

## The Chemical Compositions of the SRd Variable Stars. III. KK Aquilae, AG Aurigae, Z Aurigae, W Leo Minoris, and WW Tauri

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**ABSTRACT.** Chemical compositions are derived from high-resolution spectra for five field SRd variables. These supergiants not previously analyzed are shown to be metal poor: KK Aql with  $[\text{Fe}/\text{H}] = -1.2$ , AG Aur with  $[\text{Fe}/\text{H}] = -1.8$ , Z Aur with  $[\text{Fe}/\text{H}] = -1.4$ , W LMi with  $[\text{Fe}/\text{H}] = -1.1$ , and WW Tau with  $[\text{Fe}/\text{H}] = -1.1$ . Their compositions are, except for two anomalies, identical to within the measurement errors to the compositions of subdwarfs, subgiants, and less evolved giants of the same  $[\text{Fe}/\text{H}]$ . One anomaly is an *s*-process enrichment for KK Aql, the first such enrichment reported for an SRd variable. The second and more remarkable anomaly is a strong lithium enrichment for W LMi, also a first for field SRd variables. The Li I  $\lambda 6707$  profile is not simply that of a photospheric line but includes strong absorption from redshifted gas, suggesting, perhaps, that lithium enrichment results from accretion of Li-rich gas. This potential clue to lithium enrichment is discussed in light of various proposals for lithium synthesis in evolved stars.

### 1. INTRODUCTION

This series of papers presents and discusses determinations of the chemical compositions of the SRd variables. Of this mixed bag, we are analyzing the Population II members. In our first paper (Giridhar, Lambert, & Gonzalez 1998, Paper I), we discussed four stars—XY Aqr, RX Cep, AB Leo, and SV UMa—of which AB Leo and SV UMa were demonstrated to have a low metal abundance ( $[\text{Fe}/\text{H}] \simeq -1.5$ ). A second paper (Giridhar, Lambert, & Gonzalez 1999, Paper II) analyzed three metal-poor stars—WY And, VW Eri, and UW Lib. Here, we discuss five Population II variables (Table 1) assigned by Joy (1952) to the halo population on the basis of radial velocity measurements.

Our spectroscopic analyses are the first for these stars. The elemental abundances are compared with published results for local metal-poor dwarfs and giants at an evolutionary stage less extreme than that of our SRd variables. Local field dwarfs and giants with very few exceptions show a common  $[\text{X}/\text{Fe}]$  at a given  $[\text{Fe}/\text{H}]$ . For many elements  $[\text{X}/\text{Fe}]$  is independent of  $[\text{Fe}/\text{H}]$  over the  $[\text{Fe}/\text{H}]$  range of

our stars. Sources for the expected  $[\text{X}/\text{Fe}]$  are as follows: Barbuy (1988), Carretta, Gratton, & Sneden (2000), and Nissen, Primas, & Asplund (2000) from the  $[\text{O I}]$  lines 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 & Sneden (1987) and Chen et al. (2000) for K; Gratton (1989) for Mn; Sneden, Gratton, & Crocker (1991) for Cu and Zn; and Zhao & Magain (1991) and Gratton & Sneden (1994) for Y, La, Ce, Pr, Nd, and Sm. Many 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  $[\text{X}/\text{Fe}]$  should be accurate to about  $\pm 0.1$  dex. The lack of scatter in  $[\text{X}/\text{Fe}]$  for samples composed of stars now in the solar neighborhood but originating from quite different parts of the Galaxy suggests that an SRd, if its atmosphere is unaffected by evolutionary effects, will have the  $[\text{X}/\text{Fe}]$  derived for unevolved stars. A “cosmic” scatter in  $[\text{X}/\text{Fe}]$  is seen, but only for stars of a lower metallicity, say,  $[\text{Fe}/\text{H}] \leq -2.5$ .

TABLE 1  
THE PROGRAM STARS

Star	$V$	Spectral Type	Period (s)
KK Aql .....	11.5–12.8	G2e–G6	88.7
AG Aur .....	10.00–13.1	G2e–K0	96.0
Z Aur .....	9.20–11.7	G0e–G6	134.8
W LMi .....	10.50–13.5	G2e–K2	117.2
WW Tau .....	9.00–12.9	G4e–K2	116.4

## 2. OBSERVATIONS AND ABUNDANCE ANALYSES

Spectra were obtained at the McDonald Observatory with the 2.7 m telescope and the 2dcoudé echelle spectrograph (Tull et al. 1995). In general, each star was observed on more than one occasion, and the spectrum least contaminated by TiO bands was selected for analysis. Spectra were reduced and analyzed by procedures described in Paper I.

