THE ASTROPHYSICAL JOURNAL, 441:735–746, 1995 March 10


# A SURVEY OF LITHIUM IN THE RED GIANTS OF THE MAGELLANIC CLOUDS

VERNE V. SMITH,[1] BERTRAND PLEZ,[2] AND DAVID L. LAMBERT
Department of Astronomy, University of Texas, Austin, TX 78712-1083;
verne@astro.as.utexas.edu, plez@nbivax.nbi.dk, dll@astro.as.utexas.edu

AND

D. A. LUBOWICH[1]
American Institute of Physics, 500 Sunnyside Boulevard, Woodbury, NY 11797; and Department of Physics and Astronomy, Hofstra University; dal@pinet.aip.org
*Received 1994 May 12; accepted 1994 September 20*

## ABSTRACT

A spectroscopic search for the Li I 6707 Å resonance line has been carried out in 112 red giants from both the Small and Large Magellanic Clouds. The spectra are a mixture of high- ($R = \lambda/\Delta\lambda = 18{,}000$) and low-resolution ($R = 4000$) data, and the stars surveyed consist of spectral types M, S, and C. Most of these stars have absolute bolometric magnitude, $M_{bol}$, determinations available from various published investigations. The Li I line is detected in 35 of these red giants (29 S stars and six C stars). All stars with a measurable Li I feature are asymptotic giant branch (AGB) stars with the majority (26) being luminous S stars within the narrow luminosity range of $-7.2 \lesssim M_{bol} \lesssim 6.0$ ($\bar{M}_{bol} = -6.52 \pm 0.38$ in this subset of the stars). Abundance estimates of lithium in these stars fall in the range of log $\epsilon$(Li) $\sim$ 1.0–4.0. The presence of Li in these highly evolved AGB stars is ascribed to hot-bottom convective envelope (HBCE) burning and a comparison of the Li abundances derived here with published models of HBCE shows reasonably good agreement.

*Subject headings:* Magellanic Clouds — stars: abundances — stars: AGB and post-AGB — stars: interiors — stars: late-type

## 1. INTRODUCTION

Spectroscopy of lithium in stars is a key to understanding stellar evolution. Except for hot stars where lithium is undetectable, lithium has proved itself to be useful from main-sequence stars to red giants. In main-sequence and pre–main-sequence stars, observations of Li provide information and insights into convection, diffusion, or mass loss, as reviewed recently by Michaud (1988) or Rebolo (1991). In stars on the giant branch, Li is a monitor of the presence of the deep convective envelope, which is a consequence of red-giant evolution (Brown et al. 1989). Of particular interest to students of the very late stages of stellar evolution are studies of the presence, or absence, of Li in the atmospheres of stars evolving along the asymptotic giant branch (AGB) due to the possibility of $^7$Li production in these very luminous, cool red giants.

The AGB stars are post $^4$He-core burning objects whose internal structure consists of an electron-degenerate carbon-oxygen core, an He-rich shell, and a deep outer convective envelope. A recent detailed review of theoretical AGB evolution is provided by Iben (1991). In the helium shell, $^4$He burns quasi-periodically to $^{12}$C in a thermal runaway which releases large amounts of energy. The energy from the runaway creates a convective shell, extinguishes the H-burning shell in the layers immediately above the He shell and below the base of the convective envelope. Convection driven by the He-burning shell mixes the freshly synthesized $^{12}$C throughout this interior region of the star. When the $^4$He thermal runaway dies, the H burning is reestablished and the deep, outer convective envelope mixes $^{12}$C-rich material to the star's surface. Evolution on the AGB is terminated either by extensive mass loss, or when the degenerate C-O core reaches a Chandrasekhar mass: this maximum core mass corresponds to an upper limit on the luminosity of AGB stars of $M_{bol} \approx -7.1$. Although many details of AGB evolution are still not completely understood, the mixing into the outer atmosphere of $^{12}$C will transform a red giant of spectral type M into a $^{12}$C-rich star of spectral type S or C. In addition to $^{12}$C production during the thermal runaways (also called thermal pulses), free neutrons are liberated by either the $^{13}$C($\alpha$, $n$)$^{16}$O or $^{22}$Ne($\alpha$, $n$)$^{25}$Mg reactions, and these neutrons produce the heavy elements which chacterize the *s*-process, such as Zr or Ba and Tc whose discovery in S stars (Merrill 1952) initiated studies of nucleosynthesis in these red giants.

An intimate connection between Li and "peculiar" red giants was established spectroscopically long before the current picture of an AGB star existed; McKellar's (1940) detection of the Li I 6707 Å resonance doublet in the carbon star WZ Cas was the first detection of Li outside of the solar system. The lack of any Li I feature in 10 other C stars, which had similar Na I line strengths to WZ Cas, led McKellar to suggest that "probably the reason for the occurrence of the 6707 Å line in the spectrum of WZ Cas is an unusually high abundance of lithium in this star" (p. 407). Further observations led to the discovery of a handful of other C stars with very strong ($W_\lambda \sim 10$ Å) Li I lines: WX Cyg (Sanford 1950) T Ara (Feast 1954), and IY HyA (Abia et al. 1991). Analysis (Denn, Luck, & Lambert et al. 1991; Abia et al. 1991; Abia, Isern, & Canal 1993) of the strong Li I 6707 Å doublet shows that these stars have an Li abundance far in excess of the Li present in the main-sequence progenitors. Since Li abundances of this order of magnitude are not seen in less evolved red giants, one conclusion is clear: the carbon (AGB) stars manufacture lithium. A majority of carbon stars have about the

[1] Visiting astronomer, Cerro Tololo Inter-American Observatory (CTIO), National Optical Astronomical Observatory. NOAO is operated by AURA, Inc., under contract to the National Science Foundation.

[2] Present address: Niels Bohr Institute, Blegdamsvej 17, DK-2100, Copenhagen, Denmark.

same low Li abundance as M giants, from whom they are descended. A few stars have Li abundances intermediate between those of the majority and the high values of the super–Li-rich stars (Abia et al. 1993).

Carbon stars are not the sole AGB members to possess strong Li I lines, however. The O-rich (i.e., C/O < 1) AGB counterparts to the C stars are the S stars, and a handful of these objects have also been found to have strong Li I lines. Keenan (1967) first pointed out that the S5/6e star T Sgr possesses an exceptionally strong Li I feature. Other S stars have now been added to this category: VX Aql (Warner & Dean 1970), Henize 166 (Catchpole & Feast 1971), RZ Sgr and TT9 (Catchpole & Feast 1976), and WO 1, WO 42, and WO 43 (Lloyd Evans & Catchpole 1989).

The explanation for the presence of Li in substantial amounts in some AGB stars involves the production of $^7$Li by $^3$He($\alpha$, $\gamma$)$^7$Be($e^-$, $\nu$)$^7$Li (Cameron & Fowler 1971). The necessary $^3$He was synthesized during the main-sequence phase when the initial steps of the H-burning *p-p* chain produced $^3$He which survived in the interior outside the H-burning core because temperatures were too cool there to complete the *p-p* chain. Production through this "$^7$Be transport mechanism" requires a deep convective envelope with a base temperature greater than $\sim 20 \times 10^6$ K. A star meeting this requirement is said to have "a hot-bottomed convective envelope" (HBCE) and to experience "envelope burning." Of course, envelope burning is driven by the H-burning CN-cycle, which converts $^{12}$C to $^{14}$N and reduces the $^{12}$C/$^{13}$C ratio. Stellar models undergoing envelope burning and $^7$Li production have been investigated by various authors—see, for example, Scalo, Despain, & Ulrich (1975) and Sackmann & Boothroyd (1992).

Comparisons between theoretical predictions of envelope burning, in general, and $^7$Li production, in particular, and the observationally derived chemical compositions of the Galactic C and S stars are hampered by their very uncertain luminosities (and masses). The situation is improved considerably by observing AGB stars in the Magellanic Clouds as the distances to the Large (LMC) and Small (SMC) Clouds are well determined. Sample surveys of AGB stars in the Clouds by Smith & Lambert (1989, 1990a, hereafter SL89 and SL90) have demonstrated that the Li-rich AGB stars fall within a narrow range in luminosity at the high end of AGB luminosities: $M_{\rm bol} \sim -6$ to $-7$. In addition, the large majority of these luminous AGB stars are S stars. Plez, Smith, & Lambert (1993, hereafter PSL) concentrated on seven well-observed SMC Li-rich S stars and compared abundance patterns (Li, $^{12}$C, $^{13}$C, and the *s*-process) derived for these objects to the predictions from envelope burning. In this paper, we report on a survey of 112 red giants from the SMC and LMC and derive Li abundances for those S stars found to exhibit strong Li I features.

## 2. OBSERVATIONS AND REDUCTIONS

All spectra discussed here were obtained at the CTIO and consist of two sets of data: "high-resolution" spectra taken with the 4 m telescope plus the Cassegrain echelle spectrometer with the air-Schmidt camera, and "low-resolution" spectra, also taken with the 4 m telescope but with the Cassegrain Ritchey-Chrétien (RC) spectrometer and the air-Schmidt camera. The high-resolution spectra result from two observing runs in 1988 July and 1989 November, both using a GEC (400 × 576 pixels) CCD, and have 2 pixel resolution of 0.38 Å, or $R = \lambda/\Delta\lambda = 18{,}000$, at 6707 Å. Some of these echelle spectra formed the basis of our earlier works. Spectra at lower resolution were obtained on observing runs in 1991 February and October with the RC spectrometer using the 1200 1/mm grating-380. In 1991, February, a GEC CCD was used and yielded a 2 pixel resolution of 1.6 Å, or $R = 4200$, at the Li I 6707 Å doublet: the grating tilt was such that the spectral coverage was $\sim$6350–6800 Å. In 1991, October a Tektronix 1024 × 1024 CCD was used with the spectrometer at a resolution of 1.8 Å ($R = 3700$) and a wavelength coverage of 6300–7200 Å. All spectra were extracted to one-dimensional format using NOAO's IRAF package. Raw frames were DC-bias subtracted, flat-fielded with a quartz lamp, and summed to one dimension using the variance-weighted scheme with sky subtraction, where the "sky spectrum" consisted of an average interval from both sides of the seeing profile.

