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ABUNDANCE ANALYSES OF THE FIELD RV TAURI VARIABLES: EP LYRAE, DY ORIONIS, AR PUPPIS, AND R SAGITTAE

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ABSTRACT

Analyses of the photospheric compositions of the four field RV Tauri stars, EP Lyr, DY Ori, AR Pup, and R Sge, indicate that to varying degrees they have experienced fractionation processes that have preferentially depleted their atmospheres of elements with high condensation temperatures. The depletion, as indicated by, for instance, [S/Fe], is greatest for DY Ori, [S/Fe] = 2.5, and least for R Sge, [S/Fe] = 0.9. The initial composition, presumably indicated by the sulfur abundance, was nearly solar for AR Pup, R Sge, and DY Ori, while it was about 0.6 dex less than solar for EP Lyr. This implies that the RV Tauri stars as a group may not be as metal-poor as previously thought—they are instead "metal-depleted." The field RV Tauri's are not halo stars, but probably belong to the thick disk. This brings to seven the number of type II Cepheids that show such a trend; the other three are IW Car and V1 in ω Cen, RV Tauri stars, and ST Pup, a W Virginis star.

The $^{12}C/^{13}C$ ratios for EP Lyr and DY Ori are 9 ± 1 and 6 ± 3, respectively, indicating that CN-cycled material has been mixed with their surface layers. This is consistent with the general consensus that RV Tau stars are in a post-AGB evolutionary stage. There is also evidence that EP Lyr has a stellar mass companion, but additional observations are required to calculate an orbit; hence, EP Lyr could be a link to the group of metal-depleted, high-latitude A–F supergiants, all of which are binaries.

Subject headings: stars: abundances — stars: AGB and post-AGB — stars: variables: other (RV Tauri)

1. INTRODUCTION

This is the second in a series of studies of the chemical composition of field RV Tauri variables. These are the high-luminosity members of the type II Cepheid class of pulsating variables; they are considered to be in an advanced evolutionary stage, most certainly at or beyond the He-core burning phase (Jura 1986). Their pulsation periods are in the 30–140 day range, and variations in periods as well as in the shapes of the light curves have been reported. The study of the chemical composition of these objects is very important as it may shed light on their evolutionary histories. The RV Tauri variable class is far from being a homogeneous group (Preston et al. 1963). Earlier spectroscopic attempts by Aliev (1967), Baird (1979), Yoshioke (1979), Luck & Bond (1984, 1989) do indicate that as a group they are relatively metal poor, but a comprehensive abundance study leading to a better understanding of these objects is still lacking.

Giridhar, Rao, & Lambert 1994 (Paper I) were the first to perform a detailed high-resolution abundance analysis of a field RV Tauri variable, IW Car, using a CCD detector. The principal novel result is that IW Car's abundance pattern shares some similarities with the high-latitude peculiar A and F supergiants that have been identified as post-AGB stars: their abundance patterns correlate with the elemental depletions in the interstellar medium, i.e., the high condensation-temperature elements are strongly depleted in their atmospheres (Venn & Lambert 1990; Van Winckel, Mathis, & Waelkens 1992; Van Winckel 1995). This complicates the interpretation of the abundances of the light elements. A star's metallicity, as, for example, measured by its iron abundance, may be considerably less than the true (original) metallicity. A better measure of the original metallicity may be provided by the sulfur (Venn & Lambert) and zinc (Van Winckel et al. 1992) abundances. This apparent metal deficiency needs to be recognized in an assessment of the C, N, and O abundances, which are the most sensitive indicators of internal nucleosynthesis (H and He burning) and dredge-up. In contrast to the results presented in Paper I, Gonzalez & Wallerstein (1994) found evidence for enhancement of the CNO elements due to evolution in the atmosphere of the star V1 in ω Cen (an RV Tauri in that globular cluster); while the low value of [Al/Fe][4] and the high value of [S/Fe] in this star imply some depletion, the large spread in [Fe/H] values among ω Cen RR Lyrae stars and giants (Norris & DaCosta 1995; Butler, Dickens, & Epps 1978) does not allow us to know its initial composition. This diversity of chemical compositions among the RV Tauri stars is not surprising, because the transformation of a normal stellar atmosphere to one largely free of those elements that have condensed onto dust grains is likely sensitive to several properties; for example, Van Winckel, Waelkens, & Waters (1995) show that the most metal-poor post-AGB stars are spectroscopic binaries.

The aim of this study is to continue the exploration of the diversity of chemical compositions of the field RV Tauri stars. As a representative sample of field RV Tauri's spanning a large range in [Fe/H] and differing in other ways (e.g., infrared excess), we selected EP Lyr, DY Ori, AR Pup, and R Sge for detailed spectroscopic study. Preston et al. (1963) categorized RV Tauri variables as types A, B, or C

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[4] Some of the Al deficiency may be due to non-LTE effects. Baumüller & Gehren (1996) discuss this possibility.

according to spectroscopic characteristics. Type A are metal-rich, type B are metal-poor with enhanced carbon, and type C are metal-poor without enhancement (Preston et al. 1963; Lloyd Evans 1974; Dawson 1979; Baird 1981). (The spectroscopic types should not be confused with the photometric designations RVa and RVb, which refer to constancy and variability of the mean magnitude on long timescales, respectively). Of our stars, R Sge is type A and DY Ori, AR Pup, EP Lyr (and IW Car) are of type B. EP Lyr and R Sge were selected from the list of field RV Tauri variables given by Cardelli & Howell (1989), who find that both stars exhibit CN molecular absorption during part of their pulsation cycles. A more recent study of these two stars was undertaken by Wahlgren (1992), who included them in his medium-resolution spectroscopic survey of field RV Tauri variables. We included DY Ori in our program because it has received very little attention in recent years, even though Lloyd Evans (1985) and Raveendran (1989) have drawn attention to the star's infrared excess. While the General Catalog of Variable Stars (GCVS; Kholopov 1985, 1987) lists DY Ori's RV Tauri variable type designation as uncertain, Schmidt, Chab, & Reiswig (1995), using more recent photometry, confirm its status as an RV Tauri variable. AR Pup is classified as carbon-rich by Lloyd Evans (1974). Gaposchkin, Brenton, & Gaposchkin (1943) noted some irregularities in the period and the shape of the light curve. AR Pup shows considerable infrared excess in the 12–25 μm range, larger than in other RV Tauri variables. Gehrz & Ney (1972) included AR Pup in their infrared survey of southern RV Tauri variables. Their observations indicate that AR Pup and IW Car have very similar infrared flux distributions. This implies that these two stars have had similar recent mass-loss histories. A remarkable feature of AR Pup is the exceptionally large but time-dependent linear polarization as reported by Raveendran & Rao (1988) implying light reflection off dust. R Sge belongs to RV Tauri A class that contains mostly G and K spectral types. The infrared flux for this object is quite small, though another RV Tauri A class star, U Mon, is known to have a large infrared excess. Wahlgren (1992) reported the star to be marginally metal-deficient. Finally, we summarize the general characteristics of the program stars in Table 1.

The spectrum of an RV Tauri variable can change dramatically during a pulsation cycle. The pulsation periods of our program stars are between 2 and 3 months. Therefore, we set out to observe these variables over a period of 1–2 yr in order to sample the pulsation cycle properly as well as obtain at least one spectrum of each star near minimum light. The atmosphere on an RV Tauri star is severely perturbed by the passage of a shock, whose effects are most intense during rising light and weakest during minimum light. Our eventual goal in these studies is to determine the degree of homogeneity in the population of field RV Tauri variables, separate the evolutionary effects from the as yet poorly understood dust-gas separation processes, and compare the field to the globular cluster RV Tauri variables.

2. OBSERVATIONS

Spectra were obtained over a period of about 1.5 yr with the McDonald Observatory 2.1 m telescope equipped with a Cassegrain echelle spectrograph and a Reticon 1200 × 400 pixel CCD (McCarthy et al. 1993). This instrument limits us to $m_v \sim 12$ for a desired S/N ~ 100 and a two-pixel resolution $\sim 60{,}000$ with exposure times near 60 minutes. A few spectra were also obtained at the CTIO 4 m and McDonald 2.7 m telescopes, both equipped with echelle spectrographs and CCD detectors. Sample spectra are presented in Figures 1 and 2.

The raw spectra were bias-subtracted, trimmed, flat-fielded to remove pixel-to-pixel variations, converted to one-dimensional spectra, and normalized to the continuum

TABLE 1

BASIC PARAMETERS OF THE PROGRAM STARS

Parameter	EP Lyr	DY Ori	AR Pup	R Sge
V[a]	9.96–10.92	11.3–12.2	9.1–10.1	8.9–9.8
$B-V$[a]	0.56–0.95	(0.80–1.05)	0.60–0.92	0.81–1.35
$E(B-V)$[b]	0.45	0.81	0.61	0.28
Spectral type[c]	A4Ib-G5P	...	F0I-II-F8I-II	G0Ib-G8Ib
$\langle T_{\rm eff}\rangle$[d]	6200	5900	6300	5000
Period (days)[e]	83.4	60.3	38.89	70.6
Galactic latitude (deg)	6.7	−3.4	−3.0	−9.8
$\|z\|$ kpc[f]	0.6	0.6	0.1	0.3
IR excess?[g]	No	Yes	Yes	Yes
Spectrascopic group[h]	B	B	B	A
Photometric type[h]	RVa	?	RVb	RVb

[a] Sources of photometry are as follows: EP Lyr, Zsoldos 1995; DY Ori, Schmidt, Chab, & Reiswig 1995; AR Pup, Pollard et al. 1996; R Sge, Zsoldos 1993. For DY Ori, the $V-R$ color is given rather than $B-V$.

[b] $E(B-V)$ was estimated for EP Lyr, DY Ori, and AR Pup using the charts of Neckel & Klare 1980. The estimate for R Sge is based on the H I maps of Burstein & Heiles 1982.

[c] The spectral types are from the GCVS.

[d] The mean temperature estimates are based on our Fe line analysis and the photometry.

[e] The pulsation period estimate of AR Pup is from Pollard et al. 1996; it is difficult to distinguish the primary and secondary minima for this star, so the time between minima is given.

[f] The height above the galactic plane was estimated using the period-luminosity relation of Gonzalez (1994) assuming fundamental mode pulsation, mass = 0.5 $M_\odot$, and mean temperatures estimated from the colors.

[g] These are stars for which a significant flux has been measured by *IRAS* (Raveendran 1989).

[h] The spectroscopic groups are those defined by Preston et al. 1963. The photometric types are based on long-term photometric behavior.

