THE ASTROPHYSICAL JOURNAL, 205:448–454, 1976 April 15

ULTRAVIOLET Fe II EMISSION IN LATE-TYPE STARS

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Received 1975 September 2

ABSTRACT

Spectrograms of 44 K and M giants and supergiants have been taken with the Cassegrain and coudé spectrographs of the Mauna Kea 224 cm telescope to determine the presence and intensity of the ultraviolet emission lines of Fe II from multiplets 1, 6, and 7. The emission is nearly universal in the M stars, but not found in any of the K stars; it thus appears to be a natural consequence of stellar surface temperature. The intensity of the emission is well correlated with the strengths of the circumstellar components of the K-line of Ca II and of Hα. It is suggested that the emission arises in the circumstellar gas shell and that its intensity is a primary indicator of the extent of the shell. There is no apparent relationship between the Fe II emission intensity and the amount of infrared excess at 11 and 20 μ, the indicators of a circumstellar dust shell.

Subject headings: stars: circumstellar shells — stars: emission-line — stars: late-type

I. INTRODUCTION

The presence of ultraviolet emission lines of Fe II (multiplets 1, 6, and 7) in late-type stars have been discussed by Herzberg (1948) and Bidelman and Pyper (1963). Herzberg suggested that the emission arises in a coronal-like nebulosity surrounding cool stars. Bidelman and Pyper searched for these lines in nine late-type stars and found them in all but the two hottest stars. Geisel (1970) has reported a correlation between the presence of Fe II emission and infrared excess at 10 μ in a wide variety of astronomical objects including P Cygni stars, T Tauri stars, novae, cool giants, planetary nebulae, etc. However, Jennings and Dyck (1972) imply that the relation found by Geisel does not hold for the late-type stars,

Our survey for Fe II emission in late-type stars was undertaken to determine the prevalence of the emission and to ascertain how the emission intensity is related to other properties of the stars. The survey attempts to show what conditions favor the formation of the emission features.

II. OBSERVATIONS AND INTENSITY MEASUREMENTS

Spectra of 29 K and M giants and supergiants were obtained with the Cassegrain spectrograph of the Mauna Kea 224 cm telescope at a dispersion of 28 A mm^{-1} in the wavelength region 3100–3500 A. A grating of 1200 lines per millimeter blazed in the second order at λ3400 was used. Spectrograms of 18 late-type stars were taken with the 61 cm focal length coudé camera giving a nominal dispersion of 13.5 A mm^{-1}. However, due to the faintness of the red giants in the ultraviolet, the slit width was doubled to decrease exposure times; thus the resolution of the coudé plates and the Cassegrain plates is comparable, about 0.5 A. Four bright stars were observed at 6.7 A mm^{-1} with the 122 cm focal length camera and a narrow slit which projects to 20 μ at the plate. The coudé observations were made with a 600 line-per-millimeter grating blazed at λ4000, second order. For all the observations a Corning 9863 filter was used behind the slit to eliminate the overlapping red spectrum. The star with the strongest ultraviolet Fe II lines, α Orionis, was observed at all three dispersions.

A detailed study of the Fe II emission lines in α Orionis has been done by Boesgaard and Magnan (1975). An identification of 17 well-observed Fe II lines can be seen in their Figure 1. In agreement with Weymann (1962), they suggest that some of the emission features are mutilated by absorption which they attempt to identify with circumstellar features. To estimate the strengths of the emission lines in the stars in this survey, we have avoided those lines which appear to be mutilated in α Orionis. We have used the three strongest unmutilated lines at the longest wavelengths to determine the Fe II intensity index. These lines are λ3277.35 from multiplet 1, λ3227.73 from multiplet 6, and λ3196.07 from multiplet 7.

It is difficult to locate a realistic continuum level in this region of the spectrum, since there are so many absorption features. Instead, the central intensities of the three lines were estimated relative to nearby continuum peaks on the microphotometer tracings. The line at λ3277 was compared with continuum peaks 0.9 and 4 Å shortward, λ3228 with the surrounding continuum especially the peak ~1.5 Å shortward, and λ3196 with peaks 1 and 2.5 Å longward. Samples of these three lines for three different stars are shown in Figure 1. The intensity of the line relative to the continuum defines the intensity measure for each of the three lines. The final Fe II intensity index takes the