## 3. THE Li-STRONG RED GIANTS

### 3.1. *Sample, Selection, and Spectra*

The stars were selected from surveys of luminous red stars of the SMC and LMC. Table 1 gives the SMC and LMC stars and each sample is further divided into "O-rich" and "C-rich" stars. Finally, we separate the stars in each of these four groups into those which show the Li I 6707 Å feature in their spectra, and those which do not. We will discuss below what the approximate limits are for our detection, or lack thereof, of the Li I feature. The star designations indicate the source from which the star was selected: for the SMC, all HV designations (meaning Harvard variable), as well as the field containing NGC 371, along with star CV 78, were taken from Wood, Bessell, & Fox (1983, hereafter WBF). The BMB designations are taken from the carbon-star survey of Blanco, McCarthy, & Blanco (1980). For the stars from WBF, we used the Hodge & Wright (1977) atlas for finding charts, while the BMB C-star finding charts are in the Blanco et al. (1980) paper. In the LMC, the HV designations are again taken from WBF (with finding charts from Hodge & Wright 1967), while the RGC stars from Reid, Glass, & Catchpole (1988). The SHV designations are from the surveys of Hughes (1988), Hughes & Wood (1990), and Hughes, Wood, & Reid (1991), while WORC is from Westerlund et al. (1978), BMB is again Blanco et al. (1980), and, finally, BM stars are from Blanco & McCarthy (1990). We include in Table 1 the positions of the stars observed, and these are taken from the survey papers listed in Table 1: we list the right ascensions and declinations for epoch 1950.0, and if, in the original papers, the coordinates are given for another epoch, we have precessed them to 1950.0.

The spectra of all 112 red giants were inspected for the presence, or absence, of the Li I 6707 Å resonance doublet. As mentioned previously, the stars in Table 1 have been divided into "oxygen rich" and "carbon rich" based upon the appearance of the spectra: those red giants (M or S stars) with C/O < 1 exhibit TiO or ZrO bands, while stars (C stars) with C/O $\gtrsim$ 1 show conspicuous CN bands. Sample low-resolution spectra near 6707 Å are shown in Figures 1 and 2. Spectra of two O-rich stars are compared in Figure 1, and spectra of these S stars near 6707 Å are rich in TiO lines. The top panel shows a star with no detectable Li, while the bottom panel shows a red giant with the Li I feature clearly visible. Two TiO bandheads are labeled in Figure 1. Figure 2 shows the same region for two C-rich stars, with the top panel containing a spectrum with no apparent Li and the bottom panel showing a carbon star with a strong Li I line. In C stars, this region of the spectrum is dominated by CN and $C_2$ lines. Figure 3 shows the strong Li I

TABLE 1

OBSERVED STARS

| Star | R.A.(1950.0) | Dec(1950.0) | Low Resolution | High Resolution | $M_{bol}$ | P(days) | Li I Eq. W. (mÅ) |
|---|---|---|---|---|---|---|---|
| (a) SMC Oxygen-Rich Stars with Li I 6707 | | | | | | | |
| HV 838 | 00 53 57.4 | -73 27 56 | Oct-91 | | -7.18 | 663 | 531 |
| HV 1349 | 00 39 26.0 | -73 06 42 | ... | Nov-89 | -6.27 | 615: | 416 |
| HV 1375 | 00 41 00.9 | -74 07 17 | ... | Jul-88 | -6.24 | 512 | 816 |
| HV 1645 | 00 53 38.8 | -73 30 57 | Oct-91 | ... | -4.68 | 300 | 2192 |
| HV 1719 | 00 55 34.5 | -73 17 34 | Oct-91 | ... | -6.68 | 531 | 287 |
| HV 1865 | 01 00 00.0 | -73 00 48 | ... | Nov-89 | -6.62 | 556 | 172 |
| HV 1963 | 01 02 51.9 | -72 50 44 | ... | Jul-88 | -6.76 | 330 | 508 |
| HV 2112 | 01 08 34.3 | -72 52 49 | ... | Nov-89 | -7.22 | 608 | 457 |
| HV 11223 | 00 29 58.6 | -73 39 07 | ... | Jul-88 | -6.19 | 407: | 569 |
| HV 11295 | 00 49 01.9 | -73 08 48 | ... | Nov-89 | -6.55 | 565 | 150 |
| HV 11303 | 00 50 20.1 | -71 52 40 | ... | Nov-89 | -6.69 | 534 | 428 |
| HV 11329 | 00 51 55.6 | -73 08 55 | ... | Nov-89 | -6.52 | 390 | 767 |
| HV 11366 | 00 55 12.0 | -72 30 20 | ... | Jul-88 | -6.30 | 366 | 424 |
| HV 11452 | 01 02 05.1 | -73 49 44 | Oct-91 | ... | -6.61 | 516 | 638 |
| HV 12122 | 00 53 33.4 | -72 21 45 | Oct-91 | ... | -6.44 | 120 | 542 |
| HV 12179 | 01 03 25.8 | -72 22 59 | Oct-91 | Jul-88 | -6.51 | 440 | 624 |
| | | | | | | | 580 |
| HV 12956 | 01 07 27.2 | -71 40 08 | Oct-91 | ... | -6.40 | 518 | 480 |
| (b) SMC Oxygen-Rich Stars without Li I 6707 | | | | | | | |
| HV 859 | 01 08 57.7 | -72 51 45 | ... | Nov-89 | -7.04 | 582 | ... |
| HV 1366 | 00 40 56.0 | -73 11 36 | ... | Nov-89 | -5.48 | 293 | ... |
| HV 11427 | 00 59 51.0 | -73 04 37 | Oct-91 | ... | -5.04 | 251 | ... |
| HV 12149 | 00 57 09.4 | -72 34 45 | ... | Nov-89 | -7.01 | 742 | ... |
| N371#15 | 00 59 40.9 | -72 19 31 | Oct-91 | ... | -4.17 | 230 | ... |
| N371#29 | 01 01 24.5 | -72 17 58 | | Nov-89 | -7.36 | 530 | ... |
| N371#54 | 00 59 29.0 | -72 32 12 | Oct-91 | ... | -4.16 | 160 | ... |
| N371C12 | 01 01 35.6 | -72 25 30 | ... | Nov-89 | -7.83 | 520 | ... |
| N371R20 | 00 59 02.0 | -72 26 45 | Oct-91 | ... | -8.36 | 580 | ... |
| (c) SMC Carbon-Rich Stars with Li I 6707 | | | | | | | |
| N371#3 | 01 00 14.5 | -72 14 10 | Oct-91 | ... | -5.03 | 300 | 2447 |
| N371#33 | 01 00 56.8 | -72 25 10 | Oct-91 | ... | -4.84 | 125: | 1545 |
| (d) SMC Carbon-Rich Stars without Li I 6707 | | | | | | | |
| N371#4 | 01 00 40.1 | -72 15 35 | ... | Nov-89 | -5.56 | 340: | ... |
| N371#6 | 01 03 01.0 | -72 16 23 | Oct-91 | Nov-89 | -4.90 | 350: | ... |
| N371#8 | 01 04 21.4 | -72 16 49 | Oct-91 | ... | -4.93 | 330 | ... |
| N371#20 | 00 59 53.8 | -72 22 49 | Oct-91 | ... | -4.63 | 290 | ... |
| N371#22 | 00 59 21.6 | -72 24 22 | ... | Nov-89 | -5.07 | 330 | ... |
| N371#24 | 01 04 15.0 | -72 27 04 | ... | Nov-89 | -5.19 | 320 | ... |
| N371#28 | 01 03 06.1 | -72 17 57 | Oct-91 | Nov-89 | -4.54 | 550: | ... |
| N371#31 | 01 00 06.7 | -72 24 03 | Oct-91 | ... | -4.96 | 290 | ... |
| N371#41 | 01 04 01.5 | -72 15 27 | Oct-91 | ... | -4.89 | 270: | ... |
| CV78 | 00 47 16.1 | -73 21 42 | ... | Nov-89 | -6.19 | 480: | ... |
| BMB B-2 | 00 45 58.4 | -73 35 35 | Oct-91 | ... | -4.70 | ... | ... |
| BMB B-8 | 00 46 35.2 | -73 29 30 | Oct-91 | ... | -5.00 | | ... |
| BMB B-13 | 00 47 03.9 | -73 30 21 | Oct-91 | ... | -4.90 | ... | ... |
| BMB B-23 | 00 47 33.3 | -73 24 42 | Oct-91 | ... | -5.80 | ... | ... |
| BMB B-30 | 00 47 46.3 | -73 34 10 | Oct-91 | ... | -5.90 | ... | ... |
| BMB B-31 | 00 47 47.0 | -73 24 59 | Oct-91 | ... | -5.70 | ... | ... |
| BMB B-36 | 00 47 53.9 | -73 24 38 | Oct-91 | ... | -4.60 | ... | ... |
| BMB B-39 | 00 48 07.4 | -73 29 03 | Oct-91 | ... | -5.40 | ... | ... |
| BMB B-52 | 00 49 02.5 | -73 44 01 | Oct-91 | ... | -4.90 | ... | ... |
| BMB B-65 | 00 49 39.8 | -73 39 24 | Oct-91 | ... | -5.80 | ... | ... |
| BMB B-74 | 00 50 25.9 | -73 30 50 | Oct-91 | ... | -5.60 | ... | ... |
| (e) LMC Oxygen-Rich Stars with Li I 6707 | | | | | | | |
| HV 2572 | 05 28 58.7 | -69 22 21 | Oct-91 | ... | -6.93 | 201 | 534 |
| HV 2576 | 05 29 20.2 | -70 03 02 | Oct-91 | Nov-89 | -6.70 | 534 | 592 |
| | | | | | | | 510 |
| HV 2578 | 05 29 29.5 | -69 50 23 | ... | Nov-89 | -6.78 | 470 | 407 |
| HV 5506 | 04 58 53.4 | -66 50 11 | Feb-91 | Nov-89 | -6.69 | 618 | 910 |
| | | | | | | | 505 |
| HV 5584 | 05 05 12.8 | -70 25 39 | Oct-91 | ... | -6.27 | 500 | 310 |

