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The Chemical Compositions of the SRd Variable Stars. II. WY Andromedae, VW Eridani, and UW Librae

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ABSTRACT. Chemical compositions are derived from high-resolution spectra for three stars classed as SRd variables in the *General Catalogue of Variable Stars*. These stars are shown to be metal-poor supergiants: WY And with [Fe/H] $= -1.0$, VW Eri with [Fe/H] $= -1.8$, and UW Lib with [Fe/H] $= -1.2$. Their compositions are identical to within the measurement errors to the compositions of subdwarfs, subgiants, and less evolved giants of the same [Fe/H]. The stars are at the tip of the first giant branch or in the early stages of evolution along the asymptotic giant branch (AGB). There is no convincing evidence that these SRd variables are experiencing thermal pulsing and the third dredge-up on the AGB. The SRd variables appear to be at the cool limit of the sequence of RV Tauri variables.

1. INTRODUCTION

This series of papers presents and discusses determinations of the chemical compositions of the SRd variables for which the *General Catalogue of Variable Stars* (*GCVS*) (Kholopov et al. 1985) provides the following prosaic definition: "Semiregular variable giants and supergiants of spectral types F, G, K sometimes with emission lines in their spectra." This definition admits massive supergiants (e.g., ρ Cas) and high-velocity metal-poor low-mass supergiants (e.g., TY Vir) to the same club. Our goal is to identify and analyze the metal-poor low-mass stars by undertaking detailed abundance analyses of SRd variables listed in the *GCVS*. Presently, we have observed approximately 30 variables. Our primary interest is in the metal-poor low-mass stars.

In our first paper (Giridhar, Lambert, & Gonzalez 1998a, hereafter Paper I), we discussed four stars: XY Aqr, RX Cep, AB Leo, and SV UMa. The first two were shown to be of approximately solar metallicity and probably not variable stars. Both AB Leo and SV UMa were demonstrated to have a low metal abundance ([Fe/H] $\simeq -1.5$) and are certainly variable stars. Here, we discuss three acknowledged variables (Table 1) of high radial velocity and show that they are indeed metal-poor supergiants.

2. OBSERVATIONS AND ABUNDANCE ANALYSES

Spectra were obtained at the McDonald Observatory with either the 2.1 m telescope equipped with a Cassegrain echelle spectrograph and a Reticon 1200 × 400 pixel CCD (McCarthy et al. 1993) or the 2.7 m telescope and the 2dcoudé echelle spectrograph (Tull et al. 1995). Spectra were reduced and analyzed by procedures described in Paper I. Atmospheric parameters derived principally from the Fe I and Fe II lines are given in Table 2.

Our derived abundances are quoted to ±0.1 dex and given in Table 3 as $[X/H] = \log \epsilon(X/H) - \log \epsilon_{\odot}(X/H)$ and [X/Fe], where the H abundance is on the customary scale and solar abundances are taken from Grevesse, Noels, & Sauval (1996). The total error in the absolute abundance of a well-observed element may be about ±0.2 dex when the various sources of error (equivalent width, effective tem-

TABLE 1

THE PROGRAM STARS

Star	V (mag)	$\langle B-V \rangle$	$E(B-V)$	Spectral Type	Period (days)
WY And......	8.64–9.65	1.74	0.17	K5	109.6
VW Eri.......	9.20–11.0	1.45	0.03	K7	83.4
UW Lib......	9.30–10.6	1.48	0.01	K0	84.7

NOTE.—V and $B-V$ for WY And, VW Eri, and UW Lib from Zsoldos 1990, Eggen 1973, and Eggen 1977, respectively. $E(B-V)$ for all stars from Dawson 1979. Period for WY And from Zsoldos 1990 and *GCVS* for VW Eri and UW Lib.

perature, etc.) are considered. This does not include systematic errors arising, for example, from the adoption of LTE and the neglect of hyperfine splitting.