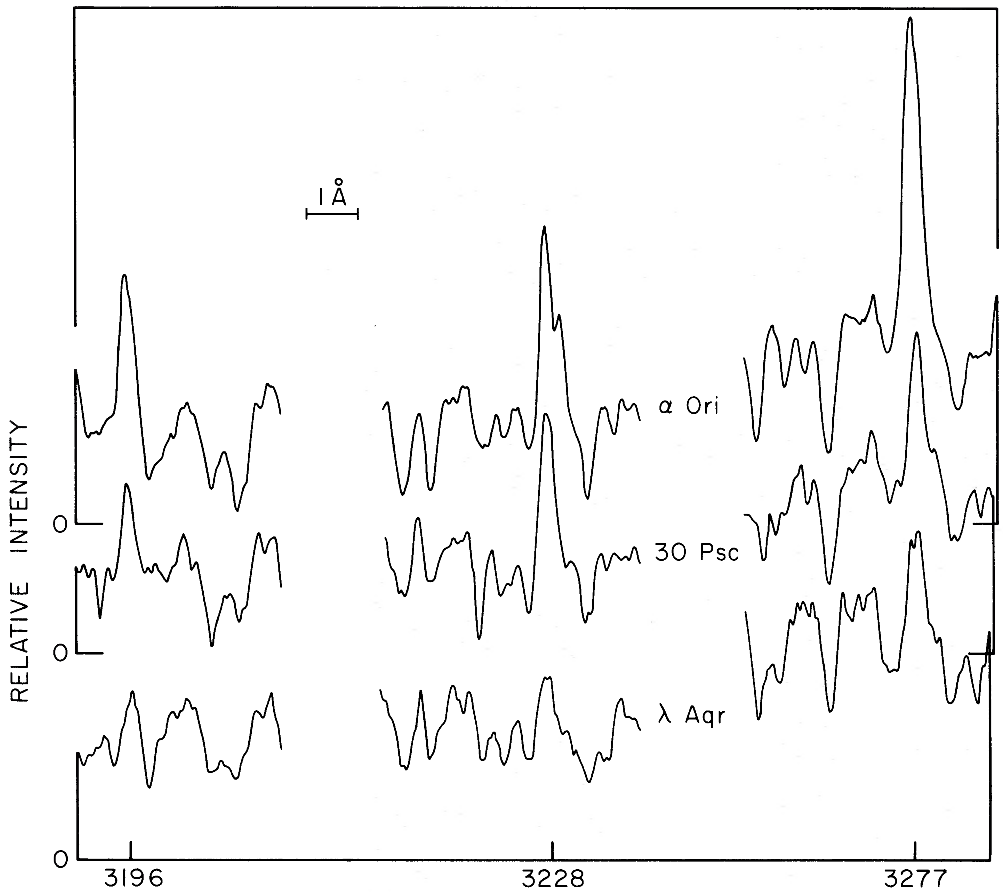

FIG. 1.—Profiles of the three Fe II emission lines used to determine the Fe II index shown for three stars of varying Fe intensity.

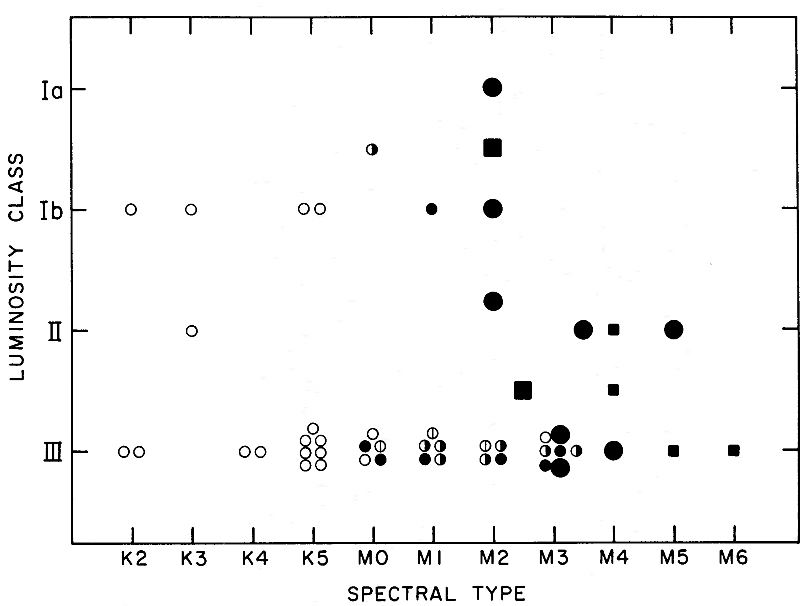

FIG. 2.—H-R diagram showing the distribution of stars with various Fe II indices. *Open circles*, no emission; *circles with vertical line*, borderline emission; *half-filled circles*, weak emission; *solid, small circles*, medium; *solid, large circles*, strong; *large squares*, very strong; *small squares*, stars of Bidelman and Pyper (1963) for which there is no value of the Fe index.

