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The Chemical Compositions of the SRd Variable Stars. I. XY Aquarii, RX Cephei, AB Leonis, and SV Ursae Majoris

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ABSTRACT. Chemical compositions are derived from high-resolution spectra for four stars classed as SRd variables in the General Catalogue of Variable Stars. Two stars—XY Aquarii and RX Cephei—are of solar metallicity and most likely not variable stars. Their spectroscopic effective temperatures and surface gravities correspond to the spectral types G0 V for XY Aqr and G8 III for RX Cep. Two stars are undisputed variables and shown here to be metal-poor supergiants: AB Leonis with [Fe/H] $\simeq -1.6$ and SV Ursae Majoris with [Fe/H] $\simeq -1.4$. The metallicities and high radial velocities show them to be halo stars.

1. INTRODUCTION

This series of papers will present and discuss determinations of the chemical compositions of the SRd variables for which the General Catalogue of Variable Stars provides the following prosaic definition: "Semiregular variable giants and supergiants of spectral types F, G, K sometimes with emission lines in their spectra." Amplitudes are said to run up to 4 mag and the periods from 30 to 1100 days. Inspection of the list of SRd variables in Volume 4 of the GCVS suggests that the class is far from homogeneous: massive supergiants such as HR 8752 (V509 Cas) and ρ Cas are grouped with metal-deficient giants UU Her and TY Vir of presumably low mass.

Our goal is to identify the metal-deficient SRd stars and through the chemical compositions attempt to place the stars in an evolutionary context. Lloyd Evans (1975) discussed the SRds in a review, noting that the general properties (periods, amplitudes) of SRds resemble those of the red variables of the metal-poor globular clusters. He further noted that two stars—SX Her and TY Vir—have a low metal abundance (Preston & Wallerstein 1963). Dawson & Patterson's (1982) declaration that the "SRd variables are about 5 to 30 times more metal-poor than the Sun and have the kinematics of an old disk or halo population" echoes Lloyd Evans's description.

In our work on the field RV Tauri variables to which the SRds might be related, we have found that the stars appear generally metal-poor ([Fe/H] $\lesssim -1$) but with relative abundances quite unlike those of unevolved and less evolved metal-poor stars: the relative abundances suggest that elements that condense easily into or onto grains have been removed from the gas that now comprises a RV Tauri photosphere (Giridhar, Rao, & Lambert 1994; Gonzalez, Lambert, & Giridhar 1997a, 1997b). One might refer to these photospheres as "metal-depleted" to distinguish them from photospheres of less evolved stars that are said to be "metal-poor." These results prompt the questions: (1) Is a low metal abundance a general characteristic of red (SRd) variables? (2) Are those SRds of low metal abundance metal-poor, or are they metal-depleted?

In this first paper, we present the chemical compositions of four stars: XY Aqr, RX Cep, AB Leo, and SV UMa. The first two are of approximately solar metallicity and probably not variable stars, but the latter pair have a low metal abundance ([Fe/H] $\simeq -1.5$) and are certainly variable stars. If this selection is typical, the SRd classification encompasses a broad range of stars.

2. OBSERVATIONS

Spectra were obtained with the McDonald Observatory 2.1 m telescope equipped with a Cassegrain echelle spectrograph and a Reticon 200 × 400 pixel CCD (McCarthy et al. 1993). The details of each observation are listed in Table 1. The raw spectra were bias-subtracted, trimmed, flat-fielded, converted to one-dimensional spectra, and normalized to the continuum using the standard programs in the ECHELLE package of NOAO IRAF. The spectra were wavelength-calibrated with a Th-Ar hollow-cathode lamp spectrum taken immediately following each stellar observation. We also obtained spectra of

TABLE 1

Details of Spectroscopic Observations

Star	UT Date	HJD (−2,450,000)	Wavelength Range (Å)	Resolving Power	S/N
XY Aqr …….	1995 Dec 11	62.60	6200–8200	40,000	100
RX Cep …….	1995 Dec 11	62.65	6200–8200	44,000	130
AB Leo …….	1995 Dec 11	62.99	6200–8200	43,000	130
SV UMa ……	1996 Apr 9	182.67	5500–6800	41,000	150
SV UMa ……	1996 Apr 10	183.69	4790–5300	49,000	90
SV UMa ……	1996 Apr 11	184.62	6200–8200	35,000	90

hot, fast rotating stars in order to remove the telluric absorption lines from the SRd spectra.