3. RESULTS AND DISCUSSION

3.1. VW Eridani

The SRd variables that are low-mass supergiants are cool stars with spectra that may contain TiO bands. Since these bands contribute many lines and reduce the number of unblended lines, we discuss the stars in order of increasing TiO band strength. Not surprisingly, the star not showing TiO bands is the most metal poor of the trio.

Our analysis shows VW Eri to have [Fe/H] = −1.8. This SRd is assigned a period of 83.4 days in the *GCVS* (Kholopov et al. 1985) and a high radial velocity by Preston (1971). Eggen (1973) published *UBVRI* photometry. Our spectrum and analysis fully confirm that the star is a metal-poor supergiant. The spectrum gives a heliocentric radial velocity of 146.5 ± 0.6 km s^{-1}, a value in agreement with Preston's results.

Our derived abundances as [X/Fe] are compared in Table 4 with those expected of an [Fe/H] = −1.8 star from analyses of metal-poor dwarfs and giants. Local field dwarfs and giants with very few exceptions show a common [X/Fe] at a given [Fe/H]. It is this common [X/Fe] for [Fe/H] = −1.8 that is given in Table 4. Sources for the expected [X/Fe] are as follows: Israelian et al. (1998) and Boesgaard et al. (1999) for O; Pilachowski, Sneden, & Kraft (1996) for Na; Gratton & Sneden (1988) for Mg; McWilliam (1997) for Al and Eu; Gratton & Sneden (1991) for Si, Ca, Sc, Ti, V, Cr, Mn, Co, and Ni; Gratton (1989) for Mn; Sneden, Gratton, & Crocker (1991) for Cu and Zn; and Gratton & Sneden (1994) for Y, La, Ce, Pr, Nd, and Sm. All of these references review previous literature on the elemental abundances and note the generally close agreement between the referenced results and other results. For many elements, the expected value of [X/Fe] should be accurate to about ±0.1 dex. The lack of scatter in [X/Fe] at a given [Fe/H] for samples composed of stars now in the solar neighborhood but originating from quite different parts of the Galaxy suggests that an SRd like VW Eri should have the expected pattern of abundances.

TABLE 2

STELLAR PARAMETERS DERIVED FROM THE Fe-LINE ANALYSES

UT DATE	MODEL[a] $T_{\rm eff}$, log g, [Fe/H]	ξ_t (km s^{-1})	Fe I[b] log ϵ	Fe I[b] n	Fe II log ϵ	Fe II n
		WY And				
1998 Jan 26..........	4300, 1.0, −1.0	2.3	6.50 ± 0.22	43	6.59 ± 0.15	8
		VW Eri				
1997 Dec 14.........	4500, 0.0, −1.8	2.3	5.78 ± 0.15	54	5.72 ± 0.16	20
		UW Lib				
1995 Jun 21, 23......	4300, 0.8, −1.3	3.5	6.29 ± 0.17	25	6.24 ± 0.19	5

[a] $T_{\rm eff}$ is in units of K, log g is in units of cgs, [Fe/H] is in units of dex.

[b] log ϵ is the mean abundance relative to H (with log $N_{\rm H}$ = 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.

