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ABUNDANCE ANALYSES OF FIELD RV TAURI STARS. V. DS AQUARII, UY ARAE, TW CAMELOPARDALIS, BT LIBRAE, U MONOCEROTIS, TT OPHIUCHI, R SCUTI, AND RV TAURI

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ABSTRACT

Abundance analyses are presented and discussed for eight RV Tauri variables. The RVB star UY Ara shows the abundance anomalies seen in other RVB stars, namely, elements that condense into grains at high temperature are underabundant, but elements of low condensation temperature are much less underabundant. This pattern is ascribed to a separation of dust from gas with accretion of gas but not dust by the atmosphere. Abundances for two RVC stars with earlier results for other RVC stars show that these intrinsically metal-poor stars do not show effects of dust-gas separation. Analyses of five RVA stars show that these cooler stars are very largely unaffected by dust-gas separation. It is proposed that the deeper convective envelope of cooler stars dilutes anomalies resulting from dust-gas separation. Possible sites for dust formation and dust-gas separation—the dusty wind off the RV Tauri variable or a dusty circumbinary disk—are reviewed and observational tests suggested.

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

1. INTRODUCTION

In this series of papers, we have been exploring the chemical compositions of RV Tauri variables in the Galactic field. This exploration continues here with abundance analyses reported for seven additional variables and an improved analysis provided for an eighth star. Beginning with the first paper in the series, an analysis of the southern variable IW Car (Giridhar, Rao, & Lambert 1994), we have shown that the atmospheric composition of a RV Tauri star may be abnormal in the sense that those elements that condense at "high" temperatures (~ 1500 K) into dust grains are underabundant (Gonzalez, Lambert, & Giridhar 1997a, 1997b, hereafter Paper II and Paper III, respectively; Giridhar, Lambert & Gonzalez 1998, hereafter Paper IV). A likely interpretation is that the atmosphere accreted gas but not dust from a site of dust formation.

The severity of the atmospheric abundance anomalies differs from one RV Tauri to another. By enlarging the sample, we hoped to ascertain the principal factors influencing the effects of a dust-gas separation on the atmospheric composition. Several clues have been provided:

1. The severity of the abundance abnormalities is not correlated with the magnitude of the infrared excess (Paper IV).

2. Variables with an intrinsic metallicity [Fe/H] $\lesssim -1$, as assessed from their S and Zn abundances, are not subject to effects of a dust-gas separation. This conclusion is confirmed by abundance analyses of similar variables in globular clusters (Gonzalez & Lambert 1997; Russell 1997, 1998; Carney, Fry & Gonzalez 1998).

3. Post-AGB stars exhibiting extreme effects of dust-gas separation are spectroscopic binaries in which the separation may occur in the circumbinary disk (Waters et al. 1992; Van Winckel, Waelkens, & Waters 1995). Van Winckel et al. (1998) have shown that AC Her, a well-studied RV Tauri variable exhibiting effects of dust-gas separation (see also Giridhar et al. 1998; Klochkova & Panchuk 1998), is a spectroscopic binary of long period. Van Winckel et al. (1999) argue that direct and indirect evidence supports a claim that "binarity is a widespread phenomenon in the RV Tauri class of objects," and that the separation occurs in the circumbinary disk and not the stellar wind off the RV Tauri star.

These clues to the intriguing physics behind dust-gas separation affecting some but not all RV Tauri variables are considered afresh and extended in this paper, in which we present abundances for the eight variables listed in Table 1 with pertinent data including the spectroscopic class (RVA, B, or C) as introduced by Preston et al. (1963) and the photometric class (RVa or RVb). The RVC stars have weak metal lines and a high radial velocity (Joy 1952), and, hence, may be presumed to be intrinsically metal poor. The RVA and RVB stars belong to the disk population. The RVB stars are generally of earlier spectral type than the RVA. Relative to MKK standards, the metal lines appear weak in the RVB but not in the RVA stars. Six of the present sample are RVA stars and triple the number of RVA stars in our survey. RVb and RVa variables differ in that the characteristic light curve of alternating deep and shallow minima with a period of 50–150 days is modulated on a long timescale (~ 600–2600 days) in the case of the RVb stars.

[1] Visiting Observer, Cerro Tololo Inter-American Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc. under contract with the US National Science foundation.

TABLE 1

THE PROGRAM STARS

Star	V[a]	$B-V$[a]	$E(B-V)$[a]	Spectral Type	Period[b]	Spectral Group[c]	Photometric Type[a]
DS Aqr	10.3–11.6	0.54	0.00	F2	78.3	C	a
UY Ara	11.1–12.2	0.81	0.15	G2	57.2	B	...
TW Cam......	10.4–11.5	1.52	0.62	G3	85.6	A	a
BT Lib	11.5–13.1	0.70	0.25	G0	75.34	C	...
U Mon........	6.1–8.1	1.03	0.03	G8	92.2	A	b
TT Oph.......	10.4–12.2	1.14	0.14	G5	61.08	A	a
R Sct	5.8–7.8	1.47	0.20	K0	140.2	A	a
RV Tau	9.8–13.3	1.57	0.07	K3	78.7	A	b

[a] Data from Wahlgren 1992, Goldsmith et al. 1987, and Pollard et al. 1996.
[b] Period in days from the GCVS (Kurkarkin et al. 1958; Kholopov et al. 1985).
[c] Data from Preston et al. 1963 and Lloyd Evans 1985.

2. OBSERVATIONS AND ABUNDANCE ANALYSES

Our abundance analysis uses the observations summarized in Table 2. A majority of the stars were observed with the McDonald Observatory's 2.7 m Harlan J. Smith reflector with the CCD-equipped 2dcoudé spectrograph (Tull et al. 1995). A spectral resolving power of 60,000 was used and a broad spectral range was covered in a single exposure. The star UY Ara, as was BT Lib, was observed with the CTIO 4 m telescope and a Cassegrain echelle spectrograph at a resolving power of 20,000.

Several stars were observed on more than one occasion. Spectra were rejected if they showed line doubling, markedly asymmetric lines, or strong emission at Hβ. (Emission was almost always present at Hα.) It is presumed that the spectra not showing these characteristics represent the atmosphere at its stablest time when standard theoretical models may be applicable. This presumption should be tested by analysis of a series of spectra taken over the pulsational cycle. This remains to be done, but in previous papers we have analyzed several stars using spectra taken at different phases and obtained consistent results. A striking example was given in Paper III where three observations of SS Gem gave widely different effective temperatures (4750, 5500, and 6500 K) but similar results for the composition. The abundance analysis was performed exactly as described in earlier papers of this series.

3. THE CHEMICAL COMPOSITIONS

Three signatures may be looked for in the chemical compositions: (1) the initial composition, (2) the effects of deep mixing during stellar evolution on the initial composition, and (3) the effects of the dust-gas separation.

The initial composition may be anticipated from published studies on less evolved stars that show a generally smooth run of [X/Fe] with [Fe/H], at least over the metallicity range appropriate for field RV Tauri variables (see Lambert 1989; Wheeler, Sneden, & Truran 1989; Edvardsson et al. (1993); McWilliam 1997).[2]

Deep mixing affects the light elements (primarily C, N, and O with, perhaps, a modest effect on Na) and the heavy or s-process elements. Although the evolutionary origins of RV Tauri variables are unknown in detail, it may be assumed that they experienced the first dredge-up that brings CN-cycled material into the atmosphere. This reduces the C abundance and increases the N abundance. If RV Tauri variables have evolved from the AGB on which they may have experienced thermal pulses and the third dredge-up, they are expected to be enriched in C and the s-process elements.

[2] Usual spectroscopic notation is adopted: $[X/Y] = \log_{10} (X/Y)_{star} - \log_{10} (X/Y)_{\odot}$.

TABLE 2

STELLAR PARAMETERS DERIVED FROM THE Fe-LINE ANALYSES

STAR	UT DATE	PULSATION PHASE[a]	MODEL[b]		Fe I[c]		Fe II	
			T_{eff}, log g, [Fe/H]	ξ_t (km s^{-1})	log ϵ	n	log ϵ	n
DS Aqr	1998 Oct 3	0.69	6500, 1.0, −1.1	2.1	6.39 ± 0.15	29	6.37 ± 0.12	8
UY Ara	1998 Jul 30	0.16	5500, 0.3, −1.0	3.7	6.47 ± 0.09	9	6.51 ± 0.11	8
TW Cam......	1998 Jan 24	0.08	4800, 0.0, −0.5	2.9	6.98 ± 0.17	50	7.04 ± 0.18	11
BT Lib	1998 Jun 06	...	5800, 1.3, −1.2	2.9	6.29 ± 0.14	36	6.28 ± 0.14	11
	1998 Jul 31	...	5800, 1.5, −1.1	3.0	6.39 ± 0.14	22	6.37 ± 0.12	11
U Mon........	1998 Jan 24	0.30	5000, 0.0, −0.8	2.5	6.73 ± 0.13	50	6.71 ± 0.16	10
TT Oph.......	1998 Oct 2	0.17	4800, 0.5, −0.8	4.3	6.66 ± 0.12	37	6.68 ± 0.11	11
R Sct	1998 May 15	0.91	4500, 0.0, −0.4	3.0	7.11 ± 0.13	31	7.12 ± 0.16	6
RV Tau	1997 Dec 14	0.56	4500, 0.0, −0.4	3.0	7.10 ± 0.14	30	7.03 ± 0.14	5

[a] Phase is measured from the deeper light minimum.
[b] T_{eff} in K, log g in cgs, [Fe/H] in dex.
[c] log ϵ is the mean abundance relative to H (with log $N_H = 12.00$). The solar value of log ϵ (Fe) is 7.50. The standard deviations of the means, as calculated from the line-to-line scatter, are given. n is the number of considered lines.

Dust-gas separation more severely depletes those elements of high condensation temperature (e.g., Ca, Ti, and Fe) than those of low condensation temperature (e.g., S and Zn, as well as C, N, and O). A correlation between the abundance [X/H] and the calculated condensation temperature T_c is taken as evidence for dust-gas separation. Here, we adopt values of T_c given by Lodders & Fegley (1998) for cooling gas of solar composition in equilibrium at a pressure of 10^{-4} bar. These estimates are in general in good agreement with the values computed by Wasson (1985) used in our previous papers. (The largest relevant difference is for Si for which $T_c^{\rm LF} = 1529$ K but $T_c^{W} = 1311$ K.) Even were dust-gas separation the paramount effect in determining the atmospheric composition, we would not expect a tight correlation between [X/H] and T_c for the obvious reasons that dust formation near a star is unlikely to occur through equilibrium condensation, and the composition of the gas will, in general, not be solar.

In the following sections, we present and discuss the compositions of our eight variables and an additional three stars with published abundance analyses. Relations between abundance anomalies and infrared excesses and other observables are given later when a review is made of the full sample of 21 RV Tauri variables.

3.1. *The RVC Star DS Aquarii*

DS Aquarii was featured in Paper IV. The present analysis is based on a new spectrum that provides broader spectral coverage and, hence, more absorption lines. Metal lines are few and weak in the spectrum, as expected of a RVC star. The Fe I and Fe II lines provide atmospheric parameters (Table 2) quite similar to those derived earlier; the iron abundance of [Fe/H] = −1.1 is within 0.1 dex of the previous value.

DS Aquarii's composition (Table 3) is that of a normal metal-poor star. With the exception of K and Ba, our new analysis confirms previous results with differences between the analyses falling within the range of +0.3 dex to −0.2 dex. Abundances are provided for the first time for C, Mg, Cr, Zn, and Eu. One characteristic of a normal [Fe/H] = −1 star is an overabundance of the α-elements. DS Aqr has this overabundance: [α/Fe] = 0.4 (Mg), 0.4 (Si), 0.3 (S), and 0.2 (Ca) for an unweighted mean of 0.3, which is typical of normal stars. The relative overabundance of Eu ([Eu/Fe] = 0.5) from a single Eu II line is also typical (Woolf, Tomkin, & Lambert 1996). Potassium, previously reported overabundant, is here shown to have a normal abundance ([K/Fe] = 0.3 from the 7699Å resonance line) according to sparse data on K abundances in metal-poor stars (Gratton & Sneden 1987); Ba, also previously reported overabundant, has an abundance ([Ba/Fe] = 0.2) that indicates little to no enhancement.

