THE ASTROPHYSICAL JOURNAL, 361: L69–L72, 1990 October 1

ON THE OCCURRENCE OF ENHANCED LITHIUM IN MAGELLANIC CLOUD RED GIANTS

VERNE V. SMITH[1] AND DAVID L. LAMBERT[1]
Department of Astronomy and McDonald Observatory, University of Texas, Austin
Received 1990 June 6; accepted 1990 July 11

ABSTRACT

High-resolution spectra have been obtained for 27 red giants in the Magellanic Clouds spanning a range in bolometric absolute magnitudes ($M_{\rm bol} \sim -5$ to -9). In a previous study, we found that five out of five luminous asymptotic giant branch (AGB) stars in the Small Magellanic Cloud (SMC) showed enhanced Li I resonance doublets (6707 Å); the extension here of our previous work reveals that the "Li-strong" red giants in both Magellanic Clouds are luminous ($M_{\rm bol} \approx -6$ to -7) stars on the AGB. Lower luminosity ($M_{\rm bol} \approx -5.0$ to -5.5) AGB stars show no Li I features, while the very luminous ($M_{\rm bol} \approx -7$ to -9) red giants that are identified as massive, core-burning supergiants also show no Li I features. We suggest that the enhanced Li abundances in these luminous AGB stars are a byproduct of envelope burning in the more massive ($M \sim 4$–8 $M_\odot$) AGB stars. We also demonstrate that these Li-strong AGB stars may be a significant source of ^{7}Li in a galaxy.

Subject headings: stars: abundances — stars: evolution

I. INTRODUCTION

The asymptotic giant branch (AGB) represents the final nuclear-burning phase of stellar evolution for stars with initial masses between $M \sim 0.8$ and 9.0 $M_\odot$. A star on the AGB has an electron-degenerate C-O core, around which a H-burning shell operates, supplemented periodically by an unstable ^{4}He-burning shell, a "thermal pulse" (Schwarzschild and Härm 1967). ^{12}C is created in the thermal pulse, along with neutron-rich isotopes due to the operation of the *s*-process.

Wood, Bessell, and Fox (1983, hereafter WBF) found that many of the luminous ($-6 < M_{\rm bol} < -7$) long-period variables (LPVs) in the Clouds exhibit enhanced absorption bands of ZrO in their spectra and suggested that these stars have dredged *s*-processed material to their surfaces and are thus luminous thermally pulsing (TP)-AGB stars. WBF found that AGB stars exist right up to the AGB luminosity limit of $M_{\rm bol} \sim -7.1$. A curious fact concerning the most luminous of the AGB stars is that they have MS or S star spectral characteristics: they are all oxygen-rich with C/O < 1. As these stars have presumably dredged up the products of ^{4}He-burning thermal pulses to their surfaces (^{12}C plus *s*-process elements), one might expect the stars to be carbon stars. The lack of luminous ($M_{\rm bol} \lesssim -6$) C stars in the Clouds has been known for some time (Blanco, McCarthy, and Blanco 1980). WBF suggested that the lack of C stars among the luminous AGB stars may be due to (1) envelope burning, in which ^{12}C produced by thermal pulses is converted in the long interpulse intervals to ^{14}N at the base of the hot convective envelope (this keeps C/O < 1); and (2) the fact that the envelope masses of these stars may be too large, and the evolutionary time scales of this phase of evolution so short ($\lesssim 10^6$ yr), that C/O never exceeds unity.