As in previous papers in this series, we employed the 1997 version of the LTE abundance code, MOOG, developed by Sneden (1973). The model atmospheres are from Kurucz (1993) and the MARCS program (Gustafsson et al. 1975); the two sets of models give very similar solutions. Atmospheric parameters (Table 2) were derived from Fe I and Fe II equivalent widths (EWs). The effective temperature,  $T_{\text{eff}}$ , is set by minimizing the correlation between the Fe I line abundances and their lower excitation potentials,  $\chi_l$ . The surface gravity,  $g$ , is determined by forcing ionization equilibrium between Fe I and Fe II. We also used Ti I, Ti II and Cr I, Cr II to cross-check the derived  $T_{\text{eff}}$ – $\log g$  pair for each spectrum. The microturbulence velocity parameter,  $\xi_t$ , is set by minimizing the correlation between the Fe I abun-

dances and their EW values. Care has been taken to avoid regions affected by molecular bands. However, being metal poor, the stars in the present study have relatively uncrowded spectra, allowing us to measure weak unblended lines. We estimate the measured EWs to be accurate to within 5%–10%. The uncertainties in  $T_{\text{eff}}$ ,  $\log g$ , and  $\xi_t$  are typically  $\pm 120$  K, 0.2 dex, and  $\pm 0.2$  km s $^{-1}$ , respectively.

Our derived abundances are given in Tables 3–7 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 tables give the standard error of the mean abundance, as calculated from the line-to-line spread of the abundances. The total error in the absolute abundance of a well-observed element is generally about  $\pm 0.2$  dex when the various sources of error (equivalent width, effective temperature, etc.) are considered. This does not include systematic errors arising, for example, from the adoption of LTE. In the comparison with the expected abundances (Table 8), we cite mean values of  $[X/Fe]$  to  $\pm 0.1$  dex.

## 3. RESULTS AND DISCUSSION

### 3.1. KK Aquilae

For this SRd, which is assigned a period of 88.7 days in the *General Catalogue of Variable Stars* (Kholopov et al. 1985), our radial velocity of  $-243.2 \pm 1.5$  km s $^{-1}$  is in good agreement with Joy's (1952) mean velocity of  $-252$  km s $^{-1}$  from seven observations spanning a range of 50 km s $^{-1}$ . Our analysis shows KK Aql to have  $[Fe/H] = -1.2$  (Table 2). Elemental abundances are listed in Table 3. The relative abundances  $[X/Fe]$  are equal to the expected values to within the errors of measurement for almost all of the elements lighter than Y. An apparent anomaly is Ca, for which  $[Ca/Fe] = 0.3$  is expected but  $-0.2$  is derived. A similar

TABLE 2  
STELLAR PARAMETERS DERIVED FROM THE Fe-LINE ANALYSES

STAR	UT DATE	MODEL <sup>a</sup> $T_{\text{eff}}, \log g, [Fe/H]$	$\xi_t$ (km s $^{-1}$ )	Fe I <sup>b</sup>		Fe II	
				$\log \epsilon$	$n$	$\log \epsilon$	$n$
KK Aql .....	1999 Nov 3	4300, 0.5, $-1.2$	2.5	$6.28 \pm 0.20$	36	$6.21 \pm 0.18$	2
AG Aur .....	1998 Jan 25	4000, 0.0, $-1.7$	3.2	$5.75 \pm 0.17$	35	$5.76 \pm 0.20$	2
Z Aur .....	1998 Jan 25	4300, 0.0, $-1.4$	2.5	$6.12 \pm 0.16$	58	$6.07 \pm 0.13$	11
W LMi .....	1999 Feb 2	4300, 0.8, $-1.1$	2.3	$6.45 \pm 0.16$	100	$6.41 \pm 0.14$	12
WW Tau .....	1998 Jan 25	4300, 0.8, $-1.1$	2.7	$6.38 \pm 0.17$	98	$6.35 \pm 0.20$	5

<sup>a</sup>  $T_{\text{eff}}$  in K,  $\log g$  in cgs,  $[Fe/H]$  in dex.

<sup>b</sup>  $\log \epsilon$  is the mean abundance relative to H (with  $\log N_{\text{H}} = 12.00$ ). The solar value of  $\log \epsilon(\text{Fe})$  is 7.51. The standard deviations of the means, as calculated from the line-to-line scatter, are given.  $n$  is the number of lines used in the analysis.

TABLE 3  
 ELEMENTAL ABUNDANCES FOR KK AQL

Species	$\log \epsilon_{\odot}^a$	[X/H]	$n^b$	[X/Fe]
O I.....	8.87	$-0.44 \pm 0.15$	2	+0.79
Si I.....	7.55	$-0.90 \pm 0.36$	3	+0.33
K I.....	5.12	-0.38	1	+0.85
Ca I.....	6.35	$-1.46 \pm 0.15$	3	-0.23
Ti I.....	4.98	$-0.83 \pm 0.20$	19	+0.40
Ti II.....	4.98	$-0.93 \pm 0.24$	2	+0.30
V I.....	4.01	$-0.95 \pm 0.17$	10	+0.28
Cr I.....	5.67	$-1.00 \pm 0.20$	3	+0.23
Cr II.....	5.67	-1.08	1	+0.15
Mn I.....	5.39	$-1.05 \pm 0.27$	3	+0.18
Fe I.....	7.51	$-1.23 \pm 0.20$	36	...
Fe II.....	7.51	$-1.29 \pm 0.18$	3	...
Ni I.....	6.25	$-1.06 \pm 0.21$	18	+0.17
Cu I.....	4.25	-1.77	1	-0.54
Y II.....	2.23	$-0.99 \pm 0.20$	2	+0.26
Zr I.....	2.60	$-0.50 \pm 0.08$	3	+0.73
Ce II.....	1.55	$-0.40 \pm 0.16$	2	+0.83
Pr I.....	0.71	$-0.36 \pm 0.22$	2	+0.87
Nd I.....	1.50	$-0.67 \pm 0.22$	7	+0.56
Sm II.....	1.00	$-0.70 \pm 0.23$	7	+0.53
Eu II.....	0.51	$-0.74 \pm 0.23$	7	+0.49

<sup>a</sup> The solar abundances are taken from Grevesse, Noels, & Sauval 1996.