average of the intensity measure of the lines, weighing the two longer wavelength lines 3 times the shorter wavelength line. (The λ3196 line has less weight, since the exposure level and continuum level is lower and thus the intensity estimate is less accurate.) In addition to the measurements made on the tracings, all the spectrograms were examined visually on a spectral comparator as a check on the relative intensity levels from star to star.

Table 1 gives the results of these measurements. Successive columns give the star name, HR number, spectral type, dispersion of spectrogram, the measured intensity of the three lines, and the Fe II index. The criteria used for the definite presence of Fe II in emission are that the intensity, relative to the continuum, of λ3277 and λ3228 must be greater than ~1.1 and of λ3196 must be greater than ~1.0. For borderline cases the presence of lines other than these three was used to confirm the reality of the emission. Stars with no emission all have an Fe II index ≤1.01.

III. RESULTS

The stars observed in this survey and those observed by Bidelman and Pyper (1962) are plotted in an

TABLE 1

Fe II Emission Intensity

Star	HR	Spectral (A/mm)	Dispersion (A/mm)	Fe II Line Intensity λ3277	λ3228	λ3196	Fe II Index
χ Peg..........	45	M2 III	13.5	1.13	1.16	0.97	1.12
7 Cet..........	48	M1 III	13.5	1.15	1.38	1.17	1.25
β And..........	337	M0 III	6.7	1.19	1.32	1.00	1.22
υ Cet..........	585	M1 III	13.5	1.09	1.17	1.11	1.13
η Per..........	834	K3 Ib	13.5	0.72	0.88	0.69	0.78
α Cet..........	911	M2 III	6.7	1.19	1.48	1.28	1.33
τ^4 Eri..........	1003	gM3	13.5	1.43	1.56	1.30	1.47
....	1155	M2 IIa	13.5	1.56	1.71	–	1.64
γ Eri..........	1231	M0 III	13.5	1.21	1.27	0.96	1.20
119 Tau........	1845	M2 Ib	28	1.47	1.67	1.40	1.55
α Ori..........	2061	M2 Iab	6.7, 13.5, 28	2.05	2.18	2.27	2.14
π Aur..........	2091	M3.5 II	28	1.44	1.95	1.48	1.66
μ Gem.........	2286	M3 III	28	1.17	1.55	1.28	1.35
σ CMa.........	2646	M0 Iab	13.5, 28	1.02	1.24	1.00	1.11
υ Gem.........	2905	M0 III	13.5, 28	1.10	1.05	0.90	1.05
31 Lyn.........	3275	K5 III	13.5	1.03	1.00	0.95	1.01
λ Vel..........	3634	K5 Ib	13.5	0.81	–	0.92	0.84
α Lyn..........	3705	M0 III	28	1.04	0.96	1.05	1.01
π Leo..........	3950	M2 III	28	1.11	1.05	1.00	1.07
μ UMa.........	4069	M0 III	28	0.98	1.00	0.78	0.96
72 Leo.........	4362	M3 III	28	1.06	1.21	1.15	1.14
ν Vir...........	4517	M1 III	28	1.14	1.00	1.08	1.07
ψ Vir..........	4902	M3 III	28	1.06	0.89	0.93	0.97
δ Vir..........	4910	M3 III	28	1.33	–	–	1.33
υ Boo..........	5200	K5 III	28	1.08	0.90	0.88	0.97
g Cen..........	5485	K5 III	28	0.88	0.70	–	0.79
σ Lib..........	5603	M4 III	28	1.59	1.91	1.39	1.70
ϕ^1 Lup.........	5705	K5 III	28	0.96	0.76	0.80	0.85
υ Lib..........	5794	K5 III	28	0.88	0.43	0.50	0.63
κ Ser...........	5879	M1 III	28	1.17	1.20	0.96	1.15
δ Oph..........	6056	M1 III	28	1.09	1.24	1.04	1.15
α Sco..........	6134	M1 Ib	13.5	1.16	1.33	1.19	1.24
α^1 Her.........	6406	M5 II	28	1.55	1.47	1.48	1.51
π Her..........	6418	K3 II	28	0.89	0.85	0.77	0.86
γ Dra..........	6705	K5 III	28	0.91	0.96	0.79	0.91
η Sgr..........	6832	M3.5 III	28	1.04	1.26	1.14	1.15
γ Aql..........	7525	K4 III	13.5, 28	0.89	0.86	0.76	0.86
γ Sge..........	7635	K5 III	28	1.05	0.83	0.90	0.93
ξ Cyg..........	8079	K5 Ib	13.5, 28	0.92	1.03	0.86	0.96
ε Peg..........	8308	K2 Ib	28	0.85	0.93	0.79	0.88
μ Cep..........	8316	M2 Ia	13.5	1.46	1.68	1.43	1.55
λ Aqr..........	8698	M2 III	13.5	1.21	1.05	1.02	1.11
β Peg..........	8775	M2 + II–III	6.7	2.16	2.13	1.70	2.08
30 Psc.........	9089	M3 III	13.5	1.48	1.92	1.43	1.66

