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SYNTHESIS OF LITHIUM AND s-PROCESS ELEMENTS IN SMALL MAGELLANIC CLOUD ASYMPTOTIC GIANT BRANCH STARS

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ABSTRACT

High-resolution spectroscopy is presented for five luminous ($M_{\rm bol} \sim -6$ to -7) asymptotic giant branch (AGB) stars in the Small Magellanic Cloud (SMC). These stars are found to be metal-poor ([Fe/H] ≈ -0.5) but *s*-process–enriched, relative to Fe-peak elements, by up to a factor of 10: these are *s*-process enhancements that are comparable to those observed in Galactic S stars; thus, these SMC AGB stars have experienced a third dredge-up. Of more interest is the fact that all five red giants have rather strong Li I resonance lines (6707 Å); an abundance analysis reveals these stars to have Li abundances that are 100–1000 times that expected in red giants. We argue that these very luminous (and probably massive) AGB stars have synthesized Li as predicted by certain stellar models of hot-bottom convective-envelope burning. We discuss the observations and models as a basis for understanding certain phases of red giant evolution and as a potentially significant source of Li in the universe.

Subject headings: abundances — nucleosynthesis — stars: abundances — stars: late-type

I. INTRODUCTION

The Magellanic Clouds have played an important role in the understanding of stellar evolution. Evolved stars that exhibit chemical peculiarities which are the result of internal stellar nucleosynthesis, such as carbon or S stars, or stars that are undergoing, or have undergone recently, extensive mass-loss, such as OH/IR stars or planetary nebulae, are observable in the Clouds in large numbers. As the distances to both Clouds are known, the luminosities of these evolved, peculiar stars can be determined much more accurately than for the majority of similar objects in the Milky Way.

Our understanding of the evolution of thermally pulsing stars on the asymptotic giant branch (TP-AGB) has been aided particularly by Magellanic Cloud studies. These stars may mix ^{12}C and *s*-process heavy elements from their He-burning shell to their surfaces (the third dredge-up) and transform an M giant into a carbon-rich and *s*-process–enhanced MS and S star or a N-type carbon star (for a review see Iben and Renzini 1983). A persistent puzzle about the Magellanic Clouds has been the absence of the predicted luminous carbon stars that come from intermediate-mass (4–8 $M_\odot$) TP-AGB stars and the unexpected presence of numerous less luminous and lower mass carbon stars (Blanco, McCarthy, and Blanco 1980; Mould and Aaronson 1982, 1983, 1986; Aaronson and Mould 1985; Reid and Mould 1984). The lack of luminous C stars ($M_{\rm bol} \lesssim -6$) has led Aaronson and Mould (1985) and Mould and Aaronson (1986) to speculate that severe mass loss terminates AGB evolution in the higher mass stars before thermal pulses may commence and transform the star to a ^{12}C-rich N star with C/O > 1.

The discovery in the Clouds of luminous, Mira variables that are massive AGB stars with strong ZrO bands (Wood, Bessell, and Fox 1983, hereafter WBF) suggest that some massive AGB stars must have enhanced *s*-process abundances (such as Zr) and thus have survived to the TP-AGB, third dredge-up stage of stellar evolution. The luminosities of these massive AGB extend from the luminosities of the most luminous C stars ($M_{\rm bol} \approx -6$) right up to the AGB limit of $M_{\rm bol} \approx -7.1$ for a core mass of 1.4 $M_\odot$. The question of why none of the more massive TP-AGB stars are true carbon stars with C/O > 1 has drawn two answers: (1) the time scale of TP-AGB evolution in massive stars is too short for the third dredge-up to drive C/O > 1 in the envelope; (2) "envelope burning" (Iben 1973; Scalo, Despain, and Ulrich 1975; Renzini and Voli 1981) occurs so that the ^{12}C (and *s*-process elements) that has been mixed to the surface burns to ^{14}N via the CN cycle at the hot base of the convective envelope.