<sup>b</sup> Number of lines. These comments also apply to the following four tables.

result was found from our analyses of cool RV Tauri variables (Giridhar, Lambert, & Gonzalez 2000). Potassium has an apparently high abundance:  $[K/Fe] = 0.8$ , but about 0.4 is expected. An important signature is the modest over-

 TABLE 4  
 ELEMENTAL ABUNDANCES FOR AG AUR

Species	$\log \epsilon_{\odot}$	[X/H]	$n$	[X/Fe]
Mg I.....	7.58	-2.22	1	-0.38
Si I.....	7.55	$-1.33 \pm 0.06$	3	+0.51
Ca I.....	6.35	$-2.15 \pm 0.12$	3	-0.31
Ti I.....	4.98	$-1.49 \pm 0.24$	16	+0.35
Ti II.....	4.98	$-1.40 \pm 0.20$	3	+0.44
V I.....	4.01	$-1.87 \pm 0.18$	3	-0.03
Cr I.....	5.67	$-2.18 \pm 0.30$	5	-0.34
Mn I.....	5.39	$-1.99 \pm 0.27$	2	-0.15
Fe I.....	7.51	$-1.83 \pm 0.15$	35	...
Fe II.....	7.51	$-1.84 \pm 0.14$	2	...
Co I.....	4.91	$-1.69 \pm 0.20$	5	+0.15
Ni I.....	6.25	$-1.80 \pm 0.17$	12	+0.04
Cu I.....	4.25	-2.14	1	-0.30
Y II.....	2.23	-1.79	1	+0.04
Zr I.....	2.60	$-1.49 \pm 0.05$	4	+0.35
Zr II.....	2.60	-1.25	1	+0.59
Ba II.....	2.13	$-2.23 \pm 0.27$	2	-0.39
Ce II.....	1.55	-1.93	1	-0.09
Nd II.....	1.50	$-1.37 \pm 0.16$	6	+0.47
Sm II.....	1.00	$-1.27 \pm 0.23$	4	+0.57

 TABLE 5  
 ELEMENTAL ABUNDANCES FOR Z AUR

Species	$\log \epsilon_{\odot}$	[X/H]	$n$	[X/Fe]
O I.....	8.87	-1.05	1	+0.36
Na I.....	6.32	$-1.59 \pm 0.14$	2	-0.18
Mg I.....	7.58	$-1.12 \pm 0.09$	2	+0.30
Al I.....	6.47	$-1.43 \pm 0.10$	3	-0.02
Si I.....	7.55	$-1.04 \pm 0.13$	9	+0.38
S I.....	7.21	-0.71	1	+0.70
Ca I.....	6.35	$-1.31 \pm 0.12$	8	+0.10
Sc I.....	3.13	$-1.27 \pm 0.19$	4	+0.15
Ti I.....	4.98	$-1.56 \pm 0.25$	8	-0.15
Ti II.....	4.98	$-1.51 \pm 0.20$	2	-0.10
V I.....	4.01	$-1.68 \pm 0.18$	11	-0.26
Cr I.....	5.67	$-1.57 \pm 0.20$	9	-0.16
Cr II.....	5.67	$-1.55 \pm 0.20$	4	-0.14
Mn I.....	5.39	$-1.82 \pm 0.27$	6	-0.41
Fe I.....	7.51	$-1.39 \pm 0.16$	58	...
Fe II.....	7.51	$-1.44 \pm 0.13$	11	...
Co I.....	4.91	$-1.38 \pm 0.18$	5	+0.03
Ni I.....	6.25	$-1.54 \pm 0.17$	15	-0.13
Cu I.....	4.25	$-1.47 \pm 0.08$	2	-0.06
Zn I.....	4.60	$-1.34 \pm 0.07$	2	+0.07
Y II.....	2.23	$-1.42 \pm 0.13$	4	-0.01
Ba II.....	2.13	-1.60	1	-0.19
Ce II.....	1.55	$-1.51 \pm 0.30$	4	-0.10
Pr II.....	0.75	-1.16	1	+0.25
Nd II.....	1.50	$-1.29 \pm 0.16$	10	+0.12
Sm II.....	1.00	$-1.45 \pm 0.03$	2	-0.04
Eu II.....	0.51	-0.99	1	+0.42

abundance of the heavy elements: the mean  $[X/Fe]$  from Y, Zr, Ce, Pr, Ng, and Sm is 0.6 dex against an average expected value of 0.0 dex. These elements to varying degrees are dominated by the *s*-process (at solar metallicity). Europium, primarily a product of the *r*-process, has  $[Eu/Fe] = 0.5$ , but this is effectively the expected value. KK Aql is the first SRd in our sample to show evidence of *s*-process enrichment, which may be presumed to have resulted from operation of the *s*-process in the He shell of an asymptotic giant branch (AGB) star. This He shell may belong to the SRd itself or to a companion star that transferred mass to the SRd, presumably at an earlier stage of evolution.