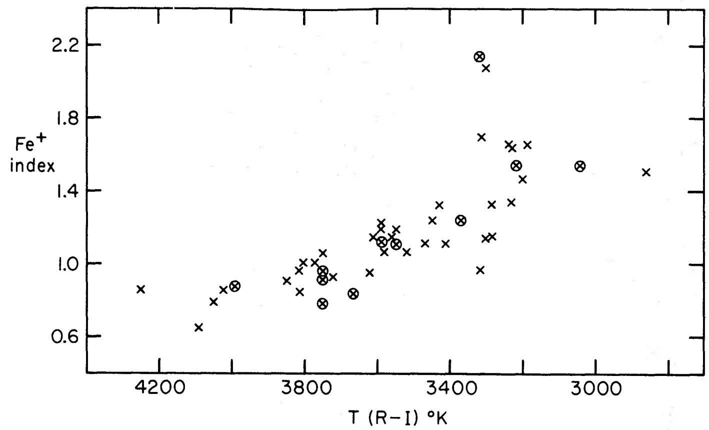

FIG. 3.—The strength of the Fe II emission as a function of the stellar temperature as derived from the $R - I$ color index. Circled crosses are the supergiant stars.

H-R diagram with different symbols indicating the strength of the Fe II emission in Figure 2. It is clear that the stars earlier than M0 do not show Fe II emission, while those M1 and cooler all show the emission features (except ψ Vir) with a tendency for the emission intensity to increase with later spectral class and higher luminosity.

Figure 3 shows the Fe II index for each star plotted as a function of stellar temperature as derived from the $R - I$ color from the calibration by Johnson (1966). The intensity of the emission tends to increase with decreasing surface temperature. The full range of intensity is present at about 3300 K.

The average Fe II index for each spectral type has been found for the giants and supergiants separately. There is a small number of stars in each group, but these averages reveal the trends with temperature and luminosity. This is shown in Figure 4. The average emission intensity increases monotonically with spectral class.

Some of these stars show infrared excesses in the near infrared and/or at the silicate features at 11 and 20 μ. We have compared the observed colors $B - V$, $V - R$, $V - I$, $V - J$, $V - K$, $V - L$, $R - I$, $I - L$, and $J - L$ (Johnson *et al.* 1966) with the intrinsic colors given by Johnson (1966) for the K stars and Lee (1970) for the M stars. If the colors are all too red by more than one spectral class we suggest that the star has near-infrared color excess (after rechecking the spectral classification). Of the nine stars with an apparent excess in $J - L$, five are supergiants and two are luminosity class II; half show weak or no Fe II emission. Some show evidence of polarization, some do not (Dyck *et al.* 1971; Dyck and Jennings 1971). Figure 5 shows histograms of the distribution of Fe II emission intensities for the stars with and without excess radiation in the near-infrared. There are few stars with an excess in the near-infrared, but they tend to show above average intensity of Fe emission.