Observations by Smith and Lambert (1989, hereafter SL) of five of WBF's luminous AGB stars showed that these stars were *s*-process–enriched to levels found for many Galactic S stars and were thus TP-AGB stars, as inferred by WBF. A more startling aspect of the observations was the result that all five stars showed a strong Li I feature at 6707 Å. As Li is destroyed throughout most of the mass of a main-sequence star and the deep convective envelope of a red giant will then dredge up material devoid of Li, the envelope of a red giant should have a very low Li abundance (Brown *et al.* 1989). A few Li-rich Galactic red giants are known, as discussed by Scalo (1976): most of these Li-rich giants are either C or S stars and, thus, are probably TP-AGB stars. However, only a relative handful of Li-rich red giants are known out of hundreds of C and S stars observed. The fact that five out of five SMC AGB stars exhibited strong Li I lines and the fact that these stars were examples of the more luminous AGB stars led SL to suggest that the Li observed in these stars was synthesized internally during evolution of these more massive AGB stars ($M \gtrsim 4$ $M_\odot$) along the upper AGB. Conditions for the formation of ^{7}Li, via the "^{7}Be transport mechanism" (Cameron and Fowler 1971), have been predicted to occur in the envelope-burning phase of evolution in certain luminous AGB stellar models (Scalo and Ulrich 1973; Sackmann, Smith, and Despain 1974; Renzini and Voli 1981) and SL identified the SMC AGB stars with strong Li I lines as the real counterparts of these model stars.

In this *Letter*, we present further observations of Magellanic Cloud red giants. The observed red giants include both lower luminosity and mass AGB stars ($M_{\rm bol} \sim -5$, $M \sim 2$ $M_\odot$), AGB stars of higher luminosity and mass ($M_{\rm bol} \sim -6$ to -7, $M \sim 4$–8 $M_\odot$), as well as very luminous and massive ($M_{\rm bol} \lesssim -7$, $M \sim 10$–15 $M_\odot$) non–AGB stars identified as core-burning supergiants. We find that the Li-strong stars are confined to the more luminous and massive AGB stars, and we discuss the implications of these observations on stellar evolution and on the chemical evolution of ^{7}Li.

II. OBSERVATIONS, ANALYSIS, AND RESULTS

Spectra of 27 SMC and six LMC red giants were obtained with the Cerro Tololo Inter-American Observatory's 4 m telescope plus the Cassegrain cross-dispersed echelle spectrometer with the air Schmidt camera and a GEC CCD detector. The

[1] Visiting Astronomer, Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

spectra were of continuous coverage from 6000 to 8000 Å at a resolution of $\lambda/\Delta\lambda = 20{,}000$ and typical signal-to-noise ratio at 6707 Å of the Li I doublet of S/N ~ 50–100; the spectra were reduced using the IRAF packages of software.

In Table 1 we list the stars observed, including the five from SL. We identify those stars in which the Li I resonance doublet at 6707 Å is clearly visible: in every case, the Li I feature was either easily visible or absent. When visible, typical equivalent widths of the Li I feature are 500–1000 mÅ, relative to the local continuum: in most cases, the stars with the stronger Li I lines had visible TiO absorption, which blankets the 6707 Å region; thus a measure of the Li I absorption relative to this blanketed continuum underestimates the true Li I equivalent width. The SMC stars, CV 78 and NGC 371 numbers 4, 22, and 24, are carbon stars. These stars show no evidence of strengthened Li I lines relative to Galactic C stars with unexceptional Li I lines taken from the list of Torres-Peimbert and Wallerstein (1966).

In Figure 1 we illustrate sample spectra of SMC red giants. In SL we showed two SMC stars with strong Li I and strong TiO absorption (all five of the SMC red giants in SL showed strong TiO absorption), while here in Figure 1 we show three SMC stars with weaker TiO absorption. We illustrate three types of stars in Figure 1: C12, in the field of NGC 371, is a very luminous ($M_{\rm bol} = -7.8$) star that WBF assigned to the core-burning phase in the evolution of a very massive star; HV 11329 is a luminous AGB star ($M_{\rm bol} = -6.5$); and HV 1366 is a lower luminosity AGB star ($M_{\rm bol} = -5.5$). In both the massive core-burning supergiant (C12) and the lower luminosity AGB star (HV 1366), the Li I doublet is absent: the weak line in C12 near the expected position of the Li I feature is probably V I (6708.10 Å). In HV 11329, however, the Li I doublet is strong (~800 mÅ relative to the local continuum): this star's distinction, relative to the other two, is that it is one of the more luminous AGB stars.