3. ANALYSIS

The procedures for model atmosphere selection using Fe I, Fe II lines were essentially those used by Giridhar, Rao, & Lambert (1994). We have used MARCS codes of Gustafsson et al. (1975). The *gf*-values for Fe I lines were generally taken from Lambert et al. (1996). A few *gf*-values from Nave et al. (1994) were also used. For longer wavelength Fe I lines, a solar *gf*-value was calculated. The *gf*-values of Fe II lines were taken from Table A2 of Lambert et al. (1996) when available; otherwise *gf*-values of Giridhar & Arellano Ferro (1995) were used. For the remaining elements, *gf*-values compiled by R. E. Luck were adapted. A line synthesis program originally written by Sneden (1973) was used in its upgraded form. The program assumes LTE and uses plane-parallel atmospheres in radiative and hydrostatic equilibrium.

Our derived abundances are quoted to ±0.1 dex, and given in Tables 2 and 3 as $[X/H] = \log \epsilon(X/H) - \log \epsilon_{\odot}(X/H)$, 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 is about ±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.

4. RESULTS AND DISCUSSION

4.1. XY Aquarii

Classification of XY Aqr as a SRd is based on photometry off Harvard plates. Gerasimovič (1927) in a report of just six lines states that the star varied from 10.1 to 9.4 mag with a period of 72.7 ± 1.1 days. No light curve was published, but 18 maxima were said to have been observed. Apparently, this

TABLE 2

Compositions of XY Aquarii and RX Cephei[a]

Species	XY Aqr		RX Cep		
	[X/H]	$n_{\rm lines}$	[X/H]	$n_{\rm lines}$	$\log \epsilon_{\odot}$[b]
Li I …….	−0.5	1	−2.4	1	3.31
C I ……..	−0.1	3	…	…	8.55
Mg I ……	…	…	−0.2	3	7.58
Al I …….	…	…	−0.3	4	6.47
Si I …….	0.3	10	0.2	12	7.55
Si II …….	0.4	2	…	…	7.55
S I ……..	0.0	2	0.1	2	7.21
K I ……..	0.1	1	…	…	5.13
Ca I …….	0.0	5	−0.1	5	6.35
Sc II ……	0.2	1	−0.2	3	3.10
Ti I …….	−0.1	2	−0.3	3	4.96
Cr I …….	0.0	1	−0.2	2	5.68
Fe I …….	−0.1	34	−0.1	32	7.50
Fe II ……	−0.1	5	−0.1	8	7.50
Ni I …….	−0.2	6	−0.2	4	6.25
Zn I …….	0.2	1	0.4	1	4.65
Y II …….	0.4	1	…	…	2.33
Ba II ……	0.2	1	0.1	1	2.20

[a] The relative abundance [X/H] and the number of lines, $n_{\rm lines}$, are given.

[b] The weighted mean of the meteoritic and photospheric abundances from Grevesse et al. 1996. The meteoritic abundance is given for Li.

