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BALLOON-BORNE ULTRAVIOLET STELLAR SPECTROGRAPH. II. HIGHLIGHTS OF FIRST OBSERVATIONAL RESULTS

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ABSTRACT

We describe a few of the most important features, visible in a first inspection of the high-resolution (0.1 Å) mid-ultraviolet spectra (2000–3250 Å) of 33 stars obtained in two BUSS flights. The profiles of the Mg II lines in early-type (B8–A2) supergiants show the existence of considerable mass flow, partly in irregular "puffs." The features in Mg II in Betelgeuse are due to a cool expanding outer shell above a hotter chromospheric region. Emission features in the shell star ζ Tau indicate infalling material, while the Be star ϕ Per has a mass outflow. We have detected some 80 emission lines of Fe I, Fe II, and Fe III in spectra of late-type giants and supergiants. The composite spectrum of the binary α Sco (M1.5 Iab + B2.5 V) is described, with particular reference to circumstellar lines.

Subject headings: line identifications — stars: Be — stars: mass loss — stars: supergiants — ultraviolet: spectra

I. INTRODUCTION

During its flights on 1976 May 19/20 and September 16/17 the Balloon-borne Ultraviolet Stellar Spectrograph (BUSS) secured 53 high-resolution (0.1 Å) spectra of 33 stars in the spectral range 2000–3250 Å. The instrument and its performance are described in the preceding paper (Kondo *et al.* 1979, hereafter Paper I).

In this paper we summarize a few of the results obtained from first inspections of the rich observational material. Our summary refers chiefly to ultraviolet Mg II lines and some inferences drawn from these lines regarding mass loss, and to chromospheric or shell-type phenomena around giants and supergiants. We also describe spectra of a few Be stars and a shell star.

II. THE Mg II LINES IN LATE-B AND A-TYPE SUPERGIANTS

The most sensitive indicators of mass loss from O and early-B supergiants are the far-ultraviolet resonance lines of C IV, N V, and Si IV. In the cooler A and F supergiants the degree of ionization is lower, and so in such stars the Mg II and Fe II resonance lines in the mid-ultraviolet spectral region are more sensitive indicators of mass loss. In Figure 1 we show the Mg II profiles of the three supergiants β Ori (B8 Ia), η Leo (A0 Ib), and α Cyg (A2 Ia) observed by BUSS. The spectrum of α Lyr (A0 V) is included for a comparison between the supergiants and a main-sequence star.

The resonance lines in α Cyg are very wide and shifted to shorter wavelengths. The short-wavelength side has a steep edge at -250 km s^{-1}. The long-wavelength side shows a less steep increase in flux from -150 km s^{-1} to $+50$ km s^{-1} with a sharp interstellar component at 0 km s^{-1} superposed on it. These profiles resemble the P Cygni profiles of the N V resonance lines in O stars observed by *Copernicus* (Snow and Morton 1976), except that in α Cyg the typical P Cygni emission component at positive velocities is suppressed by the presence of a strong underlying photospheric absorption wing. The profiles indicate that the wind from α Cyg is accelerated to a terminal velocity at the stellar surface. The many Fe II resonance lines in the BUSS spectra of α Cyg have similar profiles to those of Mg II, but in addition they show the presence of two absorption components at -125 and -195 km s^{-1}. This last component was present only during the observation of 1976 May 20 and not in 1976 September 17.

The spectrum of β Ori observed in 1976 September showed two components of the Mg II resonance lines shifted by -190 km s^{-1}. These components were not present during previous high-resolution observations in 1974 (Boksenberg *et al.* 1975) or 1975 (Selvelli, Crivellari, and Stalio 1976). Selvelli *et al.* had found that the wind in β Ori is accelerated to 530 km s^{-1} and that the degree of ionization is high. Consequently, the appearance of the shifted Mg II components indicates that significant density variations occur in the stellar wind, which results in concentrations of low-ionization species.

The Mg II lines in η Leo and α Lyr do not show the presence of mass loss as the lines are symmetric and not shifted. However, Kondo, Morgan, and Modisette (1976) found shortward-shifted excess absorption in the spectrum of η Leo, observed during a previous BUSS flight.