### 3.2. AG Aurigae

This SRd was observed at a phase when the TiO bands were strong. The radial velocity of  $-193 \pm 1.4 \text{ km s}^{-1}$  from atomic lines matches perfectly the mean velocity reported by Joy (1952) from 15 observations spanning  $25 \text{ km s}^{-1}$ . The Fe abundance corresponds to  $[Fe/H] = -1.8$ . Relative to the expected  $[X/Fe]$ , there appear to be some anomalies. The most striking are  $[Mg/Fe] = -0.4$  from a single line and  $[Ca/Fe] = -0.3$  for which the expected values for both

TABLE 6  
ELEMENTAL ABUNDANCES FOR W LMI

Species	$\log \epsilon_{\odot}$	[X/H]	$n$	[X/Fe]
O I.....	8.87	$-0.50 \pm 0.05$	3	+0.58
Na I.....	6.32	$-1.37 \pm 0.09$	3	-0.29
Mg I.....	7.58	-0.82	1	+0.26
Si I.....	7.55	$-0.87 \pm 0.15$	7	+0.21
Ca I.....	6.35	$-0.94 \pm 0.06$	5	+0.15
Sc I.....	3.13	-0.96	1	+0.12
Sc II.....	3.13	$-1.01 \pm 0.21$	6	+0.07
Ti I.....	4.98	$-1.03 \pm 0.20$	25	+0.05
Ti II.....	4.98	$-0.88 \pm 0.22$	4	+0.20
V I.....	4.01	$-0.94 \pm 0.21$	22	+0.14
Cr I.....	5.67	$-1.09 \pm 0.17$	7	-0.01
Cr II.....	5.67	$-1.07 \pm 0.16$	5	+0.01
Mn I.....	5.39	$-1.43 \pm 0.25$	6	-0.35
Fe I.....	7.51	$-1.06 \pm 0.16$	98	...
Fe II.....	7.51	$-1.10 \pm 0.13$	12	...
Co I.....	4.91	$-0.97 \pm 0.17$	3	+0.11
Ni I.....	6.25	$-1.19 \pm 0.18$	23	-0.11
Zn I.....	4.60	-1.26	1	-0.18
Cu I.....	4.25	-1.55	1	-0.37
Y II.....	2.23	$-1.06 \pm 0.22$	4	+0.02
Zr I.....	2.60	$-0.99 \pm 0.19$	5	+0.09
Mo I.....	1.92	-0.62	1	+0.56
La II.....	1.22	$-0.94 \pm 0.20$	3	+0.14
Ce II.....	1.55	$-1.17 \pm 0.16$	7	-0.09
Pr II.....	0.75	$-0.65 \pm 0.26$	2	+0.43
Nd II.....	1.50	$-0.80 \pm 0.20$	9	+0.28
Sm II.....	1.00	$-0.65 \pm 0.18$	12	+0.43
Eu II.....	0.51	-0.14	1	+0.92

TABLE 7  
ELEMENTAL ABUNDANCES FOR WW TAU

Species	$\log \epsilon_{\odot}$	[X/H]	$n$	[X/Fe]
O I.....	8.87	-0.59	1	+0.55
Na I.....	6.32	$-1.19 \pm 0.04$	2	-0.05
Mg I.....	7.58	$-1.01 \pm 0.0$	2	+0.13
Al I.....	6.47	$-0.76 \pm 0.05$	2	+0.38
Si I.....	7.55	$-0.69 \pm 0.20$	8	+0.45
Ca I.....	6.35	$-1.16 \pm 0.18$	9	-0.03
Sc II.....	3.13	$-0.84 \pm 0.18$	5	+0.29
Ti I.....	4.98	-0.89	1	+0.25
Ti II.....	4.98	$-1.04 \pm 0.12$	6	+0.10
Cr I.....	5.67	$-1.16 \pm 0.23$	6	-0.02
Cr II.....	5.67	$-1.08 \pm 0.30$	3	+0.06
Mn I.....	5.39	$-1.47 \pm 0.02$	2	-0.33
Fe I.....	7.51	$-1.13 \pm 0.18$	98	...
Fe II.....	7.51	$-1.16 \pm 0.21$	13	...
Co I.....	4.91	$-0.88 \pm 0.03$	5	+0.26
Ni I.....	6.25	$-1.17 \pm 0.19$	30	-0.03
Cu I.....	4.25	$-1.19 \pm 0.34$	2	-0.05
Zn I.....	4.60	-1.18	1	-0.04
Y II.....	2.23	$-1.02 \pm 0.12$	4	+0.12
Zr I.....	2.60	$-1.01 \pm 0.19$	5	+0.13
La II.....	1.22	-0.58	1	+0.56
Ce II.....	1.55	$-1.05 \pm 0.09$	3	+0.09
Pr II.....	0.75	$-0.86 \pm 0.23$	2	+0.28
Nd II.....	1.50	$-0.68 \pm 0.02$	2	+0.46