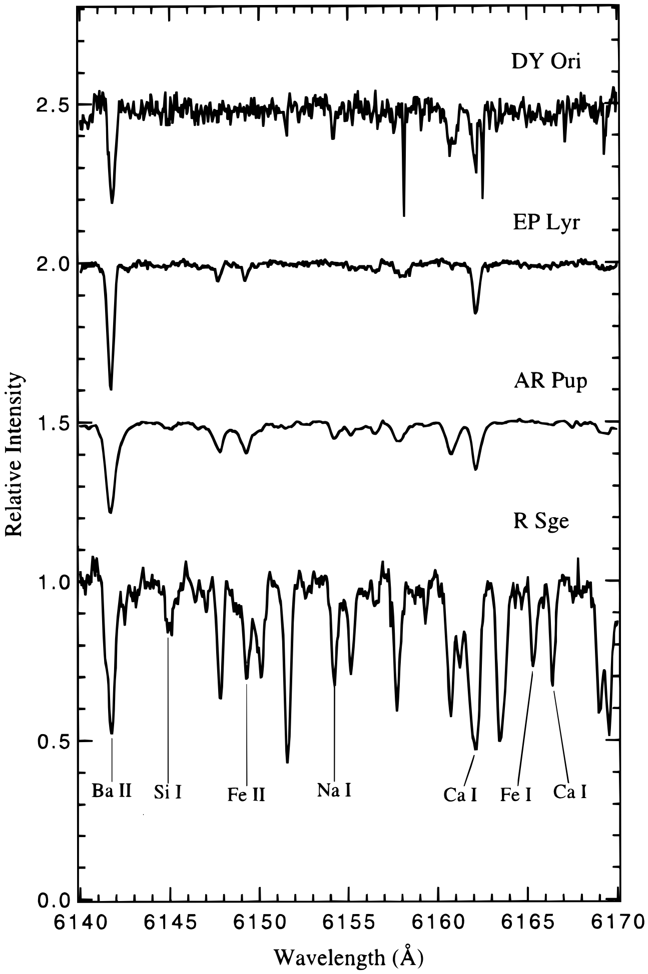

FIG. 1.—Sample spectra of the program stars. The spectra have been shifted to the rest frame, normalized to the continuum, and shifted vertically. These samples are from 1995 December 9, 1995 June 10, 1992 May 23, and 1994 July 29, for DY Ori, EP Lyr, AR Pup, and R Sge, respectively.

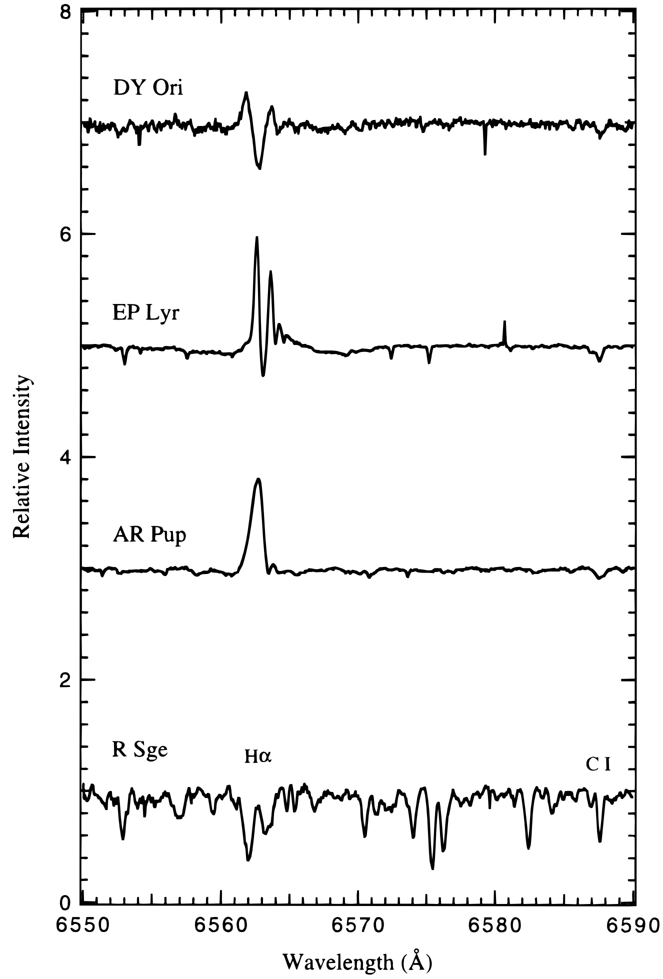

FIG. 2.—Sample spectra showing the Hα and C I lines. All else as in Fig. 1.

using the standard programs in the ECHELLE package of NOAO IRAF. The spectra were wavelength-calibrated with Th-Ar hollow-cathode lamp spectra taken immediately following each observation. We also obtained spectra of hot, fast rotating stars in order to remove the telluric absorption lines from the object spectra.

The S/N ratios average near 140 for EP Lyr, 50 for DY Ori, 250 for AR Pup, and 120 for R Sge, which are sufficiently high to perform fine abundance analyses on each of these stars. The equivalent widths (W_λ) of the absorption lines were measured using the methods available in the SPLOT package of NOAO IRAF; most estimates of W_λ were made by summing the area under the lines, but Gaussian function fitting was employed for those cases where there was some blending. Whenever possible, we measured only the cleanest lines in the spectra and avoided strong lines ($W_\lambda > 200$ mÅ) unless the line was essential in estimating the abundance of a given element. There is significant overlap between adjacent orders in some spectra (especially for $\lambda < 6500$ Å), which allowed us to combine overlapping regions to increase the S/N and identify artifacts in the spectra. The typical uncertainty of an W_λ measurement of a moderate strength line is $\pm$ 2–3 mÅ for EP Lyr, $\pm$ 8–10 mÅ for DY Ori, 2–3 mÅ for AR Pup, and $\pm$ 4–5 mÅ for R Sge. These uncertainties were reduced in those cases where a running average was applied to unblended lines; this was most often done in the spectra of EP Lyr and DY Ori.

3. ABUNDANCE ANALYSIS

3.1. *General Description of the Spectra*

Like other RV Tauri variables EP Lyr, DY Ori, AR Pup, and R Sge display emission in the hydrogen Balmer lines during most of the pulsation cycle, but it is particularly intense during rising light. We note in Table 2 the occurrences of Balmer emission in our spectra. During rising light the atmosphere of an RV Tauri variable is severely perturbed by the passage of a shock wave, which often results in severe distortions of the Balmer lines and "line doubling" for some metal lines (Gonzalez & Wallerstein 1994). For this reason the abundances derived during rising light are not expected to be reliable. We will follow the recommendations of Gonzalez & Wallerstein concerning their analysis of V1 in ω Cen and avoid the pulsation phases near rising light. This selection criterion resulted in the elimination of over half the spectra originally obtained in the course of this study; the final list of spectra selected for abundance analysis are given in Table 2.

As can be seen in Figures 1 and 2 EP Lyr, DY Ori, and AR Pup have weaker metal lines than R Sge. Also notable are the relative strengths of the carbon line; it is strong relative to the other metals in the spectra of EP Lyr, DY

TABLE 2

STELLAR PARAMETERS OF THE RV TAURI STARS DERIVED FROM THE Fe LINE ANALYSIS

OBJECT (UT Date)	PULSATION PHASE	MODEL $T_{\rm eff}$, log g, [Fe/H]	ξ_t (km s^{-1})	Fe I log ϵ	Fe I N	Fe II log ϵ	Fe II N	COMMENTS
EP Lyr								
1994 Jun 25–27	0.44	7000, 2.0, −1.5	1.3	5.92 ± 0.01	47	5.93 ± 0.03	20	No Hβ emission, no C_2, complex Hα profile
1995 Jun 10 and 12......	0.64	5750, 1.2, −1.5	2.9	5.61 ± 0.02	59	5.61 ± 0.04	10	Hβ asymmetry, moderate Hα emission, C_2
1996 Mar 3	0.83	5500, 0.9, −1.5	3.5	5.54 ± 0.02	31	5.54 ± 0.02	12	Weak Hα emission, CH, CN, C_2
DY Ori								
1995 Dec 9 and 10	0.35	6000, 1.5, −2.0	3.5	5.20 ± 0.05	9	5.15 ± 0.06	2	Weak Hα emission, C_2
AR Pup								
1992 May 23	0.92	6000, 1.5, −1.0	2.0	6.63 ± 0.06	19	6.64 ± 0.07	6	strong, narrow Hα emission, broad lines
R Sge								
1992 May 22	0.81	4500, −0.5, −0.5	4.5	6.86 ± 0.03	23	7.01 ± 0.20	6	No Hα emission, strong lines
1994 Jun 24	0.75	5750, 0.0, −0.5	3.8	7.07 ± 0.03	17	7.08 ± 0.08	3	No Hα emission, asymmetry, lines, weak C_2
1994 Jul 29	0.25	4250, −0.5, −0.5	4.5	6.75 ± 0.04	16	6.75 ± 0.16	2	No Hα emission
1995 Jun 12	0.81	5750, 0.0, −0.5	4.5	7.19 ± 0.03	10	7.14 ± 0.07	3	No Hβ emission

NOTES.—The pulsation phases for EP Lyr and R Sge were calculated using the period estimates of Zsoldos 1995 and Zsoldos 1993, respectively. The phases for DY Ori were estimated from the photometric observations of Schmidt et al. 1995; the pulsation phase of AR Pup was calculated using the half period (38.89 days) estimated by Pollard et al. 1996. In all cases, phase zero corresponds to minimum light in the V band. The expression ξ_t is the microturbulent velocity parameter, and log ϵ is the mean abundance relative to H (with log $N_{\rm H}$ = 12.00.). Also listed are the standard deviations of the means, calculated using $\sigma/(N)^{1/2}$.

Ori, and AR Pup, and weak in the spectrum of R Sge, even though it is more metal-rich. The Hα emission also differs among the four stars; it is always in emission with little change in intensity in the spectra of AR Pup, while the profile varies enormously with phase in the other variables. Measurement of the absorption lines in the spectra of EP Lyr, DY Ori, and AR Pup are straightforward. Being a relatively cooler star the spectrum of R Sge is very crowded with lines, making an abundance analysis more difficult.

3.2. *Model Atmosphere Selection and Fe Abundances*

The method of analysis we have chosen follows that employed in Paper I. We use the ATLAS (Kurucz 1993) model atmospheres, rather than the MARCS atmospheres (Gustaffson et al. 1975) used in Paper I, but the differences are small (<0.1 dex). The oscillator strengths, or *gf*-values, for the Fe I lines are from the compilation of Lambert et al. (1996, Table A1), and the Fe II *gf*-values are a compilation of recent laboratory measurements supplemented with the list of Giridhar & Ferro (1995). The W_λ's, *gf*-values, and model atmospheres were used as input to an updated version of the LTE line-analysis program MOOG (Sneden 1973), which calculates the abundance for each spectral line individually or produces a synthetic spectrum for a region of the spectrum.