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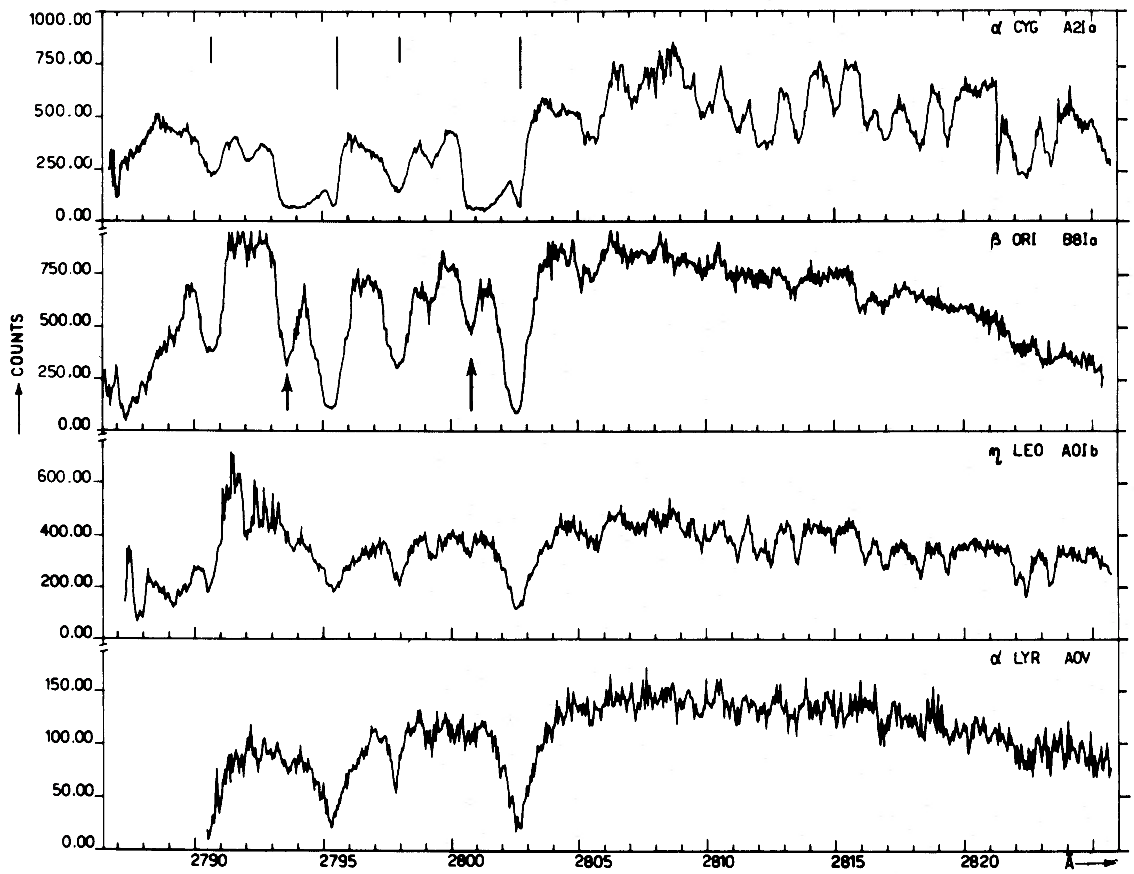

FIG. 1.—BUSS spectra of α Cyg, β Ori, η Leo, and α Lyr in the region 2787–2825 Å. The ordinate gives the flux in an arbitrary linear scale. The laboratory wavelengths of the Mg II resonance lines (*long vertical lines*) and the subordinate lines (*short vertical lines*) are indicated. The position of two extra components of the Mg II resonance lines in β Ori is indicated by arrows. These components were absent in previous observations of the spectrum.

These observations indicate that the mass loss from late-B and A-type supergiants is variable, with the occurrence of occasional stellar "puffs" superposed on a more or less regular wind. The visual spectra of both α Cyg and β Ori show irregular short time variability in Hα and in addition, α Cyg is pulsating nonradially (Lucy 1976). A possible correlation between the wind variations and the photospheric variations may give a clue to the origin of the stellar "puffs."

A more extended study of these stars and the mass-loss rates is published by Lamers, Stalio, and Kondo (1978).