TABLE 1—*Continued*

| Star | R.A.(1950.0) | Dec(1950.0) | Low Resolution | High Resolution | $M_{bol}$ | P(days) | Li I Eq. W. (mÅ) |
|---|---|---|---|---|---|---|---|
| HV 5597 | 05 06 45.2 | -69 30 41 | ... | | -6.01 | 468 | 333 |
| HV 12070 | 05 52 50.3 | -69 14 44 | ... | Nov-89 | -6.50 | 621 | 511 |
| RGC 7 | 05 41 43.8 | -67 05 11 | Feb-91 | ... | -6.07 | 249 | 770 |
| RGC 69 | 05 23 52.6 | -66 44 07 | Feb-91 | ... | -6.49 | 648 | 515 |
| SHV A12874 | 05 47 15A | -70 17 58 | Oct-91 | ... | -5.70 | 197 | 395 |
| SHV G149006 | 05 25 08.2 | -70 45 12 | Feb-91 | ... | -6.65 | 636 | 924 |
| SHV B96067 | 05 44 04.3 | -70 58 19 | Feb-91 | ... | -5.13 | 119: | 340 |
| (f) LMC Oxygen-Rich Stars without Li I 6707 | | | | | | | |
| HV 888 | 05 04 15.6 | -67 20 18 | ... | Nov-89 | -9.03 | 850 | ... |
| HV 2526 | 05 26 23.6 | -69 36 24 | Oct-91 | ... | -4.89 | 252 | ... |
| HV 2575 | 05 29 08.5 | -67 47 15 | Oct-91 | ... | -5.41 | 350: | ... |
| HV 2586 | 05 29 36.5 | -66 57 40 | Oct-91 | ... | -7.37 | 487 | ... |
| HV 2602 | 05 30 54.4 | -69 01 32 | ... | Nov-89 | -8.07 | 600 | ... |
| HV 2763 | 05 40 22.1 | -69 36 48 | Oct-91 | ... | -5.98 | 400 | ... |
| HV 5810 | 05 24 28.9 | -69 26 14 | Oct-91 | ... | -5.73 | 372 | ... |
| HV 12048 | 05 27 29.5 | -69 38 27 | Oct-91 | ... | -6.03 | 528 | ... |
| HV 12326 | 05 23 53.9 | -70 01 30 | Oct-91 | ... | -5.62 | 397 | ... |
| HV 12439 | 05 33 49.0 | -68 07 54 | Oct-91 | ... | -4.28 | 266 | ... |
| HV 12495 | 04 54 53.7 | -69 09 19 | Oct-91 | ... | -7.42 | 499 | ... |
| HV 12620 | 05 33 35.3 | -70 43 22 | Oct-91 | ... | -5.22 | 321 | ... |
| HV 12854 | 05 52 24.9 | -64 37 19 | Oct-91 | ... | -6.34 | 147 | ... |
| RGC 15 | 05 39 35.7 | -66 58 05 | Feb-91 | ... | -6.53 | 760 | ... |
| SHV D64879 | 05 00 38.5 | -68 57 22 | Oct-91 | ... | -5.50 | 187 | ... |
| SHV B120037 | 05 50 34.2 | -70 52 50 | Feb-91 | ... | -4.96 | 354 | ... |
| (g) LMC Carbon-Rich Stars with Li I 6707 | | | | | | | |
| HV 5680 | 05 14 45.8 | -68 57 52 | Oct-91 | ... | -4.63 | 151 | 1713 |
| WORC 65 | 05 02 44.0 | -66 28 33 | Feb-91 | ... | -5.60 | ... | 4431 |
| | | | Oct-91 | | | | 4252 |
| BMB 89 | 05 08 34.0 | -71 09 27 | Feb-91 | ... | -5.50 | ... | 8826 |
| SHV F4488 | 05 21 05.0 | -69 04 15 | Feb-91 | ... | -5.70 | 524 | 6410 |
| (h) LMC Carbon-Rich Stars without Li I 6707 | | | | | | | |
| WORC 67 | 05 03 07.0 | -66 04 56 | Oct-91 | ... | -6.10 | ... | ... |
| WORC 78 | 05 05 20.0 | -70 29 34 | Oct-91 | ... | -5.90 | ... | ... |
| SHV G45600 | 05 17 33.7 | -72 57 38 | Feb-91 | ... | -3.21 | 152 | ... |
| SHV A58603 | 05 34 11.7 | -70 05 15 | Feb-91 | ... | -4.98 | ... | ... |
| SHV A36948 | 05 39 33.2 | -69 29 19 | Feb-91 | ... | -4.30 | ... | ... |
| SHV D178684 | 05 17 47.0 | -69 13 03 | Feb-91 | ... | -6.14 | ... | ... |
| SHV C29647 | 05 44 39.7 | -74 07 48 | Feb-91 | ... | -5.44 | ... | ... |
| BMB R-1 | 05 17 49.1 | -68 56 31 | Feb-91 | ... | -5.40 | ... | ... |
| BMB R-12 | 05 18 50.2 | -69 02 37 | Feb-91 | ... | -5.80 | ... | ... |
| BMB R-14 | 05 18 51.1 | -69 01 09 | Feb-91 | ... | -5.30 | ... | ... |
| BMB R-27 | 05 19 31.3 | -68 56 02 | Feb-91 | ... | -5.90 | ... | ... |
| BMB R-45 | 05 21 03.1 | -69 56 26 | Feb-91 | ... | -5.90 | ... | ... |
| BMB R-60 | 05 22 09.0 | -68 54 03 | Feb-91 | ... | -4.90 | ... | ... |
| BMB 0-4 | 05 22 29.4 | -69 49 05 | Feb-91 | ... | -3.30 | ... | ... |
| BMB 0-13 | 05 23 03.2 | -69 50 37 | Feb-91 | ... | -5.80 | ... | ... |
| BMB 0-31 | 05 23 47.0 | -70 00 34 | Feb-91 | ... | -5.40 | ... | ... |
| BMB 0-80 | 05 25 10.9 | -69 58 34 | Feb-91 | ... | -4.80 | ... | ... |
| BMB 0-86 | 05 25 20.4 | -70 01 16 | Feb-91 | ... | -5.40 | ... | ... |
| BMB 0-110 | 05 26 17.9 | -69 49 16 | Feb-91 | ... | -3.80 | ... | ... |
| BMB 0-114 | 05 26 36.7 | -69 50 55 | Feb-91 | ... | -5.80 | ... | ... |
| BM 1-2 | 04 38 30.0 | -70 36 00 | Feb-91 | ... | ... | ... | ... |
| BM 2-3 | 04 38 21.0 | -68 53 54 | Feb-91 | ... | ... | ... | ... |
| BM 3-3 | 04 46 16.0 | -67 56 42 | Feb-91 | ... | ... | ... | ... |
| BM 5-5 | 04 51 20.0 | -69 13 00 | Feb-91 | ... | ... | ... | ... |
| BM 6-15 | 04 55 07.0 | -69 41 18 | Feb-91 | ... | ... | ... | ... |
| BM 7-10 | 04 58 19.0 | -73 00 36 | Feb-91 | ... | ... | ... | ... |
| BM 23-12 | 05 24 53.0 | -71 12 12 | Feb-91 | ... | ... | ... | ... |
| BM 47-1 | 05 57 46.0 | -73 07 06 | Feb-91 | ... | ... | ... | ... |
| BM 50-3 | 06 10 33.0 | -71 30 24 | Feb-91 | ... | ... | ... | ... |
| BM 51-7 | 06 12 09.0 | -68 58 30 | Feb-91 | ... | ... | ... | ... |
| BM 52-2 | 06 12 17.0 | -68 16 12 | Feb-91 | ... | ... | ... | ... |

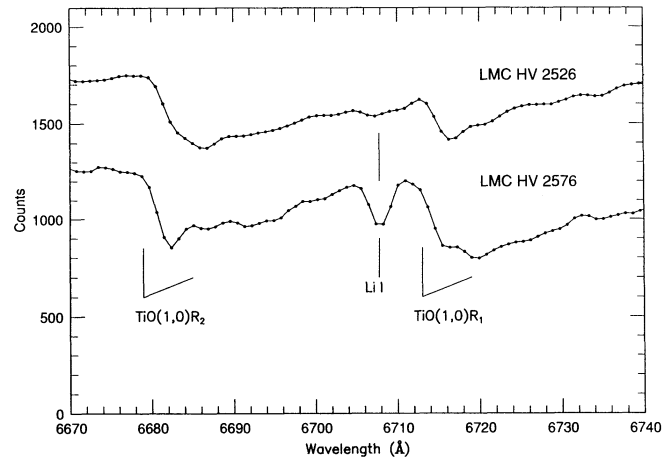


FIG. 1.—Sample spectra of S stars: one with the Li I resonance doublet and one without. The TiO bandheads near the Li I feature are labeled. HV 2526 is a lower luminosity S star with $M_{bol} = -4.9$, while HV 2576 has $M_{bol} = -6.7$.

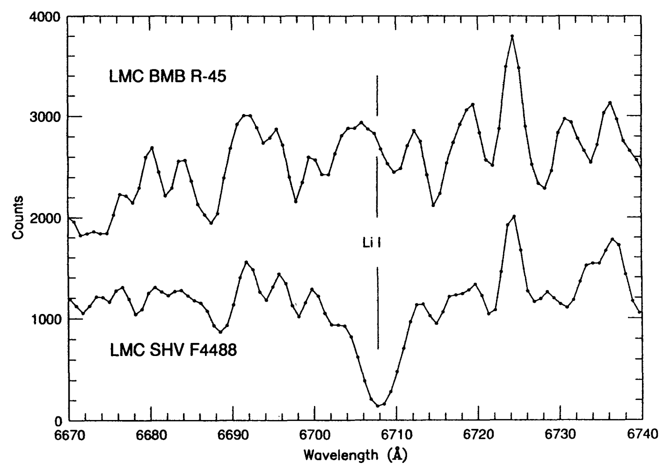


FIG. 2.—Sample spectra of C stars illustrating the presence of a strong Li I line in SHV F4488 with $M_{bol} = -5.7$, while BMB R-45 with $M_{bol} = -5.9$ shows no evidence of lithium in its spectrum.

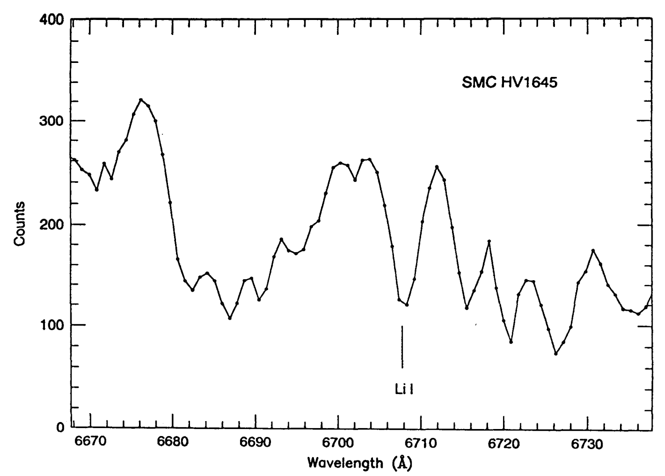


FIG. 3.—Illustration of the very strong Li I line in the rather low luminosity ($M_{bol} = -4.7$) S star HV 1645 in the SMC. The Li I feature is strong, with an equivalent width near 2 Å.

line in the lower luminosity S star HV 1645. For those stars which show a detectable Li I line, its equivalent width, relative to the neighboring local maximum intensity, is listed in Table 1. It must be kept in mind that the true "continuum" is much higher than any local maximum intensities, as this spectral region is heavily blanketed by molecular as well as atomic lines in all stars. Thus, the equivalent widths listed in Table 1 are merely indicators of the overall strength of the Li I feature in these stars. Also, for stars observed on two occasions, both "pseudo"-equivalent widths are listed; all of the red giants studied here are variable, and as can be seen from Table 1, the strength of the Li I line relative to the local pseudocontinuum can vary. In the stars for which no Li is detected, the approximate upper limits to the pseudo-equivalent width are 50 mÅ for the low-resolution data and 10–15 mÅ for the high-resolution spectra. We show no examples of the higher resolution echelle spectra here, as several examples are shown in SL89, SL90, and PSL.