The O abundance derived from the [O I] 6363 Å line is in good agreement with our earlier result based on the O I 7772–7775 Å triplet: the result, [O/Fe] = 0.8, is consistent with recent measurements from the O I 7772–7775 Å and OH lines in subdwarfs (Israelian et al. 1988; Boesgaard et al. 1999). The carbon abundance given by the C I lines at 9078, 9088, and 9111 Å is [C/Fe] = 0.15. This is comparable to the carbon abundance of subdwarfs as measured by

TABLE 3

Final Adopted Abundances for DS Aqr, UY Ara, TW Cam, BT Lib and TT Oph

		DS Aqr		UY Ara		TW Cam		BT Lib		TT Oph	
Species	log $\epsilon_{\odot}$[a]	[X/H]	[X/Fe]	[X/H]	[X/Fe]	[X/H]	[X/Fe]	[X/H]	[X/Fe]	[X/H]	[X/Fe]
C I	8.55	−1.29	−0.15	−0.16	+0.84	+0.24	+0.74	−1.25	−0.12	−0.48	+0.37
O I	8.87	−0.34	+0.80	...	...	−0.43	+0.07	−0.34	+0.79	−0.54	+0.31
Na I	6.32	...	...	+0.02	+1.04	−0.31	+0.29	−0.69	+0.44	−0.42	+0.43
Mg I	7.58	−0.70	+0.44	...	...	−0.15	+0.35	−0.90	+0.27	−0.53	+0.32
Al I	6.47	...	...	...	...	−0.41	+0.09	...	...	−0.96	−0.11
Si I, II	7.55	−0.76	+0.37	−0.43	+0.59	−0.12	+0.38	−0.70	+0.48	−0.33	+0.51
S I	7.24	−0.82	+0.32	+0.01	+1.02	−0.05	+0.45	−0.76	+0.41	+0.01	+0.86
K I	5.12	−0.81	+0.33	...	...	...	...	...	...	−0.69	+0.16
Ca I	6.35	−0.97	+0.17	−1.06	−0.04	−0.65	+0.15	−0.91	+0.27	−1.13	−0.28
Sc II	3.13	−1.17	−0.03	−1.74	−0.72	−0.43	+0.07	−0.71	+0.47	−1.09	−0.24
Ti I, II	4.98	...	...	...	...	−0.64	−0.14	−0.96	−0.22	−0.82	+0.03
V I	4.01	...	...	...	...	−0.59	−0.09	...	...	−1.02	−0.17
Cr I, II	5.67	−1.31	−0.17	−1.20	−0.17	−0.60	−0.10	−1.22	−0.04	−1.11	−0.26
Mn I	5.46	...	...	−0.72	+0.30	−0.64	−0.14	...	...	−1.27	−0.42
Fe I, II	7.50	−1.14	...	−1.02	...	−0.50	...	−1.18	...	−0.85	...
Co I	4.91	...	...	...	...	−0.62	−0.12	...	...	−0.53	+0.28
Ni I	6.25	−1.06	+0.08	...	...	−0.70	−0.20	−1.07	+0.11	−0.83	+0.02
Zn I	4.62	−1.07	+0.09	−0.29	+0.73	−0.34	+0.16	−1.06	+0.12	−0.71	+0.14
Y II	2.23	...	...	...	...	−0.49	+0.01	...	...	−1.16	−0.31
Ba II	2.17	...	...	...	...	...	...	−0.67	+0.56	...	...
La II	1.21	...	...	...	...	−0.48	+0.02	...	...	−1.13	−0.28
Ce II	1.58	...	...	...	...	−0.44	+0.06	...	...	−1.46	−0.61
Pr II	0.75	...	...	...	...	...	...	...	...	−1.26	−0.41
Nd II	1.48	...	...	...	...	−0.64	−0.14	...	...	−1.32	−0.47
Sm II	0.99	...	...	...	...	−0.12	+0.38	...	...	−1.15	−0.30
Eu II	0.52	...	...	...	...	−0.28	+0.22	...	...	−0.84	+0.01
Dy II	1.14	...	...	...	...	...	...	...	...	−0.75	+0.10

[a] The solar abundances are taken from Grevesse et al. 1996.

Gustafsson et al. (1999) from the [C I] 8727 Å line. The apparently slightly lower C abundance of DS Aqr is roughly consistent with expectations for the first dredge-up that the star must have experienced. The atmosphere is C-poor in the sense that C/O $\simeq$ 0.05.

Signatures of a dust-gas separation are absent with S, Sc, and Zn in particular, having normal abundances: [S/Fe] = 0.3 is typical for this α-element in a [Fe/H] = -1 star, and [Sc/Fe] = 0.0 is also a normal result. Zinc, not previously measured, is normal for this metallicity (Sneden & Crocker 1988).

3.2. *The RVB Star UY Arae*

Lloyd Evans (1985) assigned this star to the spectroscopic class RVB. It is not known to which photometric class (RVa or RVb) UY Ara belongs. Our abundance analysis from a CTIO Cassegrain spectrum was hampered by the lack of unblended lines. Derived atmospheric parameters are given in Table 2 and abundances in Table 3.

Inspection shows that the dust-gas separation has affected the atmosphere; a clear indicator is the high relative abundances of S and Zn ([S/Fe] = 1.0, and [Zn/Fe] = 0.7) and the low relative abundance of Sc ([Sc/Fe] = -0.7). Sulphur and Zn, if completely unaffected by the dust-gas separation, imply an intrinsic metallicity of [Fe/H] $\simeq -0.3$. There is a clear correlation (Fig. 1) between the abundances and the condensation temperature (or interstellar depletion). (Although the oxygen abundance was not measured, the atmosphere is probably O-rich: C/O < 1.)

3.3. *The RVA Star TW Camelopardis*

Preston et al. (1963) assigned the spectroscopic classification RVA to this RVa star whose light curve more closely resembles that of a Cepheid than a textbook RV Tauri variable. Our abundance analysis (Table 3) is from an excellent 2dcoudé spectrum, which provides the atmospheric parameters summarized in Table 2.

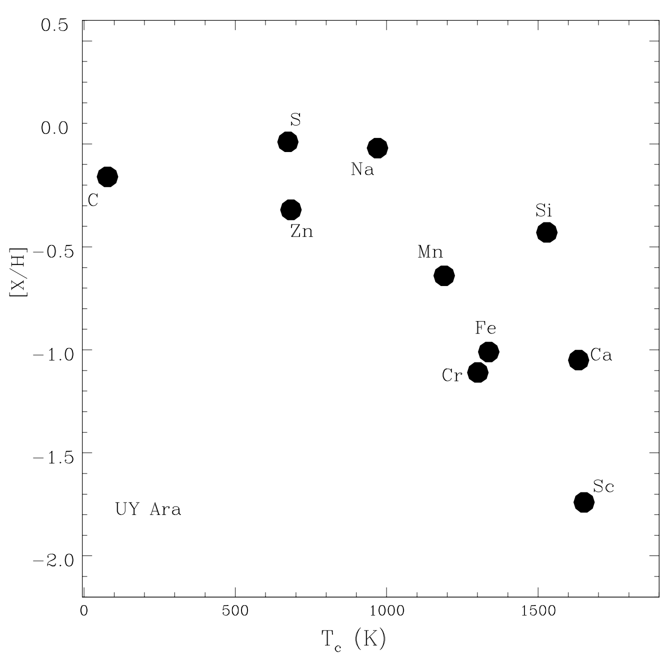

FIG. 1.—Abundance [X/H] vs. condensation temperature for UY Ara. Elements are identified by their chemical symbol.

The iron abundance is [Fe/H] = -0.5. Relative to this value, most elements have the abundance expected of such a mildly metal-poor star, i.e., dust-gas separation has not imprinted a clear signature on the composition. In particular, S and Z have roughly normal abundances ([S/Fe] = 0.5 and [Zn/Fe] = 0.1) as do Ca, Sc, Ti, and Al with higher condensation temperatures than Fe ([Ca/Fe] = -0.1, [Sc/Fe] = 0.0, [Ti/Fe] = -0.1, and [Al/Feα). The S abundance is marginally higher than normal. Abundances of the several heavy elements from Y to Eu are normal. A mild overabundance is indicated for α-elements Si, Mg, and S but not for Ca and Ti, which may reflect the fact that the spectrum is rich in lines.

Carbon provides the only abundance anomaly: [C/Fe] = 0.7 from a set of six C I lines. The O abundance from the [O I] lines is as expected for a mildly metal-poor star. This analysis shows the star to be C-rich with C/O $\simeq$ 2.

3.4. *The RVC Star BT Librae*

Remarkably few observations of any kind have been reported for this high-velocity star. The period of 75.3 days is traceable to Ashbrook (1942). Our abundance analysis is based on two spectra: a CTIO Cassegrain echelle spectrum of 5300–8400 Å and a McDonald 2dcoudé spectrum. The derived atmospheric parameters are identical to within the errors of measurement. The heliocentric radial velocity was 40 ± 2 km s^{-1} on 1998 June 6 and 36 ± 2 km s^{-1} on 1998 July 31. Although the classification RVC has not been previously given, we feel justified in assigning it based on the radial velocity and the paucity of lines in the spectra.

The composition (Table 3) is in all respects that of a normal star of [Fe/H] = -1.2. The α-elements show the expected overabundance: [α/Fe] = 0.3 (Mg), 0.5 (Si), 0.3 (S), 0.3 (Ca), and 0.3 (Ti) for an unweighted mean of 0.3 dex. Dust-gas separation has not affected this star; the abundances of S, Ca, Sc, and Zn relative to Fe are all normal.

Oxygen based on the [O I] 6300 and 6363 Å lines is overabundant, [O/Fe] = 0.9, by about the degree found for DS Aqr, and consistent with recent measurements for subdwarfs (Israelian et al. 1988; Boesgaard et al. 1999).[3] Carbon (C I) lines were not detected or [C/Fe] ≤ -0.1 and C/O $\leq$ 0.05.

3.5. *The RVA Star U Monocerotis*

This star is a fine example of a RVb photometric variable. Percy et al. (1997) give the principal period as 92.23 days and the long period as 2475 days. Pollard & Cottrell (1995) from a radial velocity study find the star to be a spectroscopic binary with an orbital period consistent with that of the long-term photometric variability.

Our abundance analysis is summarized in Table 4 where published analyses by Luck & Bond (1989) and Klochkova & Panchuk (1998) are also tabulated. There is agreement about the metallicity with the three analyses providing [Fe/H] = -0.7 to -0.8. The abundance differences between our analysis and Luck & Bond's, δ(X) = [X/H]$_{us}$

[3] These recent measurements are based on the O I 7772–7775 Å lines and the OH ultraviolet lines. Measurements of the O abundance in subdwarfs to low metallicities from the [O I] lines are difficult to impossible for subdwarfs because the line is very weak. Our measurements using the forbidden lines that are probably formed under LTE in these supergiants give support to these controversial recent measurements from the O I and OH lines.