III. THE Mg II RESONANCE DOUBLET EMISSION LINES NEAR 2800 Å IN BETELGEUSE (M2 Iab)

The Mg II resonance doublet lines are observed basically as two prominent emission lines with a central self-reversal. However, the 2795 component is pronouncedly asymmetric, while the 2802 component is reasonably symmetric; see Figure 2. This was first reported by Kondo *et al.* (1972) and was later confirmed by Kondo, Morgan, and Modisette (1975) and by Bernat and Lambert (1976). Following the suggestion by Herbig, the asymmetry has been attributed to the selective absorption by an Fe I line located at 2795.006 Å which gives rise to the fluorescence of the Fe I line at λ4204 and λ4307 (Spitzer 1939). The higher resolution attained in the current observations enables one to estimate the effect of the Fe I absorption more reliably than in the previous estimate by Modisette, Nicholas, and Kondo (1973). It is noted that the selective absorption in Figure 2 tends to favor Fe I, although Mn I may also be contributing.

In evaluating the equivalent width of the selective absorption, we employed the technique used by Modisette *et al.* It is basically a Gaussian curve fitting technique with several constraints, which results in a reasonably unique solution. The equivalent width of the Fe I absorption is 0.68 Å and the center is shifted by -12 km s^{-1} with respect to the reference frame of the Mg II emission components. If measured in the frame of the center of the self-reversal of the Mg II lines, the Fe I absorption is shifted by -17 km s^{-1} as the self-reversal is shifted $+5$ km s^{-1} with respect to the emission-line center. The width of the Fe I absorption line would be about 50 km s^{-1} if it were due entirely to turbulence.

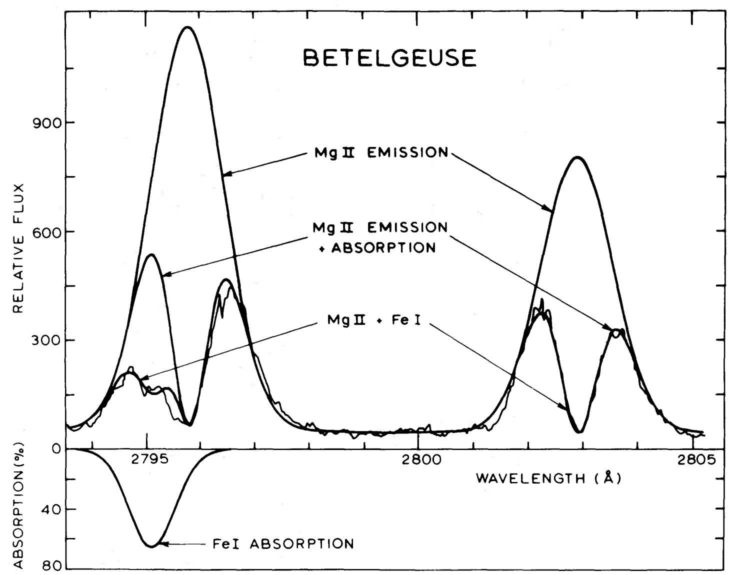

FIG. 2.—Analysis of the Mg II emission lines of α Ori in terms of a cool shell above a warmer chromosphere

The turbulence velocity in the Fe I absorbing shell has been estimated to be in the range of some 10 to 20 km s^{-1} by various workers. The broadness of the Fe I absorption profile indicates a large optical depth of the absorbing layer. The large width may also be due, in part, to the imperfection of the technique used.

IV. BE AND SHELL-TYPE STARS

Unexpected spectral features are present in the mid-UV spectra of Be stars and shell stars. Four stars of this group were observed during BUSS VIII: γ Cas (B0.5 IVel), ϕ Per (B2 Ve4p), υ Cyg (B2 Vel), and ζ Tau (B4 IIIp) (spectral types of Lesh 1968). Specimens of part of the spectra of three stars are shown in Figure 3. Of these stars ϕ Per has perhaps the most interesting spectrum, showing strong asymmetric absorption lines with short-wavelength wings extending 2.5 Å from the line center at three Fe III transitions of the same multiplet (UV 48 at $\lambda\lambda$2078.99, 2068.24, and 2061.55) whose lower level is a low-lying metastable state.

The spectra of these four stars are quite different from each other. Both ϕ Per and υ Cyg show emission lobes to the Mg II doublet lines, while ζ Tau and γ Cas do not. Also γ Cas shows no absorption in the Fe III lines. The spectra of γ Cas and ζ Tau do not show any emission line in the mid-UV and do not show the λ2842.6 line, although ζ Tau has changed markedly since the last high-resolution observations were obtained (Morgan, Kondo, and Modisette 1977). In particular, the Mg II subordinate lines are now nearly absent (the equivalent width of the λ2798 has a value of only 150 mÅ at best), and the resonance lines are very strong and sharp, which suggests an important nonphotospheric component. The noninterstellar component is shifted significantly (at least 50 km s^{-1}) toward long wavelengths, which may be evidence that at the time of the observation a new infall of shell material was occurring (Delplace and van der Hucht 1978).