The accuracy of the $M_{bol}$'s is difficult to assess due to the combination of various data sets from different authors; however, some crude estimates can be made. In a study of Galactic Mira variables (recall that most, if not all, of the red giants in this survey are Miras), Wood & Bessell (1983, Fig. 1) illustrate typical excursions in $M_{bol}$ for Miras. This difference amounts to 0.5 mag, so we might expect an intrinsic spread of $\pm 0.3$ in derived $M_{bol}$'s. Westerlund et al. (1991) tabulate derived values of $M_{bol}$ for C stars in the clouds from a number of different studies. For the same stars observed at different times by different investigators, typical differences in $M_{bol}$ are again $\pm 0.2$ mag. Thus, a rough estimate of the values of $M_{bol}$ presented here are $\pm 0.2$ to $\pm 0.3$ mag.

### 3.2. *Abundance Estimates for Lithium*

Lithium abundances are based on our analysis of the Li I 6707 Å resonance doublet in S stars. Lithium abundances are not provided for the carbon stars of our sample. Following PSL, the 6665–6735 Å region was synthesized and compared with the observed spectra. A complete discussion of the line lists and synthesis techniques can be found in PSL. This analysis differs from PSL's in that:

1. We use plane-parallel (PP) model atmospheres in the spectrum synthesis.
2. We synthesize only the 6707 Å region.
3. We include all five titanium ($^{46}$Ti–$^{50}$Ti) isotopes in the TiO line list for the spectrum syntheses. The isotopic line positions were calculated using standard formulae (Herzberg 1950), with the isotopic ratios assumed to be terrestrial.

Model atmospheres were calculated with the PP version of the SOSMARCS (Plez, Brett, & Nordlund 1992) code. Stellar parameters were derived from the photometry of WBF, Reid et al. (1988), or Hughes & Wood (1990). The $K$-magnitude, $(J-K)$ color, and period ($P$) yield $T_{eff}$, $M_{bol}$, and log $g$. For the SMC models, we take [Fe/H] = $-0.5$, with [C/Fe] = $-0.53$, [N/Fe] = $+0.30$, and [O/Fe] = $-0.20$, as discussed in PSL. For the LMC, we use [Fe/H] = $-0.25$ (Russell & Bessell 1989; Thévenin & Jasniewicz 1992) and [C/Fe] = $-0.3$, [N/Fe] = $+0.3$, and [O/Fe] = 0.0.

Observed spectra were compared to the synthetic spectra calculated for a microturbulent velocity of 3 km s$^{-1}$. The goal was to fit the TiO bandheads at 6680 and 6741 Å; if the TiO bands were not fit initially, models of both higher and lower $T_{eff}$ were tried, as well as different Ti abundances ([Ti/H]).

Changing the Ti abundance can either increase or decrease the strength of the TiO bands. Changes made to $T_{\rm eff}$ and [Ti/H] within the uncertainties of these quantities led to a good fit to the spectrum near the Li I 6707 Å line. For a few stars (HV 1645 in the SMC, along with HV 5597, RGC 69, and SHV G149006 in the LMC), we could not obtain good fits to the observed spectra: in these cases the TiO bands are unusually strong. Note that one of these stars, HV 1645, is a rather low luminosity ($M_{\rm bol} = -4.7$) S star in the SMC with a tremendously strong ($W_\lambda \sim 2$ Å) Li I line. This star deserves closer scrutiny at higher resolution. The derived Li abundances, along with the model parameters used for each star, are listed in Table 2.

A comparison of the Li abundances derived for the seven SMC AGB stars in PSL with the abundances derived here for the same spectra reveals differences in the Li abundances of $-0.25$ to $+0.75$ dex, with the present abundance being on average $+0.3$ dex larger. These differences are generally attributable to differences in the model parameters and atmospheres used: the present $T_{\rm eff}$'s are 50–200 K lower than those in PSL, with the average difference being 100 K. Naively, one might expect that, with a low-ionization species such as Li I, lower effective temperatures would lead on average to lower Li abundances. However, the "veiling" of the surrounding haze of TiO lines acts as a pseudocontinuous opacity source and increases quickly with lower temperatures. This results in higher Li abundances.

It was noted by PSL that the Li abundances derived from the 6707 Å line were systematically lower than those derived from the subordinate 8126 Å Li I line. Typical differences between abundances (8126–6707 Å) from PSL were roughly $+0.5$ dex. Since the 8126 Å is both weaker and in a less blanketed region of the spectrum than the 6707 Å resonance transition, one might suppose it to provide the more accurate abundance. It is quite possible that the core of the 6707 Å line is contaminated with a circumstellar absorption and/or emission component. On the other hand, the weak 8126 Å line may be blended with an as yet unidentified line, so resulting in a spuriously high Li abundance. Except where noted, we adopt the Li abundances derived here from the 6707 Å feature. For those red giants with no detectable Li I feature, very approximate upper limits to the Li abundance are $\log \epsilon({\rm Li}) \lesssim 0.0$ (where $\log \epsilon({\rm X}) = \log [N({\rm X})/N({\rm H})] + 12$).

TABLE 2

LITHIUM ABUNDANCES

| Star | $T_{\rm eff}$(K) | log $g$ | log $\epsilon$(Li) |
|---|---|---|---|
| | (a) SMC | | |
| HV 838 | 3400 | -0.3 | 3.2 |
| HV 1349 | 3200 | -0.3 | 1.0 |
| HV 1375 | 3200 | -0.2 | 3.0 |
| HV 1719 | 3200 | -0.3 | 1.5 |
| HV 1865 | 3200 | -0.3 | 1.0 |
| HV 1963 | 3300 | 0.0 | 3.2 |
| HV 2112 | 3100 | 0.3 | 2.2 |
| HV 11223 | 3300 | 0.0 | 3.5 |
| HV 11295 | 3300 | -0.3 | 0.0 |
| HV 11303 | 3300 | -0.3 | 1.8 |
| HV 11329 | 3500 | 0.0 | 3.2 |
| HV 11366 | 3400 | 0.0 | 1.9 |
| HV 11452 | 3300 | -0.3 | 3.5 |
| HV 12122 | 3300 | 0.5 | 1.5 |
| HV 12179 | 3300 | -0.3 | 3.5 |
| HV 12956 | 3300 | -0.3 | 2.5 |
| | (b) LMC | | |
| HV 2572 | 3300 | 0.2 | 2.5 |
| HV 2576 | 3300 | -0.2 | 3.8 |
| HV 2578 | 3200 | -0.2 | 2.5 |
| HV 5506 | 3200 | -0.2 | 2.0 |
| HV 5584 | 3200 | -0.2 | 2.8 |
| HV 12070 | 3200 | -0.2 | 2.0 |
| RGC 7 | 3100 | -0.2 | 2.5 |
| SHV A12874 | 3100 | 0.2 | 1.5 |
| SHV B96067 | 3100 | 0.2 | 2.0 |

### 3.3. *Evolutionary Status of the Red Giants*

It is important to determine which members of our sample are AGB stars and which are not. In the Introduction we pointed out that AGB evolution at high luminosities leads to the mixing of $^{12}$C and *s*-process heavy elements into the outer atmosphere, and we will use these observable signatures to ascertain which stars are on the AGB. The first, and most obvious, step is to place all of the carbon stars observed here into the AGB category, due to the fact that $^{12}$C has almost certainly been added to the atmospheres of these red giants to drive C/O > 1. Although it is known that some C stars exist at lower luminosities without *s*-process enhancements (e.g., the R stars; Dominy 1984), all of the C stars observed here are at such luminosities that the simplest interpretation would place them on the AGB. For the O-rich red giants (C/O < 1), it is more difficult to determine if the $^{12}$C abundance has been enhanced by mixing, but an enhancement of abundances of the *s*-process elements can be determined through either atomic lines or the molecule ZrO. With two different data sets (high- and low-resolution spectra), we chose two separate *s*-process indicators for the O-rich stars. At low resolution, we use the ZrO $\gamma(0, 0)R_1\ ^3\Phi$–$^3\Delta$ band at 6474 Å as an indicator of the *s*-process enrichment. As a quantitative estimate of the strength of ZrO, we measure the depths of the 6474 Å band (relative to the flux just blueward of the bandhead) and the TiO bandhead $\gamma(0, 0)R_3$ at 7055 Å. The ratio of the depths of the two bands is a measure of the relative strength of ZrO/TiO, which is a function of the Zr/Ti abundance ratio and the C/O ratio (Wurm 1939). Both the Zr and $^{12}$C abundances are expected to increase in AGB stars, so the ratio ZrO/TiO should distinguish true AGB stars from massive core-burning supergiants.