TABLE 1

STARS OBSERVED

Star	Spectral Type (if available)	$M_{\rm bol}$[a]	Period (days)[a]	Li I Visible?
		SMC		
HV 859	M7	−7.04	582	No
HV 1349[b]	...	−6.27	615	Yes
HV 1366	M6	−5.48	293	No
HV 1375	M5	−6.24	512	Yes
HV 1865[b]	...	−6.62	556	Yes
HV 1963	M4–5.5/S4	−6.76	330	Yes
HV 2112	M3–7.5	−7.22	608	Yes
HV 11223	M3/S3	−6.19	407	Yes
HV 11295	M5	−6.55	565	Yes
HV 11303	M1–7/S2	−6.69	534	Yes
HV 11329	M5/S1	−6.52	390	Yes
HV 11366	M1–3/S3–4	−6.30	366	Yes
HV 11452	M5/S1	−6.61	516	Yes
HV 12149	M6–8/S1	−7.01	742	No
HV 12179	M5/S2	−6.51	440	Yes
CV 78	C	−6.19	480	No
NGC 371 star 4	C	−5.56	340	No
NGC 371 star 22[c]	...	−5.07	330	No
NGC 371 star 24[c]	...	−5.19	320	No
NGC 371 star 29	M3	−7.36	530	No
NGC 371 C12	M1–1.5	−7.83	520	No
		LMC		
HV 888	M3	−9.03	850	No
HV 2576	M5.5/S1	−6.70	534	Yes
HV 2578	M6.5–8	−6.78	470	Yes
HV 2602	M3.5	−8.07	600	No
HV 5506	M8	−6.69	618	Yes
HV 12070	M3.5–9/S4	−6.50	621	Yes

[a] From Wood, Bessell, and Fox 1983.

[b] This star shows TiO and has C/O < 1.

[c] This star is a carbon star.

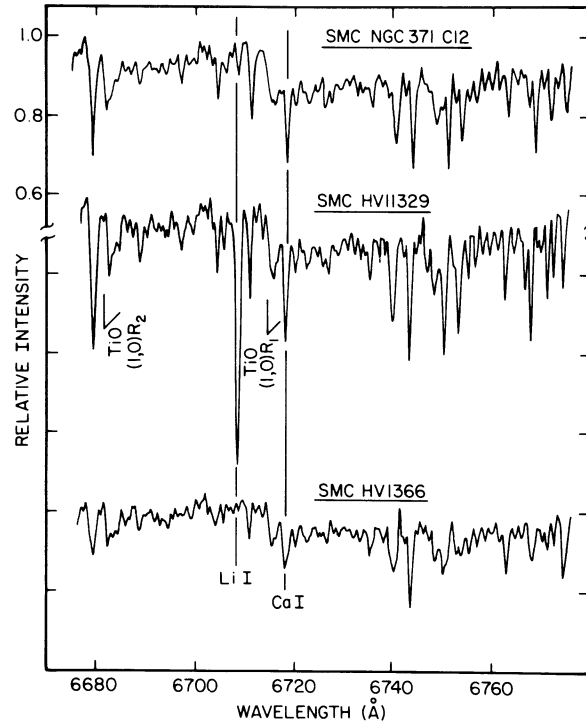

FIG. 1.—Sample spectra near the Li I resonance doublet of three SMC red giants. HV 1366 is a lower luminosity ($M_{\rm bol} = -5.48$) AGB star, while HV 11329 is a higher luminosity ($M_{\rm bol} = -6.52$) AGB star, and C12 is a luminous ($M_{\rm bol} = -7.83$) core-burning supergiant: note the strong Li I feature in the luminous AGB star (HV 11329) which is very weak, or absent, in the other two red giants.

