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THE CHEMICAL COMPOSITION OF THE RV TAURI VARIABLE IW CARINAE

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ABSTRACT

Analysis of the RV Tauri star IW Carinae shows a photospheric composition unlike that reported previously for a few other RV Tau stars but resembling that of certain post-AGB stars. IW Car is carbon-rich: several lines of C I are detected and suggest $C/O \geq 1$. The star is generally metal poor. The composition of $[Fe/H] \sim -1.0$, $[Ca/H] \simeq -1.9$ but $[Zn/H] \sim 0.0$ reflects that of gas of solar metallicity from which easily condensable elements have condensed into dust grains and been removed from the star's photosphere. Separation of gas and dust may have occurred in the present or recent stellar wind of IW Car. These characteristics also suggest that RV Tauri stars are post-AGB objects.

Subject headings: stars: abundances — stars: individual (IW Carinae) — stars: variables: other (RV Tauri)

1. INTRODUCTION

RV Tauri stars have unusual photometric and spectroscopic characteristics. The light curves show alternating deep and shallow minima. Many RV Tauri stars exhibit two dominant periods: variations with a short period ($P \sim 40$ days) of small amplitude superposed on variations of equal or larger amplitude having a much longer period ($P \sim 800$ days, for example). The spectral type which varies over the short-period cycle is earliest near light maximum and latest at light minimum. The radial velocity varies in phase with the color/spectral type variations. The photometric and spectroscopic characteristics for the short period variations are indicative of an atmospheric pulsation.

These pulsating supergiants have been identified as stars at the termination of their evolution along the asymptotic giant branch (AGB). Recall that AGB stars have C–O electron degenerate cores with a thin overlying layer of He inside a large tenuous convective H-rich envelope. Mixing between the He-shell and this envelope enriches the latter in carbon, a product of He-burning, and the *s*-process elements, a by-product of neutrons released during He-burning. Some RV Tauri stars (called type *b* by Preston et al. 1963) are evidently carbon-rich, i.e., carbon is more abundant than oxygen. IW Car, the star of our study, has been classified as carbon-rich on the basis of the strengths of the CH and CN bands seen near light minimum.

Remarkably little work has been done toward determining the chemical compositions of RV Tauri stars: U Mon was studied by Aliev (1967), AC Her by Baird (1979; see also Yoshioka 1979), R Sct by Luck & Bond (1984) and RU Cen, AI CMi, and U Mon by Luck & Bond (1989). Patterns among the compositions of RV Tauri stars and putative relatives on and off the AGB cannot be discerned because, in large measure, the studies of the RV Tauri stars are too few and too incomplete. Baird (1979) studied a large number of elements but by a curve-of-growth analysis. Luck & Bond (1984, 1989) largely ignore elements lighter than the iron peak. The five RV Tauri stars analyzed to date appear quite deficient in iron-peak elements which implies the stars' progenitors belonged to the old disk or halo populations.

In the present work, we analyze the southern C-rich RV Tauri star IW Car. This appears to be the first abundance analysis of the star. IW Car was discovered by O'Connell (1946) and a light curve published by Wisse & Wisse (1971). The star's pulsational (short) period is 67.5 days and the long period is 1500 days. However, the recent observations by Karen Pollard (1994, private communication) give a period close to 80 days. IW Car has a considerable infrared excess arising from circumstellar dust grains. The grains contain a component of silicates (Gehrz & Ney 1972; Lloyd Evans 1985).

2. OBSERVATIONS

IW Car was observed on 1992 May 22 with the Cassegrain echelle spectrometer of the 4 m telescope at the Cerro-Tololo Inter-American Observatory. A spectral region 5400–7100 Å was recorded at a resolution (FWHM) of 0.2 Å with a Tektronix 1024 × 1024 CCD. Exposures of 10 and 6 minutes were obtained. Spectra were reduced using the reduction package RESPECT (Prabhu, Anupama, & Giridhar 1987) in its upgraded version (Prabhu & Anupama 1991). Extraction of echelle orders followed Horne's (1986, 1988) algorithm. An exposure of a Th-Ar lamp obtained immediately following the stellar exposures was used for the wavelength calibration. Extracted echelle orders were linearized in wavelength using a third-degree polynomial. A pseudocontinuum was determined for each order using the highest points in the order known to be free of stellar lines. Spectra were then reduced to a normalized continuum using spline interpolated values for the pseudocontinuum. The signal-to-noise ratio at the center of the orders is ~200 at 7000 Å and 110 at 5500 Å. It is, of course, lower at the half-power points of the orders. This decrease is largely offset by the fact that, except for the reddest orders, lines near the half-power points are recorded on two adjacent orders. The accuracy of measured equivalent widths is 10% for

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lines in equivalent width range 20–50 mÅ and 5%–10% for the lines in range 50–250 mÅ. According to the ephemeris provided by Wisse & Wisse (1971), our observations were made at a phase $\phi = 0.89$ (i.e., near minimum light) where $\phi = 0.5$ corresponds to maximum light. Karen Pollard's contemporaneous observations indicates the phase of our observation to be $\phi = 0.0$ (i.e., minimum light) for the shorter period pulsation of 80 days.

3. ABUNDANCE ANALYSIS

3.1. *General Description of the Spectrum*

The General Catalogue of Variable Stars gives the spectral type of IW Car as F7–8. Our spectrum shows that the metal lines are very weak—see Figures 1 and 2 where α Per (spectral type F5Ib) is adopted as Population I standard. The spectra of α Per were taken with the McDonald Observatory's 2.1 m telescope and are at a resolution (0.3 Å) slightly inferior to that of IW Car. A distinctive but not unexpected feature of IW Car's spectrum is the presence of a large number of C I lines. The radial velocity from photospheric lines is 10.5 ± 2 km s^{-1}. We get essentially the same velocity from the lines of different metals. The Hα profile is very complex: weak blue and red emission lines, a sharp deep absorption, and a shallow broad blueshifted absorption feature comprise three obvious components (Fig. 3). The sharp deep absorption is close to the position of the expected photospheric absorption line. The shallow absorption feature is blueshifted by ~ 82 km s^{-1} with respect to the photosphere. The gas responsible for this feature would appear to be escaping from the star. The weak emission lines may come from a shell or disk near the star.