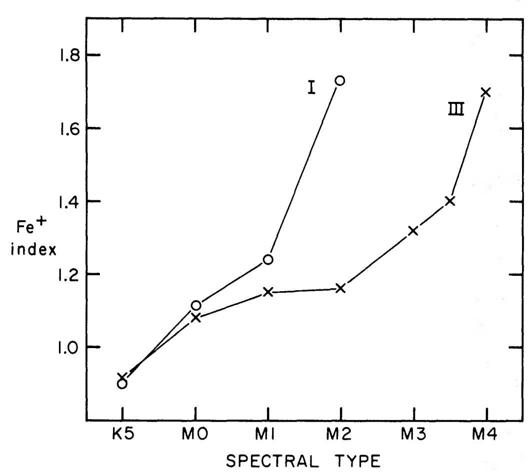

FIG. 4.—The average Fe II index at each spectral type. Crosses represent giants; circles, supergiants.

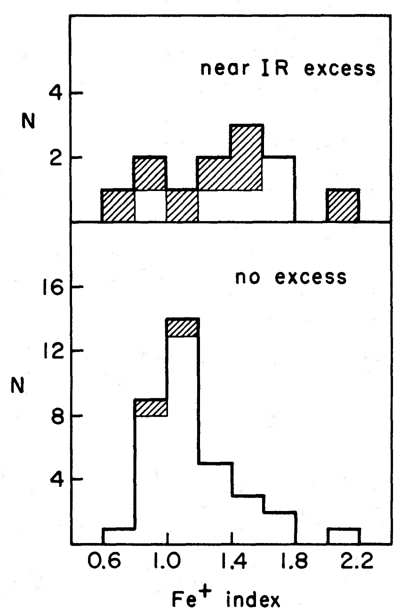

FIG. 5.—Histograms of the distribution of stars with the value of the Fe II index for stars with and without color excesses in the near-infrared. Shaded areas are the supergiant stars.

Infrared measurements at 11 μ and 20 μ have been made for some of these stars (Gillett, Merrill, and Stein 1971; Dyck *et al.* 1971; Gehrz and Woolf 1971; Jennings and Dyck 1972; Morrison and Simon 1973; Simon 1974). Table 2 lists all the stars observed here and by Bidelman and Pyper and gives the available $O - L$ ($11\,\mu - 3.4\,\mu$) and $Q - K$ ($20\,\mu - 2.2\,\mu$) data. Figures 6 and 7 show the $O - L$ and $Q - K$ indices plotted against the intensity of the Fe II emission. The full range of Fe II emission intensity is

TABLE 2

Circumstellar Features

Star	HR	Spectral Type	Near-Infrared Excess	$O - L$	$Q - K$	W(Ca) (mÅ)	W(Hα) (mÅ)
χ Peg	45	M2 III	...	...	...	100	0
7 Cet	48	M1 III	small	...	...	...	...
β And	337	M0 III	...	+0.04 to −0.1	−0.43	100	0
υ Cet	585	M1 III	...	...	...	...	0
η Per	834	K3 Ib	large	0.0	...	...	...
α Cet	911	M2 III	...	−0.05 to −0.08	−0.41	250	30
τ^4 Eri	1003	gM3	...	...	−0.56	...	...
....	1155	M2 IIa	large	...	...	...	...
γ Eri	1231	M0 III	...	...	...	70	20
119 Tau	1845	M2 Ib	large	−0.06 to −0.16	−0.93	900	41
α Ori	2061	M2 Iab	small	−0.95 to −1.07	−1.73	900	...
π Aur	2091	M3.5 II	large	...	...	500	79
μ Gem	2286	M3 III	...	−0.05 to +0.05	...	300	...
σ CMa	2646	M0 Iab	small	−0.19	...	...	...
υ Gem	2905	M0 III	...	...	...	0	...
31 Lyn	3275	K5 III	...	...	...	...	...
λ Vel	3634	K5 Ib	...	...	...	...	...
α Lyn	3705	M0 III	...	...	...	0	17
π Leo	3950	M2 III	...	−0.06 to +0.06	...	50	...
μ UMa	4069	M0 III	...	−0.16	...	0	0
72 Leo	4362	M3 III	...	−0.11	...	...	...
ν Vir	4517	M1 III	...	...	...	200	20
ψ Vir	4902	M3 III	...	...	...	155	20
δ Vir	4910	M3 III	...	−0.25	−0.46	200	28
υ Boo	5200	K5 III	...	...	...	...	...
g Cen	5485	K5 III	...	...	...	...	...
σ Lib	5603	M4 III	...	...	−0.59	400	38
ϕ^1 Lup	5705	K5 III	...	...	...	...	...
υ Lib	5794	K5 III	...	...	...	...	...
κ Ser	5879	M1 III	...	...	...	100	...
δ Oph	6056	M1 III	...	...	...	100	0
α Sco	6134	M1 Ib	medium	−0.54 to 0.63−	−1.09	300	52
α^1 Her	6406	M5 II	medium	−0.37	...	600	...
π Her	6418	K3 II	small?	...	...	...	...
γ Dra	6705	K5 III	...	−0.1	−0.37	...	...
η Sgr	6832	M3.5 III	...	...	...	...	0
γ Aql	7525	K4 III	...	...	...	...	...
γ Sge	7635	K5 III	...	...	...	...	0
ξ Cyg	8079	K5 Ib	...	...	...	...	...
ϵ Peg	8308	K2 Ib	large	...	−0.35	...	...
μ Cep	8316	M2 Ia	large	−1.8 to −2.1	−3.11	1200	...
λ Aqr	8698	M2 III	...	...	...	200	25
β Peg	8775	M2 + II–III	...	−0.04 to −0.10	−0.53	400	44
30 Psc	9089	M3 III	...	...	...	...	...
ρ Per*	921	M4 II–III	...	−0.16	−0.57	(500)	...
g Her*	6146	M6 III	...	−0.39 to −0.48	−0.99	(600)	...
δ^2 Lyr*	7139	M4 II	...	−0.21	...	(600)	(99)
χ Cyg†	7564	M5–M8	...	−1.3 to −1.75	...	...	...