In Figure 2, we summarize our results for 27 red giants in both the SMC and LMC. Following WBF, we plot the stars in an $M_{\rm bol}$-period diagram and indicate those stars which show a strong Li I doublet and those which do not. We include schematic pulsational-mass tracks for fundamental-mode pulsators taken from WBF. The maximum core mass of 1.4 $M_\odot$ for an AGB star is indicated at $M_{\rm bol} \approx -7.1$ (Paczyński 1971; Wood and Zaro 1981). It is very apparent from Figure 2 that the Li-strong red giants in the Clouds are the more luminous AGB stars ($M_{\rm bol} \sim -6$ to -7): this is the major result of this *Letter*. The luminous core-burning giants that are clearly above the AGB core-mass limit show no trace of the Li I doublet, while the four lower luminosity ($M_{\rm bol} \sim -5$ to -5.5) AGB stars also show no Li I feature. Three of the four lower luminosity AGB stars are C stars. The lone luminous AGB star ($M_{\rm bol} \leq -6$) in our sample that does not show an obvious Li I feature is also a C star (CV 78): a tentative (and perhaps shaky) addition to our main result would be that, not only is a strong Li I feature associated with the more luminous AGB stars, but also that C/O < 1.

Two of the three stars near the AGB core-mass/luminosity limit, all from the SMC, do not show Li I (HV 859 and HV 12149), while one (HV 2112) does. One signature of dredge-up on the AGB is the enhancement of the *s*-process elements and all of the Li-strong stars observed show strengthened *s*-process

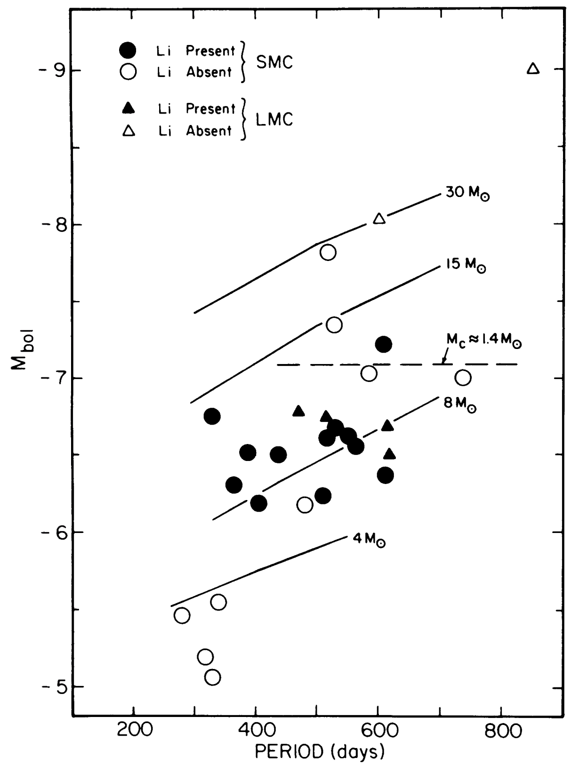

FIG. 2.—The location of the Li-strong stars in the M_{bol}-period plane: the continuous lines, from Wood, Bessell, and Fox (1983), represent models of constant mass assuming fundamental mode pulsation, while the dashed line is the AGB luminosity limit. The Li-strong stars are restricted to the oxygen-rich AGB stars near $M_{bol} \sim -6$ to -7.

atomic lines: HV 859 and HV 12149 do not, and thus these stars are probably core-burning supergiants.