TABLE 4

Elemental Abundances for U Mon

Species	log $\epsilon_{\odot}$[a]	Present Work [X/H]	Present Work [X/Fe]	LB [X/Fe]	KP [X/Fe]	Average [X/Fe]
C I	8.55	−0.18	+0.61	...	+0.77	+0.72
O I	8.87	−0.41	+0.38	...	+0.55	+0.46
Na I	6.32	−0.34	+0.45	+0.71	+0.53	+0.56
Mg I	7.58	−0.63	+0.16	...	−0.02	+0.07
Al I	6.47	−0.75	+0.04	+0.58	+0.04	+0.22
Si I, II	7.55	−0.45	+0.34	+0.30	+0.18	+0.26
S I	7.24	−0.15	+0.64	...	+0.60	+0.62
Ca I	6.35	−0.96	−0.17	+0.08	−0.02	−0.04
Sc I	3.13	−0.97	−0.18	−0.39	−0.20	−0.26
Ti I, II	4.98	−0.70	+0.09	+0.08	+0.18	+0.12
V I	4.01	−0.66	+0.13	−0.09	−0.56	−0.20
Cr I, II	5.67	−0.72	+0.07	−0.15	+0.00	−0.02
Mn I	5.46	−1.26	−0.47	−0.41	−0.17	−0.35
Fe I, II	7.50	−0.79	...	...	...	...
Co I	4.91	−0.67	+0.12	+0.03	...	+0.06
Ni I	6.25	−0.93	−0.14	−0.05	...	−0.09
Zn I	4.62	−0.71	+0.08	...	+0.20	+0.14
Y II	2.23	−1.02	−0.23	−0.56	−0.26	−0.35
Zr II	2.60	−0.56	+0.23	...	+0.09	+0.16
La II	1.21	−0.48	+0.31	−0.02	−0.21	+0.02
Ce II	1.58	−1.08	−0.29	−0.32	−0.47	−0.36
Nd II	1.48	−0.68	+0.11	−0.25	−0.55	−0.23
Sm II	0.99	−1.27	−0.48	...	−0.89	−0.68
Eu II	0.52	−0.89	−0.10	+0.04	−0.07	−0.04

[a] The solar abundances are taken from Grevesse et al. (1996).

$-[X/H]_{LB}$, are small: δ(X) is in the range ± 0.2 for a majority of the elements in common and the largest difference is -0.5 for Al. The agreement with Klochkova & Panchuk is also satisfactory; the corresponding δ(X) is less than ± 0.3 with the exception of five elements (S, Mn, V, La, and Sm) In view of this pleasing consistency, we average the abundances for the purposes of discussion; all major conclusions are valid for our analysis.

To within ± 0.2 or 0.3 dex, the relative abundances [X/Fe] for all but two elements are those expected for a normal star with [Fe/H] $\simeq -0.6$. Sodium is possibly overabundant, [Na/Fe] = 0.7. Carbon at [C/Fe] = 0.7 is overabundant, but oxygen with [O/Fe] = 0.5 is approximately normal for a metal-poor star; the atmosphere appears to be O-rich with C/O $\simeq$ 0.8.

In several key respects, U Mon resembles AC Her: both are RVb photometric variables, long-period spectroscopic binaries, and stars with a pronounced infrared excess. They differ in that AC Her has a strong signature of dust-gas separation (Paper IV; Van Winckel et al. 1998), but U Mon does not. They differ too in effective temperature, dereddened $B-V$ color, and spectroscopic class (RVA for U Mon but RVB for AC Her).

To contrast the lack of a dust-gas signature in U Mon and the strong signature in AC Her (Paper IV), we compare elemental abundances. Note that their intrinsic metallicities are equal to within the errors of measurement: [Fe/H] = -0.7 for U Mon versus the inferred initial [Fe/H] = -0.8 for AC Her. The abundance differences between U Mon and AC Her are essentially independent of condensation temperature for $T_c \leq 1600$ K but increase sharply for elements of higher T_c. If $\Delta[X/H] = [X/H]_U - [X/H]_{AC}$, where $[X/H]_U$ is the mean abundance for U Mon and $[X/H]_{AC}$ is the abundance for AC Her reported in Paper IV, we find $\Delta[X/H] = 0.41 \pm 0.15$ from 10 elements from Mg to Nd with T_c of 1300 K to 1600K. Five elements with $T_c \geq 1600$ K give Δ[X/H] from 0.7 for Sc to 1.9 for Al. At the other extreme, S and Zn with $T_c \simeq 680$ K give Δ[X/H] of 0.3 and 0.2 dex, respectively.

3.6. *The RVA Star TT Ophiuchi*

Our spectrum of TT Oph indicates that this is one of the cooler variables in the program. This RV Tauri variable has no detectable infrared excess. Derived atmospheric parameters are listed in Table 2, and abundances in Table 3.

TT Oph's atmosphere most probably has the composition expected for a star of the derived metallicity [Fe/H] = -0.8. Zinc with [Zn/Fe] = 0.0 and potassium with [K/Fe] = 0.1 suggest that, if dust-gas separation has been active, it has not affected elements with condensation temperatures cooler than that of iron. Elements with the highest condensation temperatures of the sample may indicate effects of dust-gas separation: Ca, Sc, and Ti are slightly underabundant relative to normal expectation. The observed values are [Ca/Fe], [Sc/Fe] = -0.3, [Ti/Fe] = 0.0, but expected values are approximately 0.2, 0.0, and 0.2, respectively where differences between observation and expectation are about the error of measurement.

One might contrast TT Oph and DS Aqr (and BT Lib). In the latter cases, the expected signature of a positive value of [α/Fe] was clear. It is not as uniformly seen in TT Oph, where [α/Fe] = 0.4 (Si), 0.6 (S), -0.3 (Ca), and 0.0 (Ti). We suspect that this difference is largely a reflection of the contrasting spectra. DS Aqr and BT Lib, which are warmer and more metal poor than TT Oph, have cleaner spectra that allow for more certain line identifications and more accurate measurements of equivalent widths than in the case of TT Oph.

One abundance anomaly is present, however, for TT Oph. Elements heavier than zinc are consistently underabundant: [X/Fe] = −0.3 (Y), −0.7 (Ce), −0.5 (Pr), −0.5 (Nd), and −0.3 (Sm) for elements with three or more lines. These elements have condensation temperatures higher than that of iron so that the underabundance might reflect a dust-gas separation, as was hinted at from the Al, Ca, Sc, and Ti.

3.7. *The RVA Star R Scuti*

This RV Tauri variable has been extensively observed. An abundance analysis of a spectrum obtained near the secondary light maximum was described by Luck (1981). The reported metallicity [Fe/H] = −0.9 was not exceptional, but the low abundance of *s*-process elements deservedly drew Luck's attention: [*s*/Fe] ≃ −1 is not expected for a mildly metal-poor star. Our analysis is based on a spectrum at a phase similar to Luck's observation. Derived atmospheric parameters are listed in Table 2 and abundances in Table 5.

The metallicity [Fe/H] = −0.4 is higher than the −0.9 found by Luck but equal to Preston's (1962) value from a curve of growth analysis. Elements from C to Zn have a normal abundance, [X/Fe] ≃ 0.0, with one exception: scandium with [Sc/Fe] = −1.1 is greatly underabundant. Although the Sc abundance is based on just three Sc II lines, it is clear that the abundance [Sc/Fe] = 0 is excluded by our analysis. Then, either Sc is really underabundant or the Sc II lines are weakened by anomalous excitation. Scandium is, of course, the element in our sample with the next to highest condensation temperature (T_c = 1652 K). Aluminum with T_c = 1670 K is only slightly underabundant with [Al/Fe] = −0.4. Titanium with T_c = 1600 K has a normal abundance ([Ti/Fe] = −0.1). Calcium with T_c = 1634 K is slightly underabundant: [Ca/Fe] = −0.2 according to Luck (1981), who did not measure the Al or Sc abundances but also found [Ti/Fe] = −0.1. There is no strict requirement or confident expectation that anomalies should correlate extremely well with T_c. Nonetheless, where the dust-gas separation is severe, as in AD Aql and AC Her (Paper IV), the anomalies correlate quite well with T_c. If the Sc underabundance is due to dust-gas separation, the effects seem restricted to elements of the very highest condensation temperatures with a dramatic effect only for Sc.[4]

Our analysis confirms Luck's discovery of an underabundance of elements heavier than zinc. Figure 2 shows [X/Fe] versus X's condensation temperature. As noted above, abundances are roughly consistent with [X/Fe] = 0 and independent of T_c for elements from C to Zn with the exception of Sc. Lower abundances and greater element-to-element scatter are seen for the heavy elements. The scatter may well be due to the paucity of lines; almost all determinations are based on one or two lines. If mean abundances across the sample of measured elements are considered, our mean is higher than Luck's: [X/Fe] = −0.8 from 5 elements versus −1.3, but when results for the three elements in common are averaged the difference (−0.1 dex) is not significant. There is a hint that the underabundances are correlated with T_c: Figure 3 in separate panels gives the abundances from the two analyses with the selection limited to the heavy elements plus Sc or Ca. If the Ca abundance is overlooked, Luck's data from Y to Nd suggests that [X/H]

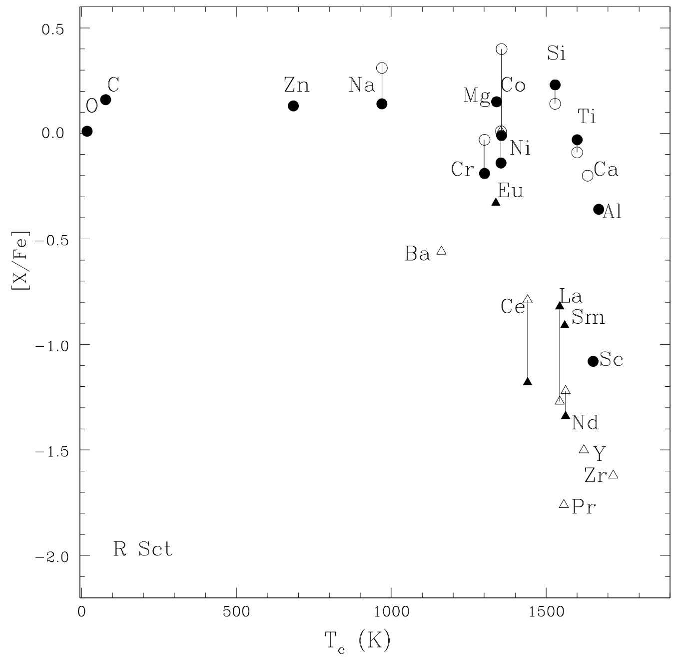

FIG. 2.—Abundance [X/Fe] vs. condensation temperature for R Sct. Filled circles denote our measurements. Open circles denote the measurements published by Luck (1981). Measurements for the same element are connected by a line. Elements are identified by their chemical symbol. The cross represents the Fe abundance [X/Fe] = 0 by definition.

TABLE 5

ELEMENTAL ABUNDANCES FOR R Sct

SPECIES	log $\epsilon_\odot$ [a]	PRESENT WORK [X/H]	PRESENT WORK [X/Fe]	LUCK [X/Fe]
C I	8.55	−0.19	+0.17	...
O I	8.87	−0.34	+0.01	...
Na I	6.32	−0.20	+0.15	+0.31
Mg I	7.58	−0.20	+0.15	...
Al I	6.48	−0.69	−0.34	...
Si I	7.55	−0.14	+0.21	+0.14
Ca I	6.35	...	...	−0.20
Sc II	3.13	−1.43	−1.08	...
V I	4.01	...	...	−0.11
Ti I	4.98	−0.38	−0.07	−0.09
Cr I	5.67	−0.56	−0.21	−0.03
Fe I	7.50	−0.35	...	...
Co I	4.91	−0.37	−0.02	+0.40
Ni I	6.25	−0.49	−0.14	+0.01
Zn I	4.62	−0.19	+0.16	...
Y II	2.23	...	...	−1.50
Zr II	2.60	...	...	−1.62
Ba II	2.17	...	...	−0.56
La II	1.19	−1.17	−0.82	−1.27
Ce II	1.60	−1.42	−1.07	−0.99
Pr II	0.75	...	...	−1.76
Nd II......	1.50	−1.70	−1.35	−1.22
Sm II......	0.99	−1.28	−0.93	...
Eu II	0.53	−0.63	+0.18	...

[a] The solar abundances are taken from Grevesse et al. 1996.

[4] According to Lodders & Fegley (1998) only Al by a margin of 22 K, Hf by 38 K, and W by 142 K have higher T_c than Sc.