V. EMISSION LINES IN THE BUSS SPECTRA OF GIANTS AND SUPERGIANTS

Ground-based spectral observations in the range 3150–3000 Å of M-type giants and supergiants show emission lines of Fe II (Herzberg 1948) which are not observed in K-type giants and supergiants (Boesgaard and Boesgaard 1976).

In the ultraviolet wavelength region observed by BUSS, notably the region 2650–3100 Å, not only Fe II emission lines but also Fe I emission lines have been found. These occur not only in the spectra of the M supergiants α Ori and α Sco, but also in the spectra of α Tau (K5 III) and α Boo (K2 IIIp). The lines are shifted to longer wavelengths by about +20 K m^{-1}. In the spectra of the four mentioned stars, 80 different emission lines have been identified (van der Hucht *et al.* 1979*b*). Figure 4 shows an example of these observations. Intensity ratios of Fe I and Fe II lines will allow an analysis of the outer layers of these late type stars.

VI. THE SPECTRUM OF α SCORPI (M1.5 Iab + B2.5 V)

The primary of the Antares system, α^1 Sco, observed in the BUSS VII flight, has the same spectral type as α Ori (Morgan and Keenan 1973), i.e., M1.5 Iab. The BUSS observations show chromospheric emission lines for both these M-type supergiants, but no photospheric absorption spectrum (for exposure times, see Paper I).

The secondary of Antares, α^2 Sco, which has a spectral type B2.5 V (Garrison 1967), is 4 mag fainter than α^1 Sco, and at an angular distance of 2''.9. It is