Since the light and color curves of RV Tauri's do not always repeat precisely from one cycle to the next, and since RV Tauri's do not in general have extensive photometric coverage, we will base the temperature estimates for the abundance analyses on the Fe lines for EP Lyr, AR Pup, and R Sge and on the photometric observations for DY Ori.

3.2.1. *Ep Lyr*

Our analysis is based on the spectra from 1994 June, 1995 June, and 1996 March obtained near primary and secondary minima. Spectra obtained on different dates during the same run of 3 or 4 days duration were combined for analysis . We used the Fe I and Fe II lines to estimate $T_{\rm eff}$, log g, and the microturbulent velocity parameter, ξ_t: $T_{\rm eff}$ was chosen so that there is no correlation between the Fe I abundances, log ϵ(Fe I), and the lower excitation potential, χ_1; log g was estimated by equating log ϵ(Fe I) and log ϵ(Fe II); ξ_t was estimated by requiring that there be no correlation between log ϵ(Fe I) and W_λ. We list the results of the Fe-line analysis in Tables 2 and 3 along with the *gf*-values and lower excitation potentials. The mean value of log ϵ(Fe) in the atmosphere of EP Lyr is 5.73 ± 0.08, where the uncertainty is the standard deviation of the mean calculated from the three abundance estimates listed in Table 2.

The uncertainty in $T_{\rm eff}$ is determined from the sensitivity of the abundance versus lower excitation potential correlation to changes in temperature: the uncertainty is $\Delta T_{\rm eff} \simeq \pm 125$ K for all three groups of Fe I lines. To calculate the uncertainties in the other parameters, we need to know the sensitivities of the Fe I, II abundance estimates to changes in the atmospheric parameters (Table 4). Combining the results of Tables 2 and 4 and neglecting possible non-LTE effects, we estimate the uncertainty in log g to be about ±0.1 to 0.15 dex. The uncertainty in ξ_t is about ±0.2 km s^{-1}. Given these estimates and the numbers in Table 4, we estimate that the uncertainty in log ϵ(Fe) is ±0.10 to 0.12 dex.

The Fe abundance derived for the 1994 June spectra, log ϵ = 5.92, is larger than that of the 1995 June, log ϵ = 5.61, and 1996 March, log ϵ = 5.4, spectra. One would not expect the Fe abundance in the atmosphere of an RV Tauri star to change with phase (see § 4.2, however). While the difference might be accounted for by the uncertainties in the Fe abundance estimates, this seems unlikely since the estimate for the 1994 June spectra differs by more than two standard deviations from the 1995 June and 1996 March spectra, which have the same Fe abundances to within the uncertainties. The atmospheric parameters of EP Lyr in 1994 June are very different from those in 1995 June or 1996 March. Not only was EP Lyr about 1500 K hotter in 1994 June, but the surface gravity was about an order of magni-

TABLE 3

INDIVIDUAL ABUNDANCE RESULTS FOR EP LYRAE USING THE MODEL ATMOSPHERES IN TABLE 2

SPECIES, log $\epsilon_{\odot}$ WAVELENGTH (Å)	Low E.P. (eV)	log *gf*	W_{λ}(mÅ), log ϵ 1994 Jun 25–27	1995 Jun 10 and 12	1996 Mar 3
C I, 8.71					
4770.00......	7.48	−2.29	35, 8.14	...	30, 8.05
4775.88......	7.49	−2.15	38, 8.06	...	63, 8.44
4817.37......	7.48	−2.51	...	17, 8.04	25, 8.16
4932.07......	7.68	−1.77	70, 8.28	93, 8.71	80, 8.47
5052.15......	7.68	−1.51	100, 8.42	82, 8.31	...
5380.32......	7.68	−1.76	68, 8.25	80, 8.54	73, 8.38
5551.55......	8.64	−2.03	...	15, 8.55	...
5794.45......	7.94	−2.83	...	17, 8.80	...
6010.66......	8.64	−2.02	...	13, 8.48	...
6012.23......	8.66	−2.30	...	6.3, 8.44	...
6014.85......	8.64	−1.71	...	23, 8.49	...
6397.98......	8.77	−1.77	...	7.0, 8.07	...
6413.55......	8.77	−2.00	16, 8.48	...	...
6587.62......	8.53	−0.94	62, 8.09	45, 8.07	...
6611.35......	8.85	−1.84	10, 8.15	...	...
6663.01......	8.85	−1.80	...	25, 8.84	...
6671.82......	8.85	−1.66	22, 8.37	...	...
6674.11......	8.85	−2.25	11, 8.61	7.0, 8.63	...
6683.95......	8.85	−2.15	10, 8.46	...	...
6828.12......	8.54	−1.28	25, 7.83	...	...
7111.45......	8.64	−1.32	50, 8.40	55, 8.70	42, 8.48
7113.17......	8.64	−0.92	44, 7.90	75, 8.57	...
7115.19......	8.64	−0.90	...	75, 8.54	...
7116.99......	8.65	−1.08	...	52, 8.43	...
7476.15......	8.77	−1.86	17, 8.40	...	...
7483.41......	8.77	−1.59	18, 8.16	...	...
N I, 7.97					
7442.23......	10.23	−0.31	21, 7.55	...	...

NOTE.—Table 3 can be found in the AAS CD-ROM, Vol. 7. Only part of the first page is shown here for form and content.

tude greater. This range in the observed surface gravity over a pulsation cycle seems too large, but a Baade-Wesselink analysis combining photometric and velocity data will be required in order to verify the spectroscopic gravity estimates.

While there is little evidence of a significant temperature dependence on abundance derived using LTE analyses in the temperature range observed for EP Lyr, Lambert et al. (1995) and Gonzalez & Lambert (1996) give some tentative evidence for a gravity-dependent non-LTE effect in LTE abundance analyses of low surface gravity stars. For instance, Gonzalez & Lambert showed that for the F supergiant α Per, an LTE Fe-line abundance analysis results in an underestimate of the Fe abundance relative to the dwarfs in the cluster by about 0.4 dex. Finally, the difference might result from the passage of the shock through the atmosphere (see § 3.3).

3.2.2. *AR Pup*

Of the six spectra of AR Pup obtained by us, only one, obtained at CTIO on 1992 May 22, is of sufficient quality for an abundance analysis. Using measurements of 19 Fe I and six Fe II lines (Table 5) and the model atmosphere in Table 2, we estimate $T_{\rm eff} = 6000 \pm 250$ K, $\log g = 1.5 \pm 0.3$ cm s^{-2}, $\xi_t = 2.0 \pm 0.4$ km s^{-1}, and [Fe/H] $= -0.87 \pm 0.09$.

3.2.3. *R Sge*

Four spectra of R Sge are listed in Table 2 along with the model atmosphere parameters and resultant Fe abundances. The mean value of [Fe/H] for these four spectra is −0.50, in agreement with Wahlgren's (1992) estimate. We list the individual measurements in Table 6. The uncertainties in $T_{\rm eff}$, log *g*, and ξ_t for the 1992 May 22 spectrum are ±150 K, ±0.3 cgs, ±0.70 km s^{-1}; the uncertainties for the 1994 June 24 are the same except for ξ_t, which is 0.30 km s^{-1}; the 1994 July 29 and 1995 June 12 spectra have larger uncertainties in $T_{\rm eff}$ (±200 and ±250 K), but uncertainties in log *g* and ξ_t similar to the 1994 June 24, spectrum. Using these estimates, we calculate the uncertainty in the mean value of [Fe/H] to be ±0.11.

3.2.4. *DY Ori*

There are a sufficient number of Fe lines available on the 1995 December 10 spectrum of DY Ori to estimate $T_{\rm eff}$, log *g*, and ξ_t; this spectrum was obtained just after maximum light. The values of the atmospheric parameters (Table 2) derived for this spectrum are similar to the values obtained for EP Lyr and AR Pup. DY Ori is the most iron-poor of the four RV Tauri's, with [Fe/H] $= -2.3 \pm 0.11$. The uncertainty in [Fe/H] was estimated assuming uncertainties in $T_{\rm eff}$, log *g*, and ξ_t of ±250 K, ±0.2 cm s^{-2}, and ±0.5 km s^{-1} and using the results of Table 4.

3.3. *Other Elements*

The abundances of the other elements are based primarily on laboratory log *gf*-values, which are either from Paper I or taken from an up-to-date database maintained by R. E. Luck at Case Western Reserve University (private communication). The individual line measurements and abundances for EP Lyr, AR Pup, R Sge and DY Ori are listed in Tables 3, 5, 6, and 7, respectively; the mean abun-

TABLE 4

SENSITIVITIES OF CALCULATED ABUNDANCES TO CHANGES IN THE MODEL ATMOSPHERE PARAMETERS FOR EP LYRAE AND R SAGITTAE

T_{eff}, log g, [Fe/H] Line, λ(Å), W_λ(mÅ)	$\Delta T_{eff} = +250$ K	$\Delta \log g = +0.5$	$\Delta \xi_t = +0.5$ km s^{-1}	$\Delta W_\lambda = +10\%$
		EP Lyr		
7000, 2.0, −1.5				
C I, 5380.32, 68	+0.02	+0.07	−0.03	+0.09
Ca I, 5588.76, 22	+0.18	−0.06	−0.02	+0.06
Ti II, 4589.92, 56	+0.10	+0.15	−0.10	+0.12
Ba II, 5853.69, 19	+0.23	+0.04	−0.03	+0.05
Fe I, 5001.87, 32	+0.17	−0.04	−0.04	+0.07
Fe I, 5328.05, 70	+0.21	−0.01	−0.21	+0.19
Fe II 5234.63, 74	+0.03	+0.18	−0.24	+0.20
5750, 1.0, −1.5				
C I, 5380.32, 80	−0.24	+0.16	−0.05	+0.09
Ca I, 6162.18, 60	+0.07	−0.02	−0.03	+0.08
Ti II, 5336.79, 43	+0.02	+0.15	−0.02	+0.06
Ba II, 5853.69, 63	+0.13	+0.11	−0.05	+0.08
Fe I, 5005.72, 21	+0.04	−0.02	−0.01	+0.05
Fe I, 5123.73, 35	+0.15	−0.03	−0.02	+0.05
Fe II, 5234.63, 103	−0.05	+0.17	−0.11	+0.16
		R Sge		
4500, −0.5, −0.5				
S I, 6052.66, 85	−0.40	+0.18	−0.07	+0.11
Ca I, 6169.04, 120	+0.31	−0.05	−0.05	+0.08
Sc II, 6604.60, 88	−0.04	+0.21	−0.02	+0.06
Ba II, 5853.69, 210	+0.05	+0.19	−0.15	+0.17
Fe I, 6165.73, 93	+0.03	−0.03	−0.03	+0.07
Fe I, 6710.31, 156	0.00	0.00	−0.05	+0.09
Fe II, 6416.92, 134	−0.23	+0.23	−0.10	+0.13
5750, 0.1, −0.5				
C I, 6587.62, 98	−0.12	+0.18	−0.05	+0.10
Si I, 6721.84, 45	+0.12	+0.01	−0.02	+0.06
Fe I, 5775.07, 54	+0.16	+0.01	−0.03	+0.06
Fe I, 6065.48, 170	+0.25	+0.01	−0.19	+0.18
Fe II, 6369.45, 131	+0.05	+0.18	−0.10	+0.12

dances are given in Table 8. The uncertainties of the $[X/H]$ values listed in Table 8 were estimated using the data in Table 4 (Table 4 was calculated for EP Lyr and R Sge, but it is also applicable to the other RV Tauri stars).

