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THE CHEMICAL COMPOSITION OF A MAIN-SEQUENCE STAR IN THE SMALL MAGELLANIC CLOUD

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ABSTRACT

High-resolution echelle spectra of a main-sequence B type star (AV 304) in the Small Magellanic Cloud are analyzed using model atmosphere techniques to derive its atmospheric parameters and chemical composition. Because AV 304 is at an early evolutionary stage, its chemical composition should reflect that of its progenitor interstellar material. A general heavy element depletion of approximately -0.6 to -0.8 dex is deduced with nitrogen being more severely depleted (< -1.1 dex) and oxygen possibly less depleted (-0.45 dex). Helium has an approximately normal abundance. The high quality of the observational data coupled with the very small projected rotational velocity implies that depletions should normally be accurate to better than ± 0.2 dex, with the oxygen abundance probably being accurate to ± 0.1 dex.

Subject headings: galaxies: Magellanic Clouds — stars: abundances — stars: early-type

I. INTRODUCTION

The chemical composition of galaxies is important to problems as diverse as the initial mass function and star formation rates, dust composition and interstellar extinction, and the evolution and mass loss of individual stars. Our nearest neighbors, the Magellanic Clouds, provide an excellent opportunity to study these problems, having heavy element depletions which may be as large as ~ 1 dex in the case of the SMC.

Abundance determinations in the Clouds have relied mainly upon observations of emission nebulae (e.g., Dufour 1984; Monk, Barlow, and Clegg 1988) or of supergiants (e.g., Spite, Barbuy, and Spite 1989; Russell and Bessell 1989). Neither are ideal for studying current galactic abundances. For example, the emission-line studies may be affected by contamination from nucleosynthesis products or sensitive to uncertainties in temperatures and semiempirical ionization correction factors. Also, the supergiants' atmospheres may be contaminated by processed material, while their Galactic counterparts have poorly understood abundance anomalies.

These problems can be overcome by studying unevolved young stars, i.e., OB type main-sequence objects, whose chemical composition should reflect that of the local interstellar medium. The O type stars are easier to observe, but their atmospheres are subject to strong non–LTE effects (Kudritzki *et al.* 1989), and only a few chemical species are available for interpretation. Also full non–LTE abundance analyses are rare even for Galactic targets (see, for example, Schönberner *et al.* 1988). By contrast, B type main-sequence stars are well studied in our own Galaxy (see, for example, Dufton *et al.* 1990 and references therein) so that a reliable abundance analysis of a relatively large range of elements is comparatively straightforward. We are therefore undertaking a program of observation of B type main-sequence stars in the Magellanic Clouds with the Anglo-Australian Telescope (AAT). One SMC star, AV 304 ($V = 14.98$), B0.5 V; Garmany, Conti, and Massey 1987), has been discovered to be exceptionally sharp-lined and therefore well-suited to detailed analysis; we report the results of a preliminary study here.

II. OBSERVATIONS

Data were obtained by using the University College London Echelle Spectrograph (Walker and Diego 1985) in 1989 November. The instrumental configuration used a 79 lines mm^{-1} echelle grating operating in orders 57–48 and with a wavelength coverage from 3900 to 4700 Å. Even with the relative large detector area (38 by 18 mm) of the Image Photon Counting System, complete wavelength coverage was not possible. The echelle was positioned so that the Si III/Si IV lines (for estimating the effective temperature) and Hγ, Hδ lines (for surface gravity) were well observed; additionally, most of the important metal lines fell in the IPCS window.

AV 304 was observed for 6.9 hr (split up into smaller exposures of approximately 1 hr and interleaved with CuAr wavelength calibration spectra), achieving an average continuum count of 1200 and a signal-to-noise ratio of approximately 35. The two-dimensional data set was reduced using the STARLINK package FIGARO (Fuller 1989). Following flat-fielding and correction for distortion due to the IPCS optics, the echelle orders were extracted into one-dimensional spectra and sky was subtracted. Wavelength calibration was performed using the CuAr emission spectra.

The spectra were analyzed using the spectral reduction package DIPSO (Howarth and Murray 1988). Spectra were added and then wavelength-shifted using the radial velocity of 157 km s^{-1} deduced from the summed spectrum. Equivalent widths for metal and nondiffuse helium lines were estimated by nonlinear least-squares fitting of single or multiple absorption profiles to the normalized spectra. The choice of profile shape was investigated by shifting a number of moderately strong lines to zero wavelength and adding them together. The resulting composite spectrum was well fitted by a Gaussian profile and in particular did not show any extended wings attributable to scattering in the echelle; this was confirmed by studying the profiles from the CuAr emission line spectra. As a further test, selected features in the stellar spectra were fitted using both Gaussian and triangular profiles, but the choice of profile did not significantly affect the derived equivalent widths (the equivalent widths listed in Table 1 are from Gaussian fits). For the hydrogen and diffuse helium lines, equivalent widths were not measured but the normalized profiles extracted directly. Further details of the methods used to measure lines strengths and profiles can be found in Dufton *et al.* (1990 and references therein).