TABLE 3

Compositions of WY And, VW Eri, and UW Lib

	WY And		VW Eri		UW Lib		
Species	[X/H]	*n*	[X/H]	*n*	[X/H]	*n*	log $\epsilon_{\odot}$ [a]
C I	−0.8	5	...	...	...	...	8.85
O I	−0.2	2	−1.0	3	−0.6	2	8.87
Na I	−1.2	1	−1.9	2	...	...	6.32
Mg I	−0.9	1	−1.5	1	−0.8	1	7.58
Al I	−1.3	3	−2.5	3	...	...	6.48
Si I, II	−0.9	5	−1.3	2	...	...	7.55
S I	−1.1	2	...	...	...	...	7.27
Ca I	−1.1	3	−1.7	14	−1.3	3	6.35
Sc I	−0.5	3	−1.7	8	−0.9	4	3.13
Ti I, II	−0.7	14	−1.4	10	−0.7	17	4.98
V I	−0.4	5	−2.2	4	−0.8	10	4.01
Cr I, II	−1.1	8	−2.1	16	−1.2	10	5.67
Mn I	−1.5	5	−2.2	8	−1.4	3	5.46
Fe I, II	−1.0	54	−1.8	74	−1.2	27	7.50
Co I	−0.6	3	−1.4	1	...	...	4.91
Ni I	−1.2	9	−1.9	21	−1.4	5	6.25
Zn I	−0.9	3	−1.8	2	...	...	4.63
Y II	−0.8	4	−1.9	6	−1.2	2	2.23
Zr I	−0.1	3	...	...	−0.5	6	2.60
Mo I	−0.5	1	...	...	...	...	1.94
Ru I	−0.2	1	...	...	...	...	1.83
Ba II	−1.0	2	...	...	...	...	2.17
La II	...	...	−1.9	3	...	...	1.20
Ce II	−1.2	5	−1.9	3	−0.9	2	1.60
Pr II	−0.4	1	−1.7	2	...	...	0.75
Nd II	−0.5	5	−1.7	14	...	...	1.50
Sm II	−0.7	13	−1.6	6	...	...	0.99
Eu II	−0.6	1	−1.1	2	...	...	0.55

Note.—The relative abundance [X/H] and the number of lines *n* are given.

[a] The weighted mean of the meteoritic and photospheric abundances from Grevesse et al. 1996.

There is surprisingly and probably fortuitously good agreement between the measured and common [X/Fe]. In particular, characteristic signatures of a metal-poor dwarf are found in the measured [X/Fe] of VW Eri: notably, an overabundance of the α-elements, an underabundance of Mn, and the underabundance of Cu in the presence of a normal Zn abundance. Two elements from Na to Eu with a difference of greater than ± 0.3 dex between observed and expected abundance are V and Eu. We assume that these differences are simply due to above average errors of measurement. Neglect of hyperfine splitting is not a likely source of error because the lines are weak. A more probable source is the possibility of blends affecting the weak lines. The strongest V I line, a 31 mÅ line, gives an abundance 0.3 dex less than the next strongest line at 14 mÅ.

The oxygen abundance is based on the 6300 Å [O I] line and the O I lines at 7774 and 7775 Å. The forbidden line gives a systematically lower abundance by about 0.4 dex. The mean abundance corresponds to [O/Fe] = 0.8, with the [O I] line giving [O/Fe] = 0.6. This discrepancy between forbidden and permitted lines is similar to the discrepancy between the same lines in spectra of subdwarfs. Israelian et al. (1998) obtain consistent determinations of the O abundance from OH ultraviolet and the O I 7770–7775 Å lines. Boesgaard et al. (1999) in an independent analysis obtain an identical result. The mean estimate from these recent determinations given in Table 4 is in good agreement with our measurement.

Heavy elements are well represented in the spectrum. The Ba II lines are rejected as unsuitable because they are very strong, with an indication that they are contaminated by a circumstellar component. With one exception, the heavy elements give [X/Fe] in the range −0.2 to +0.2, as expected from Zhao & Magain (1991) and Gratton & Sneden (1994); i.e., the star has not experienced enrichment of *s*-process products through the third dredge-up. The apparent exception is Eu, with [Eu/Fe] = 0.6. Observations of Eu show that this *r*-process element is enriched in normal metal-poor stars: Gratton & Sneden (1994; see also McWilliam's 1997 compilation) find [Eu/Fe] $\simeq$ 0.3, a value less than our estimate based on two Eu II lines.

In summary, VW Eri judged by composition is a normal

TABLE 4

Observed and Expected Compositions for VW Eri

Species	[X/Fe] Observed	Expected
O........	+0.8	+0.7
Na	−0.2	−0.2
Mg......	+0.3	+0.3
Si........	+0.4	+0.3
Ca	+0.1	+0.3
Sc	+0.1	0.0
Ti	+0.3	+0.3
V........	+0.3	0.0
Cr.......	−0.3	0.0
Mn......	−0.5	−0.4
Co	+0.3	−0.1
Ni.......	−0.1	0.0
Cu	−0.5	−0.6
Zr	0.0	0.0
Y........	−0.2	−0.2
La.......	−0.2	−0.1
Ce.......	0.0	−0.2
Pr	+0.1	+0.2
Nd	+0.1	0.0
Sm	+0.2	+0.1
Eu	+0.7	+0.3

red giant that has experienced the first dredge-up but not the third dredge-up on the asymptotic giant branch.