In Table 3 we present ZrO and TiO bandhead depths from low-resolution spectra of the O-rich red giants, along with the ZrO/TiO ratios. For the non–*s*-process enriched stars, the ZrO bandhead is not detected, and we denote this depth with a colon. For the 1991 February run, the wavelength coverage was such that 7055 Å TiO was not observed and only the ZrO depth is listed. In the top panel of Figure 4 we plot the ZrO/TiO ratios (multiplied by 10) as a function of $M_{\rm bol}$ and denote red giants with the Li I feature as filled symbols. For the three stars that lie clearly above the AGB luminosity limit, the ZrO/TiO is very low; thus, these stars are M supergiants, i.e., core-burning massive stars evolving through this region of the H-R diagram. Note also that the LMC star HV 12854, which has no detectable Li, at $M_{\rm bol} = -6.34$ does not have enhanced ZrO absorption: it is an M supergiant. Six LMC stars in Table 3 do not have measured TiO (7055 Å) absorption and thus, in our convention, do not have measured ZrO/TiO ratios. These particular stars were observed on the 1991 February run, where the spectral coverage did not reach 7055 Å. One member of this group, the LMC star RGC 15 at $M_{\rm bol} = -6.53$, which does not contain Li I, shows no measurable ZrO absorption at

TABLE 3

ZrO AND TiO BAND STRENGTHS FROM LOW-RESOLUTION SPECTRA

| Star | TiO(λ7055 Å) | ZrO(λ6474 Å) | $\frac{\text{ZrO}}{\text{TiO}} \times 10$ |
|---|---|---|---|
| | (a) SMC | | |
| HV 838 | 0.46 | 0.16 | 3.5 |
| HV 1645 | 0.85 | 0.37 | 4.4 |
| HV 1719 | 0.59 | 0.32 | 5.4 |
| HV 11427 | 0.25 | 0.06: | 2.4 |
| HV 12122 | 0.75 | 0.29 | 3.9 |
| HV 12179 | 0.44 | 0.27 | 6.1 |
| HV 12956 | 0.47 | 0.16 | 3.4 |
| N371 15 | 0.32 | 0.11 | 3.4 |
| N371 54 | 0.40 | 0.13 | 3.3 |
| N371 R20 | 0.17 | 0.02: | 1.2 |
| | (b) LMC | | |
| HV 2526 | 0.39 | 0.12 | 3.1 |
| HV 2572 | 0.56 | 0.14 | 2.5 |
| HV 2575 | 0.75 | 0.43 | 5.7 |
| HV 2576 | 0.64 | 0.21 | 3.3 |
| HV 2586 | 0.51 | 0.05: | 1.0 |
| HV 2763 | 0.79 | 0.26 | 3.3 |
| HV 5506 | ... | 0.20 | ... |
| HV 5584 | 0.63 | 0.18 | 2.9 |
| HV 5597 | 0.78 | 0.17 | 2.2 |
| HV 5810 | 0.43 | 0.14 | 3.3 |
| HV 12048 | 0.63 | 0.24 | 3.8 |
| HV 12326 | 0.63 | 0.20 | 3.2 |
| HV 12439 | 0.77 | 0.25 | 3.2 |
| HV 12495 | 0.38 | 0.04: | 1.1 |
| HV 12620 | 0.27 | 0.18 | 6.7 |
| HV 12854 | 0.27 | 0.04: | 1.5 |
| RGC 7 | ... | 0.23 | ... |
| RGC 15 | ... | 0.00: | ... |
| RGC 69 | ... | 0.17 | ... |
| SHV A12874 | 0.60 | 0.35 | 5.8 |
| SHV B96067 | ... | 0.53 | ... |
| SHV B120037 | ... | 0.26 | ... |
| SHV D64879 | 0.63 | 0.17 | 2.7 |
| SHV G149006 | ... | 0.21 | ... |

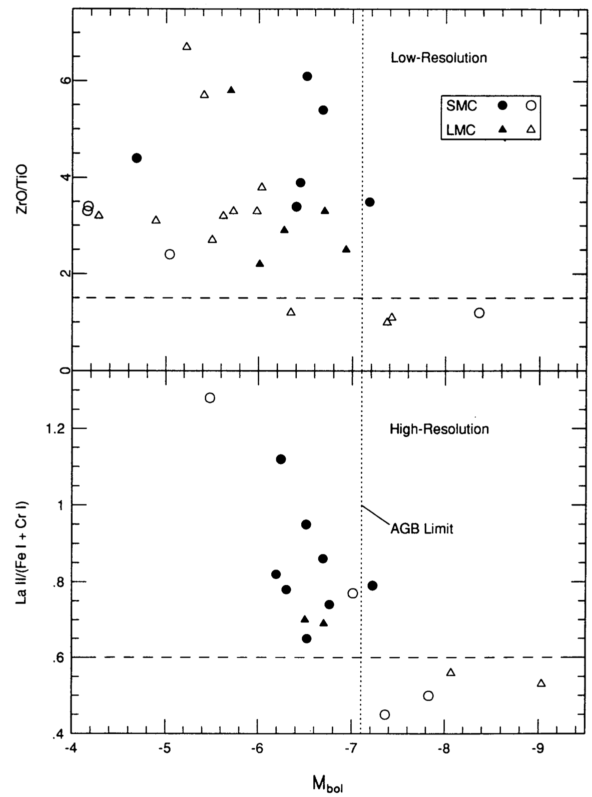


FIG. 4.—Spectral indices used to separate *s*-process enriched AGB stars from normal *s*-process abundance massive, core-burning supergiants. *Top panel*, ratio of ZrO (6474 Å) absorption relative to TiO (7055 Å) absorption is shown as a function of $M_{bol}$: this spectral index was derived from the low-resolution data. The stars with the stronger ZrO/TiO ratios (>2) have a combination of enhanced Zr and C and are AGB stars. Note that all Li-strong stars are AGB stars. *Bottom panel*, ratio of the equivalent width of an La II line to the equivalent width of a nearby blend of an Fe I and Cr I line is shown. Lathanum is an *s*-process element, and the larger values of La II/(Fe I + Cr I) indicate AGB stars. Again all stars with detectable Li I lines are AGB stars.

6474 Å and is thus also an M supergiant. All of the Li-strong stars have enhanced ZrO/TiO ratios, relative to the M supergiants. Lower luminosity stars ($M_{bol} \gtrsim -6$) also have enhanced ZrO absorption: these are O-rich AGB S stars without, in general, an Li enrichment.

As an indicator of *s*-process enhancements from the high-resolution spectra, we use the equivalent width of a strong and relatively isolated La II line at 7483.50 Å; this region is fairly free from molecular blanketing, except in extreme S stars when LaO absorption obliterates this window, and has been used to determine abundances in M, MS, and S stars by Smith & Lambert (1985, 1986, 1989, 1990b) and PSL. This particular La II line was also used as an *s*-process indicator for a sample of Galactic S stars by Smith, Lambert, & McWilliam (1987). To estimate *s*-process enhancements in each star, the equivalent width of La II 7483.50 Å was divided by the equivalent width of a nearby similar strength feature composed of a blend of Cr I (7462.37 Å) and Fe I (7461.53 Å), as was done in Smith et al. (1987). We present equivalent widths and ratios in Table 4 and plot these ratios as a function of $M_{bol}$ in the bottom panel of Figure 4. The dashed horizontal line indicates the approximate upper limit of the equivalent-width ratio [La II/(Fe I + Cr I)] from a sample of galactic M giants, and it is clear that all of the Li-strong stars have enhanced La II absorption. The most luminous of the Magellanic Cloud red giants have La II line strengths typical of M supergiants. Both panels in Figure 4 demonstrate that all of the Li-strong stars in our sample have *s*-process enhancements and are thus AGB stars. The luminosity $M_{bol} \simeq -7.1$ has been identified as the limiting luminosity for AGB stars and corresponds to a C-O core mass of the Chandrasekhar mass. (See below, however, for a comment on the luminosities of the AGB stars with an HBCE.) As expected, none of the more luminous ($M_{bol} \lesssim -7.1$) stars exhibit measurable *s*-process enhancements and all are almost certainly core-burning supergiants.

The Li-strong stars are concentrated just below the limiting luminosity $M_{bol} = -7$. An assertion that the sample of Li-rich stars is banded at the high-luminosity limit must be considered as tentative on account of the small number of stars observed with $M_{bol} \lesssim -7$. The existence of Li-rich stars at luminosities well below the high-luminosity limit is certain; the Li-rich, O-rich star HV 1645 near $M_{bol} \sim -4.6$ is quite unlikely to be a more luminous ($M_{bol} \simeq -6$ to $-7$) star misplaced owing to an incorrect estimate of $M_{bol}$. However, the large majority of Li-strong stars are found at luminosities above $M_{bol} \approx -6$. In the interval $-7.1 \leq M_{bol} \leq -6$, there are 30 AGB stars, and 24 (80%) are Li-strong. To within the limits of the samples, the SMC and LMC are indistinguishable with respect to the Li-$M_{bol}$ relation. This shows that the properties of the Li-strong

TABLE 4

La II AND Fe I + Cr I EQUIVALENT WIDTHS FROM HIGH-RESOLUTION SPECTRA

| Star | La II λ7438.48 (mÅ) | Fe I λ7461.53 + Cr I λ7462.37 (mÅ) | $\frac{\text{La II}}{\text{Fe I+Cr I}}$ |
|---|---|---|---|
| | (a) SMC | | |
| HV 859 | LaO | ... | ... |
| HV 1349 | LaO | ... | ... |
| HV 1366 | 250 | 195 | 1.28 |
| HV 1375 | 353 | 314 | 1.12 |
| HV 1865 | LaO | ... | ... |
| HV 1963 | 222 | 300 | 0.74 |
| HV 2112 | 318 | 404 | 0.79 |
| HV 11223 | 383 | 465 | 0.82 |
| HV 11295 | LaO | ... | ... |
| HV 11303 | 258 | 300 | 0.86 |
| HV 11329 | 273 | 497 | 0.55 |
| HV 11366 | 303 | 388 | 0.78 |
| HV 12149 | 270 | 351 | 0.77 |
| HV 12179 | 399 | 418 | 0.95 |
| N371 29 | 240 | 529 | 0.45 |
| N371 C12 | 247 | 490 | 0.50 |
| | (b) LMC | | |
| HV 888 | 345 | 650 | 0.53 |
| HV 2576 | 222 | 320 | 0.69 |
| HV 2578 | LaO | ... | ... |
| HV 2602 | 338 | 600 | 0.56 |
| HV 5506 | LaO | ... | ... |
| HV 12070 | 163 | 233 | 0.70 |

stars are insensitive to the difference in metallicity between the Clouds. The two carbon stars, in this 1 mag range below the limit $M_{bol} = -7.1$, appear to be normal N-type carbon stars without detectable lithium. Both are near the lower limiting luminosity $M_{bol} = -6$ where most of the Li-strong stars appear. Additional LMC Li-rich S stars brighter than $M_{bol} = -6$ are described by Reid & Mould (1990).