III. DISCUSSION

In our earlier paper (SL), we interpreted the excess Li abundances in the five observed SMC AGB stars as the result of the ^{7}Be-transport mechanism, ^{3}He(α, γ)^{7}Be(e^-, ν)^{7}Li (Cameron and Fowler 1971), operating in the "envelope-burning" phase of stellar evolution (Iben 1973; Sackmann, Smith, and Despain 1974; Scalo, Despain, and Ulrich 1975; Renzini and Voli 1981). Our results, extended here to 27 red giants which cover a range of absolute magnitudes ($M_{bol} \sim -5$ to -9), support this hypothesis. A strong Li I doublet appears in a very restricted range in absolute bolometric magnitude on the AGB: $M_{bol} \sim -6$ to -7. The only observed example of a rather luminous AGB star without an enhanced Li I feature (SMC CV 78) is a carbon star, suggesting that not only are the Li-strong red giants AGB stars, but also that they have C/O < 1: this fact is incorporated easily into the envelope-burning hypothesis.

Our observations suggest that envelope burning is producing ^{7}Li in these luminous AGB stars and that the synthesized Li is surviving and being injected into the ISM. Every luminous AGB star that we have observed that has C/O < 1 shows the Li I doublet: if the Li was being destroyed quickly, we would expect to find some of the luminous AGB stars with no detectable Li I feature. In our earlier paper, we estimated Li abundances in the five SMC stars to cover the range of log ϵ(Li) ~ 2.0–4.0. We defer a detailed abundance analysis of these stars to a longer paper. Since the Li I equivalent widths of the observed Li-strong stars are similar, we estimate that the abundance of Li in these stars can reach values as large as log ϵ(Li) ~ 4.0. In this section, we investigate the hypothesis that AGB stars control the evolution of the Li abundance in a galaxy.

Observations of Li in samples of main-sequence stars drawn from the disk and halo of our Galaxy show a smooth increase in the *maximum* abundance from log ϵ(Li) ≈ 2.1 at [Fe/H] ≲ −1.5 to log ϵ(Li) ≃ 3.3 at [Fe/H] ≲ 0.0. Among the halo stars, this maximum is shown without exception by the warmer stars. The run of the maximum Li abundance with metallicity is well illustrated by Rebolo, Molaro, and Beckman's (1988) compilation of abundances. Two fundamentally different interpretations of the trend to higher Li abundances in more metal-rich stars have been proposed:

1. As advocated by Spite and Spite (1982), who first measured the Li abundance in halo stars, the Li in these stars is identified with the primordial Li from the big bang [i.e., log $\epsilon(\mathrm{Li})_{BB} = 2.1$], and the rise of the Li abundance with metallicity is attributed to unspecified Galactic sources of ^{7}Li with a minor supplement of ^{6}Li and ^{7}Li from spallation reactions between cosmic rays and interstellar nuclei. It is assumed that the stars defining the run of the maximum Li abundance with metallicity have not experienced a depletion of their initial Li abundance.

2. The opposing interpretation assumes that Li has been depleted to an unknown extent in even the warm halo and the older disk stars. Then, until the depletion mechanisms are understood, the primordial Li abundance can only be given as log $\epsilon(\mathrm{Li})_{BB} > 2.1$, or even $\gg 2.1$, and as a concomitant, less efficient Galactic sources of ^{7}Li are required than under interpretation (1). Under this scenario, the rise of the stellar Li abundances with metallicity is a convolution of the evolution of the ISM's Li abundance (an increase or even a decrease with metallicity) with the depletion of surface Li abundance, a depletion that is presumably more severe in the metal-poor (i.e., older) stars. Several plausible mechanisms of Li depletion have been proposed, but, as yet, none have proved capable of accurate ab initio predictions (see review by Michaud and Charbonneau 1990).

In the hypothesis under test, AGB stars in the mass range M_{LOW} to M_{UP} ($\simeq$4–8 $M_\odot$) synthesize Li and return Li-enriched gas to the interstellar medium (ISM). All other stars are assumed to return gas with a negligible abundance of Li. We neglect the contribution to Li synthesis by spallation reactions between cosmic rays and interstellar C, N, and O nuclei because the solar system's ^{7}Li/^{6}Li ratio shows that spallation must contribute less than about 20%. The evolution of the Li abundance is predicted from Clayton's (1985) analytical models with linear star formation.