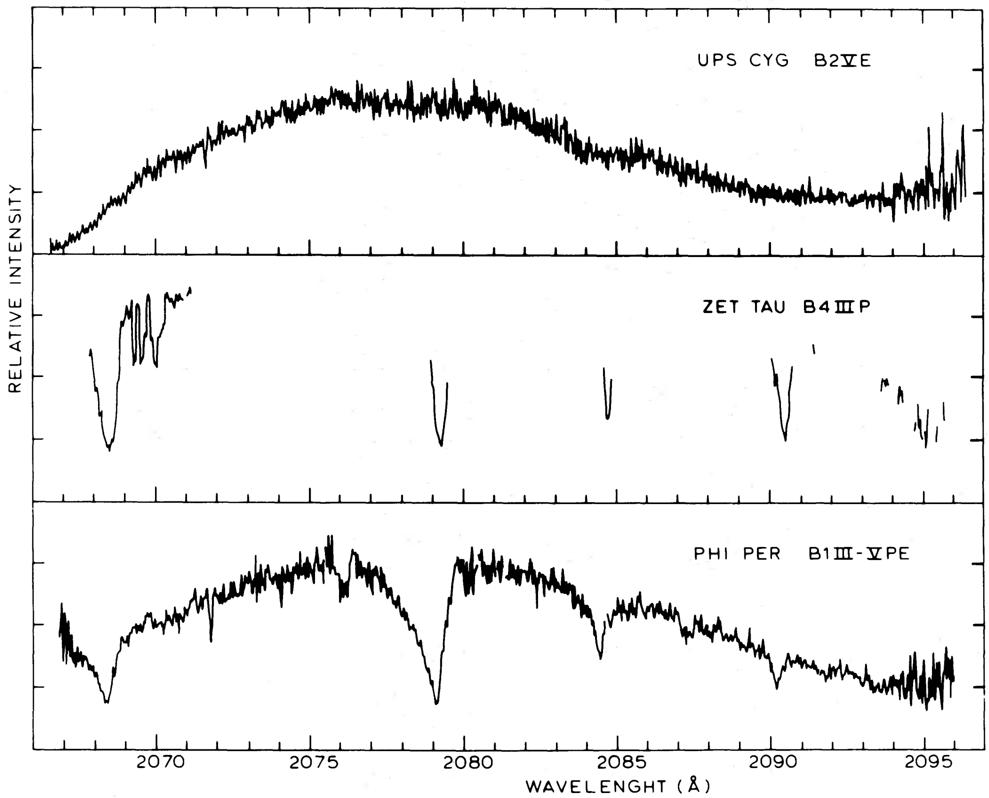

FIG. 3*a*

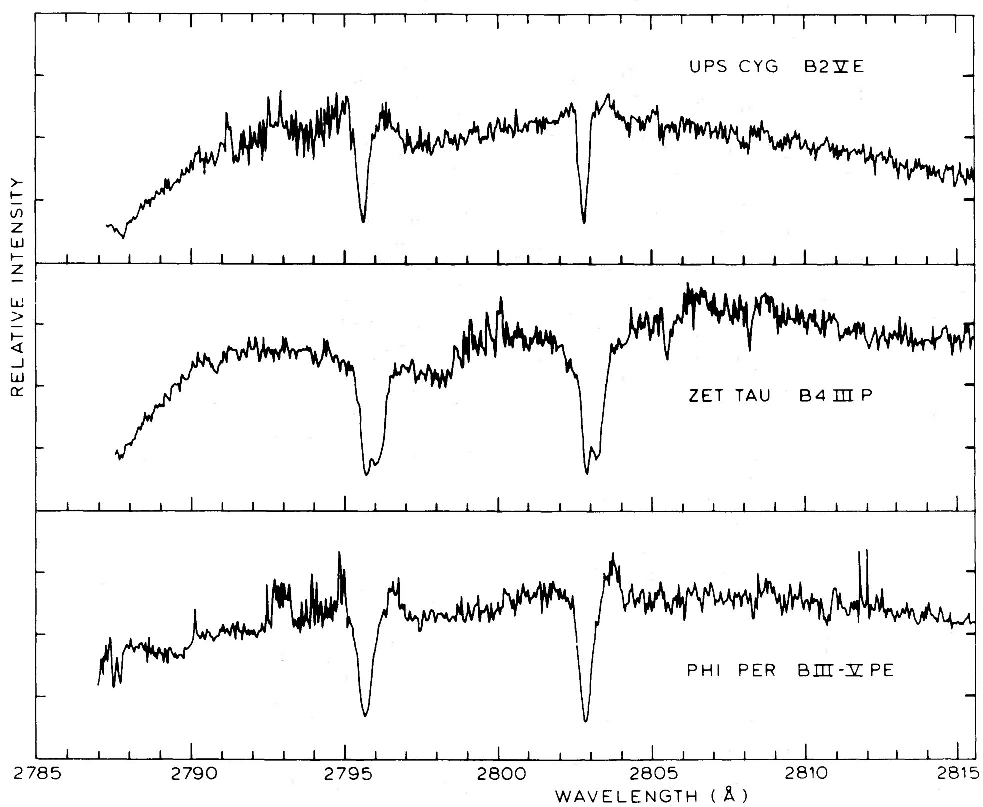

FIG. 3*b*

FIG. 3.—Spectra of the Be stars υ Cyg, ζ Tau, and ϕ Per in the spectral ranges (*a*) 2070–2095 Å and (*b*) 2785–2815 Å