The oxygen abundance for DY Ori was calculated from the O I triplet lines near 7770 Å in the 1995 January 25 spectrum (see Table 7). The atmospheric parameters corresponding to this spectrum were estimated in an indirect way, given the absence of detectable Fe I, II lines: we measured three C I and three S I lines and adjusted T_{eff} and ξ_t so that the derived C and S abundances were the same as those estimated for the 1995 December 9 and 10 spectra; we set log g to 1.0 cgs; we derived $T_{eff} = 5750$ K and $\xi_t = 4.5$ km s^{-1}. Since these lines are known to suffer from non-LTE effects, we applied the corrections of Takeda (1992) to these lines; we give the corrected mean oxygen abundance of DY Ori in Table 8. The radial velocities of the spectra of DY Ori were such that the two [O I] lines near 6300 Å were contaminated with atmospheric emission, rendering them useless for estimating the oxygen abundances.

The aluminum abundance of EP Lyr is based on a strong resonance line between the Ca II H and K lines; therefore, it should be considered highly uncertain. However, of the five field RV Tauri stars, EP Lyr has by far the most accurate and complete set of abundance estimates. There was no evidence of lithium in any of the spectra.

As will be shown below, knowledge of the sulfur and zinc abundances is critical for the proper interpretation of the abundance patterns seen in the RV Tau stars. The zinc abundance could not be estimated for AR Pup, because the one zinc line in our spectrum, at 6362 Å, is contaminated by atmospheric [O I] emission. This line is free of contamination by [O I] emission in the spectrum of R Sge, but the greater metallicity of this star makes an accurate measurement of its equivalent width more difficult due to the greater density of absorption lines in this spectral region.

As was found for the Fe line abundances of EP Lyr (see § 3.2.1), the abundances of the other elements also appear to vary with phase; the magnitude of the effect does not appear to depend on the atomic species. The most likely cause of this effect is the alteration of overlying layers by passage of the shock front (or the underlying layers, depending on the phase of the spectrum), which may significantly alter the continuous opacity.

3.4. *Molecular Lines*

Molecular lines are present in the spectra of EP Lyr, DY Ori, and R Sge during at least part of their pulsation cycles. As we have indicated in the comments column of Table 2, absorption lines of C_2 and CN are apparent in the spectra of these three variables near minimum light.

The CN lines near 8000 Å are used to estimate the $^{12}C/^{13}C$ ratio using spectrum synthesis methods; the line list was provided to us by J. A. Brown; its derivation is described in Gilroy & Brown (1991). We synthesized the spectral region spanning 7995 to 8015 Å in the 1996 March

TABLE 5

Individual Abundance Results for the 1992 May 22 Spectrum of AR Puppis Using the Model Atmosphere Listed in Tables 2

Species, log $\epsilon_{\odot}$ Wavelength (Å)	Low E.P. (eV)	log *gf*	W_{λ}(mÅ), log ϵ
C I, 8.71			
5957.56	8.64	−2.99	11.3, 9.35
5963.99	8.64	−2.64	10.9, 8.98
6010.66	8.64	−2.02	20.0, 8.69
6012.23	8.66	−2.30	7.8, 8.50
6587.62	8.53	−0.94	82.0, 8.59
6674.11	8.85	−2.25	5.2, 8.44
O I, 8.97			
6300.23	0.00	−9.75	67.9, 9.08
6363.88	0.02	−10.25	34.4, 9.15
Na I, 6.28			
6154.23	2.10	−1.57	19.6, 6.13
Mg I, 7.67			
5711.10	4.34	−1.68	35.0, 6.64
Si I, 7.40			
5708.41	4.95	−1.47	28.7, 6.87
5772.26	5.08	−1.78	25.0, 7.22
6125.03	5.61	−1.51	11.9, 7.03
6145.02	5.61	−1.48	9.9, 6.91
S I, 7.38			
6052.68	7.87	−0.63	62.3, 7.66
6743.58	7.86	−0.70	68.0, 7.80
6757.16	7.87	−0.29	104.0, 8.01
Ca I, 6.37			
5588.80	2.52	0.36	47.9, 4.66
5594.47	2.52	0.10	52.5, 4.99
5598.49	2.52	−0.09	49.6, 5.13
6162.18	1.90	−0.09	70.7, 4.87
6717.69	2.71	−0.52	29.5, 5.35
Sc II, 3.43			
5526.55	1.77	−0.13	27.8, 1.11
6604.60	1.36	−1.53	8.2, 1.44
Fe I, 7.50			
5554.90	4.55	−0.38	43.3, 6.85
5717.83	4.28	−0.98	13.1, 6.48
5859.57	4.55	−0.64	46.8, 7.16
5862.35	4.55	−0.36	28.9, 6.54
6024.06	4.55	−0.06	46.5, 6.57
6056.01	4.73	−0.40	17.1, 6.45
6065.49	2.61	−1.53	67.4, 6.55
6078.48	4.79	−0.32	13.4, 6.29
6200.31	2.61	−2.41	20.6, 6.56
6230.74	2.56	−1.28	89.4, 6.64
6252.57	2.40	−1.72	53.3, 6.29
6393.61	2.43	−1.65	87.2, 6.83
6411.66	3.65	−0.47	43.2, 6.06
6419.95	4.73	−0.09	57.1, 6.94
6421.35	2.28	−2.01	67.0, 6.68
6430.85	2.18	−2.01	77.6, 6.76
6592.91	2.73	−1.47	57.6, 6.41
6752.71	4.64	−1.20	10.3, 6.88
6806.86	2.73	−3.21	10.4, 7.10
Fe II, 7.52			
5534.83	3.25	−2.77	108.0, 6.90
6084.10	3.20	−3.80	46.1, 6.74
6369.46	2.89	−4.19	25.7, 6.44
6383.72	5.55	−2.14	17.9, 6.68
6416.92	3.89	−2.68	57.9, 6.46
6432.68	2.89	−3.58	72.9, 6.63
Ni I, 6.23			
6767.78	1.83	−2.17	11.6, 4.93
Ba II, 2.39			
5853.68	0.60	−1.00	126.0, 2.13

3 and 1995 January 25, spectra of EP Lyr and DY Ori, respectively. The spectrum of EP Lyr has a S/N ratio of about 150 at 8000 Å. Since this region of the spectrum is contaminated with telluric lines, we devided the spectrum of EP Lyr with that of a hot star after correcting for the different airmasses. The same atmospheric parameters used in the Fe-line analysis (Table 2) were also used in synthesizing the CN lines. The Gaussian smoothing of the synthetic spectrum, radial velocity shift of the observed spectrum, and C and N abundances were adjusted until the fit appeared close upon visual inspection (Fig. 3). Three synthetic spectra were generated with $^{12}C/^{13}C$ ratios of 4, 8, and 16. The best fit is obtained with a $^{12}C/^{13}C$ ratio of 9 ± 1 for EP Lyr; the quoted uncertainty is due entirely to the uncertainties in the strengths of the $^{13}C^{14}N$ lines, given that the $^{12}C^{14}N$ line strengths are very well constrained by the observations. The carbon and nitrogen abundances required to reproduce the observed CN line strengths were each about 0.5 dex greater than derived from the atomic lines. Some of this discrepancy can be accounted for by the uncertainties quoted in Table 8 for carbon and nitrogen, and the remainder can be eliminated if the temperature for the model atmosphere is reduced by about 200 K.

The $^{12}C/^{13}C$ ratio for DY Ori is derived from the 1995 January 25 spectrum. Just as in our analysis of the oxygen abundance for this spectrum, here we also adopted $T_{\rm eff} = 5750$ K and $\xi_t = 4.5$ km s^{-1}. Following the same procedure described above, we estimate the value of $^{12}C/^{13}C$ for DY Ori to be 6 ± 3.

3.5. *Abundance Patterns*

We plot in Figures 4 and 5 the abundances of the RV Tauri stars, ST Pup, and V1 in ω Cen against the condensation temperature, $T_{\rm cond}$, which is defined as the temperature at which half of a particular element in a gaseous environment condenses onto grains. We have adopted the values of $T_{\rm cond}$ given by Wasson (1985) for a solar abundance mix at a pressure of 10^{-4} atm, the pressure at which the data are most complete, supplemented by the oxygen-rich gas calculations for C, N, and O of Field (1974). The [*X*/H] diagrams can be divided into two broad categories: (*a*) those like EP Lyr with a single slope, and (*b*) those like

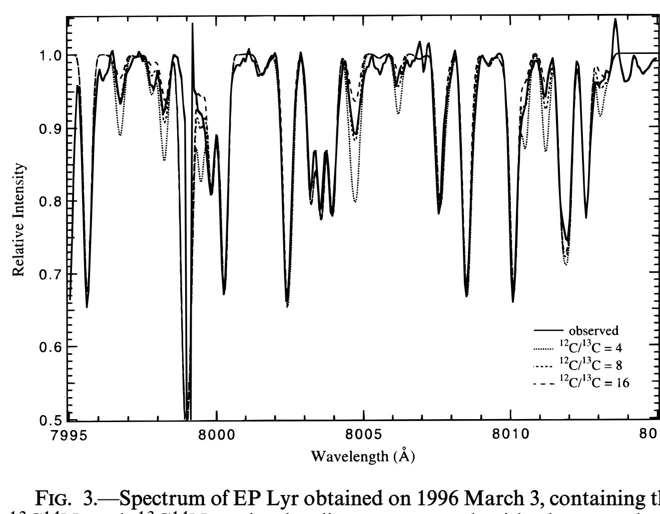

FIG. 3.—Spectrum of EP Lyr obtained on 1996 March 3, containing the $^{12}C^{14}N$ and $^{13}C^{14}N$ molecular lines superposed with three synthetic spectra with different values of $^{12}C/^{13}C$. The observed spectrum has been divided by a properly scaled hot star spectrum to remove telluric lines. The feature at 7999 Å is a defect in the observed spectrum. All the significant absorption lines in the figure are due to CN. Based upon visual inspection of this figure the $^{12}C/^{13}C$ ratio in EP Lyr is 9 ± 1.

