IUE SPECTRA OF F AND LATE A STARS[1]

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ABSTRACT

We report on IUE spectra of α CMi (F5 IV-V), β Cas (F2 IV), α Car (F0 Ib), and γ Boo (A7 III) in the context of the question as to whether chromospheres disappear in the early F-late A portions of the HR diagram. Both α CMi (Procyon) and β Cas show bright emission line spectra indicative of chromospheres and transition regions, but neither α Car (Canopus) nor γ Boo show any evidence of emission in their SWP spectra or at the Mg II lines, despite very deep exposures. These results are consistent with those recently published by Böhm-Vitense and Dettmann. We note that α CMi has emission line fluxes roughly 6 times those of the quiet Sun, but the rapidly rotating δ Scuti-type variable β Cas has surface fluxes 10-50 times those of the quiet Sun. Upper limits on emission line fluxes for α Car are 4-20 times those of the quiet Sun and for γ Boo are 15-80 times the quiet Sun. We conclude that the apparent absence of emission lines in the spectra of α Car and γ Boo should not be interpreted as due to the absence of nonradiatively heated outer atmospheres in stars hotter than spectral type F0, but rather to our inability to see emission lines with IUE against a background of scattered light and a bright photospheric absorption line spectrum either in low or high dispersion.

INTRODUCTION

We consider here the important question of whether the outer atmospheres of stars change in a fundamental way near spectral type F0 as convection zones become thin and carry little flux with increasing stellar effective temperature. The earliest-type stars with Ca II H and K line emission noted by Wilson (1966) in his 10 Å mm^{-1} photographic survey are at spectral type F5. These data, together with the empirical result that stellar rotational velocities decrease rapidly in the middle F stars (e.g. Kraft 1967) and the theoretical result that acoustic wave heating (the presumed chromospheric heating source) should decrease rapidly in the early F-type stars, led many authors to conclude that chromospheres disappear in the middle F stars. Subsequently, using higher dispersion spectra, Warner (1966,1968) found weak

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Ca II emission in Canopus (F0 Ib) and γ Vir N (F0 V), and Le Contel et al. (1970) reported occasional Ca II emission in the δ-Scuti-type star γ Boo (A7 III). Freire (1979) and Freire et al. (1977,1978) have searched for emission in the Ca II lines and ultraviolet C II and Si II lines in Vega (A0 V) and two other early A-type stars without success.

Böhm-Vitense and Dettmann (1980) have observed 21 F- and 13 A-type stars with IUE. They find that chromospheric emission lines begin to appear at (B-V) $\gtrsim$ 0.32 (about spectral type F0) on the main sequence, but at the Cepheid instability strip for the more luminous stars. Our observations confirm their identification of an empirical dividing line for the appearance of chromospheric emission lines in the Hertzsprung-Russell (HR) diagram, but we feel that the data cannot determine whether chromospheres disappear in this region of the HR diagram.

OBSERVATIONS

We summarize the stellar parameters and our IUE observations in Tables 1 and 2. Since our goal was to search for emission features superimposed on a bright background consisting of the stellar ultraviolet absorption line spectrum and scattered near ultraviolet light, we obtained several exposures including very long exposures in which the long wavelength portions of the spectra are heavily overexposed.

The composite low dispersion spectra (deleting saturated pixels) are presented in Figure 1 in absolute flux units at Earth. The calibration factors used are those described by Turnrose et al. (1980) and Cassatella et al. (1980), except that the small aperture α CMi spectra were calibrated using the low dispersion fluxes of the strong C II λ1335 and C IV λ1550 doublets cited by Brown and Jordan (1980). These data imply that the transmission of the small aperture for our α CMi observations was 0.33. Since the α CMi spectra were obtained with the small aperture, we are able to measure fluxes in the Si III λ1206 and Lα features accurately.

Clearly both α CMi and β Cas exhibit bright emission lines due to chromospheric ions (O I, C I) and ions (C II, C III, C IV, Si IV, N V) formed at temperatures of 20-200 $\times$ 10^3 K, perhaps in geometrically thin regions analogous to the solar transition region. However, neither α Car nor γ Boo show any of these emission lines in the low dispersion data. A high dispersion SWP spectrum of α Car also shows no evidence for any emission features.