Interstellar lines including the diffuse interstellar bands (DIBs) are well represented in the spectrum: the strongest are those at 5780, 5797, 6318, and 6440 Å. A component of the NaD lines redshifted by 41 km s^{-1} from the photospheric velocity coincides with the velocity obtained from the diffuse interstellar bands (e.g., 5797.1 and 6195.95 Å) thus indicating interstellar nature of these components.

3.2. *Method*

A now-standard application of model stellar atmospheres was used—see Giridhar (1983) for details. Throughout local thermodynamic equilibrium (LTE) was assumed. Model atmospheres were selected from a grid computed using the MARCS code (Gustafsson et al. 1975) by R. E. Luck and kindly made available to us by him. Equivalent widths expected of a model atmosphere were computed using a program originally written by Sneden (1973) and modified by one of us (S. G.). Defining parameters of a model atmosphere are the effective temperature (T_{eff}), the surface gravity (g) and the microturbulence (v_t) and the chemical composition. A selection of 46 Fe I lines covering a range in excitation potential (1.0–5.5 eV) and equivalent width (15–120 mÅ) were used to determine T_{eff} and v_t. Figure 4 shows the plot of derived Fe abundances as a function of equivalent width and excitation potential for Fe I and Fe II lines. The surface gravity was found by requiring that the Fe I lines and 12 Fe II lines give the same iron abundance. The *gf*-values for the Fe I and Fe II lines were taken from Fuhr, Martin, & Wiese (1988). We assume that IW Car has the standard He abundance of the MARCS grid (He/H = 0.1). Once the [Fe/H] of -1.0 was indicated, we used the model atmospheres computed for $[\text{M/H}] = -1.0$. In light of the star's carbon enrichment (see below), it is possible that the stellar atmosphere is enriched in helium and deficient in hydrogen.

In this analysis, we adopt *gf*-values from Fuhr et al. (1988) and Martin, Fuhr & Wiese (1988) for elements V to Ni, when available. For the C I lines, we take the predicted *gf*-values for Luo & Pradhan (1989) or Kurucz & Peytremann (1975). The

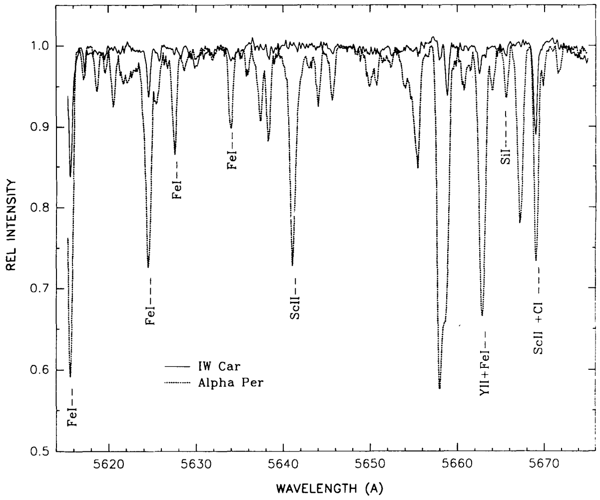

FIG. 1.—The spectrum of IW Car and α Per from 5614 to 5676 Å. Note the weakness of all lines in the spectrum of IW Car.

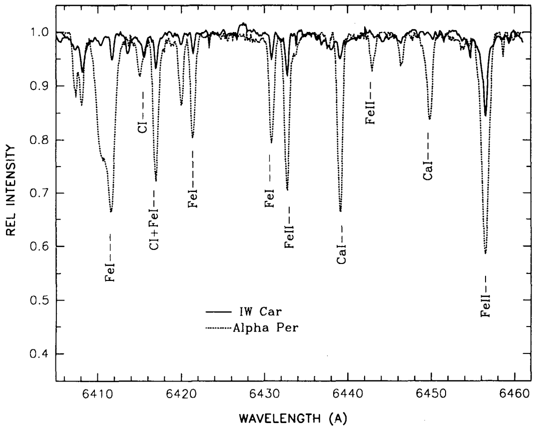

FIG. 2.—The spectrum of IW Car and α Per from 6405 to 6462 Å

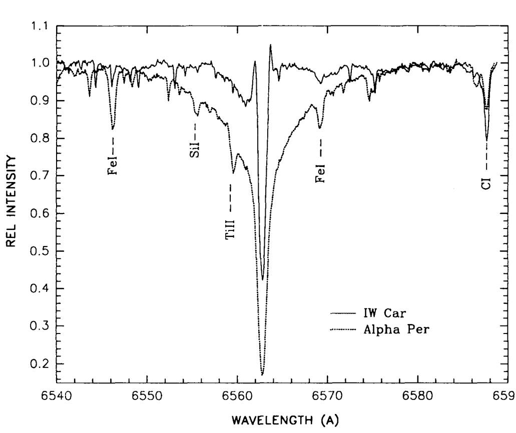

FIG. 3.—The Hα line in the spectrum of IW Car and α Per showing the complex Hα profile of IW Car.

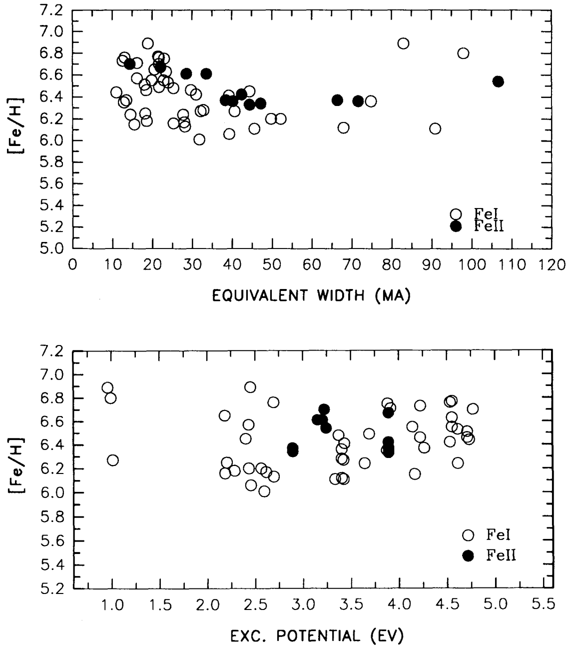

FIG. 4.—The iron abundance of IW Car shown for individual Fe I and Fe II lines as a function of a line's equivalent width and the lower excitation potential. Note: the abundance is log ϵ(Fe), not [Fe/H] as shown.