3.2. UW Librae

This SRd with a period of 84.7 days was studied extensively at low dispersion by Joy (1952), who noted the spectral type to vary from G0 to K4 and the radial velocity from 142 to 194 km s^{-1}. Photometry was provided by Eggen (1977). Our analysis is based on two Sandiford echelle spectra from 1995 June 21–23. The heliocentric radial velocity of 166 $\pm$ 2 km s^{-1} is within the range reported by Joy. The spectra provide coverage from 4450–4940 Å and 5770–7240 Å. Bands of TiO are quite prominent. The crowded spectrum limited our selection of useful lines. Results of the abundance analysis are given in Table 3. The star is clearly a metal-poor supergiant.[1]

Iron is underabundant, with [Fe/H] $= -1.3$. We consider UW Lib to have the expected composition for its [Fe/H]. The latter may be obtained for most elements by linear interpolation between the values given in Table 4 for [Fe/H] $= -1.8$ and [X/Fe] $= 0$ at [Fe/H]. The α-elements have approximately the same overabundance at [Fe/H] $= -1.0$ as at -1.8. Agreement between observed and expected values of [X/Fe] is not as good as in the case of VW Eri. We attribute this to the presence of TiO lines in many portions of the spectrum.

Oxygen based on the 6300 and 6363 Å [O I] lines has the abundance [O/Fe] $= 0.7$, which is consistent with recent measurements (Israelian et al. 1998; Boesgaard et al. 1999). The traditional α-elements have [α/Fe] $= 0.4$ (Mg), 0.0 (Ca), and 0.6 (Ti) when 0.3–0.4 is expected from analyses of the simpler spectra of warmer subdwarfs (McWilliam 1997). Given the crowded spectrum, the difference of up to 0.3 dex from expectation is plausibly attributable to measurement errors. The vanadium abundance [V/Fe] $= 0.5$ may be a reflection of our neglect of hyperfine splitting. There is marginal evidence for a mild enrichment of heavy elements with observed and expected initial abundances as follows: [Y/Fe] $= 0.2$ and -0.2, [Zr/Fe] $= 0.8$ and 0.0, and [Ce/Fe] $= 0.3$ and -0.1.

3.3. WY Andromedae

Photometry of WY And is reviewed by Zsoldos (1990), who showed the period to be about 108 days. Rosino (1951) and Joy (1952) found the spectral type to vary from G2 to K2. Our spectrum shows TiO bands with a strength greater than in the spectrum of UW Lib. Joy's radial velocity of -191 km s^{-1} is confirmed by our measurement of -193 ± 1.1 km s^{-1}. Results of our abundance analysis are summarized in Table 3.

Although there are no large differences between the observed composition and that expected for a red giant with [Fe/H] $= -1.0$ that has negotiated the first dredge-up but not yet encountered the third dredge-up, the overall agreement with expectation is noticeably inferior to that found for VW Eri and UW Lib. The α-elements do not give the expected uniform enhancement of about 0.3 dex: [Mg/Fe] $= 0.1$, [Si/Fe] $= 0$, [Ca/Fe] $= -0.3$, but [Ti/Fe] $= 0.3$. Aluminum and Mn deficiencies are in excess of expectation by about 0.2 dex: [Al/Fe] $= -0.3$ and [Mn/Fe] $= -0.6$. Heavy elements with a dominant contribution from the *s*-process are in the mean enriched with [*s*/Fe] $= 0.3$, but two of the three elements with five or more lines show no enrichment. Europium is even underabundant relative to iron: [Eu/Fe] $= -0.4$ from a single Eu II line, but [Eu/Fe] $= 0.3$ is expected. We attribute these discrepancies to the greater strength of the TiO bands in this more metal-rich star and to the enhanced probability of unsuspected blending with TiO lines. It seems unlikely that the apparent abundance anomalies in this star or UW Lib are due to the dust-gas separation that greatly affects some RV Tauri variables; Ca may be underabundant but Sc is not. Possibly, the star belongs to a stellar population whose initial composition differs from the standard or expected composition. Certainly, subdwarfs with [Fe/H] ~ -1 and anomalies relative to the standard composition are now known (Nissen & Schuster 1997; Jehin et al. 1999), but these