TABLE 8  
OBSERVED AND EXPECTED  
COMPOSITIONS

SPECIES	[X/Fe]	
	Observed	Expected
O.....	0.6	0.7
Mg.....	0.1	0.3
Si.....	0.4	0.3
Ca.....	-0.1	0.3
Sc.....	0.4	0.0
Ti.....	0.2	0.3
V.....	0.0	0.0
Cr.....	-0.1	0.0
Mn.....	-0.2	-0.4
Co.....	0.1	-0.1
Ni.....	0.0	0.0
Cu.....	-0.3	-0.3
Y.....	0.0	0.2
Zr.....	0.2	0.0
Ce.....	-0.1	-0.2
Pr.....	0.3	0.2
Nd.....	0.3	0.0
Sm.....	0.3	0.1

are 0.3. Other light elements—Si, Ti, V, Cr, Mn, Co, Ni, and Cu—provide an [X/Fe] that is the expected value to within the errors of measurement. The heavy elements—Y to Sm—show a scatter in [X/Fe], but the mean from the seven elements is close to expectation with just a hint of *s*-process enrichment. The scatter presumably reflects the difficulty of determining abundances based on measuring just a few lines in a crowded spectrum.

### 3.3. Z Aurigae

Z Aurigae is variously classified as a Mira and an SRD variable. Two studies of the AAVSO magnitude estimates have shown that the period has changed (Lacy 1973; Percy & Colivas 1999). Percy & Colivas remark that the period changed abruptly around 1929 (JD 2,425,575). Our measured radial velocity of  $-174 \pm 1.3$  km s<sup>-1</sup> is consistent with Joy's (1952) mean velocity of  $-165$  km s<sup>-1</sup> from nine observations covering 35 km s<sup>-1</sup>. The star has [Fe/H] =  $-1.4$  with abundances [X/Fe] close to the expected values. Titanium with [Ti/Fe] =  $-0.1$  and V with [V/Fe] =  $-0.3$  may be slightly anomalous; [Ti/Fe] = 0.3 and [V/Fe] = 0.0 are expected. Sulphur may be slightly overabundant, but the result is based on a single line. Europium shows the expected small enrichment relative to Fe. Other heavy elements have their expected abundances: [X/Fe] = 0.0 from five elements; Z Aur is not *s*-process enriched.

### 3.4. W Leo Minoris

The abundance analysis is based on the 1999 February 2 spectrum taken at a time when the TiO bands were very

weak; the spectrum is that of an early/mid-K giant. Other spectra containing TiO bands were examined; see below. A remarkable feature is a strong Li I  $\lambda 6707$  line with a complex profile (Fig. 1). This star does not have such an extreme radial velocity as the other stars: we find  $+51.0 \pm 1.2$  km s $^{-1}$ , which compares with Joy's (1952) mean velocity of 60 km s $^{-1}$  from 10 observations over a range of 55 km s $^{-1}$ . At  $[\text{Fe}/\text{H}] = -1.1$ , W LMi is one of two least metal poor of the five stars. The relative abundances  $[\text{X}/\text{Fe}]$  (Table 6) are all close to the expected values for a halo star; lithium is discussed below. Europium with  $[\text{Eu}/\text{Fe}] = 0.9$  appears overabundant by about 0.5 dex, but this result is based on a single line.

The remarkable feature of W LMi's spectrum is a deep broad absorption feature at 6707 Å. This is naturally identified as the Li I resonance doublet. Our spectrum synthesis (Fig. 1) clearly shows that absorption is not simply due to photospheric lithium, assumed to be  $^7\text{Li}$ . Addition of  $^6\text{Li}$  does not materially alter the predicted line profile. The abundance adopted for the "best" fit is  $\log \epsilon(\text{Li}) \simeq 1.9$ . There is clearly additional absorption present. Although the extra absorption is mainly to the red of the photospheric line, there is a mismatch between the observed and synthetic profiles in the latter's blue wing; one might question the degree to which photospheric Li is at all a contributor. The observed profile suggests that weak emission may be filling in a single broad line. The excited Li I  $\lambda 6103$  line which is present (at the edge of an order) as a single absorption line with a photospheric profile gives a much higher abundance

$\log \epsilon(\text{Li}) \simeq 3.2$ ; the line does not have either the red component or the extended blue wing of the resonance line. (The excited Li I line at 8126 Å was not recorded by our spectrum.) Judged by results of non-LTE calculations for giants of a somewhat higher surface gravity (e.g., Balachandran et al. 2000), an LTE analysis of the  $\lambda 6103$  line should return a slightly lower not a higher Li abundance than the  $\lambda 6707$  line. We suppose that the discrepancy here may be due either to a filling in of the  $\lambda 6707$  photospheric absorption line by emission or to the failure of the star's upper atmosphere to track the theoretical structure used in the synthesis. It seems obvious that lithium must be present in great abundance. The discussion that follows is not greatly dependent on identification of  $\log \epsilon(\text{Li}) \sim 2$  or 3 as the stellar abundance.