gf-values for other elements were taken from a tape compiled by R. E. Luck (1991, private communication); these are based when possible on experimental determinations of high quality. We have checked that Luck's particular choices of *gf*-values are not the origin of the unusual abundance ratios found here. Our final parameters for IW Car at the time of our observation are $T_{\rm eff} = 6700$ K, $g = 100$ cm s^{-2} and $v_t = 4.0$ km s^{-1}. We estimate the accuracies to be $\Delta T_{\rm eff} \simeq \pm 200$ K, $\Delta \log g \simeq \pm 0.25$ cm s^{-2}, and $\Delta v_t \simeq \pm 0.5$ km s^{-1}. Mean abundances are given in Table 1. A complete list of the lines used in obtaining these abundances is given in Table 2. We describe the abundance uncertainties arising from errors in the atmospheric parameters $T_{\rm eff}$, g, and ξ in Table 3.

Recent determinations of *gf*-values for Fe I lines and revisions to the solar photospheric Fe abundance affect the Fe abundances. O'Brian et al. (1991) give a table of revised *gf*-values for Fe lines: 21 of our Fe I lines are included in this table and give log ϵ(Fe) = 6.35 ± 0.26 compared to 6.43 ± 0.24 in Table 2. Our *gf*-values from Fuhr et al. (1988), the Holweger-Müller (1974) model solar atmosphere and solar equivalent widths ($W_\lambda < 100$ mÅ only) give a solar Fe abundance of 7.51 ± 0.14 independent of excitation potential. O'Brian et al.'s *gf*-values give a slightly smaller abundance. Grevesse & Noels (1993) give log ϵ(Fe) = 7.51 as their recommended photospheric iron abundance from Fe I and Fe II lines. Thus, our adopted *gf*-values for Fe I lines appear quite consistent with the now preferred solar abundance.

For the Fe II lines, the *gf*-values adopted by Fuhr et al. (1988) come principally from Blackwell, Shallis, & Simmons (1980) who derived "solar" *gf*-values using the Holweger-Müller (1974) model and the "high" Fe abundance of log ϵ(Fe) = 7.69. When these *gf*-values are corrected to the new solar Fe abundance, we obtain log ϵ(Fe) = 6.29 ± 0.14 from IW Car's Fe II lines which is in fair agreement with the Fe abundance from Fe I lines. We did not apply the small increase to the surface gravity needed to bring the Fe I and Fe II lines into perfect agreement.

An estimate of the effective temperature is also obtainable from photometry reported by Wisse & Wisse (1971). The DIBs provide a rough measure of the color excess $E(B-V)$. Since the correlation between $E(B-V)$ and the strengths of DIBs is stronger for the weaker bands, we use the 5780 and 5797 Å DIBs with equivalent widths of 106 and 40 mÅ, respectively, and Krelowski's (1989) calibration to infer $E(B-V) \simeq 0.35$. Then, the corrected color at the phase of our observation is $(B-V)_0 \simeq 0.6$ or $T_{\rm eff} \simeq 6000$ K from Flower's (1977) color-temperature relation for Population I stars. A lower $T_{\rm eff}$ is likely to result from the color-temperature relation for metal-poor stars. These photometric estimates are cooler than our

TABLE 1

CHEMICAL COMPOSITION OF IW CARINAE AND THE SUN

ELEMENT	ION	IW CARINAE log ϵ	IW CARINAE Number of lines	SUN/METEORITIES[a] log ϵ	Δ log ϵ
C	I	8.87 ± 0.24	22	8.55	+0.32
O	I	8.54 ± 0.09	3	8.87	−0.33
Na	I	6.66 ± 0.08	4	6.32	+0.34
Mg	I	6.60 ± 0.02	2	7.58	−0.98
Al	I	5.14:[b]	1	6.48	< −1.34
Si	I	6.98 ± 0.12	9	7.55	−0.57
	II	6.65 ± 0.11	2	7.55	−0.90
S	I	7.59 ± 0.15	9	7.23	0.36
Ca	I	4.38 ± 0.20	6	6.35	−1.97
Sc	II	0.96 ± 0.29	3	3.09	−2.13
Cr	II	4.70 ± 0.15	2	5.68	−0.98
Fe	I	6.43 ± 0.24	46	7.51	−1.08
	II	6.47 ± 0.14	12	7.51	−1.04
Ni	I	5.27	1	6.23	−0.96
Zn	I	4.60	1	4.64	−0.04
Ba	II	0.26 ± 0.15	3	2.17	−1.91
Sm	II	0.43	1	0.97	−0.54

[a] Anders & Grevesse 1989, but Grevesse & Noels 1993 for the C, N, O, and Fe abundances.

[b] Upper limit.