High dispersion spectra of the Mg II features in β Cas, α Car, and γ Boo are shown in Figure 2. These spectra show no clear evidence of Mg II emission, despite the very long exposure times to bring up the line cores to typically 150 DN. Böhm-Vitense and Dettmann (1980) call attention to a strong correlation between Mg II emission and the appearance of chromospheric emission lines in the SWP images. We feel that the apparent absence of Mg II emission in β Cas is probably due to rotational smearing of a weak emission feature in the core of an absorption line. Emission features appear in the 1200-1600 region of this star despite rotation smearing, because the contrast between the emission line flux and 6 Å of continuum is large. We find no evidence for Mg II emission in α Car (see Fig. 2), although Evans et al. (1975) identify emission features in their Copernicus V2 spectrum of the star. We feel that our data have higher signal-to-noise and higher spectral resolution than their data. Thus we feel that the absence of Mg II emission in our data is real. Also interstellar absorption features in the cores of the Mg II lines can suggest double emission features which may not be present.

We list in Table 3 observed fluxes at Earth and probable identifications of emission features we consider to be real. Also given are flux upper limits for α Car and γ Boo. These are estimated as roughly equal to the flux in adjacent "emission" features with widths comparable to emission lines in β Cas and measured above a curved line drawn through the low points in the spectra. These "emission" features are probably stretches of continuum between absorption lines. Thus the "noise" in the α Car and γ Boo spectra is not true noise but rather the up and down character of absorption line spectra. Our estimates of emission line flux upper limits thus refer to the maximum emission line flux that could be confused with the absorption line spectrum and thus not identified as an emission line.

The observed fluxes were then converted to stellar surface fluxes using the Barnes-Evans relation for stellar angular diameters (cf. Linsky et al. 1979). The derived angular diameters and ratios of surface flux to flux observed at Earth are given in Table 1. Listed in Table 4 are quiet Sun surface fluxes cited by Linsky et al. (1978) and the ratios of stellar surface fluxes to quiet Sun surface fluxes.

DISCUSSION

The α CMi surface fluxes are about a factor of 6 times larger than the quiet Sun, whereas those of β Cas are typically 30 times larger than the quiet Sun. Brown and Jordan (1980) estimate transition region pressures for α CMi consistent with pressures at the top of the chromospheric model derived by Ayres et al. (1974). Since transition region surface fluxes in solar plages are typically 10 times the quiet Sun, the nonradiative heating rates in the outer atmosphere of β Cas exceed those of solar plages by a factor of 3. We know that chromospheric nonradiative heating rates are well correlated with stellar rotational velocities for stars of similar spectral type (e.g. Kraft 1967, Skumanich 1972), and there is growing evidence of a correlation between nonradiative heating rates in transition regions and coronae as well (Ayres and Linsky 1980, Linsky 1980). The significant increase in emission line surface fluxes from α CMi to β Cas is consistent with this picture. An alternative explanation for the large heating rate in the outer atmosphere of β Cas is dissipation of shock waves excited by the stellar oscillations.

We feel that the upper limits on the surface fluxes for emission lines in α Car and γ Boo are significant. For example, if one added emission lines with surface fluxes comparable to those of α CMi to the observed spectrum of α Car, these emission lines would be extremely hard to detect against the bright absorption line spectrum of α Car. Similarly, emission lines with surface brightnesses even as large as those of β Cas would be undetectable against the bright absorption line spectrum of γ Boo. Thus, with IUE we are unable to determine whether or not chromospheres and transition regions cease to exist as one proceeds from the early F to hotter stars. All we can say is that our data and those of Böhm-Vitense and Dettmann (1980) show that chromospheres and transition regions cease to appear spectroscopically in the ultraviolet as observed with an instrument like IUE.