In this *Letter*, we present an abundance analysis of five luminous S stars in WBF's Small Magellanic Cloud (SMC) sample. Two questions may be addressed with our high-resolution spectra: (1) Are these stars enriched in the *s*-process elements as WBF surmised? (2) Is there evidence in the compositions for the existence of a hot-bottom convective envelope that may inhibit an AGB star's transformation to a carbon star? The principal result discussed here is that all five of the observed stars are metal-poor *s*-process–enriched stars in which substantial amounts of Li have been synthesized.

II. OBSERVATIONS, ANALYSIS, AND RESULTS

Spectra of five AGB stars in the SMC from WBF's list were obtained from 6470 to 7900 Å at a resoluion of $\lambda/\Delta\lambda \approx 20{,}000$ with the Cerro Tololo Inter-American Observatory's (CTIO) 4 m telescope, plus cassegrain cross-dispersed echelle, plus air Schmidt camera, and GEC CCD detector. Four CCD frames of each SMC star were averaged to produce a final frame with a typical S/N ≈ 50–100. Spectra were also obtained of the bright M3 III star, δ Vir, to be used as a standard star, and the extremely *s*-process–enriched S star HD 35155 (Smith and Lambert 1990).

The great surprise provided by the SMC spectra is illustrated in Figure 1: the Li I resonance doublet at 6707.8 Å is prominent in the SMC red giants (600–700 mÅ), yet virtually

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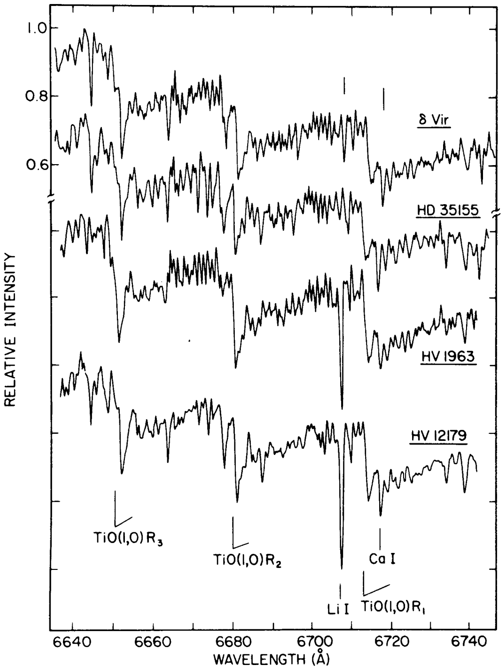

FIG. 1.—Sample spectra illustrating the Li I resonance doublet. An entire echelle order is shown: note the very strong Li I feature in the SMC stars (HV 1963 and HV 12179) as compared to the two Galactic red giants. Note also that this region is blanketed by TiO absorption.

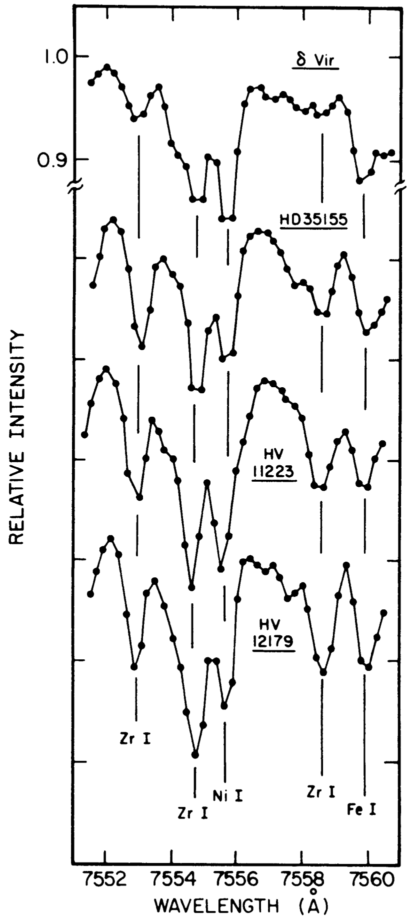

FIG. 2.—Spectra showing the increased strengths of the Zr I lines in the SMC red giants (similar to the Galactic S star HD 35155) relative to the normal abundance red giant δ Vir.

absent in both Galactic red giants. In the vast majority of Galactic red giants, including the TP-AGB S stars, the Li I feature is weak; Li has been diluted due to convective mixing with the Li-depleted deeper layers during red giant evolution (Iben 1967). A handful of Galactic red giants are known with strong Li I lines, but, as pointed out by Scalo (1976), these stars are less than 1% of the S and C stars. Clearly, the fact that the Li I doublet is strong in each of the five luminous AGB stars in the SMC aroused our interest.