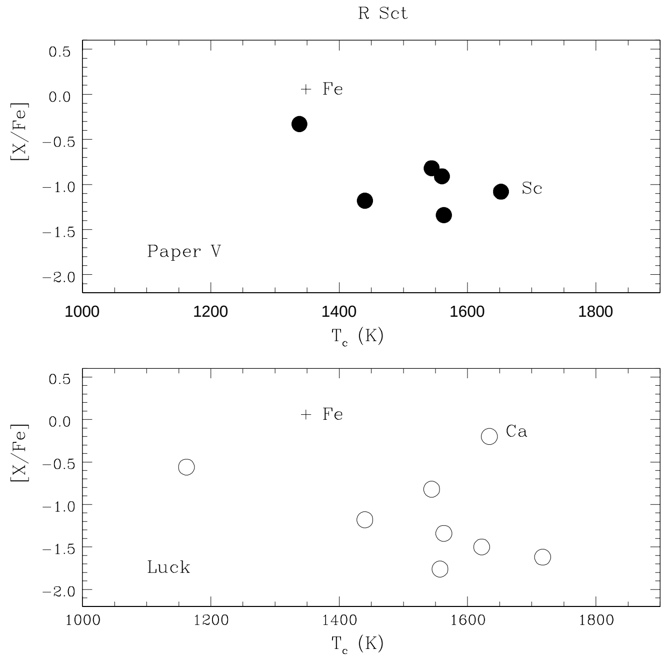

FIG. 3.—Abundance [X/Fe] vs. condensation temperature for R Sct and heavy elements. The top panel shows our results including the measurement of the Sc abundance. The bottom panel shows Luck's measurements including the measurement of the Ca abundance. The cross represents the Fe abundance for which [X/Fe] = 0 by definition.

declines with increasing T_c. Perhaps, our data also hint at a decline.

Luck & Bond (1989) provided a different explanation for the underabundance of the heavy elements in luminous stars such as R Sct. They suggested that an intense flux of Lyman photons from shocks results in an overionization of atoms and ions with ionization potentials of 13.6 eV or less. These heavy elements exist primarily as the ions X^+ under LTE conditions. Then, the relevant ionization potential is that of the singly charged ion. If a relationship exists between our [X/Fe] and the ionization potential of the ion X^+, it is less obvious than possible correlations in Figure 3. In particular, the five heavy elements in our analysis span a range of 1 dex in [X/Fe], but the ionization potentials differ by only 0.5 eV about a mean of 11.0 eV. One might note that Sc with the Sc^+ ionization potential at 12.8 eV is as underabundant as the heavy elements, Eu excepted. Titanium with Ti^+'s ionization potential of 13.58 eV right at the Lyman edge is, however, not underabundant.

Noting that a ratio $[s/\mathrm{Fe}] \simeq -1$ is normal for extremely metal-poor stars, Luck (1981) proposed that R Sct was initially an extremely metal-poor star that during evolution has become greatly enriched in helium. When analyzed on the assumption of a normal He abundance, the star is assigned a much higher abundance [Fe/H]. One expects abundance ratios such as [*s*/Fe] to be estimated without serious error leading to the apparent anomaly of a $[\mathrm{Fe/H}] \simeq -1$ star with the [*s*/Fe] ratio of a much more metal-poor star. Since $[\mathrm{Sc/Fe}] \simeq 0$ for normal stars with $[s/\mathrm{Fe}] \simeq -1$, our measurement of a drastic Sc underabundance is in conflict with Luck's ingenious scheme but qualitatively consistent with the idea of dust-gas separation.

It is known that the atmosphere of R Sct (and RV Tauri variables in general) at certain phases is not well approximated by a canonical theoretical atmosphere. Preston's (1962) study of spectra obtained over a pulsation cycle showed a line doubling at some phases. These and other effects have been interpreted by Gillet et al. (1989) as due to the passage of shocks through the atmosphere. Our analysis, as was Luck's, is based on a spectrum in which lines are single and almost symmetric. We largely rely on weak lines that are probably formed in the deeper layers and are largely unaffected by a hot layer above the photosphere. Nonetheless, in light of the remarkably specific abundance anomalies, it would be of interest to obtain and analyze spectra across the pulsation cycle in order to disentangle true abundance anomalies from atmospheric effects.

3.8. *The RV A Star RV Tauri*

The eponym is one of the coolest stars that we have analyzed. Atmospheric parameters derived from our spectrum are listed in Table 2, and abundances are given in Table 6.

An abundance analysis of RV Tauri was reported recently by Klochkova & Panchuk (1998). Their results from spectra obtained at two different phases are also listed in Table 6. Klochkova & Panchuk find an appreciably higher metallicity: [Fe/H] = 0.05 versus our −0.43. When [X/Fe] is considered, the two analyses agree to within ±0.3 dex for all elements in common except C (1.0), Sc (0.5), Cr (0.4), and Mn (−0.5) where the difference in [X/Fe] in the sense of "us-them" is given in parentheses. The difference in the carbon abundances is striking. The oxygen abundances are in good agreement. Our results imply RV Tau is C-rich ($C/O \simeq 2$), but Klochkova & Panchuk find it to be O-rich ($C/O \simeq 0.2$). Of the elements considered by Klochkova & Panchuk but not by us, one has an unusual abundance: [S/Fe] = 0.8 where [S/Fe] = 0 is anticipated for a star with

TABLE 6

ELEMENTAL ABUNDANCES FOR RV TAU

		PRESENT WORK		KP	
SPECIES	$\log \epsilon_{\odot}$[a]	[X/H]	[X/Fe]	$\phi = 0.26$ [X/Fe]	$\phi = 0.76$ [X/Fe]
C I	8.85	+0.38	+0.82	...	...
O I	8.87	−0.18	+0.26	+0.26	...
Na I	6.32	+0.15	+0.59	+0.53	...
Mg I	7.58	...	...	−0.02	−0.16
Al I	6.43	−0.43	−0.01	−0.12	+0.08
Si I, II	7.55	−0.33	+0.11	−0.05	+0.08
Ca I	6.35	−0.48	−0.04	−0.11	−0.16
Sc II	3.13	−0.35	+0.09	−0.26	−0.38
Ti I, II	4.98	−0.53	−0.09	−0.28	−0.20
V I	4.01	...	...	−0.11	−0.32
Cr I, II	5.67	−0.28	+0.16	−0.05	−0.06
Mn I	5.46	−0.40	+0.04	+0.34	−0.04
Co I	4.91	−0.50	+0.06	...	...
Ni I	6.25	−0.50	+0.06	−0.11	−0.12
Zn I	4.62	+0.02	+0.42	+0.09	+0.09
Y II	2.23	−0.95	−0.51	−0.64	−0.56
Zr II	2.60	...	...	−0.74	...
La II	1.21	−0.73	−0.29	−0.09	−0.37
Ce II	1.58	−1.03	−0.59	−0.45	−0.90
Pr II	0.75	−0.68	−0.24	...	...
Nd II	1.48	−0.63	−0.19	−0.49	−0.46
Sm II	0.99	−0.75	−0.31	−0.41	...
Eu II	0.52	−0.33	+0.11	−0.20	−0.09

[a] The solar abundances are taken from Grevesse et al. 1996.

[Fe/H] = 0.1. A high S/Fe ratio is a signature of dust-gas separation, but this is an unlikely explanation in this case because [Zn/Fe] = 0.1 and, if the S is undepleted, an extraordinary initial abundance $[Fe/H] \simeq 0.8$ is implied. Klochkova & Panchuk acknowledge the sulphur problem and suppose it reflects non-LTE effects. A search of our spectrum for S I lines was unsuccessful; upper limits to the equivalent widths of the leading lines give $[S/Fe] \leq 1.1$. Confirmation of the sulphur abundance should be sought.

The abundances suggest that RV Tau has not been subject to a dust-gas separation. With few exceptions, elements up to and including the iron peak have normal abundances for [Fe/H] = −0.4. Notably, the high-T_c elements Al, Ca, Sc, and Ti show normal (solar) ratios relative to Fe to within 0.2 dex. Sodium ([Na/Fe] = 0.6) appears overabundant, a not unusual result for supergiants. Zinc with [Zn/Fe] = 0.4 is overabundant and might indicate that all elements with $T_c > 1200$ K are depleted slightly. However, Klochkova & Panchuk find [Zn/Fe] = 0.1. Elements heavier than zinc appear slightly underabundant with a mean value [X/Fe] = −0.3. Klochkova & Panchuk's abundances give a similar underabundance.

3.9. *Other Stars*

Abundance analyses for additional stars have been reported: AI CMi (Luck & Bond 1989; Klochkova & Panchuk 1998) and RU Cen (Luck & Bond 1989). In addition, two recent analyses of AC Her have been published (Klochkova & Panchuk 1998; Van Winckel et al. 1998). Lloyd Evans (1999) has proposed that LR Sco be included among RV Tauri variables, a star previously analyzed by Giridhar et al. (1992). These data are reviewed in the light of the dust-gas scenario.

3.9.1. *AI Canis Minoris*

The iron abundance estimates agree to 0.1 dex: [Fe/H] = −1.14 (Klochkova & Panchuk) and −1.02 (Luck & Bond). Abundance ratios [X/Fe] agree to within 0.1 dex in the mean with a scatter of ±0.3 about this value. The α-elements are slightly overabundant. Judged by the Al, Ca, Sc, and Ti abundances, the atmosphere is unaffected by dust-gas separation. The zinc abundance determined solely by Klochkova & Panchuk is overabundant with [Zn/Fe] = 0.7, but it is based on a single line. Klochkova & Panchuk report a normal abundance for *s*-process elements: [*s*/Fe] = 0.0 (Y), −0.2 (Zr), 0.0 (Ba), and −0.1 (La) for elements represented by two or more lines, with *r*-process Eu at [Eu/Fe] = 0.3 showing the expected slight enrichment (Woolf et al. 1996). If the same criterion (two or more lines) is applied to Luck & Bond's analysis, the *s*-process elements appear slightly underabundant: [*s*/Fe] = −0.1 (Zr), −0.4 (La), and −0.5 (Nd) with Eu at [Eu/Fe] = 0.0.

These analyses are consistent in showing that AI CMi has an intrinsic [Fe/H] = −1.0 and is probably unaffected by dust-gas separation. We identify it as a RVC star. A radial velocity has not been published. It should be noted that it appears to be substantially cooler than the RVC stars analyzed by us; Klochkova & Panchuk estimate $T_{\rm eff}$ of 4100–4500 K from three spectra but our RVC stars have $T_{\rm eff}$ in the interval 5300–6500 K.

3.9.2. *RU Centauri*

Luck & Bond (1989) found [Fe/H] = −1.4. The Ca, Sc, and Ti abundances (relative to Fe) appear normal to within the errors of measurement, as do the two *s*-process elements Ba and Nd. The star that was reported to have a high O abundance ([O/Fe] = 1.4) is known for its strong CH band (Lloyd Evans 1974). It would be of interest to determine the C/O ratio. In light of the fact that several dust-gas affected stars show no additional depletion of Ca, Sc, and Ti (relative to Fe) but markedly anomalous S/Fe and Zn/Fe ratios, we defer a decision on whether RU Cen is affected until S and Zn abundances are provided. It is a RVB variable and, therefore, almost certainly affected (see below).