As well as an absolute abundance study, AV 304 was also analyzed relative to the standard τ Sco. High-quality observational data for this star obtained with the ESO CASPEC echelle spectrograph have been presented by Kilian and Nissen (1990). These data were rereduced by Lennon *et al.* (1990) using methods similar to those discussed above, and these values have been adopted here.

III. MODEL ATMOSPHERE ANALYSIS

Atmospheric parameters for AV 304 were deduced using the grid of line-blanketed LTE model atmospheres of Kurucz (1979) or additional models generated with his program. A normal heavy element composition was assumed, and this may not be appropriate by AV 304. However, comparison of these models with those generated using a lower metal abundances (Howarth and Lynas-Gray 1989) indicated that they have similar temperature–optical depth structures but are labeled with different effective temperatures. Hence, the use of such models should not lead to significant errors, although the adopted effective temperature for AV 304 may be too low by approximately 500–1000 K.

The effective temperature (28,000 K) was deduced from the Si III/Si IV ionization equilibria and the surface gravity ($\log g = 4.1$) from the Balmer line profiles for Hγ and Hδ (the theoretical profiles being calculated using the line broadening theory of Vidal, Cooper, and Smith 1973). The quality of the fit in the region of the Hδ line is illustrated in Figure 1. The most prominent heavy element spectrum is that of O II and is compatible with a microturbulent velocity of 5 km s^{-1}, in that

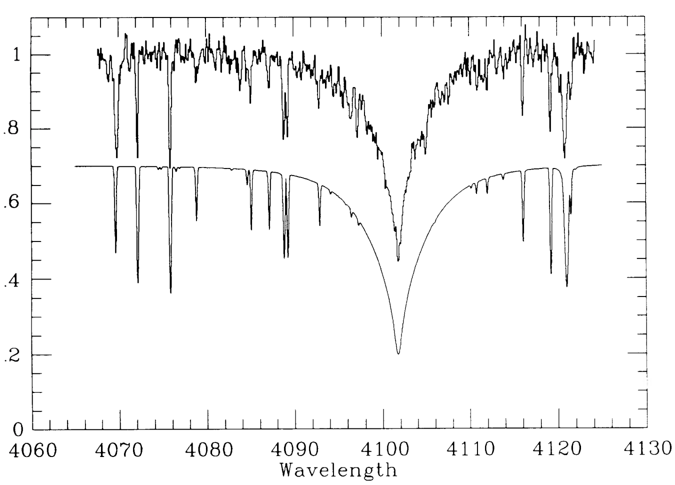

FIG. 1.—Part of the observed spectrum for AV 304 including the Hδ line and lines due to He I, O II, and Si IV. Also shown is a theoretical spectrum calculated using the abundances listed in Table 1. Some weak metal lines have not been included in the synthesized spectrum due to the lack of reliable atomic data. Excellent agreement is found between theory and observation.

there is no obvious correlation of oxygen abundance with line strength. Also such a value would be consistent with that obtained previously for LTE analyses of main-sequence B type stars (see, for example, Peters 1976). For τ Sco, the atmospheric parameters ($T_{\rm eff} = 31{,}000$ K, $\log g = 4.15$, $v_t = 5$ km s^{-1}) were taken from Lennon *et al.* (1990).

Using the adopted atmospheric parameters, abundances were deduced from the observed helium and metal line strengths in both stars. Oscillator strengths were taken mainly from Wiese, Smith, and Glennon (1966) and Wiese, Smith, and Miles (1969), exceptions being C II (Nussbaumer and Storey 1981), N II (Dufton and Hibbert 1981), Si III (Victor, Stewart, and Laughlin 1976), and Si IV (Lindgard and Nielsen 1977). For the nondiffuse helium lines, the broadening theory of Griem *et al.* (1962) was used, while for the diffuse lines, those of Barnard, Cooper, and Smith (1974) and Gieske and Griem (1969) were adopted. The blending of O II lines with the He I line at 4121 Å was explicitly included in the theoretical calculations assuming the oxygen abundance deduced from unblended O II lines. For the metal lines, radiative damping constants were deduced using oscillator strengths taken from the references given above, while electron damping constants were taken from Konjevic and Wiese (1976), apart from O II (Platisa, Popovic, and Konjevic 1975), Si IV (Platisa *et al.* 1977), and S III (Hey and Breger 1980). Note that at least for the differential abundance analysis, the choice of atomic data is not critical.