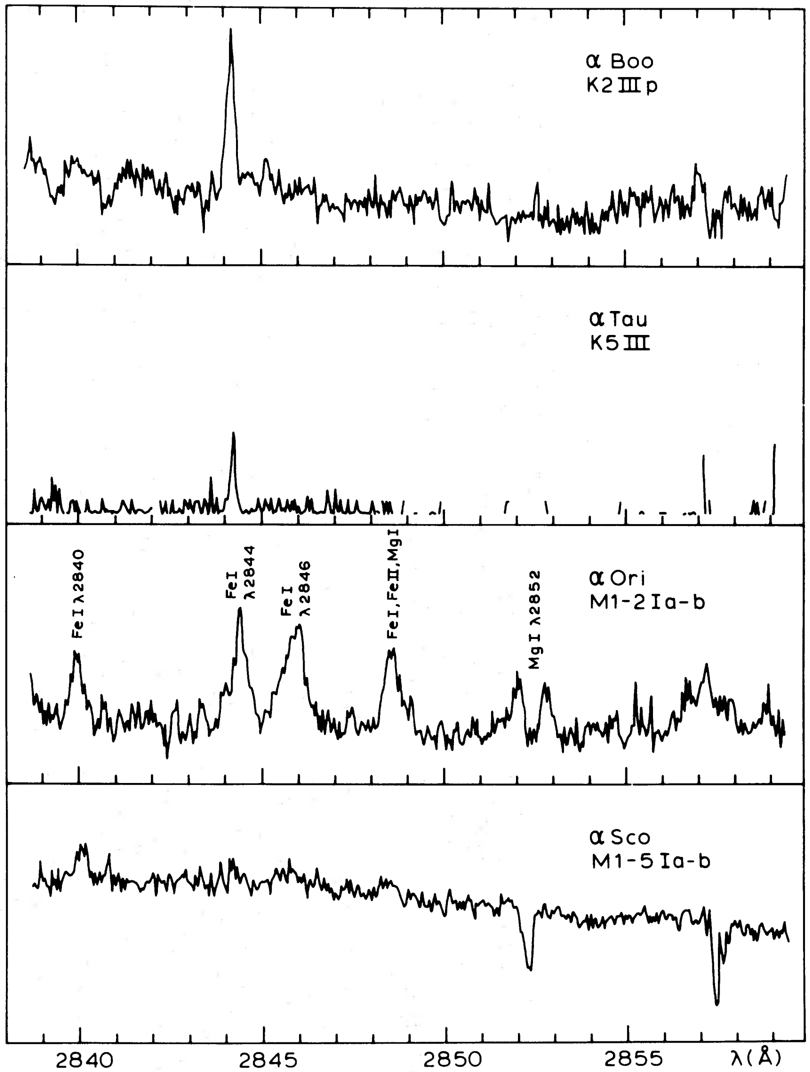

FIG. 4.—Emission lines of Fe I and Fe II in K-type giants and M-type supergiants

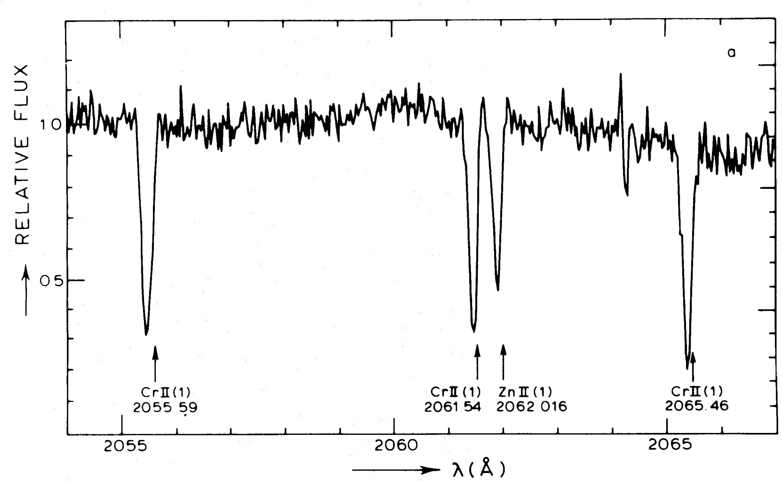

FIG. 5.—Circumstellar absorption lines of Cr II near 2060 Å in the spectrum of α Sco

thus visible within the circular 1′ entrance aperture of the BUSS spectrograph, which results in a composite spectrum. The 45 minute integration time was quite adequate to obtain also a good signal of the B star's photospheric spectrum.

M-type giants and supergiants are known to have very extended circumstellar (CS) shells. In the case of α^1 Sco, the shell extends to at least the distance of α^2 Sco (Kudritzki and Reimers 1978). Consequently the shell features are observed in absorption in the spectrum of the B star. In the BUSS UV spectrum of Antares, discussed by van der Hucht, Bernat, and Kondo (1979), shortward-shifted CS absorption lines of Cr II (UV 1) and Ni II (UV 11, 12, 13, and 14) have been identified, as well as CS contributions to absorption lines of Mg I, Mg II, Fe II, and Zn II. Figure 5 shows the Cr II CS absorption lines. They have a FWHM of ~ 0.2 Å and are shortward-shifted over -0.9 Å, corresponding to a radial velocity in the line of sight to α^2 Sco of -13 km s^{-1}. This observation allows the determination of the abundance of the various ions in the CS shell of Antares, and its mass loss.

The observations of α Sco also show, in addition to the Fe I and Fe II emission lines, emission lines of Fe III (UV 48) at $\lambda\lambda$2078.99 and 2068.24. The presence of the B star in the circumstellar shell of α^1 Sco may be the cause of these emission lines.

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