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[1] Dawson (1979) argued on the basis of reddening-corrected DDO photometry that UW Lib was a G dwarf of near-solar composition.

anomalies do not match well those found for WY And. Attribution of the latter to errors of measurement seems the most likely explanation.

Oxygen from the [O I] 6300 and 6363 Å lines corresponds to [O/Fe] = 0.7, a value that is approximately consistent with the latest estimates of the O abundance for metal-poor stars (Israelian et al. 1998; Boesgaard et al. 1999). A collection of three C I lines gives [C/Fe] = 0.3, which is the value found by Gustafsson et al. (1999) for disk dwarfs at [Fe/H] = −1. This would suggest that there has been some C enrichment following the first dredge-up's reduction of carbon on the first ascent of the red giant branch (RGB).

4. CONCLUDING REMARKS

Our analyses of WY And, VW Eri, and UT Lib and our earlier work on AB Leo and SV UMa show that the subset of SRd variables defined by weak metal lines and a high radial velocity are metal-poor supergiants with considerable similarities in composition that are traceable to the corresponding similarity of composition among metal-poor dwarfs, subgiants, and giants on the first red giant branch. To our collection may be added TY Vir (Luck & Bond 1985) and CK Vir (Leep & Wallerstein 1981).

In seeking the origins of the SRd variables, two obvious questions arise: How are the stars related to red giants on the RGB and AGB? What is the relationship between the SRd variables and the RV Tauri variables?

Clues to the answers may be sought from the theoretical "HR diagram" of log g versus log $T_{\rm eff}$. Figure 1 places our SRd stars in this diagram with RV Tauri stars drawn from our papers on the compositions of these stars (Giridhar, Rao, & Lambert 1994; Gonzalez, Lambert, & Giridhar 1997a, 1997b; Giridhar, Lambert, & Gonzalez 1998b, 1999). Because our analyses of RV Tauri and SRd variables have used common procedures, systematic differences between the two kinds of stars are unlikely to be due to errors in the analyses. Lines corresponding to constant luminosity L are drawn for log $L/L_\odot = 3.3$ and 4.3 and a stellar mass of 0.8 $M_\odot$. A theoretical isochrone for $Z = 0.0004$ or [Fe/H] $\simeq -1.6$ is also shown (Bertelli et al. 1994). Isochrones for higher metallicity are displaced to lower temperatures with very little change in the luminosity of the most luminous stars on the RGB and AGB. An increase from $Z = 0.0004$ to 0.004 shifts the RGB tip from (log g, log $T_{\rm eff}$) = (0.64, 3.64) to (0.22, 3.54) and the AGB tip from (−0.1, 3.60) to (−0.4, 3.50). The $Z = 0.0004$ isochrone is appropriate for VW Eri and AB Leo. The other stars are more metal rich, with the most metal rich (WY And) falling almost midway between $Z = 0.0004$ and 0.004.

Figure 1 shows that the SRd stars are either at the tip of the RGB or on the AGB at luminosities greater than the RGB tip. Lloyd Evans (1975) noted that red variables in metal-poor globular clusters are at the tip of a cluster's giant branch. An AGB star may be distinguished by a C and s-process enrichment provided that the third dredge-up has been activated. Our analysis is most accurate for VW Eri, which is neither C nor s-process enriched. There is a suspicion that WY And may be enriched, as may be AB Leo and SV UMa from Paper I. It remains to be discovered what sets an SRd variable apart from essentially identical giants that are not variable. Perhaps they are stars that have begun a process of strong mass loss or have lower mass envelopes as a result of earlier history.