It is important to establish whether these particular AGB stars are truly *s*-process–enriched, as suggested by WBF. In Figure 2 we show the spectrum near 7555 Å for two of the SMC stars, along with the normal red giant δ Vir and the *s*-process–enriched S-star HD 35155. Three lines of Zr I are indicated along with a line of Ni I and Fe I. Note that the Zr I lines, as expected, are relatively much weaker in δ Vir than in HD 35155 but, in the SMC stars the Zr I lines, relative to the Ni I and Fe I lines, are as enhanced as in the *s*-process–enriched S star HD 35155. Enhancements are seen in the SMC stars for other lines of Zr I, Y II, and La II. The increased strengths of these lines suggest that these SMC AGB stars must be enriched in the *s*-process elements.

An abundance analysis using model atmospheres provided quantitative estimates. We have used the data from WBF to estimate the model atmospheres' defining parameters $T_{\rm eff}$ and log g: Table 1 lists basic data. The SMC stars are variables, and we use the range in spectral types and IR colors given by WBF to estimate the mean $T_{\rm eff}$ given in Table 1. The temperature for HV 1963 is in good agreement with Brett's (1989) estimate of $T_{\rm eff} = 3350$ K from low-resolution near-IR and IR spectrophotometry. Based upon WBF's results, the observed SMC stars have $M_{\rm bol} \sim -6.5$ and, with an approximate mass of 6 $M_\odot$, these red giants will have log $g \sim -0.3$; we used models with log $g = 0.0$ from Johnson, Bernat, and Krupp (1980): these were the lowest values for surface gravities in their grid. The microturbulent velocities were estimated from Fe I lines, where the lines are required to yield consistent abundances for all equivalent widths. The abundance analysis of the Fe peak plus Y and Zr abundances is identical to that carried out for Galactic M, MS, and S stars by Smith and Lambert (1985, 1986, 1990) and involves a set of lines in the spectral region 7400–7580 Å.

An abundance analysis of the Li I doublet is complicated by the strength of this line in the SMC stars and the fact that this region of the spectrum is blanketed by TiO in the cooler red giants. In order to reduce the uncertainties arising from the great strength of the Li I doublet, we compare it to one of the analogous lines in K I, which is also quite strong in the cool giants. Potassium abundances are not expected to be altered during red-giant evolution, so a comparison of Li to K provides a measure of the Li abundance that is insensitive to the adopted model atmosphere. Lithium abundances in Galactic S stars have been reported previously by Boesgaard (1970*b*) and Catchpole and Feast (1976). In both studies, Li equivalent widths were measured relative to the "local continuum"; thus, in order to compare the SMC AGB stars to the Galactic S stars, we chose to measure the Li and K lines relative to the local continuum.

Abundances are presented in Table 1. The atomic abundances of the heavier elements are presented in the usual notation where $[{\rm X/H}] \equiv \log \epsilon({\rm X}) - \log \epsilon({\rm X})_{\delta\,{\rm Vir}}$ and $\epsilon({\rm X})$ is the abundance of element X, by number, relative to H; the atomic abundances of the SMC stars reveal them to be under-abundant in the Fe peak elements. Recent high-resolution