TABLE 3

Compositions of AB Leonis, SV Ursae Majoris, and TY Virginis[a]

Species	AB Leo		SV UMa		TY Vir[b]	
	[X/H]	$n_{\rm lines}$	[X/H]	$n_{\rm lines}$	[X/H]	$\log \epsilon_{\odot}$[c]
O I ……….	−1.0	2	…	…	−0.7	8.87
Na I ……..	−1.9	2	…	…	−1.7	6.32
Mg I ……..	…	…	−1.2	1	−1.7	7.58
Si I ………	−1.7	3	…	…	−1.1	7.55
K I ……….	−1.2	1	…	…	…	5.13
Ca I ……..	−1.6	8	−1.6	7	−1.5	6.35
Sc II ……..	−1.2	2	−1.5	4	−1.4	3.10
Ti I ………	…	…	…	…	−1.3	4.96
Ti II ……..	…	…	−1.2	2	−1.3	4.96
V I ……….	−1.8	1	−0.9	12	−1.6	4.01
Cr I ………	−1.9	3	−1.7	4	−1.8	5.68
Cr II ……..	…	…	−1.5	1	−1.2	5.68
Mn I ……..	…	…	−1.6	2	−2.4	5.53
Fe I ………	−1.6	45	−1.4	38	−1.4	7.50
Fe II ……..	−1.6	8	−1.3	7	−1.4	7.50
Ni I ………	−1.7	13	−1.4	13	−1.7	6.25
Zn I ……..	−1.7	1	−1.3	1	…	4.65
Y II ………	−1.1	1	−1.0	1	−1.3	2.23
Ba II ……..	−1.3	1	…	…	−1.2	2.20

[a] The relative abundance [X/H] and the number of lines, $n_{\rm lines}$, are given.

[b] From Luck & Bond 1985.

[c] The weighted mean of the meteoritic and photospheric abundances from Grevesse et al. 1996. The meteoritic abundance is given for Li.

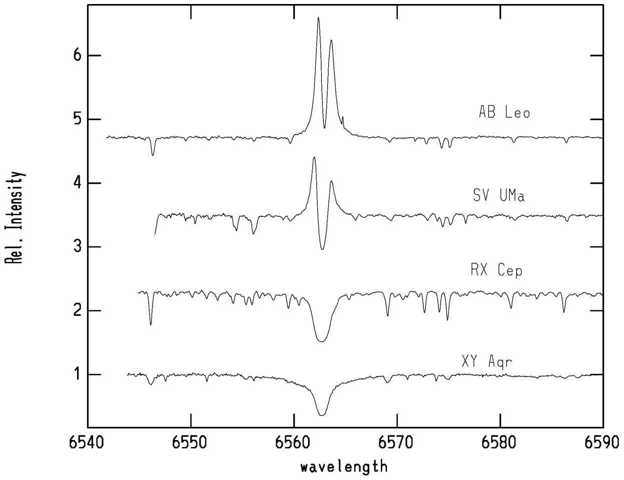

FIG. 1.—Region around the Hα line in XY Aqr, RX Cep, SV UMa, and AB Leo. Spectra have been displaced vertically for clarity of presentation but the scale of the relative intensity range (0–1) is the same for all spectra. The wavelength scale is given in angstroms.

star has not been the subject of subsequent photometric or spectroscopic studies except that a radial velocity of 10 km s^{-1} is given in Wilson's (1953) Catalogue of Radial Velocities.

The spectrum is dominated by lines of neutral iron and other iron-peak elements. Derived atmospheric parameters are an effective temperature, $T_{\rm eff}$, of 6000 ± 200 K, a surface gravity, g (in cgs units), of $\log g = 4.05 \pm 0.25$, a microturbulent velocity, ξ, of 2.5 ± 0.25 km s^{-1}, and a metallicity, [Fe/H], of about -0.1. The radial velocity is measured to be 17.5 ± 1.5 km s^{-1}, in fair agreement with Wilson's Catalogue. These are characteristics of a slightly evolved disk late-F or early-G star, not of a halo giant or supergiant.

Results of our abundance analysis are summarized in Table 2. The star is approximately of solar metallicity, with $[\mathrm{Fe/H}] = -0.1$. Relative abundances are generally consistent with the expectation that $[\mathrm{X/Fe}] = 0$ for disk stars of near-solar metallicity (Edvardsson et al. 1993). The slight overabundance of Zn, Y, and Ba is possibly not real, since in each case it is based on a single line. The slight overabundance of Si is based on several lines.

