FF II EMISSION LINE PROFILES IN SPECTRA OF HIGH LUMINOSITY NON-CORONAL STARS

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ABSTRACT
The early results of a program to study the winds of non-coronal late-type giant and supergiant stars with IUE are presented. The primary data for this study are profiles, fluxes, and velocities of the numerous Fe II emission lines which occur throughout the 2200-3230Å region of the IUE long wavelength spectrographs. In this paper, I present a sampling of the data obtained so far and discuss the apparent dependence of the Fe II profiles on stellar luminosity (surface gravity) and intrinsic line strength. In addition, I report the discovery of significant changes in the Fe II profiles in spectra of Gamma Crucis (M3 III), during the period 1978-1985, that suggest a substantial change in its outer atmosphere.

Keywords: Fe II Emission, UV Spectra, Chromospheres, Stellar Winds, Cool Stars, Mass Loss, IUE

1. INTRODUCTION
The IUE satellite in the last eight years has greatly enhanced our understanding of the outer atmospheres of late-type stars through the observations and analysis of UV spectral lines. One of the areas of the H-R diagram least studied with IUE, however, is that of the K and M bright giants and supergiants, because of the few targets that are bright in the ultraviolet. The spectra which are available of these stars show no evidence of a transition region or corona, but do show evidence of massive winds (Ref. 1) and very extended chromospheres (Ref. 2). It is unfortunate that so few observations of these stars are available since the massive winds of these high luminosity, non-coronal stars likely play a major role in stellar evolution.

I have, therefore, begun a study of a representative set of such stars, using archive and new high resolution IUE spectra of the 2200-3200Å region. A primary goal of this program is to obtain and study high resolution profiles of the numerous Fe II emission lines found throughout this spectral region since their observed wavelengths and profiles can provide information on the velocity structure of these stellar winds. This in conjunction with the observed dependence of these profiles on luminosity, intrinsic line strength, and time may provide clues regarding the nature of mass loss in this portion of the H-R diagram.

2. THE MID-UV FE II SPECTRUM
Emission lines of singly-ionized iron are seen throughout the 2200-3230Å region of IUE high resolution spectra of late-type, non-coronal stars. This is due to a fortunate combination of suitable chromospheric conditions, which produce the Fe II emission, and the low UV brightness of the continua produced by the underlying, relatively cool, photospheres. Above 2900Å, the continua do become bright enough to significantly reduce the contrast between the lines and the continua and thereby limit our ability to obtain clean chromospheric spectra of this region, although some lines are seen well into the near UV accessible from the ground (cf. Ref. 3).

The Fe II emission lines dominate the mid-UV by their sheer numbers. The 15 percent or so of the emission lines that are not due to Fe II are accounted for by relatively isolated groups of 2-5 lines each of Mg II, C II, Si II, and one line each of Al II and Mg I. Figure 1 shows several portions of a 1978 high resolution spectrum of the M giant Gamma Crucis. With the exception of the 10 or so C II and Si II lines near 2325Å, and the Al II 2869Å line, virtually all of the lines seen in this figure are due to Fe II. Although Fe II lines are seen everywhere below 2900Å, there are four major groupings of Fe II lines in the regions around 2260Å (UV multiplets 4-5), 2370Å (UV 3, 35, 36), 2600Å (UV 1 and 64), and 2740Å (UV 32, 62, and 63). Three of those regions can be seen in Figure 1.

Note that in this spectrum, the lines are relatively narrow, single-peaked features, which are easily identified with specific Fe II transitions. This is true in all other K and M giants to the best of my knowledge (see e.g., Ref. 4 on Arcturus K2 III). However, this is most emphatically not the case when we examine the spectra of the more luminous K and M stars. In these spectra the lines are considerably broader and many of them are self-reversed indicating a much higher degree of opacity in their stellar winds. The existence of the self-reversals and the detailed profiles of the lines are seen to vary
with intrinsic line strength within the spectra of a single star, as well as with the luminosity (i.e. surface gravity) of the star, and in at least one case, with time.

3. VARIATION OF Fe II PROFILES WITH INTRINSIC LINE STRENGTH

The M2 supergiant Alpha Orionis has the strongest Fe II lines yet observed in any normal individual late-type star. An examination of its spectra show that the Fe II line profiles vary with intrinsic strength of the transition producing the line (Ref. 5). The intrinsically weak lines are relatively narrow, single-peaked features very similar to those seen in giant spectra. The stronger lines are all very much broader (2x) and self-reversed. The strongest of these self-reversed lines are asymmetric to the violet, i.e. they have more flux to the violet of the self-reversal than to the red, while the remaining lines (those of average intrinsic strength) are asymmetric to the red.

This variation of line profile with line strength is illustrated in Figure 2, which shows a 20Å section of a high resolution spectrum (LWR 9600) of Alpha Ori. The lines at 2725 and 2740Å (UV 62 and 63) exhibit the violet-asymmetry and are probably formed in an outlying region with a negative velocity gradient. The line at 2728Å (UV 63) exhibits the red-asymmetry that suggests formation in a region, probably at an intermediate level in the outer atmosphere, with a positive velocity gradient. The line at 2731Å (UV 62), which is intrinsically moderately strong, likely originates in an intermediate region where the velocity gradient averages zero, between the two previously described regions. The class of narrow lines with no asymmetry is best represented by a line near 2773Å (UV 63) which is shown in Figure 4. These lines are probably formed in the lowest regions of the chromosphere where there is a very small or no velocity gradient.