3.9.3. *AC Herculis*

Our analysis of AC Her from spectra at two different phases was given in Paper IV. Two recent papers (Klochkova & Panchuk 1998; Van Winckel et al. 1998) provide independent analyses. Results of all three analyses are summarized in Table 7. A surprising result is the lack of consistency in the absolute abundances, for example, [Fe/H] = −1.4 (Paper IV), −0.8 (KP), and −1.7 (VW). It would be of interest to know how much of this spread is due to different analytical tools and how much to a failure of the common approach (theoretical static model atmospheres, assumption of LTE etc.) when applied to a pulsating star. Notwithstanding the differences in absolute abundances, all three analyses agree that the dust-gas separation is strikingly evident for AC Her. Relative abundances [X/Fe] are in generally satisfactory good agreement: the mean difference δ(X) between Paper IV and Van Winckel et al. is a pleasing -0.05 ± 0.14, and slightly larger with a bigger spread between Paper IV and Klochkova & Panchuk with the mean $\delta(X) = 0.2 \pm 0.4$. There is a difference in the C/O

TABLE 7

ELEMENTAL ABUNDANCES FOR AC Her

Species	log $\epsilon_\odot$[a]	Paper IV [X/Fe]	KP [X/Fe]	VW [X/Fe]
C I	8.85	+1.08	+0.85	+1.03
O I	8.87	+1.16	+0.34	+1.14
Na I	6.32	+0.60	+0.39	+0.78
Mg I	7.58	+0.25	−0.26	+0.37
Al I	6.43	−1.00	−0.14	...
Si I, II	7.55	+0.46	+0.05	+0.50
S I	7.27	+1.03	+0.56	+0.94
K I	5.12	+1.17	+0.37	...
Ca I	6.35	−0.08	−0.23	+0.01
Sc II	3.13	−0.30	−0.31	−0.28
Ti I, II	4.98	−0.24	−0.31	−0.28
V I	4.01	+0.08	+0.14	...
Cr I, II	5.67	−0.07	−0.03	+0.06
Mn I	5.46	+0.40	−0.08	+0.08
Co I	4.91	+0.48	...	...
Ni I	6.25	−0.01	−0.11	+0.06
Cu I	4.27	...	+0.20	+0.45
Zn I	4.62	+0.47	+0.69	+0.69
Y II	2.23	−0.48	−0.27	−0.65
Zr II	2.60	...	−0.42	−0.23
Ba II	2.17	−0.22	−0.17	+0.10
La II	1.21	...	+0.43	+0.01
Ce II	1.58	−0.20	+0.20	−0.25
Pr II	0.75	...	+0.67	+0.09
Nd II	1.48	−0.19	−0.04	−0.20
Sm II	0.99	...	+0.34	+0.13
Eu II	0.52	...	+0.44	...

[a] The solar abundances are taken from Grevesse et al. 1996.

ratio: we and Van Winckel et al. find the atmosphere to be O-rich (C/O = 0.4), but Klochkova & Panchuk find it to be C-rich (C/O = 1.5).

3.9.4. *LR Scorpii*

An identification of LR Sco as a post-AGB star was mooted by Giridhar et al. (1992) on the basis of its infrared excess and common abundance anomalies with 89 Her. In general, LR Sco's anomalies are those we now associate with dust-gas separation: low Ca and Sc abundances were noted with [Ca/Fe] = -0.3 and [Sc/Fe] = -0.6 but [S/Fe] = 0.5. One oddity is the published Zn abundance corresponding to [Zn/Fe] = -0.3 where a value closer to $+0.3$ would be expected from dust-gas separation. Possibly, the tabulated Zn abundance is a typographical error. If the Zn abundance is set aside, LR Sco appears to be mildly affected by dust-gas separation.

4. DUST-GAS SEPARATION: THE REQUIREMENTS

Atmospheres underabundant in those elements that condense out of cooling gas into dust grains have now been discovered for several types of stars: λ Boötis (main sequence) stars (Venn & Lambert 1990), the post-AGB stars (Venn & Lambert 1990; Bond 1991; Van Winckel, Mathis & Waelkens 1992), and, most recently, ST Pup, a W Vir or type II Cepheid variable, (Gonzalez & Wallerstein 1996),[5] and several RV Tauri variables. It is likely that the RV Tauri variables evolve into post-AGB stars but unlikely that all post-AGB stars have evolved from RV Tauri variables (Jura 1986). The λ Boo stars are a quite unrelated class of stars.

The basic idea that is referred to as a dust-gas separation is readily described as a four-step process: dust grains condense out of cooling gas at a site exterior to the stellar atmosphere, a "phase separation" of dust from gas occurs at the site, gas from the site is accreted by the stellar atmosphere, and the accreted gas remains in the atmosphere largely unmixed with the envelope below the atmosphere. One may identify some general requirements to produce an observable abundance anomaly and broad conditions under which the requirements may be satisfied:

Requirement A.—Accretion by a stellar atmosphere of gas of anomalous composition will result in observable abundance anomalies provided that the accreted gas is not diluted through convection or other processes with a much larger subatmospheric reservoir of normal composition.

Qualitatively, this condition is met by the λ Boo and post-AGB stars. The RV Tauri variables span a range in effective temperature. The hottest examples, F-type supergiants, overlap the cooler post-AGB stars. The coolest examples are late K to early M supergiants with presumably substantial outer convective envelopes.

Requirement B.—After dust grains have formed and been separated at least partially from the gas, the star must accrete gas. The efficiency of this accretion process is likely to depend on the relationship between the affected star and the source of the cooling gas in which the dust-gas separation occurs. Two broad possibilities may be noted:

1. The star affected by dust-gas separation may be both the source of the cooling gas and the receiver of the cleansed gas. A pertinent example is a star with dust-gas separation occurring in its stellar wind. In order to achieve the required return of gas (not dust) to the atmosphere, either the outflow must be intermittent at least near the base of the wind or asymmetric with outflow over parts of the surface with inflow of gas occurring elsewhere from layers affected by dust-gas separation.

2. The cooling gas is exterior to the affected star that accretes gas. An example might be a binary system in which gas is accreted from a circumbinary disk containing material ejected from one or other of the stars in the binary. If the ejection occurred long previously, accretion of this gas suffices to create abundance anomalies on the post-AGB star at least up to the time that the reservoir is exhausted.

Requirement C.—A mixture of dust and gas near a star is subject to radiation pressure with the dust grains experiencing by far the greater force. Thus, the separation of dust from gas is encouraged by the radiation pressure on the grains and discouraged by the drag of the gas on the grains. It is reasonable to assume that the star with the anomalous abundances is the source of the radiation pressure. The luminosity of this star is a factor promoting dust-gas separation. Since hydrogen and helium atoms outnumber all other species by a large margin, the drag on a grain is independent of the metallicity of the cooling gas, i.e., the metallicity of the star.[6]

Requirement D.—A requirement that dust form in a region from which gas may be subsequently accreted by the star is transparently obvious. Its implications, however, may be fundamental to understanding the key observables on which the observed abundance anomalies may depend. In its crudest form, the requirement means that the timescale for dust formation must be shorter than the time for which the gas is cold. Interpretation of this condition depends on the physical conditions experienced by the gas. For example, consider two identical parcels of gas with one maintained at constant temperature and density, and the other subjected to periodic shocks propagating out from a pulsating star's atmosphere. It is clear that requirement *C* will lead to different constraints on physical conditions and gas composition, and, in the second example, on pulsation properties. Metallicity will influence the time required to assemble a grain; this time at a fixed density and temperature will scale approximately as M^{-2} where M is the abundance of a grain constituent. In locations where physical conditions are changing, inadequate grain formation may occur in low-metallicity gas to sustain a dust-gas separation. Under constant physical conditions, as, perhaps, in a circumbinary disk, the limiting metallicity may be lower.

5. DUST-GAS SEPARATION: OBSERVATIONS AND CORRELATIONS

Our previous papers in this series suggested that the abundance anomalies arising from dust-gas separation were common but not universal among RV Tauri variables. This paper adds a new dimension to the circumstances under which anomalies are absent. In this section, we present the

[5] Lloyd Evans (1983) in a report on type II Cepheids noted the similarity of ST Pup's spectrum to that of the RVB variables. One presumes that the other type II Cepheids are not affected by dust-gas separation.

[6] Earlier, we implied that the drag on a grain in low-metallicity gas was higher than in high-metallicity gas because of a less favorable dust to gas ratio (Gonzalez & Lambert 1997). We thank Ruth Knill-Ngani for pointing out our error.

TABLE 8

OBSERVED AND INFERRED PROPERTIES

STAR	TYPE		P		ABUNDANCE										DG–INDEX
	Spectral	Photometric	(days)	$\langle B-V \rangle_0$	[S/H]	[Zn/H]	[Ca/H]	[Sc/H]	[Ti/H]	[S/X]	[Fe/H]	$[Fe/H]_0$	C/O	
DY Aql	A?	?	131.4	...	...	...	−1.2	−2.1	...	...	−1.0	...	...	1
TW Cam	A	a	85.6	0.90	0.0	−0.4	−0.6	−0.5	−0.7	0.0	−0.5	−0.4	2.5	0
SS Gem	A	a	89.3	...	−0.4	0.0	−1.1	−1.9	−2.0	+0.4	−0.9	−0.2	0.5	3
U Mon	A	b	92.2	1.00	−0.1	−0.6	−0.8	−1.0	−0.6	−0.1	−0.8	−0.5	0.8	0
TT Oph	A	a	61.1	1.00	0.0	−0.8	−1.1	−1.1	−0.8	−0.1	−0.8	−0.8	0.5	0–1
R Sct	A	a	140.2	1.27	...	−0.3	−0.6	−1.4	−0.4	−0.4	−0.4	−0.3	0.7	1
R Sge	A	b	70.8	...	+0.4	−0.2	−1.0	−1.5	−1.3	0.0	−0.5	+0.1	0.1	3
RV Tau	A	b	78.7	1.50	...	0.0	−0.5	−0.3	−0.5	−0.3	−0.4	−0.4	1.7	0
CE Vir	A	?	67:	...	...	−0.7	−1.5	−2.6	−1.3	−0.3	−1.2	−0.7	...	1–2
AD Aql	B	a	66.1	0.75	0.0	−0.1	−2.2	−1.8	−2.6	−0.3	−2.1	−0.1	0.4	2
UY Ara	B	?	57.2	0.66	0.0	−0.4	−1.1	−1.7	...	...	−1.0	−0.3	...	3
IW Car	B	b	72.0	...	+0.4	−0.1	...	...	...	0.0	...	+0.2	2.1	3
AC Her	B	a	75.0	0.65	−0.4	−0.9	−1.5	−1.7	−1.6	0.0	−1.4	−0.7	0.4	2
EP Lyr	B	a	83.3	...	−0.6	−0.7	−1.8	−2.1	−2.0	0.0	−1.8	−0.7	0.2	2
CT Ori	B	?	135.5	...	−0.5	−0.6	−1.8	−2.6	−2.5	+0.2	−1.9	−0.6	0.5	4
DY Ori......	B	?	60.3	...	+0.2	+0.2	−1.7	< −2.7	...	−0.3	...	+0.2	0.3	3
AR Pup	B	b	77.8	...	+0.4	...	−1.4	−2.2	...	0.0	...	+0.2	0.2	4
DS Aqr......	C	a	78.2	0.54	−0.8	−1.1	−1.0	−1.2	...	0.0	−1.1	−1.1	0.05	0
V360 Cyg ...	C	a	70.4	0.58	−0.9	−1.4	−1.3	...	−1.3	0.0	−1.4	−1.3	< 0.10	0
BT Lib	C	?	75.3	0.45	−0.8	−1.1	...	−0.7	...	0.0	−1.1	−1.1	< 0.05	0
V453 Oph...	C	a	81.3	0.45	...	...	−1.9	−2.2	−1.9	+0.2	−2.2	−2.2	0.5	0?

observational clues to the basics of dust-gas separation. Pertinent data on 21 stars given in Table 8 include the spectroscopic and photometric type, the pulsation period, the unreddened mean $B-V$ color, selected abundances as well as the inferred initial iron abundance $[Fe/H]_0$ (see Paper IV), the C/O ratio.

It must be recognized that not only the scale of the anomalies differs from one star to the next, but the pattern of the anomaly may differ. We introduce an index DG (dust-gas) to denote five gradations of the abundance anomalies:

1. *DG0*.—The abundance anomalies are absent: DG0 stars include the RVC stars (e.g., DS Aqr) and a majority of the observed RVA stars (e.g., TW Cam).
2. *DG1*.—Abundance anomalies are confined to the elements with the highest predicted T_c, i.e., Al, Ca, Sc, and Ti. Our results suggest that Sc is generally more depleted than the others and Ca and Ti may be normal (relative to Fe) when Sc is quite severely underabundant. Our prototypical DG1 star is R Sct. Possible members include DY Aql and CE Vir, for which the abundance data is incomplete at present, particularly lacking are the S, Ti, and Zn abundances for DY Aql, and the S, and Ca abundances for CE Vir.
3. *DG2*.—The abundance anomalies extend to iron and elements of a similar lower T_c than Sc with no measurable difference in magnitude, i.e., $[Sc/Fe] \simeq 0$. Representatives of this group are EP Lyr and AC Her.
4. *DG3*.—The abundance anomalies decrease with decreasing T_c, i.e., $[S/Fe] > 0$ and $[Sc/Fe] < 0$. Examples of DG3 stars are SS Gem and UY Ara.
5. *DG4*.—The pattern of abundance anomalies is that of a DG3 star but more severe, i.e., $[S/Sc] > 2$ for DG4. Examples of DG4 stars are IW Car and AR Pup.