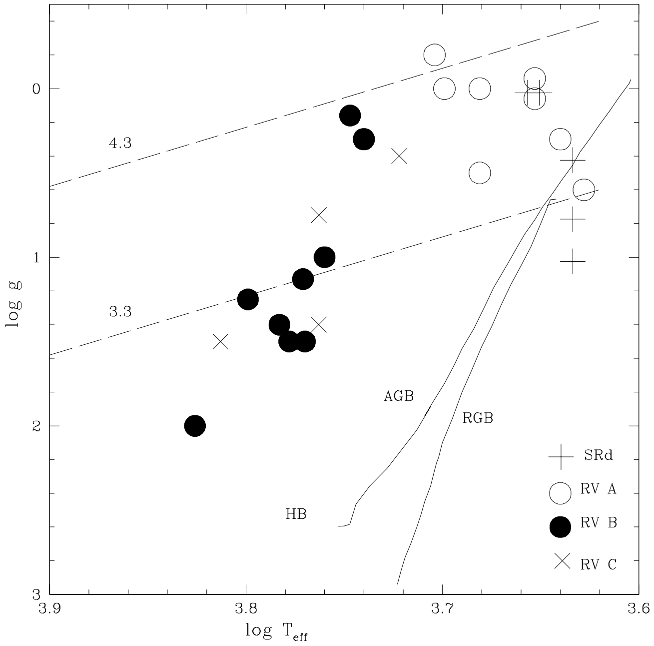

FIG. 1.—The log g vs. log $T_{\rm eff}$ diagram for SRd and RV Tauri variables. The dashed lines are tracks for a stellar mass of 0.8 $M_\odot$ evolving at the constant luminosity of log $L/L_\odot = 3.3$ (*lower line*) and 4.3 (*upper line*). A theoretical isochrone for an age of 10^{10} yr and the composition $Z = 0.0004$ or [Fe/H] $\simeq -1.6$ is shown with red giant, asymptotic giant, and horizontal branches labeled. SRd and RV Tauri variables of spectroscopic classes RV A, RV B, and RV C are distinguished by the symbols on the legend on the figure.

The period ranges for SRd and RV Tauri stars are similar, and the low-temperature end of the RV Tauri sequence abuts the SRd domain. It is difficult to accept that the stars are unrelated. Observed abundance anomalies of some RV Tauri stars (see our papers cited above) attributed to acquisition of dust-free gas by the stars are not in conflict with the suggested relation because our work (Giridhar, Lambert, & Gonzalez 1999) shows that the anomalies are not found in those RV Tauri stars that would be the closest relatives of SRd variables. RV Tauri stars that are intrinsically metal poor or cool do not exhibit abundance anomalies. A relation is suggested by Figure 1. RV Tauri variables from our series of papers on the compositions of these stars are represented by different symbols for the spectroscopic classes RV A, RV B, and RV C. It is seen that the SRd stars are at the low-temperature boundary of the RV Tauri regime, which corresponds to a belt bounded by lines of constant luminosity for log $L/L_{\odot} = 3.3$ and 4.3 assuming a stellar mass $M = 0.8\ M_{\odot}$. Evolution at constant luminosity from the red giant branch is a signature of post-AGB evolutionary tracks. The lower luminosity bound would correspond to evolution from the tip of the first giant branch. The upper luminosity bound suggests evolution off the AGB. An interpretation of Figure 1 is that SRd stars evolve into RV Tauri variables as they cross the Hertzsprung gap from low to high temperatures. Heavy mass loss has been hypothesized as the cause of the early departure from the AGB. Stellar pulsations occurring in the SRd and RV Tauri variables may be the driver of the mass loss. Premature departure from the AGB is not an unexpected phenomenon and has been invoked to account for the rarity of C-rich AGB stars in the Magellanic Clouds.

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