TABLE 6

INDIVIDUAL ABUNDANCE RESULTS FOR R SAGITTAE USING THE MODEL ATMOSPHERES IN TABLE 2

SPECIES, log $\epsilon_{\odot}$ WAVELENGTH (Å)	Low E.P. (eV)	log *gf*	W_{λ}(mÅ), log ϵ 1992 May 22	1994 Jun 24	1994 Jul 29	1995 Jun 12
C I, 8.71						
6001.12	8.64	−2.07	...	24, 8.46	...	...
6010.66	8.64	−2.02	...	23, 8.39	...	...
6587.62	8.53	−0.94	...	98, 8.20	...	...
O I, 8.97						
6300.23	0.00	−9.75	133, 8.04	...	162, 8.17	...
6363.88	0.02	−10.25	...	...	74, 8.11	...
Na I, 6.28						
6154.23	2.10	−1.57	104, 6.21	45, 6.42	131, 6.14	nodata
Si I, 7.40						
6125.03	5.61	−1.51	86, 7.43	42, 7.56	...	...
6145.02	5.61	−1.48	97, 7.51	51, 7.64	...	...
6721.84	5.56	−1.26	101, 7.20	45, 7.29	...	...

NOTE.—Table 6 can be found in the AAS CD-ROM, Vol. 7. Only part of the first page is shown here for form and content.

AR Pup with a sudden break in the slope at some value of $T_{\rm cond}$, usually near 1000 K. The possible mechanism responsible for these distinct patterns will be discussed in § 4.2.

For the field RV Tauri's and ST Pup the abundances are well correlated with $T_{\rm cond}$, especially for elements with $T_{\rm cond} > 1000$ K; the stars have nearly solar S and Zn but very low Ca and Fe abundances. The depletions display a very shallow correlation with $T_{\rm cond}$ in the case of V1 in ω Cen. Even the two moderately Fe-poor stars, AR Pup and R Sge, show strong correlations of [X/H] with $T_{\rm cond}$. Examination of Table 8 reveals that both stars have a sulfur

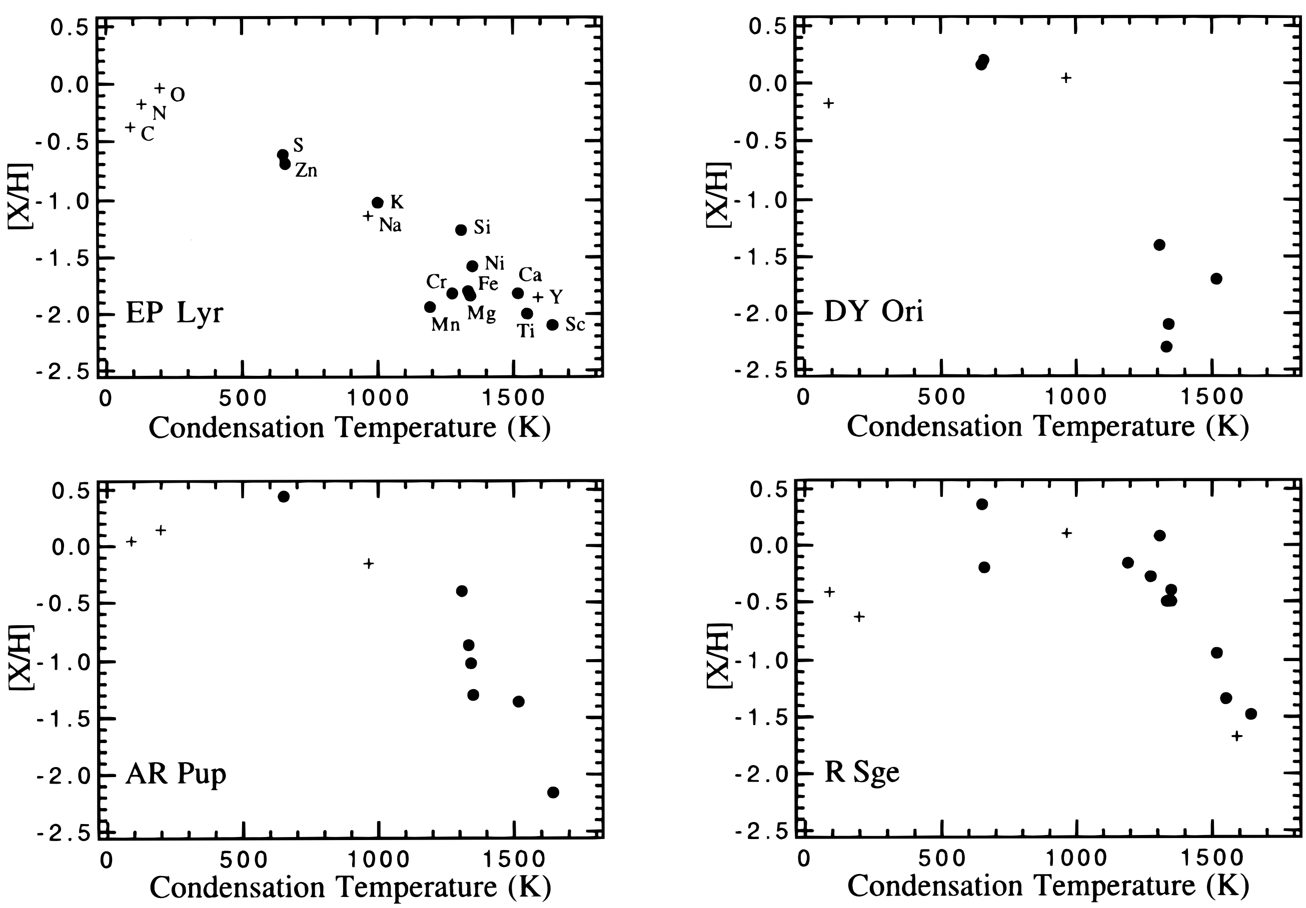

FIG. 4.—Abundances, [X/H], of the four RV Tauri stars in this study vs. the condensation temperature, $T_{\rm cond}$. The plus signs represent those elements whose abundances might be affected by dredge-up (C, N, O, Na, Y). The condensation temperatures have been calculated by Wasson (1985) assuming a solar mix and a pressure of 10^{-4} atm. Except for Zn (in AR Pup and R Sge) and Y (in R Sge), only those abundances derived for elements represented by more than one spectral line are shown.

TABLE 7

INDIVIDUAL ABUNDANCE RESULTS FOR THE 1995 DECEMBER 9 AND 10 SPECTRA OF DY ORIONIS

Species log $\epsilon_{\odot}$ Wavelength (Å)	Low E.P. (eV)	log *gf*	W_{λ}(mÅ), log ϵ
C I, 8.71			
5052.15	7.68	−1.51	117, 8.62
5380.32	7.68	−1.76	87, 8.55
6587.62	8.53	−0.94	68, 8.31
7111.45	8.64	−1.32	56, 8.65
O I, 8.88			
7771.83	9.14	0.33	290, 9.61
7774.05	9.14	0.19	274, 9.59
7775.27	9.14	0.04	226, 9.35
Na I, 6.28			
5682.65	2.10	−0.71	85, 6.14
5688.22	2.10	−0.40	115, 6.15
6160.75	2.10	−1.27	84, 6.68
Mg I, 7.67			
5172.69	2.71	−0.38	187, 5.62
5528.42	4.34	−0.34	55, 5.50
Si II, 7.40			
6347.09	8.12	0.26	33, 5.99
S I, 7.38			
6052.68	7.87	−0.63	77, 7.66
6748.80	7.86	−0.44	74, 7.42
Ca I, 6.37			
6162.18	1.90	−0.09	74, 4.67
Sc II, 3.43			
5526.55	1.77	−0.13	<14, 0.70
Fe I, 7.50			
5049.83	2.28	−1.35	21, 5.18
5194.95	1.56	−2.06	33, 5.43
5232.94	2.94	−0.08	72, 5.26
5266.56	3.00	−0.39	24, 4.96
5269.54	0.86	−1.32	116, 4.99
5369.97	4.37	0.54	23, 5.28
5405.78	0.99	−1.85	80, 5.23
5434.53	1.01	−2.12	54, 5.23
5586.76	3.37	−0.12	34, 5.21
Fe II, 7.50			
5197.58	3.23	−2.25	43, 5.09
5234.63	3.22	−2.24	54, 5.21
Zn I, 4.57			
6362.54	5.79	0.27	67, 4.78
Ba II, 2.39			
5853.68	0.60	−1.00	73, 0.76

NOTE.—The O I triplet lines listed here were measured on the 1995 January 25 spectrum. The quoted oxygen abundances have not been corrected for non-LTE effects. See § 3.3 for details.