The index assigned to individual stars is given in Table 8.

5.1. *Infrared Excesses*

A simple model of dust-gas separation would predict a correlation between the abundance anomalies and an infrared excess that measures the circumstellar dust. Near-infrared excesses were measured and discussed by Lloyd Evans (1985) and Goldsmith et al. (1987). In Figure 4 we present the two-color diagram $J-K$ versus $K-L$ based on their measurements. Stars are identified by name and distinguished according to the presence (filled circle denotes DG1, 2, 3, and 4 stars) or absence (open circle denotes DG0 stars) of abundance anomalies. (A finer distinction between DG1, 2, 3, and 4 is uninformative, perhaps because the sample sizes are small.) A few stars are not plotted for lack of measurements. The presence or absence of an infrared excess can be judged from the $J-H$ versus $H-K$ diagram for three additional stars: AD Aql has a very slight excess, and DS Aqr and V453 Oph have the colors of unreddened stars. Three stars—V360 Cyg, EP Lyr and CE Vir—lack published *JHKL* photometry. Infrared excesses detected from *JHKL* photometry arise from warm dust, i.e., dust close to the star. For stars (UY Ara, RU Cen, AC Her, BT Lib, and R Sge) without a substantial excess at longer wavelengths, Goldsmith et al. estimated dust shell radii in the range of 4–12 stellar radii and dust temperatures of 600 to 2000 K.

Spectral energy distributions published by Goldsmith et al. show that the principal flux excess of some RV Tauri stars occurs at longer wavelengths indicating the presence of cooler dust. Gehrz (1972) and Gehrz & Ney (1972)

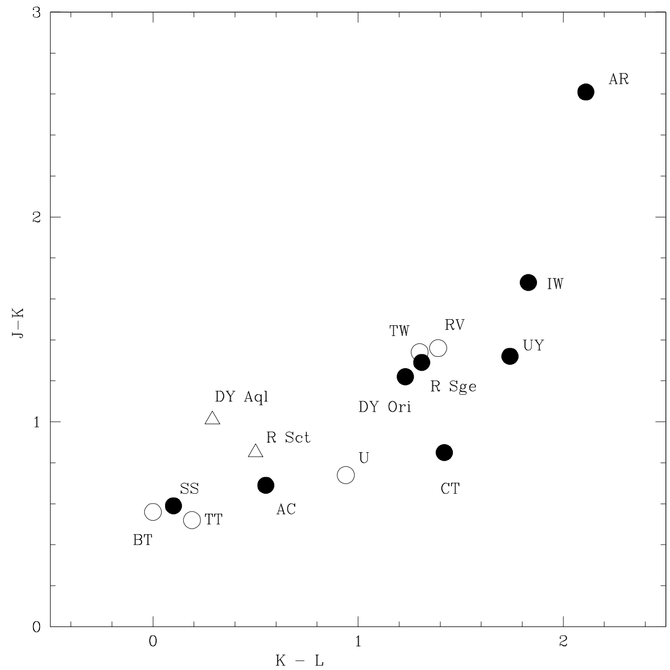

FIG. 4.—Color-color $J-K$ vs. $K-L$ plot. Open circles denote stars unaffected by dust-gas separation (DG0 stars; see text). Filled circles denote stars affected by the dust-gas separation (DG1–4 stars; see text). Stars are identified by their GCVS designation omitting the name of the constellation except that, to avoid confusion, DY Ori, DY Aql, R Sge and R Sct are noted in full.

reported 11.3 μm photometry for many of our stars. We put the *IRAS* 12 μm fluxes on the Gehrz scale to provide results for additional stars. Data for 16 of our 21 stars are shown in the $J-K$ versus $J-[11.3]$ diagram (Fig. 5).

Inspection of Figures 4 and 5 suggests one firm conclusion: an infrared excess is not a guarantee that the star is affected by dust-gas separation. At $J-K \lesssim 1.5$ and $J-[11.3] \lesssim 6.5$, unaffected (DG0) and affected (DG1-4) stars are intermixed: dusty RV Tau and U Mon show no convincing evidence for dust-gas separation, and AD Aql and SS Gem with striking abundance anomalies show little evidence for a dusty shell. It is true that the reddest trio of stars in both figures are severely affected by dust-gas separation so perhaps there is a critical infrared excess above which dust-gas separation is necessarily pronounced.

Infrared excess is an incomplete measure of the total presence of dust; the strength of the excess depends on the chosen wavelengths or, equivalently, on the temperature distribution of the dust. This is well shown by inspection of the *IRAS* colors (Raveendran 1989): ranked by the [12]–[25] index, the reddest five objects in our sample in order of decreasing index are DY Ori, AC Her, IW Car, CT Ori, and RV Tau, but ranked by $K-L$ color the reddest five are AR Pup, IW Car, UY Ara, CT Ori, and RV Tau. It appears that the presence of an infrared excess is not a sufficient requirement for an atmosphere to show effects of dust-gas separation. The reddest object at [12]–[25] is the RVB star RU Cen, a run of the mill object in $J-[11.3]$ (= 4.9) and $K-L$ (= 0.50). Unfortunately, too little is known presently about its composition to determine if dust-gas separation has occurred. It probably has as all RVB stars in our sample are affected.

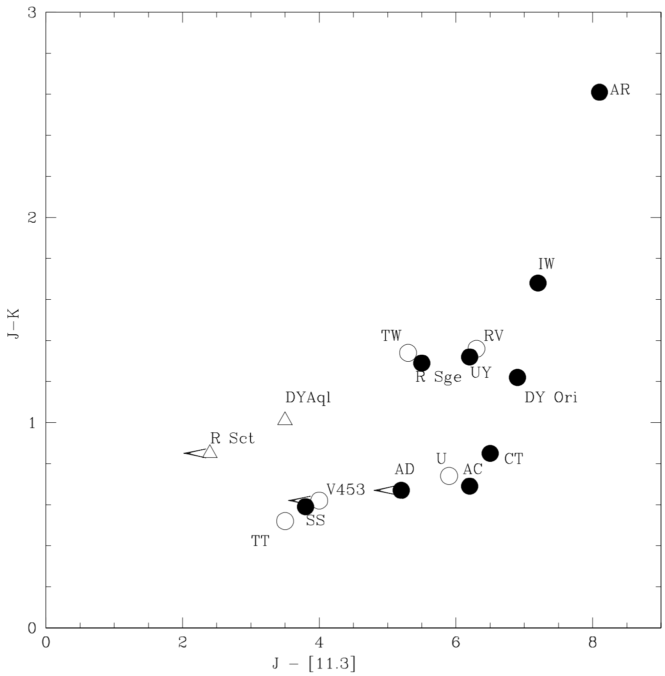

FIG. 5.—Color-color $J-K$ vs. $J-[11.3]$ plot. Open circles denote stars unaffected by dust-gas separation (DG0 stars—see text). Filled circles denote stars affected by the dust-gas separation (DG1-4 stars; see text). Stars are identified by their GCVS designation omitting the name of the constellation except that, to avoid confusion, DY Ori, DY Aql, R Sge, and R Sct are noted in full. Three stars are marked by arrowheads because an upper limit not a measurement of their [11.3] is available.

5.2. *Effective Temperature*

Inspection of Table 8 shows that *all* RVB stars are affected by dust-gas separation, but only two (R Sge and SS Gem) of the RVA stars are markedly affected. This dichotomy in large measure was anticipated by the spectroscopic definition of the RVB stars: blue spectra show strong bands of CH and CN, but the metal lines are weak relative to MKK standards. In contrast the RVA stars show strong metal lines. A second difference may hold a key to understanding the dust-gas separation: the RVA stars are generally of later spectral type and so cooler than the RVB stars. Lloyd Evans (1974) provides a clear statement of the defining spectroscopic characteristics of the RVA, B, and C stars.

A simple measure of the difference between RVA and RVB is provided from the temperatures derived from our spectra. Recall that spectra were selected for analysis only if the lines were single and symmetric, a condition met only over a particular phase range in the pulsation. The derived temperatures for the RVB stars are clearly warmer than for the RVAs. A temperature $T_{\rm eff} < 5000$ K is common for the RVAs but the minimum temperature recorded for a RVB is 4750 K at one phase for SS Gem with two other observations providing 5500 K and 6500 K. The difference in $T_{\rm eff}$ between the two classes may be fundamental for controlling the dust-gas separation (see discussion of requirement *A* above) but not entirely responsible for the differences in their spectra to which the differences in composition arising from dust-gas separation must be a contributor.

Temperatures measured for the field RVC stars, which show no evidence for dust-gas separation, are in the same range as the RVB stars, with the exception of the cool RVC AI CMi. Of the variables in globular clusters,[7] three of the five analyzed by Gonzalez & Lambert (1997) and V1 in ω Cen analyzed by Gonzalez & Wallerstein (1994) are in the temperature range of the field RVC and RVB stars. Two may be cooler. Only V1 shows any signs of gas-dust separation, with its low [Al/Fe]. The range of [Fe/H] among ω Cen giants is quite large, -2.0 to -0.5 (Norris & Da Costa 1995 and references therein), so it is possible V1's original metallicity was much higher than its present [Fe/H] $= -1.8$. It seems safe to claim that the absence of dust-gas separation in the RVC (and some of the cluster) variables and in the RVA variables occurs for different reasons.

5.3. *Chemical Composition*

One striking correlation between abundance anomalies and metallicity noted earlier is confirmed here by the analyses of BT Lib, and V453 Oph. RVC variables do not show effects of dust-gas separation. Their composition is that expected of a star having the derived Fe abundance, i.e., α-elements are slightly enhanced. The fact that they are high-velocity objects also implies that they are intrinsically metal-poor. Similar variables in globular clusters confirm this result; the variables have the composition of red giants of their host cluster. Our small sample of RVC stars spans the metallicities [Fe/H] $= -2.2$ to -1.1. The warmer globular cluster stars are from clusters with [Fe/H] $= -1.2$ and -1.5. Metallicity, not effective temperature, appears to be the key parameter separating the immune RVC stars from the affected RVB stars, and distinguishing the RVC stars from the similarly immune RVA stars.

In discussing the metallicity of the RVB stars, the question arises as to what is the relevant metallicity: the measured [Fe/H] (or other abundance such as [Si/H] or [Mg/H]) or the [Fe/H] inferred from the (assumed) undepleted [S/H] and [Zn/H], a quantity designated $[\mathrm{Fe/H}]_0$ in Table 8 (see Paper IV)? The measured [Fe/H] range from -0.9 to -2.3 with $[\mathrm{Fe/H}]_0$ in the range 0.2 to -0.7. On noting that the lower limit for $[\mathrm{Fe/H}]_0$ is similar to the upper limit for the RVC stars, we could speculate that $[\mathrm{Fe/H}]_0 \simeq -0.8$ is a critical metallicity: dust-gas separation is effective for stars with initial [Fe/H] > -1.0 but ineffective for more metal-poor stars.