Lithium is not significantly depleted. Lithium in unevolved F stars of near-solar metallicity has a maximum abundance in the range $\log \epsilon = 3.0$–3.3. XY Aqr is slightly depleted (-0.2 to -0.5 dex) relative to this range. Main-sequence stars of XY Aqr's effective temperature are generally only slightly depleted. Clearly, XY Aqr fits this pattern. Stars that on the main sequence had effective temperatures near 6700 K are seriously depleted of lithium; see Boesgaard & Tripicco's (1986) discovery of the Li gap. Apparently, XY Aqr has not evolved from the Li gap. In addition, the star is too hot for its surface lithium to have been diluted by the growth of the deep convective envelope that is characteristic of giant stars.

Our conclusion is that XY Aqr is a normal disk F star. Confirmation of the range, periodicity, and nature of the variability reported by Gerasimovič should be sought.

4.2. RX Cephei

Appearance of RX Cep in the GCVS is traceable to an account of visual photometry from the previous century (Knott 1882). Zsoldos & McAdam (1993) conclude from modern observations and from a reanalysis of earlier series of observations extending back to Knott's that RX Cep is not a variable: "It is a star of constant magnitude." This conclusion serves to remove the star from the SRd class.

Nonetheless, we undertook an abundance analysis, whose results are summarized in Table 2. With $T_{\rm eff} = 5000 \pm 200$ K, $\log g = 2.25 \pm 0.25$ cgs, a microturbulence $\xi = 2.8 \pm 0.3$ km s^{-1}, and a metallicity $[\mathrm{Fe/H}] \simeq -0.1$, RX Cep appears to be a normal disk giant; a spectral type G8 III is indicated. A radial velocity of -8.7 ± 1.0 km s^{-1} from our spectrum confirms the value (-6 km s^{-1}) in Wilson's catalog and is another indicator of membership of the Galactic disk.

The relative abundances are as expected ($[\mathrm{X/Fe}] \simeq 0.0$) with the possible exception of the two heaviest elements, Zn and Ba (the Ba II line is affected by a blend). The lithium 6707 Å line is weakly present blended with Fe I at 6704.4 Å. The resulting Li abundance (see Table 2) is not atypical of solar metallicity giants. If the initial lithium abundance was $\log \epsilon(\mathrm{Li}) \simeq 3.0$, lithium in RX Cep has been depleted by a factor of 120, about as expected for dilution of the main-sequence star's Li content by the red giant's convective envelope with a factor of 2 or 3 additional depletion introduced before the star left the main sequence.

5. AB LEONIS

AB Leo is a variable star (Joy 1952); Dawson (1979) found a period of 130.2 days. Joy reported the spectral type to vary from F8 to G3 and the radial velocity to run from 163 to 208 km s^{-1}. The Hα line that has strong blue and red emission with a deep central absorption is representative of cool high-luminosity stars (Fig. 1). In sharp contrast, the Hα profiles of XY Aqr and RX Cep show broad photospheric absorption profiles without emission. On this evidence, AB Leo would appear to be a variable of the halo population.

Our spectrum provides the atmospheric parameters: $T_{\rm eff} = 4300 \pm 100$ K, $\log g = 0.4 \pm 0.25$ cgs, and $\xi = 2.6 \pm 0.2$ km s^{-1}. The iron abundance is $[\mathrm{Fe/H}] = -1.6$. Dawson's analysis of DDO photometry from two epochs gave $T_{\rm eff}$ of 4580 and 4640 K, gravity of $\log g = 1.0$ and 0.9, and $[\mathrm{Fe/H}] \simeq -1.2$. The spectroscopic and Dawson's photometric results are in fair agreement except, perhaps, for $\log g$. The radial velocity of 172 ± 1 km s^{-1} from our spectrum is within the limits found by Joy.