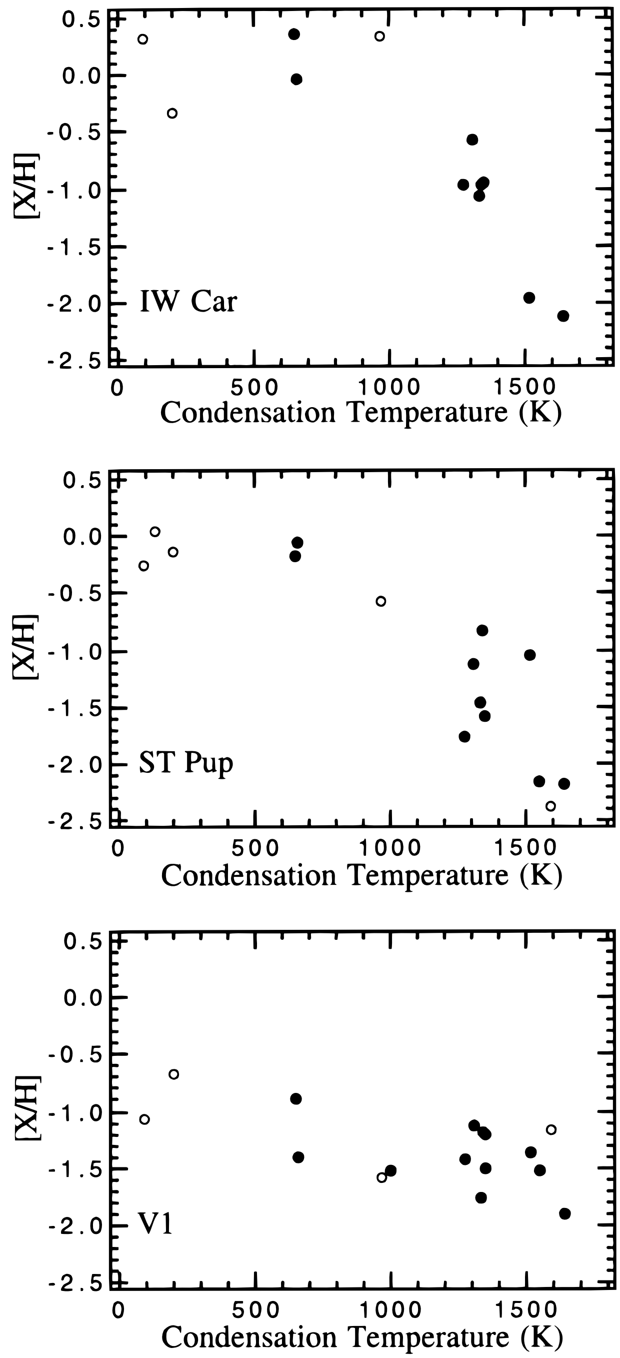

FIG. 5.—Same as Fig. 4 but for IW Car, ST Pup, and V1 in ω Cen

abundance possibly in excess of solar with a subsolar Fe and even lower Ca abundance. Scandium, which has the highest value of $T_{\rm cond}$, is just as strongly depleted in these two stars as it is in the other other stars presented in Figures 4 and 5. These are trademarks of interstellar depletions.

One point deserves emphasis. These abundance patterns are not typical of unevolved or only slightly evolved metal-poor stars. For example, the many published studies of these stars (Lambert 1989; Wheeler, Sneden, & Truran 1989) show that stars similar to EP Lyr and DY Ori with [Fe/H] ~ -2 show [S/Fe] $\sim +0.4$ and [Zn/Fe] ~ 0.0 not (+1.2, +1.0) and (+1.0, +2.5), respectively, as given in Table 8. The abundance patterns are also quite distinct from solar metallicity supergiants. As an illustration of the anomalously large S/Fe ratio in the RV Tauri stars, we present in Figure 6 a portion of the spectrum of AR Pup overplotted with the same region of α Per containing one of the S I lines used in the abundance analysis. Although the stars have similar values of $T_{\rm eff}$ and log *g*, the Fe I ad Ni I lines are much weaker in the spectrum of AR Pup, but the S I lines are only slightly weaker.

Studies of RV Tauri and related stars previous to Paper I did not always include sulfur and/or zinc in their analyses of these stars. However, Baird (1981), in his analysis of AC Her, noted that its zinc abundance is enhanced relative to iron by about an order of magnitude, but dismissed it as a likely error in the analysis. Interestingly, Luck & Bond (1989; their Table 8) listed the mean abundances for several elements for the type II Cepheid, RV Tauri, and UU Herculis classes of variables. Among the RV Tauri stars, [Sc/Fe] is low and [Zn/Fe] high; among UU Herculis stars,

TABLE 8

FINAL ADOPTED ABUNDANCES FOR EP LYRAE, AR PUPPIS, R SAGITTAE, AND DY ORIONIS

	EP LYR		AR PUP		R SGE		DY ORI	
Species (1)	[X/Fe] (2)	[X/H] (3)	[X/Fe] (4)	[X/H] (5)	[X/Fe] (6)	[X/H] (7)	[X/Fe] (8)	[X/H] (9)
C I	1.43 ± 0.05	−0.37 ± 0.09	0.92 ± 0.13	0.05 ± 0.29	0.09 ± 0.08	−0.41 ± 0.16	2.12 ± 0.08	−0.18 ± 0.26
N I	1.63 ± 0.19	−0.17 ± 0.21	...	...	...	...	...	
O I	1.76 ± 0.09	−0.04 ± 0.12	1.01 ± 0.04	0.14 ± 0.26	−0.14 ± 0.08	−0.64 ± 0.37	2.31 ± 0.08	0.01 ± 0.30
Na I	0.66 ± 0.07	−1.14 ± 0.10	0.72 ± 0.26	−0.15 ± 0.11	0.60 ± 0.02	0.10 ± 0.16	2.34 ± 0.18	0.04 ± 0.21
Mg I	−0.05 ± 0.06	−1.85 ± 0.08	−0.16 ± 0.26	−1.03 ± 0.07	...	...	0.19 ± 0.06	−2.11 ± 0.10
Al I	0.98 ± 0.10	−0.82 ± 0.25	...	...	...	...	...	...
Si I, Si II	0.54 ± 0.16	−1.26 ± 0.17	0.48 ± 0.08	−0.39 ± 0.09	0.58 ± 0.06	0.08 ± 0.09	0.89 ± 0.15	−1.41 ± 0.11
Si	1.19 ± 0.05	−0.61 ± 0.08	1.31 ± 0.10	0.44 ± 0.28	0.87 ± 0.33	0.37 ± 0.40	2.46 ± 0.12	0.16 ± 0.28
K I	0.77 ± 0.17	−1.03 ± 0.19	...	...	...	...	...	...
Ca I	−0.02 ± 0.05	−1.82 ± 0.08	−0.50 ± 0.11	−1.37 ± 0.13	−0.45 ± 0.09	−0.95 ± 0.22	0.60 ± 0.15	−1.70 ± 0.11
Sc II	−0.31 ± 0.06	−2.11 ± 0.09	−1.29 ± 0.16	−2.16 ± 0.19	−0.98 ± 0.04	−1.48 ± 0.17	< −0.43	< −2.73
Ti I, Ti II	−0.21 ± 0.07	−2.01 ± 0.09	...	...	−0.84 ± 0.10	−1.34 ± 0.15	...	...
Cr I, II	−0.03 ± 0.04	−1.83 ± 0.08	...	...	0.22 ± 0.17	−0.28 ± 0.18	...	...
Mn I	−0.15 ± 0.03	−1.95 ± 0.06	...	...	0.34 ± 0.09	−0.16 ± 0.22	...	...
Fe I, Fe II....	...	−1.80 ± 0.10	...	−0.87 ± 0.09	...	−0.50 ± 0.11	...	−2.30 ± 0.11
Co I	...	...	...	...	0.11 ± 0.06	−0.39 ± 0.08	...	...
Ni I	0.21 ± 0.07	−1.59 ± 0.10	−0.43 ± 0.26	−1.30 ± 0.07	0.00 ± 0.08	−0.50 ± 0.10	...	...
Zn I	1.10 ± 0.11	−0.70 ± 0.14	...	...	0.31 ± 0.16	−0.19 ± 0.18	2.51 ± 0.15	0.21 ± 0.08
Y II	−0.07 ± 0.11	−1.87 ± 0.14	...	...	−1.18 ± 0.09	−1.68 ± 0.17	...	...
Ba II	0.21 ± 0.15	−1.59 ± 0.18	0.61 ± 0.26	−0.26 ± 0.18	−1.40 ± 0.14	−1.90 ± 0.24	0.67 ± 0.15	−1.63 ± 0.17
Ce II	0.69 ± 0.10	−1.11 ± 0.13	...	...	...	...	...	...

NOTE.—The abundances are averages of the results listed in Tables 3, 5, 6 and 7. The standard deviations of the means listed in columns (2), (4), (6), and (8) were estimated from the line-to-line scatter; those listed in columns (3), (5), (7), and (9) were estimated from the results of Table 4. For a value of [X/Fe] based on a single abundance estimate, such as Al I and Ce II, the standard deviation of the Fe I lines of the spectrum containing the line is quoted instead.

[Al/Fe] and [Sc/Fe] are low and [S/Fe] slightly high. These studies suggest that the abundance patterns we have found for our sample may be a common characteristic among the RV Tauri and possibly also the UU Herculis classes.

4. DISCUSSION

4.1. *Sources of Abundance Patterns*

The chemical compositions of our quartet of RV Tauri stars together with that determined for IW Car (Paper I) will be discussed here in relation to the few published determinations of compositions for this class of variable star. The RV Tauri stars are commonly said to span a range in metallicity. As a rough measure of the range, we show in Figure 7 a histogram of the [Fe/H] determinations by Wahlgren (1994) for a sample of field RV Tauri stars, which he analyzed by fitting synthetic spectra to low-resolution spectra. Undoubtedly, the [Fe/H] distribution is distorted by selection effects, but we think they may be of minor influence.[5] RV Tauri stars are also found among the globular clusters: six variables in six clusters whose metallicities range from −0.8 to −2.3. Of the five variables in our sample, three (IW Car, AR Pup, R Sge) sample the principal [Fe/H] range in Figure 7. The remaining two stars—DY Ori and EP Lyr—are very metal poor stars of which EP Lyr is the sole example contributing to the [Fe/H] histogram. Note that our and Wahlgren's [Fe/H] estimates for the two stars in common are in excellent agreement, and, therefore, it is unlikely that there is a significant offset between our scales. We argue below that some low estimates of [Fe/H] result from loss of Fe (and other easily condensable elements) from the stellar atmosphere as dust grains are driven off with the wind. Hence, the intrinsic distribution function for [Fe/H] is likely much narrower than implied by Figure 7. In particular, there may be very few, if any, very metal poor ([Fe/H] ≤ −1.5) RV Tauri stars in the field.

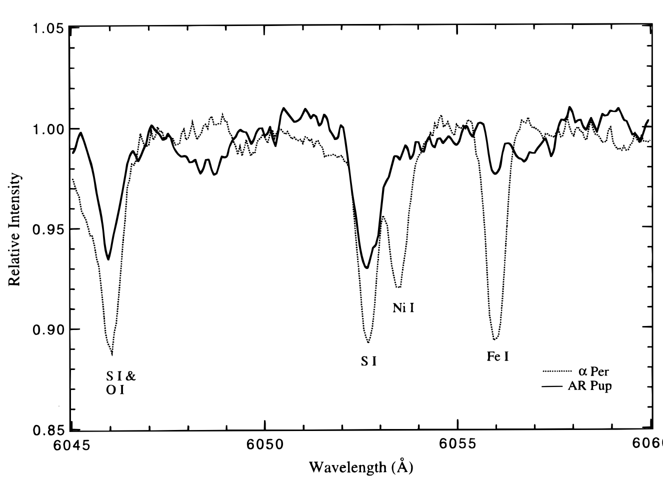

FIG. 6.—Sample spectrum of AR Pup containing a S I line used in the abundance analysis obtained on 1992 May 23. Overplotted is a spectrum of α Per obtained with the same instrument. The value of T_{eff} for α Per is 6200 K (Gonzalez & Lambert 1996), only 200 K warmer than AR Pup at the time its spectrum was obtained. Note the weakness in strength of the Fe I and Ni I lines in the spectrum of AR Pup.