TABLE 2

LINES USED IN THE ABUNDANCE ANALYSIS OF IW CARINAE

Wavelength (Å)	Atom	Low EP (eV)	W_λ (mÅ)	log gf	log ϵ
5817.700	C I	8.87	7	-.287E+01	9.04
5912.580	C I	9.00	25	-.262E+01	9.49
5963.990	C I	8.64	14	-.264E+01	8.94
5969.400	C I	7.95	15	-.308E+01	8.83
6001.120	C I	8.64	26	-.207E+01	8.67
6007.178	C I	8.64	20	-.218E+01	8.65
6010.679	C I	8.64	26	-.202E+01	8.63
6012.213	C I	8.66	15	-.230E+01	8.63
6014.843	C I	8.64	54	-.171E+01	8.72
6016.448	C I	8.64	69	-.182E+01	8.98
6108.530	C I	8.87	16	-.258E+01	9.11
6120.812	C I	8.85	11	-.242E+01	8.78
6292.442	C I	9.00	26	-.219E+01	9.09
6413.550	C I	8.77	27	-.200E+01	8.75
6587.620	C I	8.54	123	-.930E+00	8.61
6605.800	C I	8.89	11	-.231E+01	8.72
6611.350	C I	8.85	32	-.228E+01	9.17
6671.820	C I	8.85	34	-.165E+01	8.58
6674.110	C I	8.85	15	-.228E+01	8.82
6688.780	C I	8.85	38	-.215E+01	9.15
6711.300	C I	8.54	32	-.247E+01	9.12
6828.120	C I	8.54	60	-.151E+01	8.55
6155.980	O I	10.74	15	-.660E+00	8.45
6156.770	O I	10.99	17	-.450E+00	8.51
6158.180	O I	10.74	42	-.290E+00	8.66
5682.626	Na I	2.10	125	-.710E+00	6.61
5688.220	Na I	2.10	170	-.400E+00	6.78
6154.225	Na I	2.10	38	-.157E+01	6.56
6160.750	Na I	2.10	73	-.127E+01	6.68
5528.410	Mg I	4.34	149	-.340E+00	6.59
5711.095	Mg I	4.34	30	-.168E+01	6.61
6696.030	Al I	3.14	2	-.132E+01	<5.14
5690.470	Si I	4.95	18	-.187E+01	7.11
5708.410	Si I	4.95	25	-.147E+01	6.88
5772.260	Si I	5.08	17	-.178E+01	7.09
5948.550	Si I	5.08	40	-.123E+01	6.96
6091.920	Si I	5.87	7	-.140E+01	6.96
6125.030	Si I	5.61	12	-.151E+01	7.12
6145.020	Si I	5.61	5	-.148E+01	6.71
6555.465	Si I	5.98	10	-.115E+01	7.00
6721.844	Si I	5.56	15	-.126E+01	6.96
6347.090	Si II	8.12	121	.260E+00	6.80
6371.360	Si II	8.12	66	-.500E–01	6.50
5696.630	S I	7.86	28	-.121E+01	7.44
5700.240	S I	7.87	48	-.980E+00	7.49
5706.110	S I	7.87	62	-.800E+00	7.49
6041.920	S I	7.87	47	-.100E+01	7.51
6045.990	S I	7.87	64	-.790E+00	7.51
6052.630	S I	7.87	80	-.630E+00	7.54
6743.580	S I	7.86	83	-.700E+00	7.66
6748.790	S I	7.86	114	-.440E+00	7.74
6757.160	S I	7.87	146	-.290E+00	7.93
5588.760	Ca I	2.52	13	.360E+00	4.05
5594.470	Ca I	2.52	13	.100E+00	4.31
5598.490	Ca I	2.52	9	-.900E–01	4.33
5601.290	Ca I	2.52	7	-.520E+00	4.66
6122.210	Ca I	1.90	29	-.320E+00	4.59
6162.180	Ca I	1.90	26	-.900E–01	4.32
5526.890	Sc II	1.77	11	.130E+00	0.62
5657.880	Sc II	1.51	9	-.500E+00	0.93
5669.040	Sc II	1.50	6	-.109E+01	1.32
5502.092	Cr II	4.17	33	-.199E+01	4.85
5508.600	Cr II	4.14	14	-.211E+01	4.55
5487.755	Fe I	4.14	23	-.710E+00	6.55
5497.475	Fe I	1.01	41	-.285E+01	6.29
5501.477	Fe I	0.96	83	-.295E+01	6.80
5506.778	Fe I	0.99	98	-.280E+01	6.81
5543.944	Fe I	4.22	13	-.114E+01	6.75
5554.900	Fe I	4.55	20	-.440E+00	6.55
5565.713	Fe I	4.61	15	-.230E+00	6.24
5569.631	Fe I	3.42	46	-.540E+00	6.11
5572.849	Fe I	3.40	68	-.310E+00	6.12
5576.099	Fe I	3.43	39	-.100E+01	6.49
5586.770	Fe I	3.40	75	-.210E+00	6.10
5615.652	Fe I	3.33	91	-.140E+00	6.11
5624.543	Fe I	3.42	32	-.900E+00	6.28
5658.826	Fe I	3.40	33	-.920E+00	6.29
5662.510	Fe I	4.16	16	-.473E+00	6.15
5684.400	Fe I	4.53	22	-.620E+00	6.76
5709.378	Fe I	3.37	25	-.124E+01	6.48
5753.132	Fe I	4.26	14	-.760E+00	6.45
5863.002	Fe I	4.22	30	-.410E+00	6.46
5859.596	Fe I	4.55	22	-.620E+00	6.77
5862.366	Fe I	4.55	24	-.420E+00	6.63
5934.500	Fe I	3.91	16	-.117E+01	6.64
5984.830	Fe I	4.71	18	-.300E+00	6.51
6003.022	Fe I	3.88	23	-.112E+01	6.74
6008.540	Fe I	3.87	13	-.101E+01	6.35
6020.180	Fe I	4.61	24	-.270E+00	6.53
6024.070	Fe I	4.53	31	-.120E+00	6.42
6056.013	Fe I	4.73	11	-.460E+00	6.45
6065.490	Fe I	2.61	28	-.153E+01	6.17
6078.360	Fe I	4.77	22	-.360E+00	6.70
6136.620	Fe I	2.45	39	-.140E+01	6.06
6137.720	Fe I	2.59	32	-.140E+01	6.07
6191.570	Fe I	2.43	50	-.160E+01	6.38
6230.690	Fe I	2.56	52	-.128E+01	6.20
6252.565	Fe I	2.40	44	-.169E+01	6.38
6256.330	Fe I	2.45	19	-.262E+01	6.92
6265.050	Fe I	2.18	21	-.255E+01	6.66
6335.337	Fe I	2.20	18	-.223E+01	6.30
6336.835	Fe I	3.69	22	-.105E+01	6.49
6411.660	Fe I	3.64	28	-.820E+00	6.34
6419.960	Fe I	4.71	19	-.240E+00	6.46
6421.355	Fe I	2.28	19	-.203E+01	6.18
6430.854	Fe I	2.18	25	-.201E+01	6.22
6593.885	Fe I	2.43	16	-.242E+01	6.63
6677.979	Fe I	2.69	28	-.147E+01	6.18
6945.205	Fe I	2.69	13	-.248E+01	6.80
5534.848	Fe II	3.24	107	-.293E+01	6.54
5991.378	Fe II	3.15	34	-.374E+01	6.47
6084.100	Fe II	3.20	29	-.393E+01	6.70
6113.336	Fe II	3.22	14	-.431E+01	6.70
6147.740	Fe II	3.89	42	-.292E+01	6.42
6149.250	Fe II	3.89	40.	-.292E+01	6.39
6238.350	Fe II	3.89	44	-.280E+01	6.33
6247.520	Fe II	3.89	72	-.251E+01	6.36
6407.290	Fe II	3.89	22	-.349E+01	6.67
6416.930	Fe II	3.89	38	-.285E+01	6.30
6432.654	Fe II	2.89	47	-.374E+01	6.44
6516.050	Fe II	2.89	67	-.345E+01	6.37
6767.780	Ni I	1.83	10	-.217E+01	5.27
6362.354	Zn I	5.79	40	.270E+00	4.60
5853.680	Ba II	.60	31	-.100E+01	0.47
6141.730	Ba II	.70	68	-.800E-01	0.10
6496.908	Ba II	.60	61	-.380E+00	0.23
6725.880	Sm II	.00	11	-.189E+01	0.43