It is important to recognize the instrumental and astrophysical reasons behind the latter statement. The instrumental limitations of IUE are its limited signal-to-noise, sensitivity of the short wavelength cameras to scattered long wavelength light, halation in the image converters, and the potential for SEC Vidicon damage when oversaturating the long wavelength portion of an image to bring up the relatively weak short wavelength portion of the spectrum. As a result, we would caution future observers against taking even deeper exposures of early F- and late A-type stars, and we expect that deeper exposures would not be productive in any case. The High Resolution Spectrograph (HRS) now being built for Space Telescope (Brandt et al. 1979) will not have many of the limitations of IUE as it will include a solar blind, photon-counting detector capable of very high signal-to-noise, large dynamic range, and up to 1.2×10^5 resolution. With this instrument we expect that chromospheric emission lines will be detected in the late A-type stars until at some spectral type we will run into the fundamental astrophysical limitation of detecting weak emission features against a very bright photospheric absorption line spectrum.

Finally, we expect that most stars hotter than spectral type F0 probably contain nonradiatively heated outer atmospheres. This is based on the detection by Einstein of X-rays from many types of hot stars including O-type and WR stars, the A-type dwarfs Sirius A and Vega, and α Car (Vaiana et al. 1980). Also, Underhill (1980) has presented evidence for nonradiatively heated outer atmospheres (mantles) for O, B, and A-type supergiants. Thus nonradiatively heated outer atmospheres can be produced even in the absence of deep convection zones. Linsky (1980) and Underhill (1980) argue that magnetic fields, both remnant and dynamo regenerated, are responsible for nonradiative heating in most if not all stars.

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REFERENCES

Ayres, T. R. and Linsky, J. L. 1980, Ap. J., in press.
Ayres, T. R., Linsky, J. L., and Shine, R. A. 1974, Ap. J., 192, 93.
Böhm-Vitense, E. and Dettmann, T. 1980, Ap. J., 236, 560.
Brandt, J. C. et al. 1979, SPIE, 172, 254.
Brown, A. and Jordan, C. 1980, in Proc. Second Year of IUE, Tubingen, in press.
Cassatella, A., Holm, A., Ponz, D., and Schiffer, F. H. 1980, NASA IUE Newsletter, No. 8, p. 1.

Evans, R. G., Jordan, C., and Wilson, R. 1975, M.N.R.A.S., 172, 585.
Freire, R. 1979, Astr. Ap., 78, 148.
Freire, R., Czarny, J., Felenbok, P., and Praderie, F. 1977, Astr. Ap., 61, 785.
_____. 1978, Astr. Ap., 68, 89.
Johnson, H. L., Mitchell, R. I., Iriarte, B., and Wisniewski, W. Z. 1966, Comm. Lunar Planetary Lab., 4, 99.
Kraft, R. P. 1967, Ap. J., 150, 551.
Le Contel, J. M., Praderie, F., Bijaoui, A., Dantel, M., and Sareyan, J. P. 1970, Astr. Ap., 8, 159.
Linsky, J. L. 1980, Proc. Workshop on Cool Stars, Stellar Systems and the Sun, S.A.O. Special Report, in press.
Linsky, J. L. et al. 1978, Nature, 275, 389.
Linsky, J. L., Worden, S. P., McClintock, W., and Robertson, R. M. 1979, Ap. J. Suppl., 41, 47.
Skumanich, A. 1972, Ap. J., 171, 565.
Turnrose, B., Bohlin, R., and Harvel, C. 1980, NASA IUE Newsletter, No. 8, p. 28.
Uesugi, A. and Fukuda, I. 1970, Cont. Inst. Ap. and Kwasan Obs., Univ. of Kyoto, No. 189.
Underhill, A. B. 1980, preprint.
Vaiana, G. et al. 1980, submitted to Ap. J.
Warner, B. 1966, Observatory, 86, 82.
_____. 1968, Observatory, 88, 217.
Wilson, O. C. 1966, Science, 151, 1487.

Table 1

STELLAR PARAMETERS

Star	HD	Spectral Type	V[a]	V-R[a]	Ang. Dia. (milliarcsec)	F/f[b]	v sin i[c] (km s^{-1})
α CMi	61421	F5 IV-V	0.37	0.42	5.94	4.82(15)	6
β Cas	432	F2 IV	2.27	0.31	1.99	4.29(16)	72
α Car	45348	F0 Ib	-0.75	0.24	6.97	3.50(15)	0
γ Boo	127762	A7 III	3.02	0.14	1.01	1.67(17)	145

[a]From Johnson et al. (1966).

[b]Ratio of surface flux to flux observed at Earth.

[c]Rotational velocities from Uesugi and Fukuda (1970).