Two possible ways to account for the critical [Fe/H] come to mind. Suppose that the pulsation controlling the stellar wind of the RV Tauri variable is determined in part by the metallicity of the envelope, that is likely to be unaffected by dust-gas separation. If dust-gas separation occurs in the wind, it is the initial metallicity that (indirectly) determines the separation process. The critical [Fe/H] implies then that pulsational properties and their influence on dust-gas separation in the winds is weak for an initial [Fe/H] < -1 and strong for [Fe/H] > -1. A quite differ-

[7] Zsoldos (1998) has argued that the light curves of the half-dozen stars in globular clusters classified as RV Tau variables fail the photometric criteria of this class (as determined from the field RV Tau's), in particular the lack of alternating minima. While Zsoldos does make useful points concerning the real differences between the light curves of field and globular RV Tau's, we do not believe the differences are sufficient justification to remove them from the RV Tau class. Variations in the minima of globular cluster RV Tau's are in fact seen in the light curves (e.g., Martin 1938, 1940) and velocities (Wallerstein 1958). We suggest a new subcategory specific to globular cluster RV Tau's, RV(g).

ent example of control is possible if the dust-gas separation site is remote from the star, as in the case of gas ejected earlier by the star and recaptured. In the case of a binary, gas having the initial composition may be ejected by either star and stored in the circumbinary disk. If the metallicity is low, gas may escape the storage site before dust grains can form and dust-separation can begin. For neither of these examples is it yet possible to justify that the critical metallicity is the empirical limit of $[Fe/H] \simeq -1$.

The C/O ratio (Table 8) of the RVA and RVB stars indicates that the great majority of the stars are O-rich with a mean C/O of about 0.4 (the solar ratio) with a suspicion that C/O is higher for the RVA stars and, hence, for the DG0 and DG1 stars. Three stars are C-rich, the DG0 stars TW Cam and R Sge, and the DG4 star IW Car. The RVC stars are very C-poor with $C/O \sim 0.05$. To within the measurement errors, the C/O ratios of the O-rich stars are consistent with the idea that the stars have not experienced C enrichment through evolution on the AGB or by other means; the C/O ratios including those of the RVC stars are roughly consistent with initial abundances and a reduction of C at the first dredge-up.

Despite the few elements analyzed, often one element per star, it is clear that the stars are not enriched in the *s*-process elements. Enrichment is assessed by comparing abundances of *s*-process elements and abundances of iron-group elements of the same T_c. Table 8 gives the estimated $[s/X]$, which in some cases are revised from those in Paper IV. Not one star is convincingly enriched in *s*-process products. Certainly, none exhibit the enrichment typical ($[s/X] \sim 1$) of AGB stars that have experienced the third dredge-up. Unless there is a subtle systematic error in the abundance analyses or in the interpretation in terms of T_c, we must conclude that RV Tauri variables are not descended from thermally pulsing AGB stars.

5.4. *Binarity*

All severely affected ($[Fe/H] \lesssim -3$) post-AGB stars are in binary systems (Van Winckel et al. 1995), as are some of the less affected stars. What are thought to be single post-AGB stars are less affected by dust-gas separation. In addition, it is argued that some but not all of the binary post-AGB stars present evidence for a warm dusty disk (cf. Van Winckel et al. 1999) that was suggested by Waters et al. 1992 to be the site for the dust-gas separation. (One star—BD $+39°4926$—is well known for its lack of an infrared excess!)

This suggestion motivated Van Winckel et al. (1999) to search for a (causal) link between RV Tauri variables affected by dust-gas separation and binarity. Spectroscopic binary orbits have been determined for just three stars: AC Her (Van Winckel et al. 1998), U Mon (Pollard & Cottrell 1995), and EN TrA (Van Winckel et al. 1999). AC Her is seriously affected by dust-gas separation, but the RVA U Mon is unaffected. The composition of EN TrA is unknown. Other stars certainly show long-term velocity variations indicative of orbital motion: good examples are IW Car (Pollard et al. 1997), and EP Lyr (Paper II), both greatly affected by dust-gas separation.

Various proposals have been made identifying the long-term light variations of the RVb variables as a consequence of orbital motion (Percy 1993; Fokin 1994; Pollard et al. 1997). Van Winckel et al. (1999) extend an association of RVb and binary stars to include the RVa stars by noting that, if the dust around the stars is primarily located in the orbital plane, stars viewed at low inclination to the plane may show photometric variations with a period equal to the orbital period. A similar binary viewed at higher inclination will be deemed a RVa variable. Van Winckel et al. further adduce evidence, some previously forwarded by others, in support of a claim that the dust and gas around RV Tauri variables is trapped and stored in a circumbinary disk, and not in an outflowing wind fed by the star.

In Van Winckel et al.'s scenario, the RV Tauri stars affected by dust-gas separation are long-period binaries. Since their assumption was that all RVA and RVB variables are affected, their bold claim that " binarity is a widespread phenomenon in the RV Tauri class of objects " followed. Although our present results show that the RVA's are very largely immune, the proposed scenario is not directly refuted; the immunity of the RVA's may be due to more severe dilution of accreted gas by the thicker convective envelope of a cooler star. The alternative explanation that RVB's are binaries and RVA's are not is less plausible, not just because the RVA U Mon is a spectroscopic binary, but because it is difficult to understand why the small difference in effective temperature between the coolest RVB and the warmest RVA star is due to the presence of a companion to the RVB star. Van Winckel et al. appear to have overlooked the RVC stars and their immunity to dust-gas separation.

An extension of Van Winckel et al.'s proposal that 'binarity is a widespread phenomenon' to 'binarity is a universal phenomenon' for RV Tauri variables may be rejected on the grounds that it implies that the stellar pulsations are controlled by the presence of a companion. Peculiar stars owing their origin to membership in a binary are certainly known: the Barium stars are an outstanding example in which the " peculiar " composition of the Barium star is due to mass transferred from the companion that evolved first and reached the AGB before transferring *s*-process and C enriched material. But it is difficult to accept that the RV Tauri's pulsation is controlled by a distant companion. There is no evidence that the composition of RV Tauri stars is dominated by mass transfer to the extent that the envelope composition that determines pulsational properties are determined by a companion. Just conceivably, tidal distortion of the star's envelope influences the onset and form of the pulsation. That theoretical models (Tuchman et al. 1993; Fokin 1994) successfully identify the pulsations as driven by the partial ionization of the stellar envelope is evidence that the RV Tauri phenomenon is triggered inside the star and is unlikely to be controlled by an orbiting companion. Discovery of a well-defined single period-luminosity law for RV Tauri (and W Virginis) stars of the Large Magellanic Cloud (Alcock et al. 1998) suggests that the RV Tauri pulsations cannot be influenced greatly by a companion; such an influence would be expected to induce scatter in a *P-L* relation. Dust-gas separation effects may well be influenced by binarity but binarity is unlikely to be a universal phenomenon for RV Tauri stars. There is, however, a possible way to accommodate binarity. Many of the RV Tauri variables have luminosities corresponding to that of evolution off the early-AGB (or the RGB) at constant luminosity. Such early evolution is indicated by the fact that abundances of *s*-process elements are not enhanced relative to abundances of iron and other elements of similar condensation temperatures to the *s*-process elements. Perhaps, stars evolve prematurely off the AGB or RGB as a

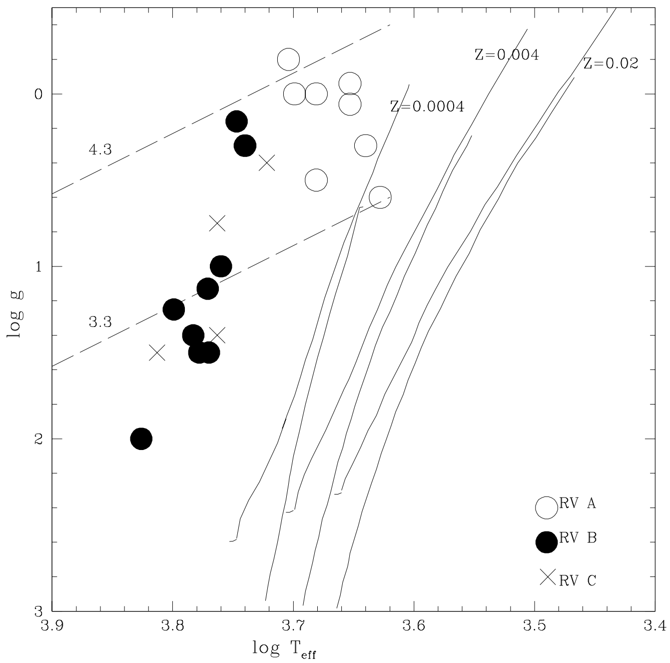

FIG. 6.—The log g vs. log $T_{\rm eff}$ diagram for RV Tauri variables. The dashed lines are tracks for a stellar mass of 0.8 $M_\odot$ evolving at the constant luminosity of log $L/L_\odot = 3.3$ (*lower line*) and 4.3 (*upper line*). The theoretical isochrones for an age of 10^{10} years and compositions $Z = 0.0004$, 0.004, and 0.02 (solar) include the RGB and the AGB that begins from the horizontal branch. The RV Tauri stars are denoted by their Preston spectroscopic class according to the legend on the figure.

result of mass-loss stimulated by the presence of a companion.

5.5. *Luminosity, Effective Temperature, and Surface Gravity*

A solid claim may now be made from the luminosities of the RV Tauri variables in globular clusters and especially of those in the Large Magellanic Cloud (Alcock et al. 1998) that the RV Tauri stars are loss mass objects evolving from red giants. The most luminous variables are most probably post-AGB stars evolving at constant luminosity (Schönberner 1993). RV Tauri stars of short period, W Vir, and BL Her variables have luminosities less than that of the tip of the first red giant branch and, therefore, could be post-RGB or post-AGB. Theoretical calculations (Gingold 1976) to support a post-AGB interpretation have been reported.

In the absence of accurate distance estimates[8] field RV Tauri variables, we compare observations and theory through the log g versus log $T_{\rm eff}$ HR-diagram (Fig. 6). Theoretical isochrones from Bertelli et al. (1994) are shown for three compositions from solar ($Z = 0.02$) to metal-poor $Z = 0.0004$ ([Fe/H] $\simeq -1.6$)

The period-luminosity law for RV Tauri (and W Vir) stars in the LMC (Alcock et al. 1998) provides accurate estimates of the stars' luminosities. If the bolometric correction is ignored, a 75 day RV Tauri has log $L/L_\odot = 3.7$, an estimate that increases by 0.1 to 0.2 dex depending upon the chosen bolometric correction. The slight metal deficiency of the LMC is typical of the field RVA stars. Variables in globular clusters provide a similar luminosity for metal-poor stars like the RVC variables (Gonzalez & Lambert 1997). Since the tip of the first giant branch is at log $L/L_\odot = 3.3$, these RV Tauri stars may be identified as post-AGB stars rather than post-RGB stars. Luminosities of our field RV Tauri stars may be calculated from the atmospheric parameters $T_{\rm eff}$, log g, and an assumed mass (here, 0.8 $M_\odot$). The mean value log $L/L_\odot = 3.4 \pm 0.2$ from 17 stars with periods in the range 60– 95 days is the luminosity of the tip of the red giant branch.

RV Tauri stars are compared in Figure 6 where log g is plotted versus log $T_{\rm eff}$. For stars observed more than once, straight means of log g and $T_{\rm eff}$ are plotted. In the event that the real stellar atmosphere is represented adequately by a standard (static) atmosphere, analysis of the stellar spectrum should return the correct g and $T_{\rm eff}$ and, hence, the actual L subject to an assumption about the stellar mass. Under such conditions, analyses of spectra obtained at different phases should fall on a line of constant L (log $g = 4$ log $T_{\rm eff}$ + log M/L). Multiple analyses of SS Gem and R Sge satisfy this requirement but those of EP Lyr and CE Vir may indicate a steeper slope. Several interesting correlations are revealed in Figure 6. The RVC and RVB stars define a single well-defined relation that is much steeper than a line of constant L. A great majority of these stars have periods in a narrow range (60–95 days) and, therefore, the relations seems unlikely to be a reflection of the P-L law directly. The slope could be accounted for if the isoperiod lines in the HR diagram have positive slope: more luminous stars being cooler than less luminous stars of the same period. Stars in our sample with the shortest (AR Pup) and longest (CT Ori) period are in the middle of the RVB distribution in Figure 6. Metallicity whether it is the initial or the current atmospheric value would seem not to affect the relation because RVB and RVC stars greatly differ in their metallicity. The temperature difference between RVA and RVB stars is striking in Figure 6 with the boundary at $T_{\rm eff} \simeq 5200$ K.