TABLE 3

DIFFERENTIAL ABUNDANCES OF Fe I AND Fe II WITH RESPECT TO THOSE DERIVED USING A MODEL WITH $T_{\rm eff}$ = 6700 K, log g = 2.0, v_t = 4.0

		Δ log ε								
		log g = 2.5			log g = 2.0			log g = 1.5		
$T_{\rm eff}$	v_t	1.0	4.0	7.0	1.0	4.0	7.0	1.0	4.0	7.0
6500	Fe I	+0.01	−0.15	−0.18	+0.03	−0.13	−0.16	+0.05	−0.10	−0.13
	Fe II	+0.40	+0.13	+0.09	+0.25	−0.02	−0.07	+0.10	−0.17	−0.22
6700	Fe I	+0.13	−0.03	−0.05	+0.15	0.00	−0.03	+0.18	+0.03	0.00
	Fe II	+0.42	+0.15	+0.11	+0.28	0.00	−0.04	+0.14	−0.14	−0.18
7000	Fe I	+0.32	+0.16	+0.13	+0.35	+0.19	+0.16	+0.39	+0.24	+0.21
	Fe II	+0.47	+0.29	+0.15	+0.34	+0.07	+0.01	+0.20	−0.08	−0.13

spectroscopic value, as expected for a star with a substantial infrared excess and, hence (unknown), circumstellar reddening.

4. CHEMICAL COMPOSITION

4.1. *IW Carinae's Anomalous Abundances*

Inspection of Table 1 shows several interesting and expected facets of IW Car's chemical composition, i.e., the atmosphere is carbon-rich with C/O ≃ 1.5 and metal-poor with [Fe/H] ≃ −1.0. A low metallicity has also been reported for other RV Tau variables—see Table 4 where we compare the differential estimates of [X/H] for IW Car with those of R Sct (Luck 1981) and RU Cen (Luck & Bond 1989) as representatives of oxygen and carbon-rich stars, respectively. Small differences between our and published estimates of [M/H] surely arise because of differences in the adopted solar abundances. Such differences, however, are negligible with respect to the standard deviations (often, $\sigma \simeq 0.2$–0.4) of the abundances reported for R Sct and RU Cen. Luck & Bond (1989) give mean values of [M/Fe] compiled from five RV Tauri variables. Their values for an adopted [Fe/H] = −1.0, which is approximately the mean metallicity of the quintet, are also given in Table 4. Very similar abundances result if models of solar composition ([Fe/H] = 0) are adopted. Inspection of Tables 1 and 4 shows that IW Car's composition differs in striking ways from its presumed initial composition (i.e., the composition of unevolved and less evolved stars of [Fe/H] ∼ −1) and from the composition of other RV Tauri stars analyzed to date. Apart from the carbon enrichment, the differences are striking because they are not easily attributable to enrichment of IW Car's atmosphere with internal (or external) products of nucleosynthesis. Perhaps, the most striking results are the low Ca and Sc abundances and the high S and Zn abundances.

TABLE 4

ELEMENTAL ABUNDANCES OF IW CARINAE AND OTHER RV TAURI VARIABLES

	[M/H]			
ELEMENT	IW Car[a]	R Sct[1 b]	RU Cen[c]	Mean[d]
C	+0.32	...	...	...
O	−0.33	...	−0.05	...
Na	+0.34	−0.57	−1.17	−0.45
Mg	−0.98	...	−1.55	−0.51
Al	< −1.34	...	...	−0.47
Si	−0.57	−0.74	−0.98	−0.72
S	+0.36	...	...	...
Ca	−1.97	−1.08	−1.45	−1.00
Sc	−2.13	...	−1.63	−1.49
Cr	−0.98	−0.92	−1.86	−1.10
Fe	−1.06	−0.88	−1.44	−1.00
Ni	−0.96	−0.87	−1.26	−0.92
Zn	−0.04	...	...	−0.70
Ba	−1.91	−1.44	−1.13	−1.38
Sm	−0.54	...	...	−1.61

[a] This paper.

[b] Luck 1981.

[c] Luck & Bond 1989.

[d] From Luck & Bond 1989, Table 8, for [Fe/H] = 1.0.

In what follows we comment on the determination of certain elemental abundances and conclude this section with a suggested interpretation of the anomalous abundances. Data on compositions of normal Fe-poor stars are taken from reviews by Lambert (1989) and Wheeler, Sneden, & Truran (1989).

The C and O abundances are derived from C I and O I lines. (Potential N I lines on our spectra are of low transition probability such that no useful limit has been set on the N abundance.) The spectrum contains many C I lines of which we use 22. The *gf*-values computed by Luo & Pradhan (1989) were available for half of the line sample. We used the semi-empirical *gf*-values of Kurucz & Peytremann (1975) for the remaining lines. There is no systematic difference as to the mean value and scatter between the C abundances from the two sets of *gf*-values. Lines of the strongest O I multiplet were synthesized—see Figure 5. All three lines are well fitted with the O abundance of log ε(O) ≃ 8.5. Other O I lines are present but blended.