In Table 1, we list for each line the absolute abundance for AV 304 and its differential abundance relative to τ Sco. Also given are the mean values for each element where the quoted errors are the sample standard deviations. If the errors in the estimates from individual lines are randomly distributed, the errors in the mean values will be smaller.

IV. DISCUSSION

Relative to τ Sco, AV 304 exhibits a systematic underabundance of heavy elements consistent with other SMC studies. Besides random errors due to observational errors, these results could be affected by errors in the adopted atmospheric parameters. To illustrate their importance, we have considered changes of ± 1000 K in the effective temperature, ± 0.2 dex in the logarithmic gravity and ± 3 km s^{-1} in the microturbulent velocity for AV 304 and τ Sco. These change the absolute (and hence differential) abundance by generally less than 0.1 dex and always by less than 0.2 dex. Hence, we conclude that errors in the observational data or the atmospheric parameters should normally lead to uncertainties of 0.2 dex or less in the differential abundances. Below we discuss the individual abundances in more detail.

Helium.—The differential analysis implies a modest helium deficiency in AV 304; however, the absolute helium abundance is similar to that found in the analysis of Galactic B type stars (see Lennon, Brown, and Dufton 1988 and references therein). This discrepancy may arise from the He I lines spectrum in τ Sco being more affected by non–LTE effects due to its higher effective temperature. Indeed, Auer and Mihalas (1973, 1974) found that while non–LTE effects were small at effective temperatures below 30,000 K, they increased rapidly at higher effective temperature (e.g., at 35,000 K, the non–LTE equivalent width for the line at 4471 Å was approximately twice the LTE value). Also they found good agreement between non–LTE theory and observation for the stronger He I lines in τ Sco for a helium abundance of 11.00 dex. We conclude that

TABLE 1

ABUNDANCE ANALYSIS

Line/Species	AV 304	τ Sco	$\left[\frac{X}{H}\right]$	$\Delta\left[\frac{X}{H}\right]$
4009.27 He I	360	...	10.98	...
4026.3 He I	890	900	10.91	−0.27
4120.9 He I	165:	150	10.88	−0.12
4168.97 He I	65	75	11.04	−0.28
4437.55 He I	80	70	10.94	−0.11
4713.3 He I	215	240	10.87	−0.41
Helium abundance	...	...	10.94 ± 0.06	−0.25 ± 0.12
4267.2 C II	55	95	6.83	−0.75
Carbon abundance	...	...	6.83	−0.75
3995.00 N II	<16	80	<6.6	< −1.4
4041.32 N II	<12	60	<6.9	< −1.3
4043.53 N II	<12	35	<7.0	< −0.9
4447.03 N II	<15	45	<7.0	< −1.0
4630.55 N II	<25	70	<7.1	< −1.1
Nitrogen abundance	...	...	<7.0	< −1.1
3945.05 O II	30	...	8.07	...
3954.37 O II	50	85	8.08	−0.80
3982.72 O II	30	65	8.09	−0.86
4069.8 O II	135	155	8.28	−0.43
4072.16 O II	80	95	8.12	−0.47
4075.9 O II	95	110	8.16	−0.47
4078.86 O II	20	40	7.90	−0.68
4087.16 O II	25	40	7.92	−0.48
4089.29 O II	55	75	8.14	−0.44
4092.94 O II	25	35	8.10	−0.47
4119.22 O II	60	85	7.97	−0.51
4121.48 O II	40	45	8.33	−0.34
4185.46 O II	40	50	7.95	−0.35
4189.79 O II	45	65	7.91	−0.50
4303.82 O II	30	55	7.93	−0.60
4317.14 O II	75	75	8.33	−0.32
4319.63 O II	65	80	8.19	−0.53
4345.56 O II	55	60	8.47	−0.33
4347.42 O II	45	55	8.38	−0.36
4349.43 O II	105	110	8.44	−0.38
4351.27 O II	65	75	8.34	−0.37
4395.95 O II	50	40	8.54	−0.08
4414.91 O II	115	110	8.29	−0.26
4416.98 O II	90	95	8.24	−0.37
4590.97 O II	65	90	8.03	−0.58
4596.17 O II	65	80	8.19	−0.45
4661.64 O II	85	95	8.32	−0.44
4676.23 O II	65	70	8.18	−0.39
4699.21 O II	55	80	8.07	−0.57
4705.36 O II	55	75	7.91	−0.51
Oxygen abundance	...	...	8.17 ± 0.18	−0.45 ± 0.16
4409.30 Ne II	15:	45	8.09:	−0.46:
Neon abundance	...	...	8.0:	−0.4:
4481.3 Mg II	60	95	6.93	−0.64
Magnesium abundance	...	...	6.93	−0.64
4529.0 Al III	<20	40	<5.7	< −0.7
Aluminum abundance	...	...	<5.7	< −0.7
4567.87 Si III	110	115	7.16	−0.62
4574.78 Si III	55	75	6.91	−0.81
4088.86 Si IV	65	230	6.94	−0.54
4116.22 Si IV	45	130	6.85	−0.70
Silicon abundance	...	...	6.96 ± 0.13	−0.67 ± 0.11
4253.59 S III	50	80	6.31	−0.77
4332.71 S III	20	30	6.47	−0.54
Sulfur abundance	...	...	6.39	−0.65