TABLE 1

OBSERVED STARS, PHYSICAL PROPERTIES, AND ABUNDANCES

						RELATIVE TO δ Vir					
STAR	SPECTRAL TYPE	T_{eff} (K)	log g	ξ (km s^{-1})	log ϵ(Li)	[Ti/H]	[Cr/H]	[Fe/H]	[Ni/H]	[Y/H]	[Zr/H]
δ Vir	M3 III	3650	1.3	2.3	0.7	...	...	...	...	...	...
HD 35155	S 3/2	3650	0.8	2.7	0.2	-0.34 ± 0.15	-0.65	-0.53 ± 0.18	$+0.34 \pm 0.12$	$+0.27$	$+0.46 \pm 0.08$
HV 1375	M5	3000	0.0	3.0	2.5	-0.65 ± 0.22	-0.82	-0.49 ± 0.15	-0.25 ± 0.14	$+0.59$	$+0.39 \pm 0.11$
HV 1963	M4-5/S4	3200	0.0	2.8	2.2	-0.93 ± 0.14	-0.40	-0.59 ± 0.20	-0.40 ± 0.17	-0.25	-0.24 ± 0.14
HV 11223	M3/S3	3400	0.0	3.5	3.8	-0.58 ± 0.10	-0.25	-0.32 ± 0.09	-0.32 ± 0.21	$+0.52$	$+0.26 \pm 0.10$
HV 11366	M1-3/53	3400	0.0	3.0	2.2	-0.60 ± 0.07	-0.60	-0.45 ± 0.18	-0.32 ± 0.06	$+0.12$	-0.08 ± 0.19
HV 12179	M5/S2	3000	0.0	4.0	3.7	-0.86 ± 0.13	-0.75	-0.50 ± 0.15	-0.34 ± 0.10	$+0.46$	$+0.29 \pm 0.13$

abundance analyses of eight SMC F supergiants by Russell and Bessell (1989) and three F and G supergiants by Spite, Spite, and François (1989) both yield [Fe/H] = -0.65 ± 0.20. Our mean result for the five giants is [Fe/H] = -0.47 ± 0.10; however, our analysis is hampered by the use of solar-abundance model atmospheres. Use of lower metallicity atmospheres would decrease our derived abundances somewhat. Abundance ratios of elements whose lines are formed at roughly equal depths in the atmosphere over the narrow wavelength interval will not be affected to any great degree by the use of solar-metallicity model atmospheres: our average derived ratios of the Fe peak elements for the five AGB stars become [Ti/Fe] = -0.25 ± 0.14, [Cr/Fe] = -0.09 ± 0.24, and [Ni/Fe] = $+0.14 \pm 0.10$, i.e., [M/Fe] $\simeq 0.0$ on average, as found by Spite, Spite, and François (1989) and Russell and Bessell (1989) for F and G supergiants. The results for the *s*-process elements Y and Zr show real differences between the F and G supergiants and the AGB stars. Spite, Spite, and François (1989) find [Y/Fe] = 0.00 ± 0.21 and [Zr/Fe] = $+0.24 \pm 0.04$ and Russell and Bessell (1989) derive [Y/Fe] = $+0.11 \pm 0.30$ and [Zr/Fe] = -0.03 ± 0.28. In contrast, the AGB stars yield [Y/Fe] = $+0.76 \pm 0.30$ and [Zr/Fe] = $+0.59 \pm 0.24$ which are typical *s*-process enhancements for Galactic S stars. A range of *s*-process enhancements is observed: for example, HV 1963's enhancement is barely significant with [Y/Fe] = $+0.34$ and [Zr/Fe] = $+0.35$. The suggestion by WBF that these luminous SMC AGB stars are *s*-process–enriched is thus supported by our quantitative analyses.

The Li/K abundance ratios are the result of measuring equivalent widths relative to the local continuum. The Li I doublet at 6708 Å and the K I line at 7700 Å were synthesized and the features integrated to obtain theoretical equivalent widths and Li/K ratios. Lithium abundances (i.e., Li/H) given in Table 1 are computed from the Li/K ratios and an assumption that [K/Fe] = 0.0. Galactic stars satisfy the latter assumption down to the metallicity of SMC stars (Gratton and Sneden 1987). The derived Li abundances of δ Vir and HD 35155 are typical of Galactic red giants (Luck and Lambert 1982; Brown *et al.* 1989). Table 1 reveals that the luminous SMC AGB stars have Li/K abundances that are more than 100–1000 times that for the typical Galactic red giant.

III. DISCUSSION

The obvious interpretation of the high Li abundances is that the SMC stars have synthesized Li. This conclusion is not unique to the SMC; as discussed above, a handful of Galactic S and N stars have produced Li. However, the fraction of Li-rich Galactic red giants, relative to other red giants, is 1% or less (Scalo 1976). By contrast we have identified a sample of SMC AGB stars in which Li is enhanced in 100% of the stars and whose luminosities are known along with their approximate evolutionary phases.