The relative abundances are close to the values found for the majority of unevolved stars of this metallicity. There is the expected enhancement of O (relative to Fe), but Ca (and Si) seems underabundant by about 0.3 dex: $[\mathrm{Ca/Fe}] \simeq 0.0$, not the value of 0.3–0.4 expected for a star with [Fe/H] $\simeq -1.6$. Perhaps heavy elements are overabundant, but the Y and Ba abundances depend on a single line in both cases. There is a similarity between AB Leo and TY Vir analyzed by Luck & Bond (1985); see Table 3. TY Vir has also been analyzed by Preston & Wallerstein (1963), Leep & Wallerstein (1981), and Proust (1986), with the former two references reporting [Fe/H] to be slightly lower than that found by Luck & Bond. Proust claimed a higher value: [Fe/H] $\simeq -1.0$.

5.1. SV Ursae Majoris

SV UMa is a variable star (Joy 1952); Dawson (1979) gives the period as 76 days. The spectrum is that of a cool supergiant; Rosino (1951) quoted a spectral type range of G1 Ib–K3p Ia. High luminosity is confirmed by the strong emission at Hα: the blue emission feature is stronger than the red feature on our spectrum (Fig. 1). Halo membership is indicated by the radial velocity of -100.5 ± 1.2 km s^{-1} in good agreement with Rosino's tabulated value of -100 km s^{-1} from Redman (1931) and the range of -80 to -101 km s^{-1} found by Joy (1952).

Analysis of our spectra gives the atmospheric parameters: $T_{\rm eff} = 4500 \pm 100$ K, $\log g = 0.0 \pm 0.25$ cgs, $\xi = 4.5 \pm 0.5$ km s^{-1}, and [Fe/H] $\simeq -1.4$. Dawson (1979) obtained similar effective temperatures (4580–4640 K) and metallicity ([Fe/H] $\simeq -1.2$) to the above values. His photometric gravities ($\log g \simeq 1.0$) are higher than the present spectroscopic gravity.

Results of the abundance analysis are summarized in Table 3. To within the likely uncertainties, the relative abundances or [X/Fe] are as expected for metal-poor stars, i.e., [X/Fe] = 0 for most elements with [X/Fe] = 0.3 for so-called α-elements Mg and Ti. The α-elements Ca seem slightly underabundant, e.g., [Ca/Fe] $\simeq -0.3$, relative to the expectation [Ca/Fe] $\simeq$ 0.3. Yttrium is slightly overabundant based on two lines that appear unblended. Unfortunately, C I and O I lines are too weak to be detectable. The [O I] lines at 6300 and 6363 Å are hopelessly blended. The Li I 6707 Å doublet is weak and undetectable.

The composition of SV UMa resembles closely that of TY Vir (Luck & Bond 1985). The metallicities of the two stars are similar: [Fe/H] = -1.3 and -1.4 for SV UMa and TY Vir, respectively. In addition, both stars (and also AB Leo) have similar [Ca/Fe] ratios that conflict with expectation. Perhaps this is the signature of non-LTE effects in these tenuous atmospheres. One striking difference is that Luck & Bond found TY Vir to be very deficient in manganese ([Mn/Fe] = -1.0) but SV UMa has the Mn abundance expected of halo stars ([Mn/Fe] = -0.2), as reported by Gratton & Sneden (1988, 1991). A deficiency [Mn/Fe] $\simeq -1.0$ is seen only in extremely metal-poor stars, [Fe/H] ≤ -3.5 (McWilliam 1997). If TY Vir truly has [Mn/Fe] $\simeq -1$ at [Fe/H] = -1.4, it is a remarkable object. A Mn deficiency "by an additional factor [relative to Fe] of about 4" was noted by Preston & Wallerstein (1963).

6. CONCLUSIONS

Our small sample together with the remarks provided in § 1 show that the SRd stars in the GCVS are a mixed bag. Two of our four stars are likely not variables: RX Cep has been declared on good evidence to be of constant magnitude, and the evidence of photometric variability for XY Aqr has never been published. (The reported period of XY Aqr, if interpreted as a pulsation, is inconsistent with the star's temperature and gravity.) Both are disk stars of nearly solar metallicity. The list of SRd stars should be pruned of this pair of stars.