When compared to metal-poor stars in the halo, the abundance patterns of EP Lyr and DY Ori are quite different. The S/Fe ratio, in particular, is much higher than in typical metal-poor stars. There are two scenarios that could be proposed to explain such a high S/Fe ratio: (1) a star begins with a low Fe abundance and produces S in its interior, which gets mixed to the surface; or (2) it begins with roughly solar S and Fe abundances and somehow depletes Fe without affecting S. The first case is not a viable option

[5] Dawson (1979) provides [Fe/H] from DDO photometry for a sample of stars, but Wahlgren advances cogent reasons for preferring his spectroscopic estimates.

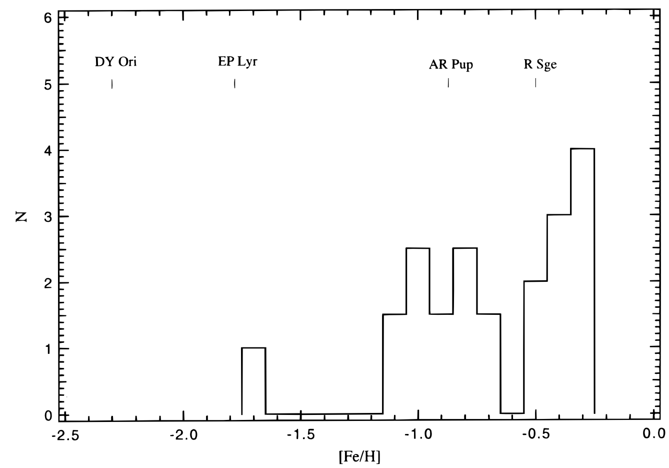

FIG. 7.—Histogram showing the distribution of [Fe/H] estimates for field RV Tauri's determined by Wahlgren (1992) from low-resolution spectra. Our estimates of [Fe/H] for the four program stars are also shown.

for RV Tauri stars, which have masses near 0.6 $M_{\odot}$ (Gingold 1985; Jura 1986). We will discuss in § 4.2 a scenario in which the second case may occur.

Even the most metal-rich star of our sample, R Sge with [Fe/H] $= -0.5$, does not have the composition expected of such a midly metal-poor star. Perhaps, the two most notable abundance anomalies are (1) the relative underabundance of Ca and Ti ([Ca/Fe] $= -0.5$ and [Ti/Fe] $= -0.8$) instead of the expected overabundance ([Ca/Fe] $\cong$ [Ti/Fe] $\cong +0.4$), and (2) the very low abundance of the heavy elements ([Y/Fe] $\simeq -1.2$ and [B/Fe] $\simeq -1.4$). The composition of R Sge is reminiscent of that of R Sct, an RV Tauri variable analyzed by Luck (1981). While the C, N, O and even Na anomalies may be attributable to internal nucleosynthesis and mixing, it is difficult to imagine how (relative) underabundances of Ca, Ti, Y, and Ba can be assigned this same origin (overabundances of Y and Ba would be a sign of *s*-processing). Luck speculated that R Sct was intrinsically a very metal-poor star, but thanks to extensive mixing, the star's atmosphere is greatly enriched in helium, which reduces the atmospheric opacity (absorption per gram) and strengthens the absorption lines. Thus, an analysis performed on the assumption that the He/H ratio is normal results in an overestimate of abundances with respect to hydrogen. Abundance ratios, say Ba to Fe, might be expected to be little affected by erroneous assumption regarding the He/H ratio; the low Y/Fe and Ba/Fe ratios are characteristic of very metal-poor stars (Wheeler et al. 1989). While this ingenious explanation for the low abundances of heavy elements in R Sct might also account for R Sge, we prefer an alternative explanation: a separation of dust and gas in the stellar wind of dust (and some gas) removing some elements that condensed onto grains and with gas falling back onto the photosphere.

4.2. *A Dusty Wind*

The RV Tauri stars have long been known to have a strong infrared excess, the signature of circumstellar dust grains (see, for example, Gehrz & Ney 1972). Jura's (1986) analysis of the *IRAS* colors of a sample of RV Tauri stars is considered here. Jura estimates the mass-loss rate from the 12 μm flux, an adopted emissivity of dust, an assumed outflow velocity of 10 km s^{-1}, and a distance calculated from a period-luminosity law. A mass-loss rate for the dust, $\dot{m}_d$, of about 2×10^{-8} $M_{\odot}$ yr^{-1} is representative. One supposes the dust to drag along some gas. If the dust-to-gas ratio is 1% by mass, the mass-loss rate would be $\dot{m}_w \simeq \dot{m}_d + \dot{m}_g \simeq 2 \times 10^{-6}$ $M_{\odot}$ yr^{-1}.

This mass loss is fed by a stellar envelope. It is quite possible that the wind may deplete the envelope in a short timescale. A star evolving from the asymptotic giant branch (AGB) to the planetary nebular phase and the white dwarf cooling track has an envelope mass $m_e \sim 10^{-3}$ $M_{\odot}$ (Schönberner 1981). Other scenarios link metal-poor RV Tauri stars to "blue loops" from the AGB at lower luminosities: Gingold (1974) modeled the post-HB evolution of a 0.6 $M_{\odot}$ metal-poor star and found that such a star does not start moving off the AGB until the envelope mass drops down to about 0.005 $M_{\odot}$. Thus, it is likely that the envelope mass of a typical RV Tauri star is about 10^{-3} $M_{\odot}$ but no more than about 0.005 $M_{\odot}$.

Obviously, there are likely combinations of $\dot{m}_w$ and m_e that result in loss of the envelope on a timescale ($t_e \simeq m_e/\dot{m}_w$) that is short relative to lifetime on the AGB and on the post-AGB phase. More intriguing is Jura's discovery from the spectral shape of the infrared excess that the mass-loss rate for the RV Tauri stars was higher about 500 yr ago. This result is possibly an indication that $t_e \sim 500$ yr.[6] Raveendran (1989) argues, however, that the *IRAS* photometry measurements are consistent with continuous ejection of dust.

The wind is fed from the stellar photosphere, a thin covering of the stellar envelope. The photosphere contains a mass $m_{\rm ph} \sim 10^{6}$ $M_{\odot}$, which cannot feed the wind for very long; even the inferred rate of loss through dust ($\dot{m}_d \sim 2 \times 10^{-8}$ $M_{\odot}$ yr^{-1}) strips the photosphere in less than a century. Consequently, the photosphere eats progressively and aggressively into the envelope. In such a dynamic situation, there is no guarantee that the photospheric composition will remain unaffected. If the wind removes all elements with equal efficiency, the photosphere retains the same composition as it eats steadily into the envelope. A difference of chemical composition seems inevitable by the very nature of the wind. Since some elements condense easily onto grains and, at low gas densities, the coupling of the gas to the grains will be weak, it is likely that a dusty wind will effect a chemical fractionation which, if gas falls back to the photosphere, will be reflected in the chemical composition of the photosphere.[7] The impact of the fractionated gas on the chemical composition of the photosphere will be greater the lower the efficiency with which the base of the photosphere is mixed with the entire envelope. For a strong wind and inefficient mixing, variations of composition over a pulsational cycle may even occur. If the mixing is efficient, the consequences of the wind on the photospheric composition

[6] Note that $m_e \sim 1 \times 10^{-3}$ $M_{\odot}$ and $\dot{m}_w \simeq 2 \times 10^{-6}$ $M_{\odot}$ yr^{-1} combine to give $t_e \sim 500$ yr.

[7] Photospheres of RV Tauri variables are too warm to initiate dust formation. At the high altitudes where the temperature may be less than condensation temperature for dust, the gas density in hydrostatic equilibrium is too low to sustain a dusty wind. We suppose that the pulsations characteristic of RV Tauri variables periodically enhance the gas and dust density at high altitudes. Between these episodes of replenishment of gas, we suppose some gas may fall back into the photosphere.

may not be evident until mass loss has reduced the envelope to little more than a photosphere.

In this scenario, the abundance anomalies of the photosphere should correlate with properties measuring the propensity of an element to condense onto grains. A strong correlation of IW Car's photospheric abundances with those of the interstellar gas, and hence T_{cond}, was a principal result of Paper I. As noted above, a similar correlation is found here for EP Lyr and DY Ori and also for ST Pup by Gonzalez & Wallerstein (1996). The dust-gas separation has worked very effectively in these stars. On the assumption that the circumstellar shell achieves depletions like those seen in ζ Oph's diffuse cloud (Savage, Cardelli, & Sofia 1992; Federman et al. 1993), the present photospheres contain about 1% or less of the original gas and about 99% fractionated gas. Our assumption is that elements exhibiting little depletion in interstellar clouds betray a star's original metallicity. In this regard, S and Zn are preferable as metallicity indicators to C, N, and O, whose surface abundances are likely altered in the process of evolution from the main sequence.

As mentioned above, the $[X/\mathrm{H}]$-T_{cond} diagrams appear to have a sharp break at $T_{cond} \sim 1000$ K, except for EP Lyr, which is characterized by a single slope. In the framework of the dusty wind model, we might account for these patterns if we assume that the minimum temperature at which the grain formation occurs varies from star to star. Therefore, we find that the minimum temperature of grain condensation was a few hundred degrees K in the circumstellar environment of EP Lyr, while for R Sge it was about 1200 K. This implies that the original metallicity of EP Lyr may not be the same as that given by the present sulfur and zinc abundances. Interestingly, R Sge has the smallest depletion of the field type II Cepheids in Figures 4 and 5; this may be related to its large minimum condensation temperature.

It is a curious fact that EP Lyr, for which the dust-gas separation has worked efficiently, does not have a strong infrared excess. EP Lyr has been detected by *IRAS* only in the 25 μm passband with a flux of 0.5 Jy; this is much less than the smallest flux at 25 μm quoted by Raveendran (1989) in his list of 17 RV Tauri stars detected by *IRAS*. Perhaps, this star has a very thin outer envelope that preserves the compositional changes caused by dust that has now been expelled to great distances from the star. Dust formation has apparently ceased temporarily or permanently. Among the very metal poor post-AGB stars for which a dust-gas separation is implied, BD $+39°4926$ is similarly lacking in infrared excess.