The key issue is that lithium has been added to W LMi's atmosphere since its birth. W LMi's initial Li abundance would have been close to that of the Spite plateau,  $\log \epsilon(\text{Li}) \simeq 2.2$ , but in evolution from the main sequence to the red giant branch, atmospheric lithium would have been greatly diluted, and, in addition, lithium may have been destroyed on the main sequence. In short, the surface lithium has been replenished, presumably after the initial dilution as a red giant.

Recent observations have shown that lithium enrichment occurs, albeit rarely, in highly evolved low-mass metal-poor O-rich stars. Carney, Fry, & Gonzalez (1998) found lithium enrichment in the RV Tauri-like variable V42 in the globular cluster M5. Kraft et al. (1999) and Smith, Shetrone, & Keane (1999) each discovered an Li-rich red giant in a globular cluster. Hill & Pasquini (1999) found an Li-rich giant at a luminosity higher than that of He core burning clump stars in an open cluster of metallicity  $[\text{Fe}/\text{H}] = -0.5$ . We presume that the same unknown mechanism of lithium enrichment that operated in these cluster stars was at work in W LMi.

Our spectra provide a clue to that mechanism—the Li I  $\lambda 6707$  line and other resonance and strong low-excitation lines are double with a strong redshifted absorption component. In the 1999 February 2 spectrum, the Na D, K I  $\lambda 7699$ , and the Ba II  $\lambda 4554$  resonance lines show a double absorption profile similar to that of the Li I  $\lambda 6707$  line in Figure 1. The separation of the two components is consistent with the 21.5 km s $^{-1}$  measured for the  $\lambda 6707$  line. The Na D lines also show blueshifted components at  $-64$  and  $-89$  km s $^{-1}$ , which are presumably interstellar lines. Strong low-excitation lines also show the red component, as in the Mg I  $\lambda 8807$  line and the Ba II  $\lambda \lambda 5853, 6141, \text{ and } 6497$  lines. A similar broad, likely double, profile was observed by Smith et al. for the Li I  $\lambda 6707$  line, as well as the K I  $\lambda 7699$  line, in the Li-rich giant in the globular cluster NGC 362. This cluster star, an SRd with a period of about 100 days, is similar to W LMi, being about 400 K cooler but of similar metallicity and surface gravity.

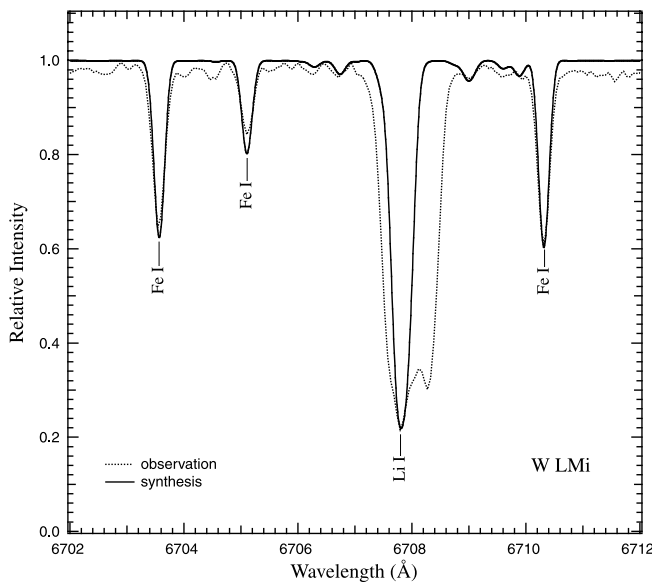


FIG. 1.—The spectrum of W LMi around 6707 Å. The dotted line is the observed spectrum from 1999 February 2. The solid line is a synthesis for a lithium abundance  $\log \epsilon(\text{Li}) = 1.9$ . Three Fe I lines are identified. Note the mismatch between the predicted photospheric Li I profile and the broad double line.

Examination of other spectra of W LMi taken at times when the TiO bands were stronger shows that the line doubling is probably present at all phases (Fig. 2). The line separation remains about constant, i.e., the red component shifts with the pulsational velocity. This component of the Li I  $\lambda 6707$  line presumably originates in the upper atmosphere in cool gas. One possibility is that we are detecting infalling gas from a circumstellar shell or gas ejected at an earlier pulsation cycle. The velocity of infall of about  $20 \text{ km s}^{-1}$  is approximately half the expected free-fall velocity. Alternatively, the doubling of the absorption lines may signify the presence of a shock in the upper atmosphere, with the shock separating cooler and hotter gas. If the latter scenario is correct, we would expect to see a stronger phase dependence of the strength and separation of the blue and red components. Such prominent line doubling is not unique among SRd variables to W LMi. Resonance lines, especially the Na D lines, are doubled in Z Aur, AB Leo, and WW Tau. The Na D splitting for AB Leo and Z Aur is about  $15 \text{ km s}^{-1}$ . Z Aur's Na D components near zero heliocentric velocity are plausibly attributed to interstellar sodium but appear also split by about  $15 \text{ km s}^{-1}$ , a presumably fortuitous similarity with the stellar line splitting.