Clayton's models assume that the star formation rate is linearly proportional to the mass of gas M_G. If infall of gas is neglected (the "closed box" solution), it is readily shown that the Li abundance of the ISM and, hence, of young stars is

$$\epsilon(\mathrm{Li}) = \epsilon(\mathrm{Li})_0 \exp(-\lambda t) + \epsilon(\mathrm{Li})_{AGB} \frac{R(\mathrm{LOW,\ UP})}{R(t,\ \infty)} [1 - \exp(-\lambda t)] ,$$

where $\epsilon(\mathrm{Li})_0$ is the initial (primordial) Li abundance of the ISM and $\epsilon(\mathrm{Li})_{AGB}$ is the abundance of Li in the Li-rich massive AGB stars with masses from M_{LOW} to M_{UP} and an assumed mass-independent Li abundance $\epsilon(\mathrm{Li})_{AGB}$. The quantity $R(a,\ b)$, which gives the mass of ejecta returned to the ISM by stars in the range m_a to m_b, is

$$R(a, b) = \int_{m_a}^{m_b} (m - w_m)\phi(m)\, dm ,$$

where the normalized initial mass function (IMF) $\phi(m)$ is taken from Tinsley (1980), and the stellar remnants are assigned masses $w_m = 0.7\ M_\odot$ for $m < 8\ M_\odot$ and $2\ M_\odot$ for $m > 8\ M_\odot$. The "time constant" $\lambda = \omega R(t, \infty)/(1 - R(t, \infty))$, where depletion of gas through star formation and the return of gas from dying stars gives the defining equation for ω: $dM_G/dt = -\omega M_G$.

The ISM's lithium abundance in the closed box saturates at

$$\epsilon(\mathrm{Li})_{\max} = \epsilon(\mathrm{Li})_{\mathrm{AGB}} \frac{R(\mathrm{LOW, UP})}{R(t, \infty)} \quad \text{as } t \to \infty .$$

For the adopted IMF, and the inferred masses $M_{\mathrm{LOW}} = 4\ M_\odot$ and $M_{\mathrm{UP}} = 8\ M_\odot$, $\epsilon(\mathrm{Li})_{\max} \simeq 0.25\ \epsilon(\mathrm{Li})_{\mathrm{AGB}}$. If our working hypothesis is valid, $\epsilon(\mathrm{Li})_{\max}$ must equal or exceed the Li abundance of young Galactic stars [log $\epsilon(\mathrm{Li}) \simeq 3.3$] and, hence, log $\epsilon(\mathrm{Li})_{\mathrm{AGB}} \gtrsim 3.9$ is demanded. We assume $\epsilon(\mathrm{Li})_{\mathrm{AGB}}$, M_{LOW}, and M_{UP} to be independent of metallicity. The required value of $\epsilon(\mathrm{Li})_{\mathrm{AGB}}$ is well within the range found from our observations of the Magellanic Clouds and the few available abundance determinations of Li in Galactic Li-rich AGB stars.

The above argument neglects mass loss as a possible mechanism to end the evolution along the AGB before the stars reach the stage to synthesize ^{7}Li: as discussed by Reid, Tinney, and Mould (1990), there are a smaller number of luminous AGB stars in the Clouds than expected from the observed numbers of Cepheid variables. If the potential ^{7}Li-producing AGB stars die before they synthesize Li, then those stars which survive to the Li-producing stage must produce more ^{7}Li if they are to impact the chemical evolution of Li. Reid *et al.* suggest that perhaps only 115 AGB stars exist out of an expected 500–600 in a region of the LMC. The luminosity function of Hughes and Wood (1987) suggests that between $M_{\mathrm{bol}} \sim -6$ and -7 (the absolute magnitudes of the Li-strong AGB stars), stars are continuously leaving the AGB due to complete envelope mass loss: this is near the luminosity where we observe the ^{7}Li to be synthesized. Taken together, both Reid *et al.* and Hughes and Wood (1987) suggest that only some fraction, f, of AGB stars survive to the luminous AGB phase of evolution, with this fraction being somewhere in the neighborhood of $f \sim \frac{1}{5}$–1. The possibility of mass loss removing some of the AGB stars may mean that our estimates of $\epsilon(\mathrm{Li})_{\mathrm{AGB}}$ should span the range of log $\epsilon(\mathrm{Li})_{\mathrm{AGB}} \sim 3.9$–4.6: our still crude abundance estimates are close to this limit. We think it unwise to push this interpretation further until more is known from both improved observational constraints and theoretical studies.