4.3. *Evolution and Abundances*

Stars that are as highly evolved as the RV Tauri variables cannot have preserved their original chemical compositions. Prior to the AGB, the first dredge-up on the giant branch brings CN-cycled material into the deep outer convective envelope (and atmosphere) so reducing the CN and $^{12}C/^{13}C$ ratios. Substantial mass loss seems necessary for a star to reach the horizontal branch or, if metal-rich, the "clump" as a He-core burning star. This mass loss may well lead to additional alterations of the C, N, and possibly O abundances. On the AGB, the repeated occurrences of the third dredge-up may increase the C abundance and enrich the atmosphere in products of *s*-processing. Although the predictions of "standard" stellar evolution are not confirmed exactly, the broad expectations are supported by observations of red giants (Smith & Lambert 1990. Then, prior to the onset of the dust-gas separation, the RV Tauri stars are most likely to have the C, N, O, and *s*-process abundances of normal giants. The evolutionary stage of RV Tauri stars is not clear. Some may have evolved from or be on the early AGB (i.e., the third dredge-up has not yet commenced) and others may have experienced the third dredge-up. The *s*-process abundances may be a discriminant here. A deep convective envelope and associated dredge-up have presumably ended or RV Tauris would be unable to sustain a fractionated photosphere.

As predicted and observed, the alterations to the C, N and especially the O abundances are minor: e.g., a factor of 2 reduction of C by the first dredge-up and a restoration such that C/O ~ 1 for carbon stars, which are produced as ^{12}C is dredged up on the AGB. Therefore, unless the dust-gas separation is highly effective for C, N, and O, these elements on average betray a star's initial metallicity. Table 8 and earlier results for IW Car suggest this metallicity was approximately solar. If we adopt sulfur as a reference element unaffected by stellar evolution and the dust-gas separation, we expect the various phases of dredge-up to leave $[\mathrm{O/S}] \sim [\mathrm{C/S}] \sim 0$. Table 8 with the result for IW Car gives mean values $[\mathrm{C/S}] = -0.3 \pm 0.4$ and $[\mathrm{O/S}] = -0.4 \pm 0.7$, i.e., these light elements and not Fe and other depleted metals reflect the star's initial metallicity. The low $^{12}C/^{13}C$ ratios found for DY Ori and EP Lyr show, as found for nonvariable giants, the presence of CN-cycled products in the atmosphere.

The O/S ratios and sulfur abundances would seem to imply that the stars are of near solar metallicity. Fractionation in the circumstellar shell may affect the C/O ratio of the photosphere. Silicate dust will form in O-rich gas; at temperatures above 1000 K most of the condensates contain oxygen (Field 1974). Hence, these grains will remove some oxygen (more, in the unlikely event that temperatures drop low enough for the grains to acquire a water-ice coating, but the chances are improved if a circumstellar disk forms as in the case of the protostar AFGL 2136 IRS 1; Kastner & Weintraub 1996). The gas that falls back will enhance the C/O ratio of the photosphere as its metallicity decreases. The lower metallicity will likely lead to less efficient formation of dust and perhaps to a cessation (and preservation) of the fractionation process. If freshly synthesized ^{12}C could be added and the photosphere made C-rich, formation of graphite grains would lead to a restoration of the dusty wind! The propensity to form dust depends presumably on the excess of C or O. This would maintain the C/O ratio of the photosphere close to unity. Perhaps, this mechanism (without fractionation) explains why cool carbon stars have a C/O ratio close to unity (Lambert et al. 1986).

Enrichment of *s*-process elements is expected and observed for AGB stars but not for single giants in an earlier evolutionary stage. The *s*-process abundances should then distinguish those RV Tauri's that evolve off the AGB from those that evolve from the horizontal branch or the early AGB. Three of the five stars have $[\mathrm{Ba/Fe}] > 0.6$. They are EP Lyr[8], DY Ori, and AR Pup. The first two are affected greatly by the dust-gas fractionation, but as the fractionation is unlikely to be less severe in Ba than Fe (Paper I), we suppose the unfractionated photosphere must have had a somewhat greater *s*-process enrichment, and,

[8] The ratio $[\mathrm{Ba/Eu}] \sim +0.8$ is also indicative of *s*-process enrichment.

hence, the stars have evolved off the AGB (conceivably, they are evolved barium stars, i.e., stars that gained their *s*-process enrichments at an earlier stage by mass transfer from an evolved companion). R Sge is *s*-process poor (relative to Fe): [Y/Fe] = -1.2 and [Ba/Fe] = -1.4. While these ratios might be produced by fractionation, R Sge is not very iron poor ([Fe/H] = -0.5). In this regard, it resembles R Sct (Luck 1981).

While an accurate luminosity estimate requires a Baade-Wesselink type of analysis, we can obtain rough estimates from the stellar parameters derived from the Fe-line analysis (Table 2). Assuming the RV Tauri stars have a mean mass of 0.6 $M_{\odot}$, then we find that EP Lyr, DY Ori, and AR Pup have luminosities near 10^3 $L_{\odot}$, but R Sge is an order of magnitude more luminous. This confirms their status as post-AGB stars. The greater luminosity of R Sge may be due to a larger core mass.

4.4. *Origin of RV Tauri Stars*

Do the metal-depleted RV Tauri stars derive from a halo or disk population? Normally, we might expect to answer this question using either Galactic distribution (or kinematic) or abundance characteristics. In the case of these stars, knowledge of the height above the Galactic plane, *z*, offers a chance to infer the mean initial metallicity of the stars. In Table 1 we give estimates of $|z|$ for each variable (the corresponding value for IW Car is 0.3 kpc). The mean value for the five RV Tauri stars is 0.4 kpc, which is not very sensitive to errors in the distances given the stars' generally low galactic latitudes. This estimate is consistent with an origin from the population of disk G dwarfs, say [Fe/H] ~ -0.2. This inference is quite consistent with that made from the C, N, O, and S abundances as is indirect evidence for fractionation producing the low metallicities.

This is not to suggest that all RV Tauri stars are of solar metallicity. There are also RV Tauri stars in globular clusters: Gonzalez & Wallerstin (1994) estimated [Fe-H] = -1.77 and [S/Fe] = 0.88 for V1 in ω Cen, implying some depletion but an initial metal-poor abundance pattern. Unfortunately, the initial metallicity of V1 is not known a priori given the large spread in [Fe/H] in ω Cen. Since the dust content of a cool circumstellar metal-poor O-rich shell will be lower than for a solar metallicity shell, it is quite possible that the efficiency of fractionation is reduced for metal-poor photospheres. The field RV Tauri stars are initially of near solar metallicity, and fractionation drives the metallicity of their photospheres down to a limit set by the competing efficiency of the fractionation and mixing with the envelope. Members of the spectroscopic group C field RV Tauri stars may be metal-poor, as opposed to metal-depleted. However, fine abundance analyses of this group will be required to test this possibility.

4.5. *Single or Binary Stars?*

Van Winckel et al. (1995) have shown all the known metal-depleted post-AGB A–F supergiants to be spectroscopic binaries. Waters, Trams, & Waelkens (1992) argue that the dust-gas separation occurs in a circumbinary disk with the A–F supergiant accreting gas but not dust from this disk. A demonstration that an RV Tauri star is a spectroscopic binary is not as straighforward as it is for the A–F supergiants: the atmospheric pulsations, often less than regular, may mask the orbital radial velocities. Gonzalez & Wallerstein (1996), however, have demonstrated that the metal-depleted W Virginis star ST Pup is a spectroscopic binary.

While we do not yet have a sufficient quantity of velocity measurements to derive orbital parameters of possible companions around our RV Tauri sample, EP Lyr, the star for which we have the most data, shows evidence of a velocity perturbation other than pulsation: the 1994 October 19 heliocentric radial velocity (hrv) = 14.3 ± 0.4 km s^{-1}, 1995 June 21 (hrv = 4.3 ± 0.1 km s^{-1}), and 1996 February 28 (hrv = 29.7 ± 0.7 km s^{-1}) spectra, all obtained at nearly the same pulsation phase, have heliocentric radial velocities that span about 25 km s^{-1}. This is not likely to be caused by pulsational irregularities given that EP Lyr's light curve has been stable in recent years (Zsoldos 1995). The other RV Tauri stars require additional observations (both photometric and spectroscopic) before we can reach firm conclusions regarding binarity.

The presence of a binary companion may provide a simple mechanism for producing the two types of depletion-$T_{\rm cond}$ curves described above. For stars such as AR Pup and R Sge with a sharp increase in the depletion for $T_{\rm cond}$ above about 1000 K, the dust condensation might have taken place relatively near the photosphere in a warm wind. For EP Lyr the presence of a binary might instead lead to the formation of a circumbinary disk, where some of the dust condensation would take place at cooler temperatures and allow elements with smaller values of $T_{\rm cond}$ to condense; if the condensation occurs over a range of temperatures, then a linear depletion curve, like the one observed for EP Lyr, can be generated.

At present there are two competing hypotheses concerning the formation of metal-depleted atmospheres: pulsation/wind and binarity. If it can be shown that all metal-depleted type II Cepheids have binary companions, then it becomes less likely that pulsation plays a significant role in the fractionation process. If even one metal-depleted type II Cepheid is found not to have a stellar companion, then pulsation will need to be considered as a likely mechanism.

5. CONCLUSIONS

The RV Tauri stars have chemical compositions unlike those of less evolved stars of the same metallicity (Fe/H). The abundance anomalies parallel those of the post-AGB A–F supergiants. We suggest that the anomalies are caused by a fractionation of elements via dust grain formation in the wind blown off an RV Tauri star. Estimates of mass-loss rates and masses of the photosphere and outer envelope suggest the proposed mechanism is plausible. Our abundance analyses have also shown that not all RV Tauri stars can be considered to be members of the halo, but rather their membership resides mostly with the disk stars.

In the case of the post-AGB A–F supergiants, the fractionation is enhanced when the star is in a binary system. Intensive radial velocity campaigns are desired in order to determine if the metal-depleted RV Tauris are also spectroscopic binaries. An easier task, also of greate value, is to extend the abundance analyses to a larger sample of RV Tauri's to determine the range of the abundance anomalies and their patterns. In this regard, the variables in globular clusters should be investigated as, with the exception of ω Cen, the initial metallicity of the variables is known. Finally, an attempt should be made to determine the chemical composition of a few stars over a broad phase interval with the principal purpose of uncovering systematic errors in the abundance analyses.

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