Table 2
SUMMARY OF IUE OBSERVATIONS

Star	Spectral Type	IUE Image	Exp. Time (Min.)	Aperture[a]	Dispersion[b]
α CMi	F5 IV-V	SWP 1306	30	S	L
		SWP 1317	30	S	HI
		SWP 1318	6	S	L
		SWP 1319	10	S	L
		SWP 1320	20	S	L
β Cas	F2 IV	SWP 2372	26	L	L
		SWP 2373	6.5	L	L
		LWR 2156	11	L	HI
α Car	F0 Ib	SWP 2302	30	L	HI
		SWP 5439	1	L	L
		LWR 2083	0.67	L	HI
		LWR 4703	3	L	HI
γ Boo	A7 III	SWP 2395	24	L	L
		LWR 2172	16	L	HI

[a] S = small, L = large.
[b] L = low, HI = high.

Table 3
SUMMARY OF OBSERVED FLUXES[a]

Wavelength	Ion	α CMi	β Cas	α Car[c]	γ Boo[c]
1175	C III		1.1(-12)		
1206	Si III	3.5(-12)			
1216	H I[b]	4.1(-11)	1.6(-11)	<8(-12)	
1239	N V	1.5(-12)	3.2(-13)	<5(-12)	<2(-13)
1253	S II?		3.9(-13)		
1273	C I	2.8(-12)	4.4(-13):		
1304	O I	3.1(-12)	2.3(-12)	<5(-12)	<4(-13)
1316		6.9(-13):	3.5(-13):		
1335	C II	7.5(-12)	2.0(-12)	<5(-12)	<4(-13)
1354	O I	1.2(-12):	5.5(-13)		
1371	O V	1.0(-12):			
1394	Si IV	1.1(-12)	7.3(-13)	<5(-12)	<4(-13)
1403	Si IV+O IV	6.6(-13)	1.1(-12)	<5(-12)	<4(-13)
1440		2.0(-12):			
1466	C I	3.8(-12)			
1549	C IV	1.1(-11)	4.7(-12)	<1(-11)	<8(-13)

[a] Fluxes at Earth (ergs cm^{-2} s^{-1}).
[b] Uncorrected for interstellar absorption.
[c] Upper limits.

Table 4

STELLAR SURFACE FLUXES AND STELLAR/QUIET SUN SURFACE FLUX RATIOS

Feature	Quiet Sun[a]	α CMi[b]		β Cas		α Car[c]		γ Boo[c]	
		SF	SF/QS	SF	SF/QS	SF	SF/QS	SF	SF/QS
N V 1239	8.6(2)	7.2(3)	8	1.4(4)	16	<1.8(4)	<21	<3.3(4)	<38
C IV 1550	5.8(3)	5.3(4)	9	1.8(5)	31	<3.5(4)	<6	<1.3(5)	<22
Si IV 1394	1.7(3)	5.3(3)	3	3.1(4)	18	<1.8(4)	<11	<6.7(4)	<39
Si IV+O IV 1403	9.4(2)	3.2(3)	3	4.6(4)	49	<1.8(4)	<19	<6.7(4)	<71
C III 1175	1.6(3)			4.5(4)	28				
Si III 1206	3.4(3)	1.7(4)	5						
C II 1335	4.6(3)	3.6(4)	8	8.6(4)	19	<1.8(4)	<4	<6.7(4)	<15
O I 1304	4.0(3)	1.5(4)	4	1.4(5)	35	<1.8(4)	<5	<6.7(4)	<17
O I 1355	3.2(2)	5.8(3):	18:	2.4(4)	75				
H I 1216	2.1(5)	2.0(5)[d]	1	6.9(5)[d]	3	<2.8(4)[d]	<0.1		

[a]Quiet Sun fluxes cited by Linsky et al. (1978). Units ergs cm^{-2} s^{-1}.

[b]Absolute flux calibration by comparison with C II λ1335 and C IV λ1549 low dispersion fluxes in Brown and Jordan (1980).

[c]Upper limits estimated as equal to typical "noise" features in the spectra, which are probably sections of continuum between absorption features.

[d]Uncorrected for interstellar absorption.