Sodium and aluminum are diagnostics of H-burning at the elevated temperatures at which the ON-cycles operate. Four Na I lines give consistent abundances where the weaker two are included in Figure 5. The abundance [Na/Fe] ≃ +1.4 represents a large Na overabundance (relative to normal Fe-poor stars) and differs from what has been found previously for RV Tauri stars ([Na/Fe] ≃ −0.5; see Table 4.) Aluminum has eluded us. The Al I λλ6696 and 6698 lines fall within our bandpass but the latter is irretrievably blended and the former, which is not present, provides the limit [Al/H] ≲ −1.3 or [Al/Fe] ≲ −0.3.

Silicon is represented by nine Si I and two Si II lines. The Si I lines give consistent abundances. The Si II lines give a Si abundance that is 0.3 dex less than that from the Si I lines. The latter give [Si/Fe] ∼ +0.5 which is a normal value for a Fe-poor star and similar to that for R Sct ([Si/Fe] ≃ +0.2) and RU Cen ([Si/Fe] ≃ +0.5). Magnesium represented by two Mg I lines in IW Car gives [Mg/Fe] ≃ +0.1 which is similar to the [Mg/Fe] ≃ −0.1 found for RU Cen; [Mg/Fe] ≃ +0.4 is expected for a Fe-poor star.

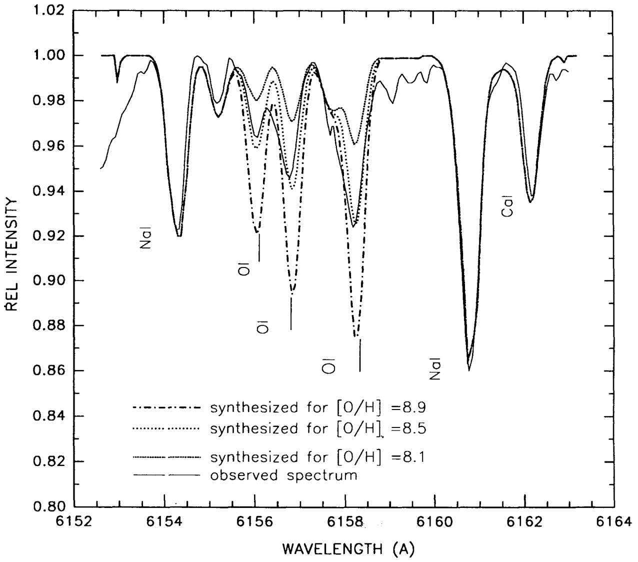

FIG. 5.—The observed and synthetic spectra of IW Car around the O I triplet at near 6156–6158 Å.

IW Car's peculiarities are betrayed by the S and Ca abundances: [S/Fe] $\simeq +1.4$ and [Ca/Fe] $\simeq -0.9$ are unknown ratios for normal metal-poor stars for which [S/Fe] = [Ca/Fe] $\simeq +0.5$ is found. Both elements are well represented on our spectra: S by nine S I lines and Ca by six Ca I lines. A Ca I line is included in Figure 5. Sulfur has not been measured in other RV Tau variables.

The iron-group (Sc to Ni) elements available for analysis are underabundant but, unlike normal Fe-poor stars, the abundances do not satisfy the null result [X/Fe] = 0. Scandium is noticeably underabundant ([Sc/Fe] = -1.1). The Sc abundance is based on three weak Sc II lines but the null abundance of [Sc/Fe] = 0 would correspond to lines much stronger than are observed.

Zinc, a key to our interpretation of IW Car's peculiar composition, is represented by a single line but this line is moderately strong and well resolved from neighboring lines. Other potential lines of Zn I lie, unfortunately, in unobserved parts of the spectrum. Zinc, like sulfur, has a solar abundance ([Zn/H] $\simeq 0.0$).

The Ba abundance is based on three good lines. We put little weight on the Sm abundance based on one weak line. If Ba is representative of the heavy elements, [Ba/Fe] $\simeq -0.8$ for IW Car is a more extreme deficiency than is found for other RV Tauri stars (see Table 4). For unevolved stars of a metallicity [Fe/H] $\simeq -1$, one expects [Ba/Fe] $\simeq 0$. If IW Car evolved along the AGB and experienced *s*-process enrichment, one expects [Ba/Fe] $\simeq 1$. Clearly, barium (relative to iron) is appreciably underabundant relative to expectations.

It is certainly worth remarking that within the constraints of standard model atmospheres and local thermodynamic equilibrium, it is not possible to reduce IW Car's spectrum to the set of abundances expected for a metal-poor star. Consider, for example, the Ca/Fe ratio. The lower first ionization potential of Ca suggests that a higher $T_{\rm eff}$ will raise [Ca/Fe]. It does, but an increase of 300 K increases [Ca/Fe] by only 0.02 dex. Since one seeks to raise [Ca/Fe] from -0.9 to $+0.4$, it is clear that no plausible change of $T_{\rm eff}$ (or log g and v_t) can be found. In view of the magnitude of the change and the rather similar behavior of Ca and Fe, it seems unlikely that even adaptations of theoretical model atmospheres will result in [Ca/Fe] $\simeq +0.4$. Perhaps, serious non-LTE effects are present; i.e., Lyman emission in lines and continuum overionizes Ca much more than Fe. This speculation, however, is unlikely to explain the low Sc abundance since the Sc abundance is based on Sc II lines. Observations at several different phases would be useful to test these speculations about the inadequacies of the analysis. If these are severe, they are remarkably unobtrusive.

4.2. *Nucleosynthesis and Other Factors*

RV Tau variables are identified as stars at or just beyond the terminal phases of evolution along the AGB (Gingold 1986). With $T_{\rm eff} = 6700$ K, IW Car may be identified as a post-AGB star. As such, the residual envelope may be contaminated with the products of H and He burning. The high C abundance is likely a product of He burning. (Nitrogen presumably also has a high abundance: two weak lines near 6423 and 6436 Å do suggest higher nitrogen abundances but the equivalent widths are not reliable.) Oxygen is also enriched relative to iron ([O/Fe] $\sim +0.7$) and relative to the initial [O/Fe] ($\simeq +0.4$) expected of a [Fe/H] $\simeq -1$ star. The additional O may also be a product of He burning. Addition of material with C/O $\sim$ 2–3 will transform the presumed initial mix into the observed one. Synthesis of sodium from Ne is possible through nuclear reactions that run concurrently with the ON-cycles, but the abundance [Na/Fe] $\simeq +1.4$ seems implausibly high for a product of transmutation from Ne.