Lithium-enriched giants of near-solar metallicity are known, and several proposals for enriching a stellar atmosphere in lithium have been offered (see the review by Charbonnel & Balachandran 2000). All but one of the proposals invokes conversion of  $^3\text{He}$  to  $^7\text{Li}$  in the interior of the Li-rich star; the exception is lithium enrichment resulting from accretion of a planet, an idea first advocated by Alexander (1967). Accretion of a terrestrial planet will enhance the lithium abundance to levels possibly in excess of the star's initial abundance. Early accretion of the planet

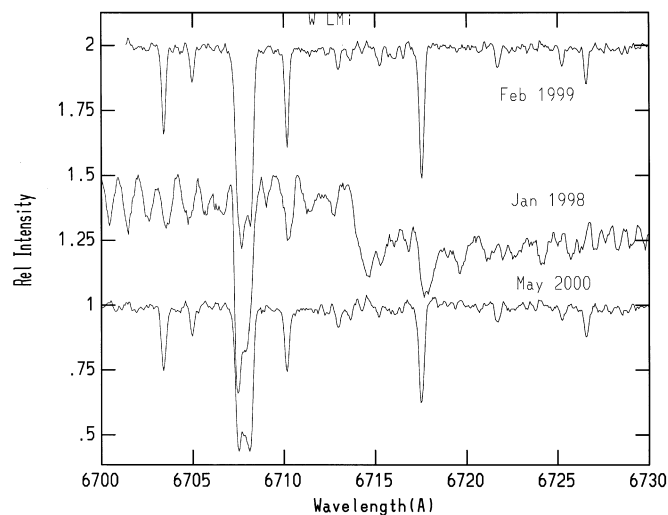


FIG. 2.—The spectrum of W LMi around  $6707 \text{ \AA}$  on 1998 January 24, 1999 February 2, and 2000 May 13. The strong Li I  $\lambda 6707$  line is present in all spectra as an apparent blend of two lines separated by about  $20 \text{ km s}^{-1}$ .

is likely followed by its destruction at the base of the convective envelope; lithium enrichment in this (and most other) scenarios is a passing phase. Terrestrial planets might be expected to orbit close to a star and so be accreted early in a giant's life with the possibility that lithium is destroyed subsequently. Therefore, the planet scenario seems ill-suited as an explanation for W LMi, a highly evolved red giant. Moreover, terrestrial planets are unlikely to form around metal-poor stars. Accretion of a brown dwarf will not greatly enhance the stellar lithium abundance. (A simpler process of mass transfer from an Li-rich AGB companion star seems improbable too. W LMi does not presently have such an AGB companion or a luminous post-AGB derivative. We cannot exclude a white dwarf descendant, but, as accretion of Li-rich material may be continuing, it seems to be necessary to invoke long-term storage of the companion's ejecta.)

Production, if it is the key to lithium replenishment for W LMi, was most probably by the Cameron & Fowler (1971) mechanism involving the reaction sequence  $^3\text{He}(^4\text{He}, \gamma)^7\text{Be}(e^-, \nu_e)^7\text{Li}$  initiated at high temperatures but which to be efficient must occur in a convective or explosive layer such that the  $^7\text{Be}$  and  $^7\text{Li}$  are transported rapidly to cool layers and avoid losses due to proton capture. The  $^3\text{He}$  is a fruit of incomplete *pp*-chain processing of hydrogen. Since the opening reaction of the *pp*-chain is controlled by the weak interaction and is, therefore, very slow, the participating  $^3\text{He}$  nuclei must be survivors of production during the main sequence.

Theory predicts that a very luminous AGB star experiences H burning at the base of its convective envelope and may enrich the surface in Li via the Cameron-Fowler mechanism (Scalo 1976; Sackmann & Boothroyd 1992). In the case of metal-poor stars, Lattanzio, Forestini, & Charbonnel (2000) show that the surface ratio of C/O stays below unity for a considerable fraction of the star's life on the AGB; loss of C to N to H burning via the CN cycle is offset by the dredge-up of freshly synthesized  $^{12}\text{C}$  in the deeper He-burning shell. These calculations are fully consistent with respect to luminosity and lithium abundance with the observations of Li-rich S stars in the Magellanic Clouds (Smith & Lambert 1989, 1990; Smith et al. 1995).

W LMi is obviously O rich because the spectrum at the appropriate phases is cluttered with TiO bands and not  $\text{C}_2$  bands. This tidy explanation of W LMi's lithium has two serious drawbacks. Present calculations predict Li synthesis to occur only in intermediate-mass AGB stars, say,  $M \sim 4 M_{\odot}$ , although calculations for metal-poor AGB stars have not yet been extended to low mass. Nonetheless, it seems likely that a metal-poor star like W LMi that is of low mass, say,  $M \sim 1 M_{\odot}$ , will not develop the necessary hot bottomed convective envelope. In addition, the Cameron-Fowler mechanism is not triggered until a star has experienced many He shell flashes and subsequent third

dredge-up of carbon and *s*-process elements; the Magellanic Cloud Li-rich giants are recognized as S stars. W LMi, however, is not enriched in the *s*-process elements.