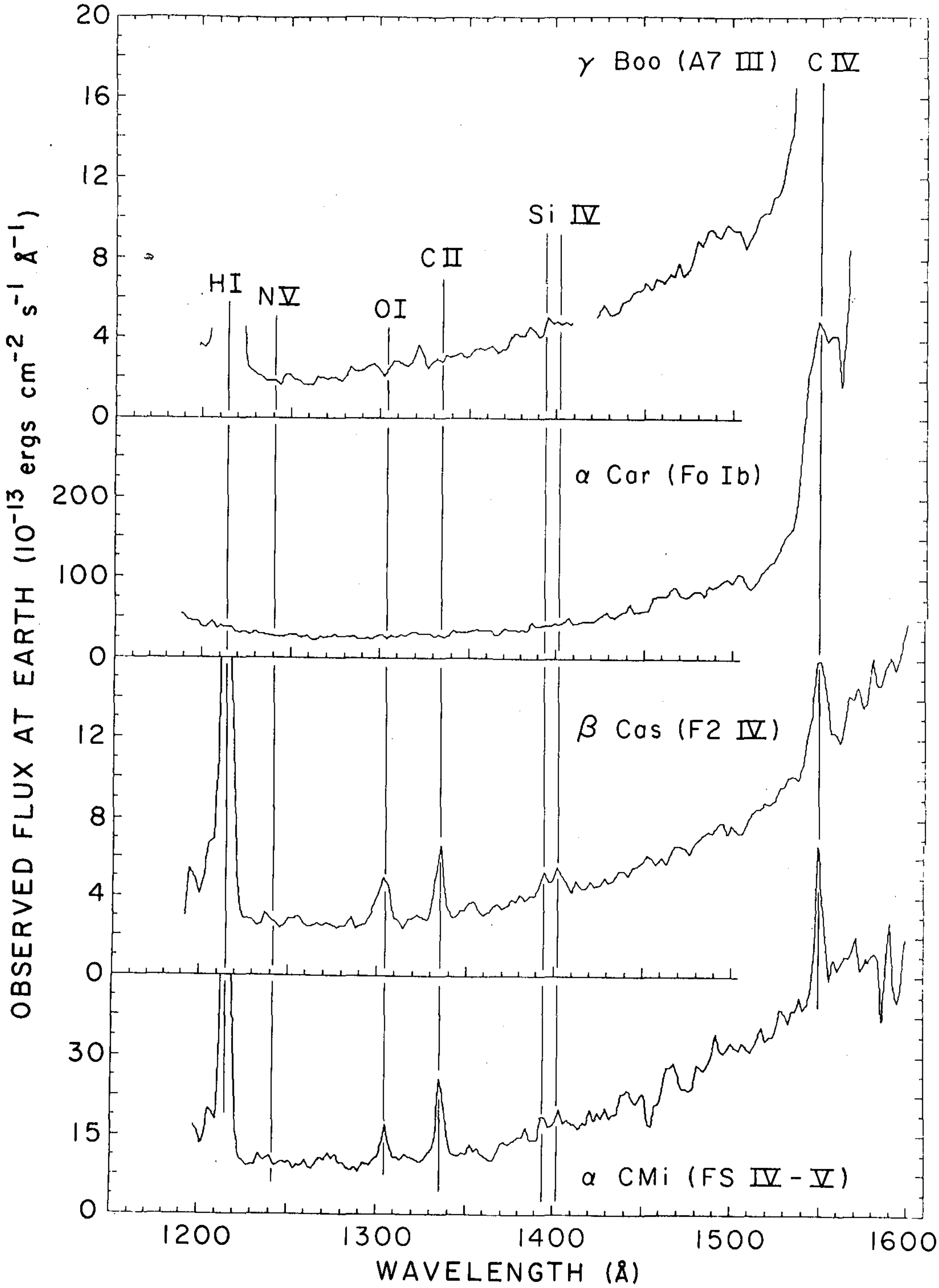

Fig. 1. Composite low dispersion spectra in absolute flux units at Earth. Vertical lines indicate the location of important emission lines that are present in the spectra of β cas and α CMi but absent in the spectra of γ Boo and α Car. These spectra are saturated beyond about 1600 Å, and scattered light is probably a major contributor to the apparent continua.