Although nucleosynthesis may reasonably be invoked to account for the C, O, and (partially) the Na abundances, it fails as an obvious explanation for the unusual ratios such as S/Fe, Ca/Fe, and Zn/Fe. Examination of the now extensive set of abundance analyses for metal-poor dwarfs and giants shows no stars with the ratios found here for IW Car (Lambert 1989; Wheeler et al. 1989.) There is a slight similarity between IW Car and post-AGB stars having effective temperatures generally hotter than those of RV Tau variables. Table 5 compares the abundances of several elements in IW Car and three post-AGB stars with reported Fe abundances similar to that of IW Car.

The similarity is particularly strong between IW Car and HD 46703, but Ca is a glaring exception, with O, Zn, and Ba also providing notable exceptions. This similarity, even if incomplete, prompts a discussion of IW Car in terms of the explanation proposed to account for the post-AGB stars exhibiting more extreme Fe deficiencies than those of the stars in Table 4, say [Fe/H] $\simeq -4$ to -5 as obtained for HR 4049 (Lambert, Hinkle, & Luck 1988). Venn & Lambert (1990) drew

TABLE 5

CHEMICAL COMPOSITION OF IW CARINAE AND POST-AGB STARS

Quantity	IW Car	HD 47603[a]	HR 4912[b]	HR 7671[c]
[Fe/H]	-1.0	-1.7	-1.2	-1.1
[C/Fe]	$+1.4$	$+1.7$	0.0	-0.4
[O/Fe]	$+0.7$	$+1.6$	$+0.9$	-0.3
[S/Fe]	$+1.4$	$+1.3$	$+0.2$	$+0.2$
[Ca/Fe]	-0.9	$+0.7$	$+0.2$	$+0.4$
[Zn/Fe]	$+1.0$	$+0.4$	...	$+0.3$
[Ba/Fe]	-0.8	-0.2	-0.1	$+0.3$

[a] Luck & Bond 1984, Bond & Luck 1987, and McCarthy, Uglesich & Lambert 1994.

[b] Luck et al. 1983.

[c] Luck et al. 1990.

attention to the similarities between the composition of certain post-AGB stars and that of interstellar gas. Interstellar gas is highly depleted in those elements that condense into (or onto) grains at low temperature. This selective removal of elements results in abundance ratios not seen in normal stars. For example, the gas comprising the interstellar clouds toward ζ Oph has [S/Fe] $\sim +2.5$. The proposal is that the atmosphere of a post-AGB may be Fe-poor because Fe (and other) atoms have condensed into grains which have been removed from the gas now comprising the stellar photosphere (Lambert 1991; Bond 1991.) This idea received welcome support with van Winckel, Mathis, & Waelkens (1992) discovery of a normal Zn abundance for the very Fe-poor post-AGB star HD 52961; Zn does not easily condense into grains and is only very slightly depleted in interstellar gas.

To investigate the applicability of the proposal to IW Car, we compare the stellar abundances [X/H] and the depletions observed in the interstellar gas. We adopt those depletions measured for the principal cloud along the line of sight to ζ Oph to be representative of the interstellar depletions. This cloud at a heliocentric radial velocity of -15 km s^{-1} is especially well studied. Recent observations of weak ultraviolet lines obtained with the *Hubble Space Telescope* have provided new or improved estimates of the depletions $D(X/\mathrm{H})$ given here relative to the solar abundances. The depletions used here are taken from Cardelli (1994), Cardelli et al. (1991, 1993), Federman et al. (1993), and Morton (1975). Jenkins (1987, 1989) reviews the observational and theoretical data on elemental depletions in the interstellar gas.

The abundances [X/H] of IW Car and the interstellar depletions D(X/H) are well correlated (see Fig. 6). Calcium and aluminum are the most highly depleted of the many elements investigated in the ζ Oph cloud. This pair are similarly the pair showing the greatest deficiencies in IW Car. At the other extreme, zinc and sulfur are either slightly or not depleted at all in interstellar gas and in IW Car. Carbon and oxygen fit the trend in Figure 4 but are not included because the stellar abundances likely to be affected by internal nucleosynthesis and mixing. Sodium, also not plotted, with [Na/H] $\simeq +1.4$ but D(X/H) $= -0.9$ (Morton 1975; also see Cardelli et al. 1991 for new measurements of weak Na I lines), falls above the trend but sodium may also be a fresh product of nucleosynthesis. Three additional elements from Table 1 are not plotted in Figure 6: Sc, Ba, and Sm. Since interstellar depletions are generally correlated with the nebular condensation temperatures (see Cardelli 1994), we may estimate the expected depletions using condensation temperatures tabulated by Wasson (1985). Scandium has a higher condensation temperature than either Ca or Al and, hence, it is not surprising that [Sc/H] $\lesssim$ [Ca/H] for IW Car. Samarium and calcium are predicted to have very nearly identical condensation temperatures but [Sm/H] $\simeq -0.5$ when [Ca/H] $\simeq -2.0$. At first sight, this pairing seems at odds with the proposal that elements that condense at "high" temperatures should be underabundant by similar factors. One might suppose the explanation to be that IW Car was enriched in *s*-process elements during evolution along the AGB. Since [Sm/H] $\sim +1.5$ is not unusual for AGB stars, [Sm/H] $\simeq -0.5$ would then be expected, as observed. Wasson (1985) does not list a condensation temperature for Ba but one might suppose it to be similar to that of its fellow alkaline earth Ca. The observed [Ba/H] $\simeq -1.9$ seemingly confirms this supposition but this overlooks the *s*-process enrichment expected for post-AGB stars and apparently revealed by Sm. As noted above, the Sm abundance is considered to be of low weight because it is based on a single line. Until stellar abundances are derived for additional heavy elements and the expected depletions of Ba and the rare-earths like Sm are better understood, it is not profitable to interpret further the relative abundances of Ba and Sm.