Post-AGB evolution occurs at approximately constant L. This implies that many RV Tauri variables evolve off the early AGB at a luminosity slightly in excess of log $L/L_\odot$ = 3.3. They are first RVA stars[9] and evolve to RVB stars developing the signature of dust-gas separation as the convective envelope disappears with increasing effective temperature. RV Tauri stars of lower luminosity presumably evolve even earlier from the AGB (or the RGB). Schönberner (1993) provides evolutionary tracks for post-AGB stars that run at constant luminosity to higher $T_{\rm eff}$ from the cool end of his calculations (log $T_{\rm eff} \simeq 3.8$). The predicted luminosity runs from log $L/L_\odot$ = 3.1–4.2 4.2 for core masses of 0.546 and 0.836 $M_\odot$, respectively. The luminosity spread of the RV Tauri stars is roughly consistent with the mean mass of about 0.6 $M_\odot$ for field white dwarfs.

Our demonstration that the s-process elements have a normal abundance would seem to preclude that the stars' predecessors were AGB stars that experienced the third dredge-up. Alcock et al. show that a single period-luminosity law fits RV Tauri variables and the shorter period W Vir or type II Cepheids. We estimate log $L/L_\odot \simeq$ 2.5 for a variable with a period of 8 days. These lower luminosities are consistent with theoretical proposals that

[8] The *Hipparcos Catalogue* has a parallax entered for eight of the stars in Table 8 but the errors are large in all cases. In no case is the quoted error less than 30% of the measurement.

[9] A phase as a SRd variable may occur first (Giridhar et al. 1999).

stars with a low-mass envelope pulsate like RV Tauri variables (Tuchman et al. 1993) and evolve into the instability strip from the AGB to which they may not return (Gingold 1976). Intriguingly, a low-mass envelope is a prerequisite for dust-gas separation to result in observable abundance anomalies.

6. WORKING HYPOTHESES AND OBSERVATIONAL PROGRAMS

General requirements for effective contamination of an atmosphere with gas from a region that experienced a dust-gas separation were stated earlier. Translation of such requirements into a theory making quantitative predictions is difficult. As an interim measure and a guide to observing programs, we advance a few working hypotheses that tie together the requirements and the observational clues. We offer two hypotheses according to whether the key processes operate in a single star (S) or a binary star (B).

The S hypothesis is as follows:

1. Abundance anomalies present in RVB stars result from a process of dust-gas separation in a star's circumstellar shell fed by a wind driven by the stellar pulsation.
2. The absence of the anomalies in a majority of the RVA stars is not necessarily due to the failure of dust-gas separation but to inefficient return of gas to the atmosphere and/or to the dilution of this gas by the deeper convective envelope of these cooler stars.
3. The absence of anomalies in the RVC stars is due to the inability of the dust-gas separation occurring in the stellar wind to operate efficiently in stars of low intrinsic metallicity.
4. The presence of RVB stars with an atmospheric iron abundance less than that of some RVC stars implies that the dust-gas separation is controlled by the abundance of an incondensable element and/or the controlling composition is that of the deep envelope that retains the star's initial composition.

The B hypothesis is as follows:

1. The extreme abundance anomalies seen in post-AGB stars that are long-period spectroscopic binaries result from dust-gas separation in material stored in a circumbinary disk of normal composition from which gas is accreted by the post-AGB star.
2. Binarity is a widespread phenomenon among RV Tauri stars.
3. Abundance anomalies of RV Tauri stars in long-period binaries result primarily from the process that operates in the post-AGB spectroscopic binaries.
4. The absence of anomalies in many RVA stars is accounted for as in the S hypothesis.
5. That the most metal-poor RV Tauri atmosphere is more metal-rich by a factor of about 100 than the most metal-poor post-AGB star is due to a combination of factors: the wind off the RV Tauri star reduces the rate of accretion from the circumstellar disk, atmosphere-envelope mixing is more effective for the RV Tauri stars, and the abundance anomalies of the RV Tauri stars have not yet achieved their maximum values owing to lack of time.
6. The lack of anomalies in RVC stars is due to the low metallicity of the circumbinary gas that inhibits grain formation and therefore the dust-gas separation; gas accreted by the star is not depleted in condensable elements.

The S and B hypotheses may operate in tandem. It seems improbable that a RV Tauri star must belong to a binary in order to pulsate in the characteristic manner of the class. A determination of the viability and relative importance of the hypotheses should be possible from continued observational efforts on two fronts: (1) abundance analyses should be extended to additional RV Tauri stars of all spectroscopic classes, and (2) a radial velocity program is needed to test the idea that spectroscopic binaries are unusually common among these variables. The latter test requires a long-term program to search for small amplitude orbital changes in the presence of a pulsational change. The need for theoretical work on dust-gas separation in the context of the S and B hypotheses is obvious.

Closer scrutiny of the accuracy of the abundance analyses is warranted. Particularly instructive would be a study of representative RVA, B, and C stars over a full pulsational cycle. Confidence in the present standard analysis will be enhanced if it can be shown that the derived composition is independent of the phase of the observation except over limited intervals. These spectroscopic campaigns may also serve to track gas flows out and back into the top of the stellar photosphere and, perhaps, so to see the dust-gas separated material flow into the atmosphere.

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REFERENCES

Alcock, C., et al. 1998, AJ, 115, 1921
Ashbrook, M.D. 1942, Ann. Harvard Coll. Obs., 109, No. 7
Bertelli, G., Bressan, A., Chiosi, C., Fagotto, F., & Nasi, E. 1994, A&AS, 106, 275
Boesgaard, A. M., King, J. R., Deliyannis, C. P., & Vogt, S. S. 1999, AJ, 117, 492
Bond, H. E. 1991, Evolution of Stars: the Photospheric Abundance Connection, ed. G. Michaud & A. V. Tutukov (Dordrecht: Kluwer), 211
Carney, B., Fry, A. M. & Gonzalez, G. 1998, AJ, 116, 2984
Edvardsson, B., Andersen, J., Gustaffson, B., Lambert, D. L., Nissen, P. E., & Tomkin, J. 1993, A&A, 275, 101
Fokin, A. B. 1994, A&A, 292, 133
Gehrz, R. D. 1972, ApJ, 178, 715
Gehrz, R. D., & Ney, E. P. 1972, PASP, 84, 768
Gillet, D., Duquennoy, A., Bouchet, P., & Gouiffes, C. 1989, A&A, 215, 316
Gingold, R. A. 1976, ApJ, 204, 116
Giridhar, S., Lambert, D. L., & Gonzalez, G. 1998, ApJ, 509, 366 (Paper IV)
Giridhar, S., et al. 1999, PASP, 111, 1261
Giridhar, S., Rao, N. K., & Lambert, D. L. 1992, J. Astrophys. Astron, 13, 307
———. 1994, ApJ, 437, 476 (Paper I)
Goldsmith, M. J., Evans, A., Albinson, J. S., & Bode, M. F. 1987, MNRAS, 227, 143
Gonzalez, G., & Lambert, D. L. 1997, AJ, 114, 341
Gonzalez, G, Lambert, D. L., & Giridhar, S. 1997a, ApJ, 479, 427 (Paper II)
———. 1997b, ApJ, 481, 452 (Paper III)
Gonzalez, G., & Wallerstein, G. 1994, AJ, 108, 1325
———. 1996, MNRAS, 280, 515
Gratton, R. G., & Sneden, C. 1987, A&A, 178, 179

Grevesse, N., Noels, A., & Sauval, A. J. 1996, in ASP Conf. Ser. 99, Cosmic Abundances, ed. S. S. Holt & G. Sonneborne (San Francisco: ASP), 117
Gustafsson, B., Karlsson, T., Olsson, E., Edvardsson, B., & Ryde, N. 1999, A&A, 342, 429
Israelian, G., García López, R., & Rebolo, R. 1998, ApJ, 507, 805
Joy, A. H. 1952, ApJ, 115, 25
Jura, M. 1986, ApJ, 309, 732
Kholopov, P. N., Samus, N. N., Durlevich, O. V., Kazarovets, E. V., Kireeva, N. N., & Tsvetkova, T. M. 1985, General Catalogue of Variable Stars (4th ed: Moscow: Nauka)
Klochkova, V. G., & Panchuk, V. E. 1998, Astron. Lett., 24, 650
Kukarkin, B. V., Parenago, P. P., Yu, N., & Kholopov, P. N. 1958, General Catalogue of Variable Stars (2d ed.; Moscow: Academy of Sciences of USSR)
Lambert, D. L. 1989, in AIP Conf. Proc. 183, Cosmic Abundances of Matter, ed. C. J. Waddington (Woodbury: AIP), 168
Lloyd Evans, T. 1974, MNRAS, 167, 17p
———. 1983, Observatory, 103, 276
———. 1985, MNRAS, 217, 493
———. 1999, in IAU Symp. 191, Asymptotic Giant Branch Stars, ed. T. Le Bertre, A. Lèbre, & C. Waelkens (San Francisco: ASP), 453
Lodders, K., & Fegley, B. 1998, in The Planetary Scientist's Companion (New York: Oxford Univ. Press)
Luck, R. E. 1981, PASP, 93, 211
Luck, R. E., & Bond, H. E. 1989, ApJ, 342, 476
Martin, W. C. 1938, BAN, 8, 290
———. 1940, BAN, 9, 60
McWilliam, A. 1997, ARA&A, 35, 503
Norris, J. E., & Da Costa, G.S. 1995, ApJ, 447, 680
Percy, J. R. 1993, in ASP Conf. Ser. 45, Luminous High-Latitude Stars, ed. D. D. Sasselov (San Francisco: ASP), 295
Percy, J. R., Bezuhly, M., & Milanowski, M. 1997, PASP, 109, 264
Pollard, K. R., & Cottrell, P. L. 1995, in ASP Conf. Ser. 83, Astrophysical Applications of Stelllar Pulsation, ed. R. S. Stobie & P. A. Whitelock (San Francisco: ASP), 409
Pollard, K. R., Cottrell, P. L., Kilmartin, P. M., & Gilmore, A. C. 1996, MNRAS, 279, 949
Pollard, K. R., Cottrell, P. L., Lawson, W. A., Albrow, M. D., & Tobin, W. 1997, MNRAS, 286, 1
Preston, G. W. 1962, ApJ, 136, 866
Preston, G. W., Krzeminski, W., Smak, J., & Williams, J. A. 1963, ApJ, 137, 401
Raveendran, A. V. 1989, MNRAS, 238, 943
Russell, S. C. 1997, A&A, 326, 1069
———. 1998, PASP, 15, 189
Schönberner, D. 1993, in IAU Symp. 155, ed. R. Weinberger & A. Acker (Kluwer: Dordrecht), 415
Sneden, C., & Crocker, D. A. 1988, ApJ, 335, 406
Tuchman, Y., Lèbre, A., Menessier, M. O., & Yarri, A. 1993, A&A, 271, 501
Tull, R. G., MacQueen, P. J., Sneden, C., & Lambert, D. L. 1995, PASP, 107, 251
Van Winckel, H., Mathis, J. S., & Waelkens, C. 1992, Nature, 356, 500
Van Winckel, H., Waelkens, C., Fernie, J. D., & Waters, L. B. F. M. 1999, A&A, 343, 202
Van Winckel, H., Waelkens, C., & Waters L. B. F. M. 1995, A&A, 293, L25
Van Winckel, H., Waelkens, C., Waters, L. B. F. M., Molster, F. J., Udry, S., & Bakker, E. J. 1998, A&A, 336, L17
Venn, K. A., & Lambert, D. L. 1990, ApJ, 363, 234
Wahlgren, G. M. 1992, AJ, 104, 1174
Wallerstein, G. 1958, ApJ, 127, 583
Wasson, J. T. 1985, Meteorites: Their Record of Early Solar System History (New York: Freeman)
Waters, L. B. F. M., Trams, N. R., & Waelkens, C. 1992, A&A, 262, 37
Wheeler, J. C., Sneden, C., & Truran, J. W. 1989, ARA&A, 27, 279
Woolf, V. M., Tomkin, J., & Lambert, D. L. 1996, ApJ, 453, 660
Zsoldos, E. 1998, Acta Astron., 48, 775