* From Bidelman and Pyper 1963. The Fe II index is taken to be 1.43, the mean of the medium and strong emission index for the survey stars.

† From Merrill 1947. The Fe II index taken as 1.58, the mean of the strong emission index, and based on Merrill's eye estimate of the strength of λ3277.

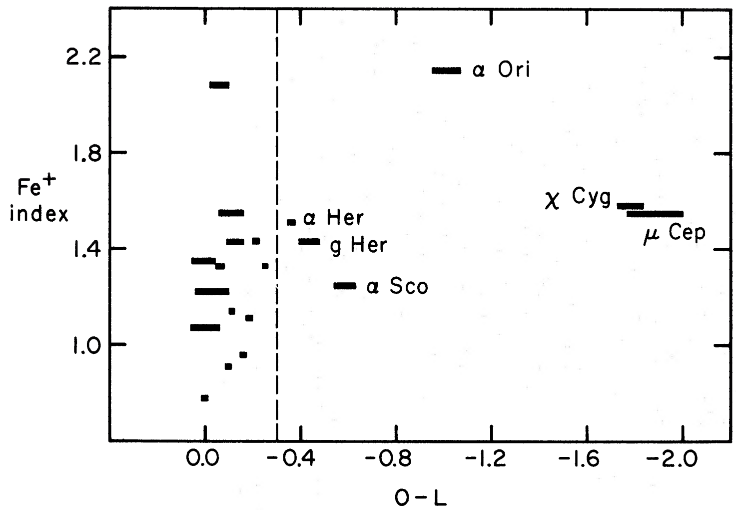

FIG. 6.—Fe II index as a function of the $O - L$ (11 μ – 3.5 μ) color index. Stars to the right of the dashed vertical line show excess radiation at 11 μ due to the silicate feature.

present for stars with no excess at 11 μ or 20 μ. Only a few stars show the excess due to silicates, but the excess appears to be unrelated to the Fe II intensity. The stars with large excesses at 11 μ and 20 μ are those of higher luminosity.

Deutsch (private communication 1967) has measured the strength of the circumstellar (CS) feature of the *K*-line of Ca II. One of us (AMB) has previously measured the equivalent width of the asymmetric blueshifted portion of the Hα line for some of the stars; this feature is presumably formed in the upper chromosphere or the CS shell. These equivalent widths are given in Table 2, and Figures 8 and 9 show the relationship of the strength of the Fe II emission with the features formed in the CS gas shell. According to Boesgaard and Magnan (1975), the Fe II lines in α Ori are formed in a shell extending to 2.5 R_*, and are part of the CS gas shell. There is a clear correlation between the strength of the Fe II emission and the thickness (optical or physical) of the CS gas shell as indicated by Hα and Ca II. All three features increase in strength with advancing spectral type; however, they are better correlated with each other than with spectral type or temperature.