AB Leo and SV UMa (also TY Vir) are metal-deficient. The [Fe/H] values of -1.4 to -1.6 are similar to values reported for disk RV Tau variables to which SRds may be related (Giridhar et al. 1994; Gonzalez et al. 1997a, 1997b). There is, however, a distinct difference in the compositions of these three high-velocity SRds and the disk RV Tau variables. The latter show strong evidence for a photosphere affected by severe dust-gas separation. Since Zn does not easily condense onto grains but Sc does so even more readily than Fe (at least, in O-rich gas), a signature of dust-gas separation is an anomalously high [Zn/Fe] and an unusually low [Sc/Fe] ratio: [Zn/Fe] $\sim +1$ and [Sc/Fe] ~ -0.9 for field RV Tau variables belonging to the disk (Gonzalez & Lambert 1997). In contrast, [Zn/Fe] is -0.1 and 0.0 for AB Leo and SV UMa, respectively. Even though the Zn abundance is based on a single line, a RV Tau–like abundance is certainly excluded, since it implies a very strong Zn I line. The [Sc/Fe] ratios of the SRds are $+0.4$ (AB Leo), -0.1 (SV UMa), and 0.0 (TY Vir), which are markedly larger than the mean ratio of -0.9 for the RV Tau variables. In short, the absence of anomalous [Zn/Fe] and [Sc/Fe] ratios for the three SRds shows that these stars are not affected by a dust-gas separation, as are the disk RV Tau variables.

This result is not too surprising. The cool SRds almost certainly possess an extensive convective envelope that must negate the effects of a wind in which the dust-gas separation occurs. In addition, analyses of RV Tau–like variables in metal-poor globular clusters and high-velocity field RV Tau variables of similar metallicity to AB Leo and SV Uma do not show abundance anomalies attributable to a dust-gas separation; see Gonzalez & Lambert (1997), who suggest that the dust-to-gas ratio in a wind off a truly metal-poor star is so low that the dust cannot drift out against the drag exerted by the gas. It may also be noted that there is no observational evidence for a dusty circumstellar shell around AB Leo and SV UMa; neither star appears in the *IRAS* catalog. In short, AB Leo, SV UMa, and TY Vir are metal-poor, not metal-depleted.

If SRd stars are to be identified as representatives in the field of the red variables of the metal-poor globular clusters, AB Leo and SV UMa deserve the appellation. We find them to be almost identical to TY Vir and also to CK Vir (Leep & Wallerstein 1981). All are luminous variables with prominent emission at Hα. Perhaps our continued analysis of the SRd stars will confirm our suspicion that a more homogeneous class would result if the conditions "weak lined" and "high radial velocity" were appended to the GCVS definition. To these conditions might be added the appearance of the Hα profile in emission with a central reversal (Fig. 1).

It would be of great interest to derive accurate abundances of heavy elements in order to determine if the SRd variables, as AB Leo and SV UMa appear to be, are *s*-process enriched. Enrichment would suggest that the stars belong to the asymptotic giant branch rather than the first-ascent red giant branch. More detailed abundance analyses might also be used to probe the evolutionary link between the SRd variables like TY Vir, AB Leo, and SV UMa and the RV Tauri variables. Luminosities of our SRd variables estimated from the standard relation between luminosity, effective temperature, surface gravity and mass (a mass $M/M_{\odot} \sim 0.8$ is assumed) put AB Leo at $\log(L/L_{\odot}) \simeq 3.4$ and SV UMa at $\log(L/L_{\odot}) \simeq 3.9$. Given the inevitable uncertainties of these estimates and the fact that the tip of the red giant (first-ascent) branch is at $\log(L/L_{\odot}) \simeq 3.3$, assignment of the stars to the asymptotic giant branch is probably appropriate but not certain. Accurate abundances of *s*-process elements should clarify the evolutionary status of these stars.

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