1}\). The magnitude of the red wing shifts increases with increasing luminosity and decreasing effective temperature. (3) The asymmetry of the k line exceeds that of the h line for stars showing an enhanced red emission, while the reverse is true for stars with an enhanced blue peak.

To date, no suitable explanation exists for the differences in the h and k line profiles in the high-luminosity, cool stars. One possibility is that they result from non-LTE radiative transfer effects in a moving, spatially extended, and inhomogeneous atmosphere. A specific effect worth investigating is the interaction between the red wing of the k line and the blue wing of the h line. At present, the most sophisticated radiative transfer calculations have included the effects of non-LTE, partial redistribution, and an extended atmosphere (see, e.g., Drake & Linsky 1983) but still assume a homogeneous structure, spherical symmetry, no line blanketing effects, and a monotonically increasing velocity field. Results are also typically only derived for the k line. When both h and k lines are calculated (e.g., Harper 1992; Luttermoser, Johnson, & Eaton 1994) using models designed to fit the integrated fluxes, it is found that the base widths of the lines often disagree with observations, with the h line being narrower than the k line. This dominance of the k line width persists when the widths are adjusted by introducing microturbulent and macroturbulent velocities into the model.

If we assume that the widths of the h and k lines in the chromosphere are significantly different, then the observed relative shift in the red wing of the lines can simply be explained as this difference in width. The approximate agreement of the blue wings (in the scaled plots) could then result from the effects of absorption within a thin, high-speed wind. Since the k line has an optical depth approximately twice that of the h line, the blue wing of the k line would be substantially more attenuated, thereby equalizing the measured intensities.

High-speed winds have long been recognized in hybrid stars, where they appear as discrete, often variable absorption features in the blue wing, with velocities reaching as high as \(-200\) km s\(^{-1}\) (e.g., Hartmann et al. 1985). It is often assumed that this absorption marks the location of the wind's terminal velocity (e.g., Hartmann, Dupree, & Raymond 1981), though this implies that the wind must have a substantial optical depth at the height where the terminal velocity is reached. An alternative theory was suggested by Mullan (1984), who proposed that the absorption resulted from the presence of corotating interaction regions which result from the interaction of fast and slow wind streams in the stellar atmosphere. The interaction forms a region of high density and fairly narrow velocity which then results in an absorption feature. In either case, if the column density of the wind were to decrease sufficiently, the discrete absorption would disappear, though the effects of the wind in the acceleration region would remain. Using \(\gamma\) Dra as an example (Fig. 5), we see that the relative profiles of the \(h\) and \(k\) lines in a hybrid star are very similar to those seen in more normal giant and supergiant stars. It shows the same relative shift in the red wings and the same near agreement in the blue wings. Note that in the scaled plots the blue wing of the \(k\) line is actually weaker than that of the \(h\) line. An investigation of seven other hybrid stars obtained from the IUE archives shows that this behavior is typical. Since many of the noncoronal stars studied here occupy the same region of the H-R diagram as the hybrids, it is possible that in addition to the well-known slow wind, which is responsible for the line asymmetries, they too have a high-speed wind, though not as well developed as for the hybrids.

To account for the supposed depression in the blue wings would require a Mg \(k\) line optical depth of order 0.5. This implies a column density of approximately \(5 \times 10^{12}\) cm\(^{-2}\) in Mg \(n\) within the high-speed wind or a hydrogen column density of only \(10^{17}\) cm\(^{-2}\), assuming solar abundance and a high ionization fraction for Mg. This is much smaller than found in the circumstellar shells in such stars as \(\alpha\) Ori and is likely to be overlooked by most of the techniques for observing the circumstellar medium in giant and supergiant stars, which are typically sensitive to relatively cool gas.

Other effects which are worth looking into are the influence of outwardly moving shocks, which have been suggested as a major heating mechanism in these high-luminosity stars (e.g., Cuntz 1990) and the (remote) possibility that there is an actual differential velocity between the regions forming the \(h\) and \(k\) emission features.

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