IV. CONCLUSIONS

We conclude that the *presence* of Fe II emission in late-type stars is a natural consequence of stellar temperature. The ultraviolet continuum flux is low, and the emission lines are visible. Fe II emission is virtually ubiquitous in stars cooler than spectral type M0. In those stars where the Fe II emission is visible, the *intensity* of the emission is related to the strength of other features (Ca II K-line, Hα) that are present in the circumstellar gas shell. The stars that show evidence of circumstellar dust shells through the presence of the 11 μ or 20 μ silicate features and/or polarization are generally the supergiants. The intensity of the Fe II emission is unrelated to the strength of the silicate dust features. For example, μ Cep and 119 Tau both show strong Fe II emission, but μ Cep has strong silicates while 119 Tau has none.

The Fe II emission in α Ori comes from a region above the photosphere out to $\sim$2.5 R_* (Boesgaard

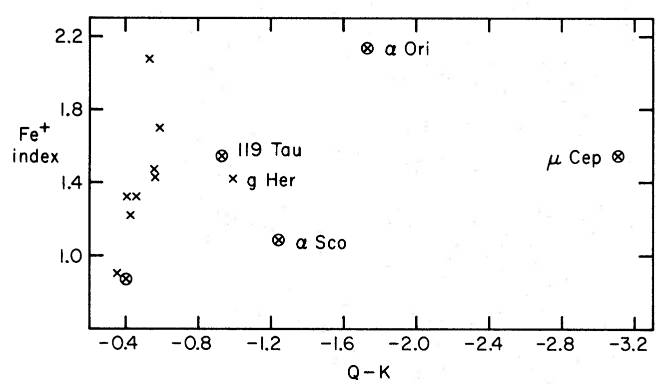

FIG. 7.—Fe II index plotted against the $Q - K$ (20 μ – 2.2 μ) color index. The circled crosses are the supergiants.

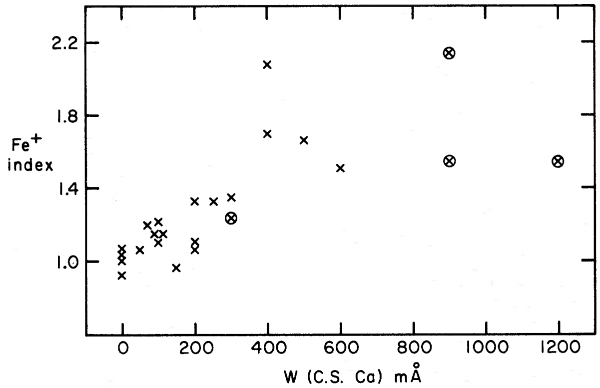

FIG. 8.—The Fe II index plotted against the equivalent width of the circumstellar Ca II K-line. Circled crosses are the supergiants.

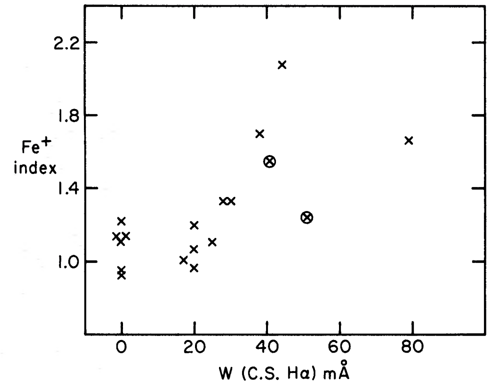

FIG. 9.—The Fe II index plotted against the equivalent width of the circumstellar Hα line. Circled crosses are the supergiants.

and Magnan 1975); by analogy, it is likely that this is the case for all of these stars. The intensity of the unmutilated Fe II emission lines appears to be a primary indicator of the extent (thickness) of the CS gas shell and thus an indicator of mass loss in M giants and supergiants. (For double stars like α Her and α Sco the shells are probably altered by the presence of the companion.) Those stars with weak Fe II emission may represent stars at an early stage in the development of a circumstellar shell.

We are indebted to Charles Beichman for important preliminary data reduction work on the Cassegrain spectrograms and to Wendy Hagen for her energy and skill in making the microphotometer tracings. We have had valuable conversations with Dr. H. M. Dyck during the course of the research. This work has been supported in part by a National Science Foundation grant, GP-41516.

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