Then, one must suppose that the conversion of  $^3\text{He}$  to  $^7\text{Li}$  occurs at a different (and earlier) stage of evolution. One is tempted given the location of the Li-rich star in NGC 362 to invoke the helium core flash as the trigger for mixing and production. Of the published conversion mechanisms (mostly, speculative musings), only one imagines mass loss to accompany or closely follow lithium production. De la Reza et al. (1996, 1997) suggested that lithium production was associated with mass ejection; a correlation with infrared excesses arising from circumstellar dust promoted this suggestion. If the infalling gas is associated with an extended envelope or circumstellar shell, W LMi suggests a link between an Li-rich atmosphere and an external gas reservoir that is also Li rich. The link, however, may not be directly as imagined by de la Reza and his colleagues because the solar-metallicity Li-rich giants are, as shown by Charbonnel & Balachandran (2000), all found at a similar luminosity but below the luminosity of W LMi. Given that the luminosity of these Li-rich giants is rather tightly defined, it would seem that lithium enrichment is a transitory phase.

### 3.5. WW Tauri

Our measured radial velocity of  $-114.0 \pm 1.1 \text{ km s}^{-1}$  is in good agreement with the  $-110 \text{ km s}^{-1}$  mean velocity obtained by Joy (1952) from six observations over a range of  $20 \text{ km s}^{-1}$ .

WW Tau has a normal composition for an  $[\text{Fe}/\text{H}] = -1.1$  star. Calcium appears slightly underabundant at  $[\text{Ca}/\text{Fe}] = 0.0$ , but a slight apparent underabundance of Ca is common among SRd variables and may indicate a systematic error such as non-LTE effects. Scandium may be slightly overabundant. The heavy elements do not show evidence of enrichment: the mean abundance from five elements each represented by two or more lines is  $[X/\text{Fe}] = 0.2$ .

## 4. CONCLUDING REMARKS

Table 8 shows the mean observed and the expected  $[X/\text{Fe}]$  for the five stars. In compiling this table, we have included only elements measured in four or five stars of this paper, and for the heavy elements we omitted KK Aql (*s*-process enriched) and included elements measured in three or four stars. For the “metals” from Na through the iron group to Cu and Zn, the stars have the relative abundances expected from studies of metal-poor dwarfs and less evolved giants. In particular, we note the underabundance of Mn and Cu that is seen also in normal stars;  $[X/\text{Fe}]$  for Mn and Cu for normal stars are slightly dependent on

$[\text{Fe}/\text{H}]$ . (Luck & Bond [1985] found a remarkable Mn deficiency for TY Vir.) We earlier alluded to the slight discrepancy between the observed and expected value of  $[\text{Ca}/\text{Fe}]$  and to the similar discrepancy found for cool RV Tauri variables. Adjustments to the atmospheric parameters made to eliminate the Ca underabundance create additional anomalies. An alternative contributing factor may be non-LTE effects on the Ca I lines. Drake (1991) predicted a nearly 0.2 dex increase in the Ca abundance when non-LTE effects were included for a model atmosphere at  $T_{\text{eff}} = 4500 \text{ K}$  and  $\log g = 1$ . We consider it quite unlikely that the Ca underabundance can be taken as indicating that these stars are descendants of the  $\alpha$ -poor subdwarfs discovered by Nissen & Schuster (1987).

These five stars, like the metal-poor SRd variables analyzed in Papers I and II, are on the AGB or near the tip of the red giant branch (RGB), and as such they may be the immediate progenitors of those RV Tauri variables that are intrinsically metal poor. What seems remarkable is the widespread lack of an *s*-process enrichment. A similar surprise was offered by the metal-poor RV Tauri variables (Giridhar et al. 2000). Only KK Aql is clearly enriched out of the sample of 11 SRd stars analyzed by us. A couple of stars hint at mild enrichments ( $[s/\text{Fe}] \simeq 0.2$ ), but the remainder are resolutely unenriched. This result would seem to imply that SRd variables evolve off either the RGB or the AGB before thermal pulses have enriched the envelope in *s*-process products and carbon from the He shell. A thorough analysis of the C, N, and O elemental and isotopic abundances for SRd variables and, in particular, a detailed comparison of the composition of the *s*-process enriched KK Aql with other SRd variables should be instructive.

An outstanding result is the presence of lithium in and/or near W LMi’s atmosphere. This is the first example of lithium enrichment in our survey of SRd variables. In common with the Li-rich star in the globular cluster NGC 362 (Smith et al. 1999), the lithium enrichment may be associated with Li-rich circumstellar gas, suggesting that lithium production in the star was followed by ejection of material that is now returning to the star. One hopes that completion of our survey of SRd variables will reveal additional Li-rich examples (V Pyx is just such a case), and fresh insights into lithium enrichment. Two extreme scenarios may be envisaged: Is the rarity of observed lithium enrichment the result of effective lithium production occurring in very few stars or does production occur in all stars to be followed by rapid destruction?

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