We compare Li abundances and *s*-process enhancements (in the form [Zr/Ti]) for the SMC AGB stars along with a sample of Galactic S stars whose Li and Zr abundances have been determined by Boesgaard (1970*a*, *b*) and Catchpole and Feast (1976). Boesgaard determined Li/Ca abundance ratios, and we converted her values to Li abundances by assuming that [Ca/K] = 0 for near solar-metallicity giants (Lambert 1989). Most of the S stars studied by Boesgaard (1970*b*) have a Li abundance comparable to that of the G, K, and M giants; however, three stars analyzed by Boesgaard (1970*b*) have larger Li abundances (SU Mon, T Sgr, and HR 8714) but similar *s*-process enhancements to the "Li-normal" S stars. RZ Sgr, a star found by Catchpole and Feast (1976), is also a member of this group of Li-rich S stars. The SMC AGB stars closely resemble the Li-rich Galactic S stars, and the obvious inference is that these stars, drawn from two different stellar populations, represent a common phenomenon in stellar evolution.

The possibility that ^{7}Li may be synthesized in red giants was recognized by Cameron and Fowler (1971) who proposed the so-called ^{7}Be-transport mechanism in which ^{7}Li is created via the sequence $^3\mathrm{He}(\alpha, \gamma)^7\mathrm{Be}(e^-, \nu)^7\mathrm{Li}$ in a convection zone where the ^{3}He is a product of prior H-burning and the ^{7}Li (and ^{7}Be) is transported by the convection to cooler layers of the red giant before it is destroyed by protons. Luminous AGB stars are predicted to develop high temperatures ($T_b \simeq 20$–60×10^6 K) at their base where the ^{7}Be-transport mechanism and H-burning will occur. Theoretical studies suggest that, under certain conditions, ^{7}Li may be created and mixed to the surface of luminous AGB stars (Iben 1973; Sackmann, Smith, and Despain 1974; Scalo, Despain, and Ulrich 1975). Scalo *et al.* refer to such stars as possessing "hot-bottom convective envelopes" (HBCEs). It is tempting to associate the Li-rich SMC stars with the occurrence of an HBCE. Scalo, Despain, and Ulich (1975) predict that an HBCE develops in AGB stars with $M_{\mathrm{bol}} \lesssim -5.4$ and all of our SMC stars have $M_{\mathrm{bol}} \simeq -6$ to -7.

The hypothesis that Li production is a consequence of an HBCE would seem to demand that the atmospheres of the Li-rich AGB stars contain the products of H-burning that must also occur at the base of the convective envelope. In particular, the atmospheres should be N-rich and possibly C-poor; C that is converted to N may be replenished through the thermal pulses. Brett (1989) used low-resolution near-infrared and infrared spectra plus spectrum synthesis of molecular bands to estimate the C, N, and O abundances of a sample of luminous SMC AGB stars that included two of our stars—HV 1963 and HV 12179. He concluded that the abundances suggest that these AGB stars have experienced the third dredge-up but have not developed an HBCE; i.e., the envelopes have been enriched in C but remain O-rich. A full analysis must await improved IR spectra.

Finally, we note that Li-rich S stars may account for substantial ^{7}Li production in the SMC and the Galaxy. Examination of the SMC AGB abundances suggest that these S stars are currently a major influence on the evolution of that galaxy's Li abundance. Our identification of intermediate-mass AGB stars as a potentially important source of Galactic ^{7}Li confirms Scalo's (1976) conclusion based on mass loss from HBCE AGB stars.

IV. CONCLUSIONS

Our analysis of the luminous SMC AGB stars shows that they are *s*-process–enriched as WBF suggested solely on the basis of the ZrO bands seen in low-resolution spectra. The *s*-process enrichment and the C/O estimates (Brett 1989) show that these stars are experiencing the third dredge-up. The highlight of our analyses is surely the discovery that all five of the observed SMC stars are Li-rich. We suggest that synthesis of Li occurs via the ^{7}Be-transport mechanism at the hot base of the convective envelope in these most massive of the AGB stars.

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