Figure 2. Variation of Profile Asymmetry with Intrinsic Line Strength
4. VARIATION OF Fe II PROFILES WITH LUMINOSITY CLASS (SURFACE GRAVITY)

The observed dependence of the Fe II profiles on the luminosity of the star is perhaps even more dramatic than the observed variation with intrinsic line strength within a single stellar spectrum. The basic dependence is well-illustrated in Figures 3 and 4. Figure 3 shows a group of five lines from UV multiplets 1 and 64 in the region around 2755Å in spectra of three stars of nearly the same spectral class: Gamma Cru (M3 IIII), Beta Peg (M2 II-I), and Alpha Ori (M2 Ia-la-bc). The "F/2" and "Fx2" on the plot indicate that the Alpha Ori flux has been divided by 2 and the Beta Peg flux multiplied by 2 for ease in viewing on this scale. The line profiles start as narrow, single-peaked features in the giant and gradually broaden and begin to self-reverse as the stellar luminosity increases. As the lines begin to self-reverse in the bright giants, they show a red-asymmetry. The line profiles turn out to be very sensitive to small changes in the luminosity of the star. The lines near 2600Å clearly separate stars with Ia-ib, Ib-II, II-I, and III luminosity classes and may thus be useful luminosity and gravity diagnostics for the late-type non-coronal stars.

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An examination of the spectra of the highest luminosity late-type stars yet observed with IUE indicates that lines asymmetric to the violet are relatively rare in these chromospheric spectra. In fact, the only star other than Alpha Ori whose spectra are known to contain violet-asymmetric lines is 119 Tau (M2 Ia-Ib). Figure 5 shows a portion of IUE spectra of Alpha Ori, Sigma CMa (K7 Ib), and Lambda Vel (K4 Ib-II), which shows several lines that are violet-asymmetric in Alpha Ori, but red-asymmetric in the other stars. Since the Fe II line at 2755Å is the intrinsically strongest and, therefore, the first line in a spectrum to cross over to a violet asymmetry, it makes sense to check it in a search for violet-asymmetric lines. Figure 6 shows the region near 2755Å in the three most luminous non-coronal stars other than Alpha Ori that have been observed to date with IUE. As the Figure shows, only the 119 Tau data shows a violet-asymmetric profile. Note that 119 Tau and Alpha Ori are the most luminous as well as the latest in spectral type of the four stars. This suggests that only in the most luminous and coolest stars is the wind massive enough to be sufficiently opaque to produce the violet-asymmetric lines, which are presumably formed in the outermost reaches of the wind/chromosphere.

Figure 3. Fe II Line Profiles: Variation with Luminosity Class

Figure 4. Fe II Line Profiles: Variation with Luminosity Class

Figure 5. Fe II Profiles in Highest Luminosity Cool Stars
5. VARIATION OF FE II PROFILES WITH TIME

Since all of these "normal" late-type stars are variable to some degree, it has been somewhat surprising that over the last eight years we have not seen evidence of significant changes in their chromospheric Fe II spectra. I can now report the discovery of the first clear evidence of substantial changes in the Fe II spectrum of a single, late-type non-coronal star in the form of high resolution IUE spectra of the M giant *Crucifix.*

Figure 7 shows the region around 2595Å in three spectra of Gamma Cru taken over the period April 1978 to January 1985. The April 1978 spectrum has been reprocessed with current software to eliminate the possibility of early processing errors. It is clear that the Fe II lines have undergone significant broadening and developed self-reversals since the original 1978 spectrum was taken and that the spectrum is beginning to resemble that of a very weak bright giant. The Mg I 2852Å line, which is double-peaked in all three spectra, is red-asymmetric in the first spectrum, but nearly symmetric and stronger in the later spectra.

These changes indicate an increase in the opacity of the stellar wind and suggest that mass has been added to the chromosphere of this star through a one-time ejection of mass or perhaps through an increase in the star's mass loss rate. The later less-exposed spectrum taken in January 1985 indicates that the increased line strengths and broader, self-reversed line profiles seen in April 1984 persist and that they may be still increasing in strength. Further observations in the current observing year are planned to monitor the development of this event and to help determine whether it is a part of a long continuous increase in mass-loss, a one time event, or part of a series of increases and decreases in chromospheric activity.

6. SUMMARY

I have presented a sampling of the data acquired during the early stages of a program to study the winds of late-type, non-coronal stars with IUE. These spectra show that the profiles of the Fe II lines in the 2200-3200Å region of high resolution IUE spectra vary with the intrinsic strength of the line, the luminosity of the star, and, in at least one case, with time. Further observations to extend the number of stars sampled and to improve the wavelength coverage for some stars previously observed are now underway.

The Fe II profiles in all these stars will be analyzed to investigate the radial dependence of the wind velocity for each star and to determine the variation of the velocity fields with spectral type and luminosity class. Measures of relative Fe II fluxes will be used in a probability-of-escape model to determine the opacity and hydrogen column density versus height in the chromosphere of each star. And, finally, the profiles and strengths of the other lines (e.g. Mg II, Al II, Mg I, and C II) will be used to further probe the chromospheric winds of these cool, high luminosity stars.

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8. REFERENCES