All of the lower luminosity red giants in our sample ($M_{bol} \gtrsim -6$), are either carbon or S stars; none are M stars. It is at these lower luminosities that many of the carbon stars observed by us do not have have measured periods. Also, for 11 of the C stars we do not have estimates for $M_{bol}$, although all carbon stars are less luminous than $M_{bol} \approx -6$. Below $M_{bol} = -6$, three S stars have detectable Li I features; one star is near $M_{bol} = -6$ with weak Li I absorption (SHV A12874 in the LMC at $M_{bol} \sim -5.7$). SHV 896067 in the LMC is near $M_{bol} = -5$, and this presumably means that the appearance of Li at $M_{bol} = -6$ is not a strict limit. Of particular interest is the SMC star HV 1645, at $M_{bol} \sim -4.7$ with one of the strongest Li I lines yet observed in an S star: we illustrated the spectrum at the Li I region in HV 1645 in Figure 3. HV 1645 deserves closer scrutiny; it is also quite a strong S star as can be seen from its position in the top panel of Figure 4.

Six carbon stars were found with detectable Li I. These six stars span the luminosity range $-5.7 \lesssim M_{bol} \lesssim -4.6$. Three LMC C stars have very strong Li I and deserve the title "super–Li-rich," as is often used to describe such Galactic examples as WZ Cas. Two of these carbon stars were detected in previous surveys (WORC 65 by Richer, Olander, & Westerlund 1979, and BMB 89 by Richer 1981), while SHV F4488 is a new addition to this select group. These three super–Li-rich C stars are all near our dividing line of $M_{bol} \approx -6$ (from $-5.5$ to $-5.7$). BMB 89 was classified as an SC star by Richer & Frogel (1980) and assigned the luminosity $M_{bol} \simeq -5.5$, an estimate revised to $M_{bol} = -5.2$ by Richer (1981). Crabtree, Richer, & Westerlund (1976) found an Li-rich carbon star in the LMC with $M_{bol} = -6.5$.

One interesting aspect of the six carbon stars with detectable Li I is that they have enhanced $^{13}$CN absorption, relative to the other C stars in this survey. Earlier work on spectra of LMC carbon stars (Richer, Westerlund, & Olander 1978; Richer et al. 1979; Richer 1981) found that most luminous carbon stars tended to show strong $^{13}$C bands. Although our sample is small, it seems that the stars with a detectable Li I feature have even stronger $^{13}$C bands.

### 3.4. *The $M_{bol}$-P Diagram*

In a discussion of Mira variables in the Magellanic Clouds, WBF introduced the $M_{bol}$-$P$ diagram, which may be considered a form of H-R diagram with the period $P$ as a substitute for effective temperature $T_{eff}$. Evolutionary tracks in the $M_{bol}$-$P$ diagram resemble those in the usual $M_{bol}$-$T_{eff}$ diagram: as a star evolves to higher luminosity and lower effective temperature, its radius increases, and hence, the pulsational period also increases. WBF prefer this type of diagram as it represents largely observational quantities: periods are directly observable, and adequate IR photometry, coupled with the distances to the Clouds, leads to fairly accurate $M_{bol}$'s. One drawback is that not all stars observed in our survey have measured periods: 73 red giants out of 112 observed have known periods. All but two of the stars with a detected Li I feature have a measured pulsational period. In Figure 5 we plot $M_{bol}$ versus $P$

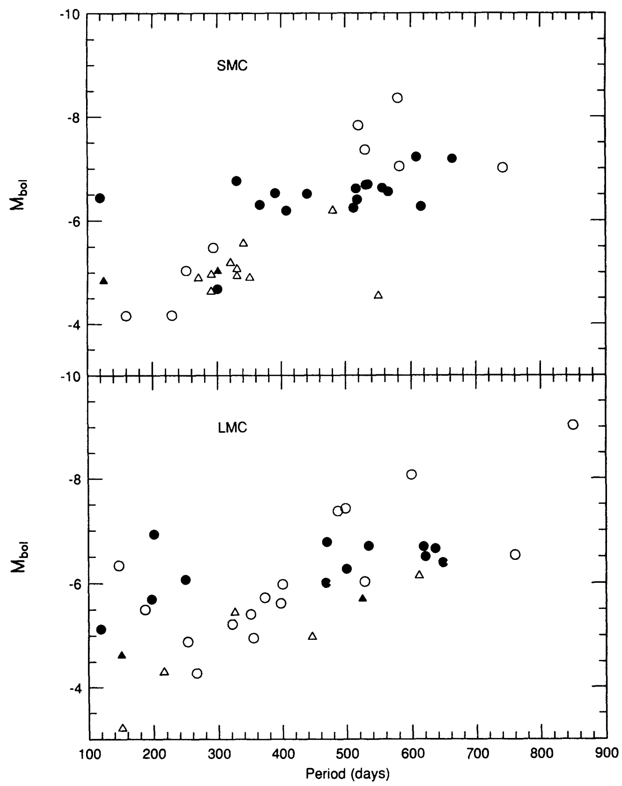


FIG. 5.—Absolute bolometric magnitude: period diagrams for the red giants with published periods in the SMC (*top panel*) and the LMC (*bottom panel*). Filled symbols are stars with a detected Li I feature, circles are oxygen-rich stars, and triangles are carbon stars. This figure shows how the Li-strong stars concentrate in a band $-7 < M_{bol} < -6$, with the large majority of Li detections occurring in the oxygen-rich AGB (i.e., S-type) stars. No apparent difference is observed between the SMC and LMC Li-strong stars in this type of diagram.

for the SMC (*top panel*) and LMC (*bottom panel*), with C-rich and O-rich stars represented by triangles and circles, respectively, and filled symbols for those red giants which show a detectable Li I line. As noted in § 3.3, the vast majority of the Li-rich giants are concentrated in the 1 mag interval of $M_{bol}$ below the predicted limit for the AGB ($M_{bol} = -7.1$). We note that in Figure 5 there is no significant difference between the positions of the Li-strong stars in the SMC compared to the LMC, and hence, we combine the systems in Figure 6. Evolutionary tracks from WMF are superimposed on Figure 6. These tracks assume that the Miras are pulsating in the fundamental mode. On this assumption, the masses of the Li-rich stars with $-7 \lesssim M_{bol} \lesssim -6$ are $M \geq 4\ M_{\odot}$. Wood (1990) has given improved evolutionary tracks including a dependence on chemical composition. These tracks for a metallicity $Z = Z_{\odot}/2$ appropriate to the LMC indicate the Li-rich stars to have a mass range $M \gtrsim 3\ M_{\odot}$. At the composition ($Z \simeq Z_{\odot}/4$) of the SMC, a Mira is ~0.2 mag more luminous and the lower mass limit is slightly lower. Masses inferred from the tracks refer to the *current* masses. Initial masses ($M_i$) will have been higher because stars are sure to have shed mass in evolving from the main sequence to the AGB. Stars with $M_i \gtrsim 3\ M_{\odot}$ are referred to as "intermediate-mass" stars.

Identification of the mode of pulsation of Miras has long been a contentious issue. The supposition that Miras pulsate in the fundamental mode derives very largely from models of the pulsating atmospheres (see reviews by Willson 1983; Wood 1990). Evidence in favor of a first-overtone pulsation comes primarily from estimates of the radii of Miras obtained by combining effective temperatures derived from photometry with absolute luminosities from an empirical period-luminosity relation. Very recently, Turnhill et al. (1994) combined their precise measurement of the angular diameter of R Leo with the trigonometric parallax measured by Gatewood (1992) to obtain an estimate of the stellar radius that exceeds by a factor of 2.5 the radius predicted for a fundamental pulsator. This result requires that R Leo pulsate in a first, or a higher, overtone mode. Of course, this particular result does not demand that the Miras in the Magellanic Clouds pulsate in an overtone mode, but as noted, there is other evidence that radii of Miras are generally too large for the stars to be pulsating in their fundamental mode. At a given period, the mass assigned to a Mira is approximately halved if the star is supposed to pulsate in the first overtone rather than the fundamental mode (WBF, Figs. 6 and 7). Then, the current masses of the Li-rich stars with $-7 \leq M_{bol} \leq -6$ are $M \simeq 2$ to $7\ M_{\odot}$. Even after this reduction, the majority of the Miras would appear to correspond to intermediate-mass AGB stars.

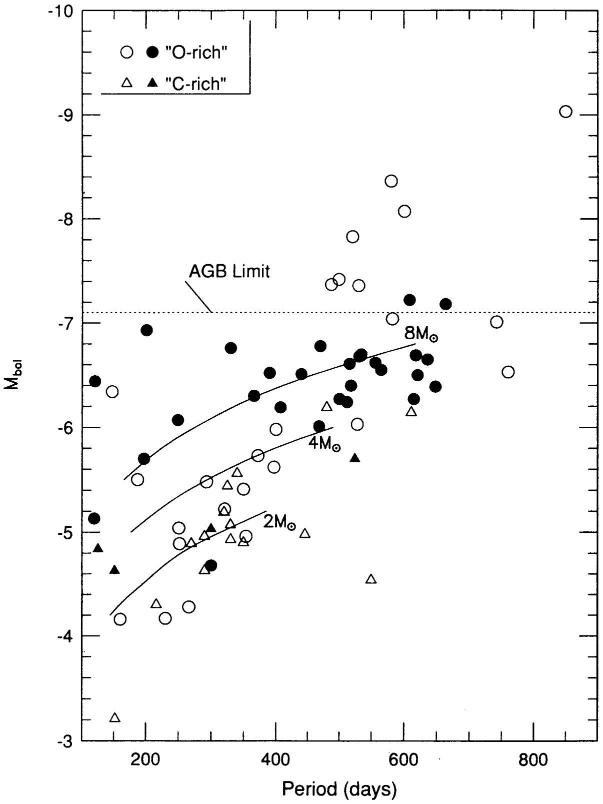


FIG. 6.—Combined $M_{bol}$-$P$ diagram for the Magellanic Clouds with the filled symbols denoting the Li-strong stars. The segregation of the Li-strong stars to the most luminous of the AGB stars is striking. Note that no AGB stars with detectable Li I are found at luminosities significantly exceeding the AGB limit. A few AGB stars with $M_{bol} > -6$ show detectable Li I lines. The solid curves denote evolutionary tracks for AGB stars taken from the equations given in Wood et al. (1983) for fundamental pulsators.

## 4. AGB EVOLUTION AND NUCLEOSYNTHESIS

The most luminous AGB stars are, as sketched in the Introduction, predicted to develop an HBCE in which the H-burning layers are an integral part of the giant's deep convective envelope. Here we discuss two consequences of an HBCE: Li production and the reconversion of a carbon star to an oxygen-rich or S star.