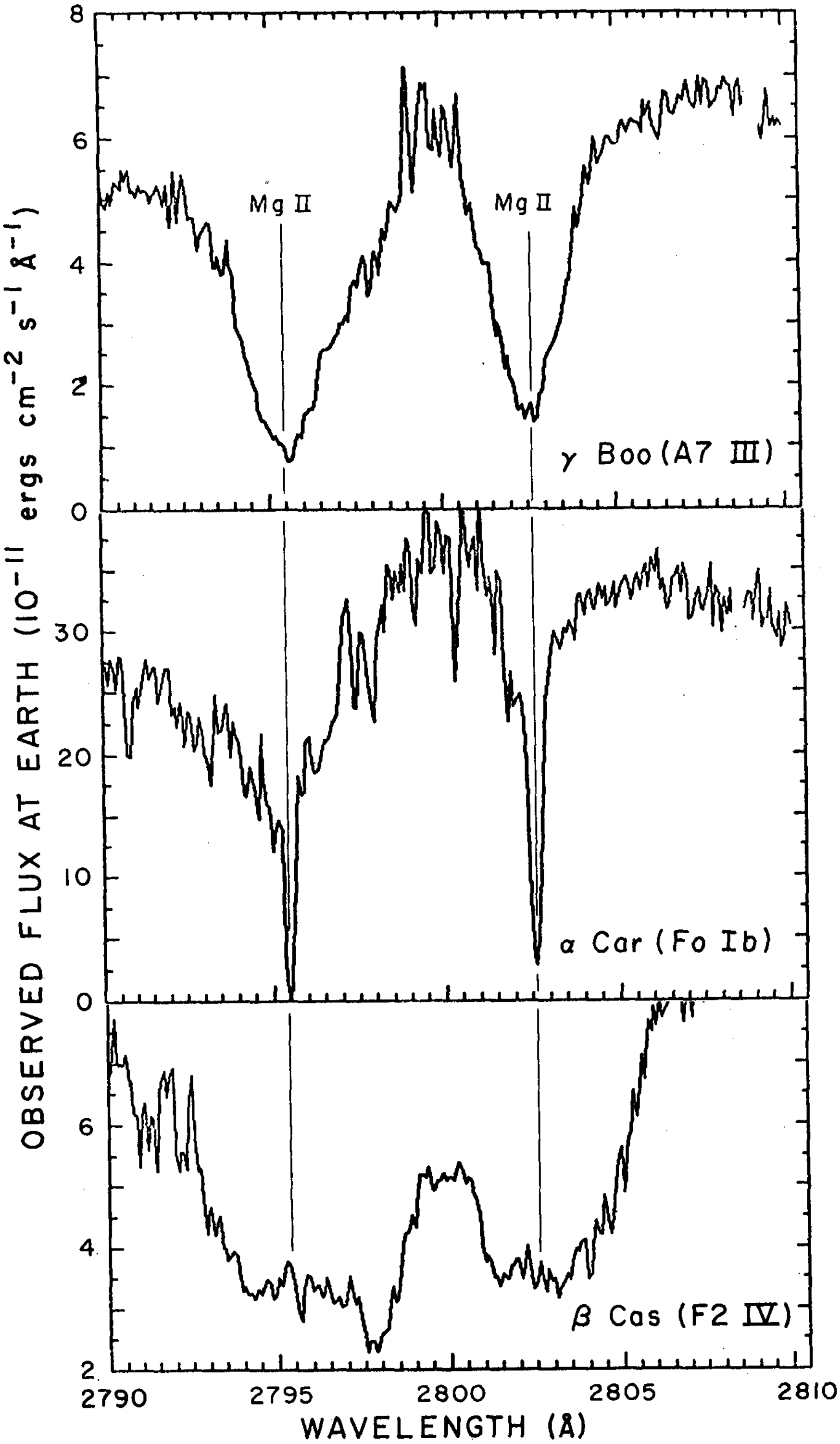

Fig. 2. High dispersion spectra in absolute flux units at Earth, obtained by merging the two echelle orders containing the Mg II lines. Despite the deep exposures used to bring up the cores of the Mg II lines, there are no apparent emission features. The deep absorption features in the Mg II lines of α Car are interstellar.