there is no significant evidence for a real helium depletion in AV 304.

Carbon.—The carbon abundance is based on only one C II line at a wavelength of 4267 Å, which is known to be susceptible to non–LTE effects (Lennon 1983; Eber and Butler 1988). Hence the abundance for this element should be treated with caution (although the differential value should be more reliable); however, we note that the depletion is compatible with that found for other elements.

Nitrogen.—No nitrogen lines were observed in the spectra of AV 304. Upper limits were estimated for the stronger N II lines by (*a*) taking the equivalent width plus one standard error deduced from a nonlinear squares fit with the Gaussian fixed at the rest wavelength (note that if the errors are distributed normally this will provide a reliable upper limit in over 80% of cases) and (*b*) using the method of Pettini and West (1982). The values listed in Table 1 are the larger of these two estimates for each line. A range of *minimum* depletions is deduced ranging from -0.9 to -1.4 dex, and we estimate the nitrogen depletion to be < -1.1 dex. Non–LTE effects in the N II spectrum have been found to be relatively small (Dufton and Hibbert 1981; Becker and Butler 1989) and hence should not affect this limit.

Oxygen.—The oxygen abundance is well determined being based on 30 separate O II lines. Assuming that the individual abundance estimates are normally distributed, an error for the mean value of ± 0.03 dex is implied. Additionally, uncertainties due to errors in the atmospheric parameters and due to non–LTE effects (Brown, Dufton, and Lennon 1988; Becker and Butler 1988) are relatively small for this element. Hence the differential oxygen abundance is probably reliable to ± 0.1 dex.

Neon, magnesium, silicon, and sulfur.—The abundances are based on relatively small numbers of lines. However, the silicon value is found from four lines in two ionization stages and should be reliable (Lennon *et al.* 1986), and Becker and Butler 1990 find non–LTE effects to be small for these ions), while both the magnesium and sulfur lines are well observed. The neon results are based on a marginal detection of a weak line in AV 304. Hence, the estimate should be treated with caution and probably reflects an upper limit for the neon abundance in AV 304.

These abundances are in reasonable agreement with those deduced previously for the SMC from analyses of late-type supergiants (Russell and Bessell 1989; Spite, Barbury, and Spite 1989) and emission-line objects (see, for example, Russell and Dopita 1990). Our carbon abundance is in better agreement with that found for the supergiants rather than the lower value found from ultraviolet lines in H II regions (see, for example, Dufour 1984). Recently, Reitermann *et al.* (1990) have discussed analyses of two B type stars, one of which (NGC 330/3) is in the SMC. Reitermann *et al.* classify both stars as giants (class II or III), while their positions in the Hertzsprung-Russell diagram indicate that they have evolved well away from the main sequence. Surprisingly, Reitermann *et al.* find a very different chemical composition for NGC 330/3 than that of AV 304. In particular, they find a general metal depletion of approximately 1.0 dex with nitrogen less depleted and suggest that this may be due to products of CNO burning being mixed to the surface. Although the abundances deduced for NGC 330/3 may reflect those of its progenitor interstellar material, the different chemical compositions deduced for the B type stars emphasize the importance of ensuring that targets are at an early evolutionary stage and if possible on the main sequence.

In summary, AV 304 appears to have a normal helium abundance and a mean metal depletion of approximately 0.7 dex. However, nitrogen is significantly more underabundant, while there is some evidence for oxygen being less depleted. As AV 304 lies on the main sequence, these results should not be affected by theoretical uncertainties or contamination by material which has undergone nucleosynthetic processing during an earlier evolutionary stage. Hence its chemical composition should reliably reflect that of the interstellar material from which it is formed.

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