### 4.1. Li *Production*

Lithium production from $^3$He by the $^7$Be transport mechanism was first associated with AGB stars possessing HBCEs by Scalo et al. (1975). Sackmann & Boothroyd (1992) report on a detailed investigation of Li production by a sequence of AGB models spanning the mass range $M = 3$–$7\ M_{\odot}$ at two metallicities ($Z = Z_{\odot} = 0.02$ and $Z = Z_{\odot}/20 = 0.001$). Figure 7 compares the derived Li abundances (Table 2) with predictions of the $Z = 0.02$ models for two stellar masses. Overall, the model predictions of an extremely rapid increase in the $^7$Li abundance at a threshold luminosity of $M_{bol} \sim -6.0$ to $-6.2$

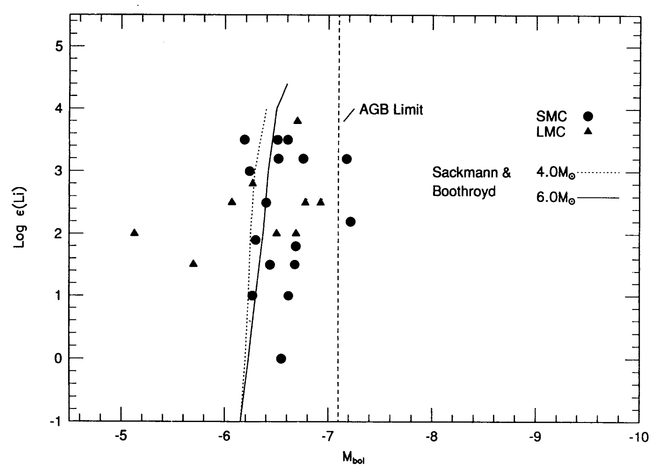


FIG. 7.—Derived lithium abundances for the oxygen-rich stars with detected Li I 6707 Å line as a function of $M_{bol}$. Model abundances for HBCE burning from Sackmann & Boothroyd (1992) are shown for two different masses with solar metallicities. The general agreement between the derived abundances and the model predictions is good.

is in excellent agreement with the derived abundances. Sackmann & Boothroyd (1992) suggest that the lithium enrichment declines after the temperature at the base of the convective envelope has reached the temperature at which $^7$Be produced from $^3$He + $\alpha$ is burned through $^7$Be($p$, $\gamma$)$^8$Be($e^-$, $\nu$)$^8$Be(2$\alpha$) before it can be convected to cooler regions to $e^-$-capture to $^7$Li. The upper limit to the $^7$Li abundance is estimated to log $\epsilon$($^7$Li) $\sim$ 4.5–5.5. Our derived upper limit to the Li abundance, from Figure 7, appears to be closer to log $\epsilon$(Li) $\sim$ 4.0, as was also found in the more detailed abundance analysis of PSL who noted that Li abundances from the 6707 Å line were systematically lower than those from the weaker 8126 Å line. If the mean difference of 0.5 dex is added to the Li abundances in Figure 7, the observed and predicted abundances for $M_{bol} \gtrsim -6$ are in fine agreement. It would be of interest to have predictions for metallicities appropriate to the individual Clouds.

Sackmann & Boothroyd predict copious Li production in stars with initial masses $M \simeq 5$–$6\ M_\odot$ for the composition $Z \simeq Z_\odot$. A 7 $M_\odot$ star ignited carbon in the core to bypass the HBCE AGB phase. A 4 $M_\odot$ star develops an HBCE but no detectable lithium at the surface. The predicted range of initial masses of 4 $M_\odot < M < 7\ M_\odot$ for Li-rich luminous AGB stars may be compared with that estimated from $M_{bol}$-$P$ diagrams like Figure 6. If, as in Figure 6, the Miras are assumed to pulsate in the fundamental mode and predictions are taken from WBF, the mass estimate $M > 4\ M_\odot$ from pulsation theory seems consistent with the predicted mass range for copious Li surface enrichment. This comparison overlooks the fact that the pulsation theory provides *current* masses and the model masses cited by Sackmann & Boothroyd are initial or main-sequence masses. Sackmann & Boothroyd include a prescription for mass loss which leads to very little reduction (say, 5%–15%) of mass up through the phase of Li production.

Two alternative $M_{bol}$-$P$ predictions lead to lower estimates of the masses. If the predictions for fundamental pulsators are taken from Wood (1990), the mass range $M \gtrsim 2\ M_\odot$ is obtained. If the Miras are identified as first-overtone pulsators, $M \gtrsim 2\ M_\odot$ is also obtained from WBF's predictions; lower masses are expected from Wood (1990) but he does not give specific predictions.

In summary, the predictions and observations of Li enrichment for the most luminous AGB stars are in fair agreement with respect to the Li abundances and to the mass range of the stars. Lower luminosity Li-rich stars at $M_{bol} > -6$ remain an enigma and deserve closer scrutiny. Four stars in our sample of Li-strong stars are close to 1 mag or more below $M_{bol} = -6$ and may require additions to the models constructed up to now for envelope burning.

### 4.2. *Reconversion of Carbon Stars*

After objective prism surveys of the Clouds in the early 1980s reported their results for carbon stars, the surprising lack of luminous carbon-rich AGB stars generated theoretical speculation as to the explanation (Iben 1981). WBF suggested that the luminous S stars (i.e., O-rich) would have been C-rich stars but for the onset of envelope burning that reduced the C/O ratio to less than unity by converting C to N through the CN-cycle H-burning reactions. WBF's hypothesis was strengthened by our (SL89, SL90) discovery of the Li I line in these luminous AGB stars and the demonstration that these stars were enriched in $s$-process elements. In Figure 8 we illustrate the statistics on the appearance of the Li I line in the Cloud AGB stars and compare this to BMB's C-star luminosity function as first discussed by Iben (1980). In the top panel we show the fraction of AGB stars which exhibit a detectable Li I feature as a function of $M_{bol}$ (binned by 0.5 mag intervals) for 84 S and C stars from this survey. The bottom panel of Figure 8 shows the carbon-star luminosity function. It is no coincidence that a large increase in the fraction of AGB stars which show an Li I feature at $M_{bol} \approx -6$ occurs right at the luminosity where the C-star luminosity function ends; envelope burning is responsible for this "coincidence."

Clearly, our spectroscopy suggests that virtually every AGB star surveyed in the Clouds above $M_{bol} \sim -6$ undergoes envelope burning and reduction of the C/O ratio with production of $^7$Li. Since these stars are presumed to be near the end of their lives, with AGB evolution terminated by severe rapid mass loss, considerable amounts of Li will be returned to the interstellar medium. To assess their contribution to galactic enrichment in Li, one needs to know the fraction (and masses) of the stars that evolve to become these luminous S stars. Several studies suggest that the luminous AGB stars are less common than predicted from the known population of Cepheids (immediate progenitors of the same masses) and standard models (i.e., no or very little mass loss) of AGB evolution; for example, see Reid et al. (1988), Reid, Tinney, & Mould (1990), and Hughes & Wood (1990). The discrepancy between the observed and predicted populations of luminous AGB stars is a factor of 2–4. It is generally supposed that severe mass

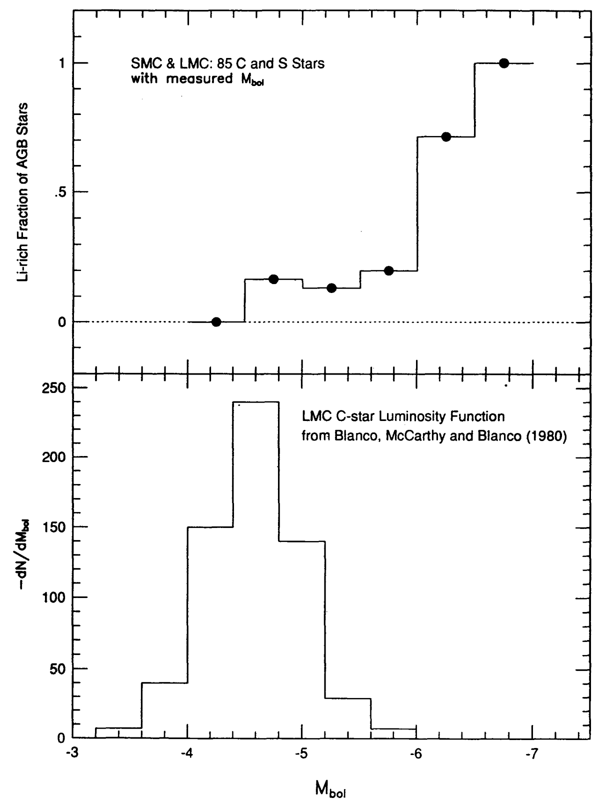


FIG. 8.—*Top panel*, fraction of stars which show an Li I feature as a function of $M_{bol}$, binned in intervals of 0.5 mag in $M_{bol}$, as plotted. Note the large increase in $f$(Li) to nearly 1.0 between $M_{bol}$ of $-6$ to $-6.5$. *Bottom panel*, luminosity function for carbon stars in the LMC, taken from Iben's (1980) discussion, is shown. Note the complete "cutoff" of C stars at luminosities higher than $M_{bol}$, which occurs at the same point that the Li I appears in large numbers in the S stars. This comparison suggests that C stars are converted to S stars at $M_{bol} = -6$ due to HBCE burning.

loss accelerates AGB evolution and may even prevent some stars from evolving to the luminosity of the Li-rich S stars.

## 5. CONCLUDING REMARKS

Our spectroscopic scrutiny of the most luminous AGB stars in the Clouds shows that they possess HBCEs which reconvert the C-rich to O-rich envelopes and synthesize large amounts of $^7$Li. It remains to show that these Li-rich S stars are N-rich, as predicted from CN cycling, but their low $^{12}C/^{13}C$ ratios (PSL) are as predicted for an HBCE. It is likely that these stars are significant contributors and, perhaps the dominant contributor of $^7$Li to the Clouds (see PSL).

Questions remain concerning the range of initial masses represented among the Li-rich S stars. The suggestion that these are intermediate-mass AGB stars could be tested spectroscopically (Lambert 1991). These AGB stars are predicted to run the *s*-process by the $^{22}$Ne($\alpha$, $n$) neutron source at a high neutron density. A signature of the $^{22}$Ne source is a large surface overabundance of the $^{25}$Mg and $^{26}$Mg (relative to $^{24}$Mg) isotopes which is, in principle, measurable from MgH lines. The predicted high neutron density in the He shell also leads to production of $^{96}$Zr whose presence is detectable from ZrO bandheads at 6922 Å. In addition, rubidium, as $^{87}$Rb, is produced readily at high neutron densities and may be measured through the Rb I 7800 Å line. At low mass ($M \lesssim 3\ M_\odot$), the neutron source is expected to be $^{13}$C($\alpha$, $n$)$^{16}$O, and the neutron density is predicted to be too low to cause significant production of either $^{96}$Zr or $^{87}$Rb. A spectroscopic search for $^{25}$Mg, $^{26}$Mg; and $^{96}$Zr could sort the stars into low- and intermediate-mass AGB stars. This then might offer a clue to whether these Miras pulsate in the fundamental mode (intermediate-mass AGB star) or in the first-overtone mode (low-mass AGB star).