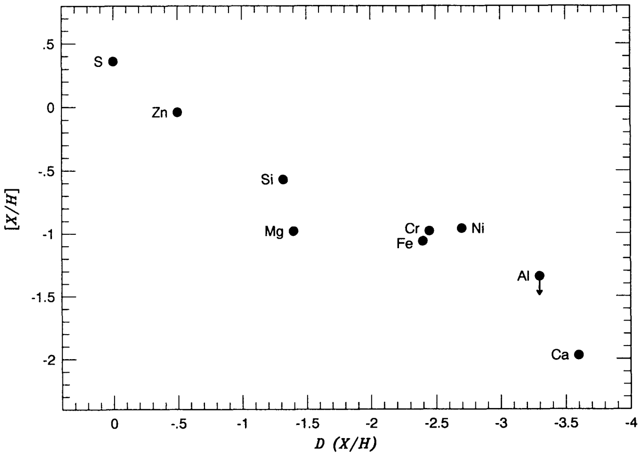

FIG. 6.—Stellar abundance [X/H] vs. the depletion D(X/H) observed in the diffuse clouds along the line of sight to ζ Oph.

Even if the measurement errors afflicting [X/H] and D(X/H) were all very small, the presence of scatter in Figure 6 does not necessarily invalidate the idea that IW Car's photosphere represents gas from which elements have been removed selectively by grain formation. Interstellar grains have endured harsh conditions in interstellar space since their formation in red giant winds and at other sites, and depletions existing at the site of grain formation (i.e., a red giant's wind) may have been modified; for example, the depletions depend on a cloud's velocity. Conditions in a red giant wind must vary with stage of evolution and from giant to giant. The initial stellar composition may not have been solar or a directly scaled modification of solar (i.e., [X/Fe] $\neq 0$); for example, even slightly metal-poor stars show [Mg/Fe] ≥ 0. Remarkable too is the fact that IW Car's present atmosphere is probably C rich (with C/O ≥ 1.0) and presumably the dust now forming consists of carbon grains, graphite, and silicon carbide, but the photospheric abundances correlate well with interstellar depletions in clouds where silicate grains are the primary component of the dust grains. In this connection, IW Car resembles the very much more Fe-poor post-AGB star HR 4049, also C-rich and even with a 11.3 μm emission feature attributed to SiC grains. This may suggest that these photospheric compositions were established while the stars were O-rich. Lloyd Evans (1985) points out that both oxygen-rich and carbon-rich RV Tauri stars (including IW Car) show the silicate emission feature at 9.7 μm. Possibly both types of grains form, as in nova V1370 Aql of 1982 in which the presence of 2500 Å absorption feature indicates the presence of amorphous carbon and the 9.7 μm feature indicates silicates (Snijders et al. 1987). These reservations, however, are almost irrelevant because the correlation displayed in Figure 6 is evidently strong. Since the correlation is not obviously attributable to nucleosynthesis or to initial stellar composition, we infer that it results from a selective change of composition caused by expulsion of dust grains from gas now comprising a major fraction of the stellar photosphere. The most depleted elements are those predicted to condense out at the highest temperatures in an expanding and presumably cooling flow.

Post-AGB stars such as the RV Tau variables must have a thin envelope in order to have evolved off the AGB. A mass $M_{\text{env}} \sim 10^{-3}\ M_{\odot}$ is expected to within a factor of ~ 3 (Schönberner 1983). An RV Tau's photosphere is a thin layer ($M_{\text{ph}} \simeq 10^{-6}\ M_{\odot}$; Mathis & Lamers 1992) atop the envelope. One presumes that pulsations driven from the envelope must result in some level of continuous mixing of the photosphere and envelope. In addition, mass loss from IW Car continues so that the photosphere is gradually receding into the envelope. These factors mean that IW Car's anomalous composition may extend over a mass of up to $M_{\text{env}} \sim 10^{-3}\ M_{\odot}$. The star's initial metallicity was approximately solar, as judged by the present abundances of S and Zn ([S/H] $\simeq +0.3$ and [Zn/H] $\simeq 0.0$); S and Zn should be neither depleted in dusty environments nor synthesized in the course of evolution along the AGB.

Separation of dust and gas may occur in the IW Car's past or present wind. The contemporary wind may be initiated as the gas density in the upper cool atmosphere is enhanced during a pulsation. Dust condensing out in the upper atmosphere is driven outward by radiation pressure. At a sufficiently low gas density, little of the remaining gas is dragged out by the grains. After removal of the dust, one supposes the gas now with an anomalous composition falls back and is mixed into the photosphere. The cycle of dust formation followed by separation of dust and gas may be repeated at each pulsation. Mathis & Lamers (1992), who investigate this process in the context of a steady wind off a post-AGB star show that a mass loss of order $\dot{M} \simeq 10^{-6}\ M_{\odot}\ \text{yr}^{-1}$ may result in a mass of the order of the photosphere ($M_{\text{ph}} \sim 10^{-6}\ M_{\odot}$) having anomalous abundances after 10–100 yr. The present mass loss rate for IW Car remains to be determined but $\dot{M} \simeq 10^{-6}\ M_{\odot}\ \text{yr}^{-1}$ is quite plausible. Since it is apparent that IW Car is an exception among the small sample of RV Tau variables whose compositions have been determined, its wind may be exceptionally efficient in effecting a clean separation of dust and gas and the return of the gas to the photosphere.

Evidence is accumulating that these post-AGB stars with extreme deficiencies of Fe and other metals are binaries (Waelkens & Waters 1993; Waters 1993). Perhaps, IW Car is also a binary. Mathis & Lamers (1992) discuss the capture of gas from a companion star with the dust-gas separation achieved in an accretion disk fed from the companion. This seems improbable for the reason discussed by Mathis & Lamers; the companion must also be highly evolved, which implies the initial masses of the two masses were very nearly equal. Perhaps, the accreted gas was ejected earlier by IW Car and stored in a circumbinary disk—from where the dust was ejected.

5. CONCLUDING REMARKS

Our analysis of IW Car shows a photospheric composition unlike that reported previously for other RV Tau variables. The composition appears to reflect that of gas from which easily condensable elements have condensed into dust grains and have been removed. This separation may occur in the present or recent stellar wind off IW Car. Clearly, there is much to be gained by analyzing a large sample of RV Tau (and related) stars. Of especial importance is a study of IW Car at several phases of its pulsation. A demonstration that the chemical composition is phase invariant would enhance confidence that systematic errors are small. It is also important to extend the abundance analysis to additional elements to explore further the correlation between the stellar abundances and interstellar depletions or nebular condensation temperatures. In particular, spectra in the blue are desired.

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