One possible weakness of our survey is the relative paucity of stars with $M_{\rm bol} < -7$. The presumption has been that *all* of these stars are massive core-burning stars (supergiants, not AGB stars) and that AGB stars obey the core mass-luminosity relation terminating in a Chandrasekhar mass at $M_{\rm bol} = -7.1$. Blöcker & Schönberner (1991; see also Lattanzio 1992; Sackmann & Boothroyd 1992) showed that AGB stars experiencing an HBCE do not fit the core mass-luminosity relation and, unless mass loss terminates their evolution, they evolve to $M_{\rm bol} < -7$ into the domain of the red supergiants. It would be of interest to examine a large sample of Cloud "supergiants" ($M_{\rm bol} < -7$) to search for AGB stars: a low-resolution survey for enhanced ZrO bands may suffice to identify the few AGB interlopers.

Finally, it may be noted that Li-rich S stars may be used as a standard candle to obtain distances to nearby galaxies. As there appear to be no major differences between the SMC and LMC Li-strong stars, we combine the sample of oxygen-rich stars from both galaxies and, in Figure 9, plot the frequency histogram of $M_{\rm bol}$. Note the exceptional S star SMC HV1645 at $M_{\rm bol} \sim -4.7$, the small "tail" of stars between $-6 \lesssim M_{\rm bol} \lesssim -5$, and the large, narrow distribution in the interval $M_{\rm bol} \sim -6$ to $-7.2$ (the bin intervals are 0.2 mag). Ignoring the small tail of stars leading to the dominant population of Li-strong S stars, we derive a mean $M_{\rm bol}$ for this majority of luminous AGB stars to be $\bar{M}_{\rm bol} = -6.52 \pm 0.33$. This is a very narrow range in luminosity, and it would be interesting to search for these most luminous AGB stars in other galaxies of the Local Group; WBF and Wood et al. (1992) demonstrate that AGB stars and massive core-burning supergiants can be separated using IR colors and periods.

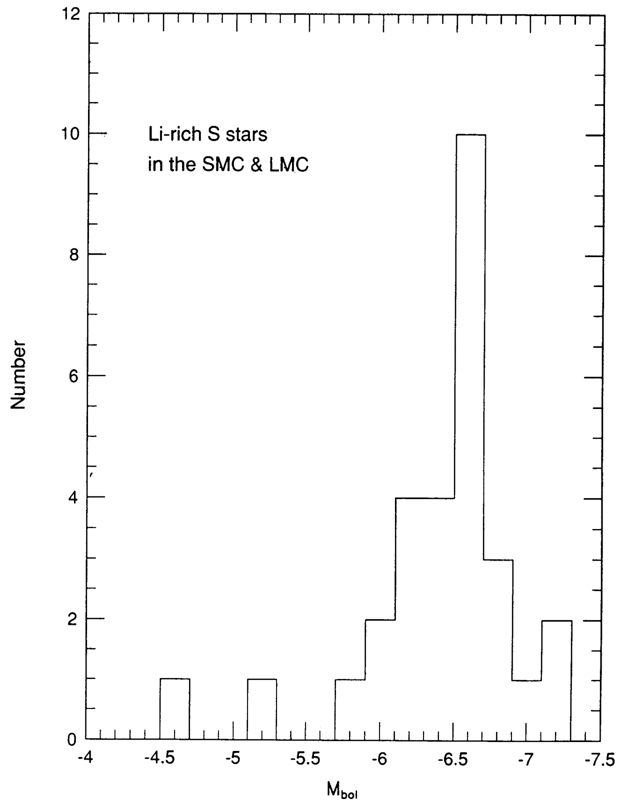


FIG. 9.—Frequency histogram of the SMC and LMC S stars which show Li I (number versus $M_{\rm bol}$). The sharp peak near $M_{\rm bol} = -6.5$ is obvious. Excluding the small "tail" extending to lower luminosities, the Li-strong S stars are characterized by a well-defined average $M_{\rm bol}$ ($= -6.52$) with a small dispersion ($\pm 0.3$)

We thank A. I. Boothroyd and J. L. Lattanzio for helpful comments. This research has been supported in part by the National Science Foundation (grants AST 91-15090 and 93-15124) and the Robert A. Welch Foundation. D. A. L. acknowledges Hofstra University for a Faculty Research and Development Grant.

## REFERENCES

Abia, C., Boffin, H. M. J., Isern, J., & Rebolo, R. 1991, A&A, 245, L1
Abia, C., Isern, J., & Canal, R. 1993, A&A, 275, 96
Blanco, V. M., & McCarthy, M. F. 1990, AJ, 100, 674
Blanco, V. M., McCarthy, M. F., & Blanco, B. M. 1980, ApJ, 242, 938
Blöcker, T., & Schönberner, D. 1991, A&A, 244, L43
Brown, J. A., Sneden, C., Lambert, D. L., & Dutchover, E., Jr. 1989, ApJS, 71, 293
Cameron, A. G. W., & Fowler, W. A. 1971, ApJ, 164, 111
Catchpole, R. M., & Feast, M. W. 1976, MNRAS, 175, 501
———. 1971, MNRAS, 154, 197
Crabtree, D. R., Richer, H. B., & Westerlund, B. E. 1976, ApJ, 203, L81
Denn, G. R., Luck, R. E., & Lambert, D. L. 1991, ApJ, 377, 657
Dominy, J. 1984, ApJS, 55, 27
Feast, M. W. 1954, Les Processus Nucléaires dans les Astres (Liège Symp. 5) (Louvain: Ceuterick), 413
Gatewood, G. 1992, PASP, 104, 23
Herzberg, G. 1950, Molecular Spectra and Molecular Structure I. Spectra of Diatomic Molecules (New York: Van Nostrand)
Hodge, D. W., & Wright, F. W. 1967, The Large Magellanic Cloud (Washington, DC: Smithsonian Press)

Hodge, D. W., & Wright, F. W. 1977, The Small Magellanic Cloud (Seattle: Univ. Washington Press)
Hughes, S. M. G. 1989, AJ, 97, 1634
Hughes, S. M. G., & Wood, P. R. 1990, AJ, 99, 784
Hughes, S. M. G., Wood, P. R., & Reid, N. 1991, AJ, 101, 1304
Iben, I., Jr. 1981, ApJ, 246, 278
———. 1991, in Evolution of Stars: The Photospheric Abundance Connection, ed. G. Michaud & A. V. Tutukov (Dordrecht: Kluwer), 257
Keenan, P. C. 1967, AJ, 72, 808
Lambert, D. L. 1991, in Evolution of Stars: The Photospheric Abundance Connection, ed. G. Michaud & A. V. Tutukov (Dordrecht: Kluwer), 299
Lattanzio, J. 1992, Proc. Astron. Soc. Australia, 10, 120
Lloyd Evans, T., & Catchpole, R. M. 1989, MNRAS, 237, 219
McKellar, A. 1940, PASP, 52, 407
Merrill, P. M. 1952, ApJ, 116, 21
Michaud, G. 1988, in Atmospheric Diagnostics of Stellar Evolution: Chemical Peculiarities, Mass Loss, and Explosion, ed. N. Nomoto (Berlin: Springer), 3
Plez, B., Brett, J. M., & Nordlund, Å. 1992, A&A, 256, 551
Plez, B., Smith, V. V., & Lambert, D. L. 1993, ApJ, 418, 812 (PSL)
Rebolo, R. 1991, in Evolution of Stars: The Photospheric Abundance Correction, ed. G. Michaud & A. V. Tutukov (Dordrecht: Kluwer), 85
Reid, I. N., Glass, I. S., & Catchpole, R. M. 1988, MNRAS, 232, 53
Reid, I. N., & Mould, J. R. 1990, ApJ, 360, 490
Reid, N., Tinney, C., & Mould, J. 1990, ApJ, 348, 98
Richer, H. B. 1981, ApJ, 243, 744
Richer, H. B., & Frogel, J. A. 1980, ApJ, 242, L9
Richer, H. B., Olander, N., & Westerlund, B. E. 1979, ApJ, 230, 724
Richer, H. B., Westerlund, B. E., & Olander, N. 1978, ApJ, 219, 452
Russell, S. C., & Bessell, M. S. 1989, ApJS, 70, 865
Sackmann, I. J., & Boothroyd, A. I. 1992, ApJ, 392, L71
Sanford, R. F. 1950, ApJ, 111, 262
Scalo, J. M., Despain, K. M., & Ulrich, R. K. 1975, ApJ, 196, 805
Smith, V. V., & Lambert, D. L. 1985, ApJ, 294, 326
———. 1986, ApJ, 311, 843
———. 1989, ApJ, 345, L75 (SL89)
———. 1990a, ApJ, 391, L69 (SL90)
———. 1990b, ApJS, 72, 387
Smith, V. V., Lambert, D. L., & McWilliam, A. 1987, ApJ, 320, 862
Thévenin, F., & Jasniewicz, G. 1992, A&A, 266, 85
Tuthill, P. G., Haniff, C. A., Baldwin, J. E., & Feast, M. W. 1994, MNRAS, 266, 745
Warner, B., & Dean, C. A. 1970, PASP, 82, 904
Westerlund, B. E., Azzopardi, M., Breysacher, J., & Rebeirot, E. 1991, A&AS, 91, 425
Westerlund, B. E., Olander, N., Richer, H. B., & Crabtree, D. R. 1978, A&AS, 31, 61
Willson, L. A. 1983, in Pulsations in Classical and Cataclysmic Variable Stars, ed. J. P. Cox & C. J. Hansen (Boulder: Univ. Colorado), 284
Wood, P. R. 1990, in From Miras to Planetary Nebulae: Which Path for Stellar Evolution? ed. M. O. Mennessier & A. Omont (Gif-sur-Yvette: Editions Frontières), 67
Wood, P. R., & Bessell, M. S. 1983, ApJ, 265, 748
Wood, P. R., Bessell, M. S., & Fox, M. W. 1983, ApJ, 272, 99 (WBF)
Wood, P. R., Whiteoak, J. B., Hughes, S. M. G., Bessell, M. S., Gardner, F. F., & Hyland, A. R. 1992, ApJ, 397, 552
Wurm, K. 1939, ApJ, 91, 103