Our observations and interpretation suggest that the massive AGB stars are a, and perhaps the, major source of ^{7}Li in a galaxy. Although it is not yet possible to provide firm quantitative predictions of the Li-age or Li-[Fe/H] relations, our identification of a leading site of ^{7}Li synthesis suggests that the primordial Li abundance was close to the value now displayed by the warm halo stars, i.e., log $\epsilon(\mathrm{Li})_{\mathrm{BB}} \simeq 2.1$. In addition, we note that if the Li-rich phase of stellar evolution is restricted to a narrow range in M_{bol}, these stars may provide a potentially useful distance indicator for nearby galaxies. Also, we have described these luminous AGB stars as having degenerate C-O cores; the possibility remains, however, that these most luminous of AGB stars may have O-Ne-Mg cores as described by Nomoto and Hashimoto (1988).

This research has been supported in part by the National Science Foundation (AST89-02835) and the Robert A. Welch Foundation of Houston, Texas. We thank V. Radhakrishnan for pointing out the possibility of using the Li-rich stars as standard luminosity indicators.

REFERENCES

Blanco, V. M., McCarthy, M. F., and Blanco, B. M. 1980, *Ap. J.*, **242**, 938.
Brown, J. A., Sneden, C., Lambert, D. L., and Dutchover, E., Jr. 1989, *Ap. J. Suppl.*, **71**, 293.
Cameron, A. G. W., and Fowler, W. A. 1971, *Ap. J.*, **164**, 111.
Clayton, D. D. 1985, *Ap. J.*, **288**, 569.
Hughes, S. M. G., and Wood, P. R. 1987, *Proc. Astr. Soc. Australia*, **7**, 147.
Iben, I., Jr. 1973, *Ap. J.*, **185**, 209.
Michaud, G., and Charbonneau, P. 1990, preprint.
Nomoto, K., and Hashimoto, M. 1988, *Phys. Rept.*, **163**, 13.
Paczyński, B. 1971, *Acta Astr.*, **21**, 417.
Rebolo, R., Molaro, P., and Beckman, J. E. 1988, *Astr. Ap.*, **192**, 192.
Reid, N., Tinney, C., and Mould, J. 1990, *Ap. J.*, **348**, 198.
Renzini, A., and Voli, M. 1981, *Astr. Ap.*, **94**, 175.
Sackmann, I. J., Smith, R. L., and Despain, K. H. 1974, *Ap. J.*, **187**, 555.
Scalo, J. M. 1976, *Ap. J.*, **206**, 795.
Scalo, J. M., Despain, K. H., and Ulrich, R. K. 1975, *Ap. J.*, **196**, 805.
Scalo, J. M., and Ulrich R. K. 1973, *Ap. J.*, **183**, 151.
Schwarzschild, M., and Härm, R. 1967, *Ap. J.*, **150**, 961.
Smith, V. V., and Lambert, D. L. 1989, *Ap. J.* (*Letters*), **345**, L75 (SL).
Spite, F., and Spite, M. 1982, *Astr. Ap.*, **115**, 357.
Tinsley, B. M. 1980, *Fund. Cosmic Phys.*, **5**, 287.
Torres-Peimbert, S., and Wallerstein, G. 1966, *Ap. J.*, **146**, 724.
Wood, P. R., Bessell, M. S., and Fox, M. W. 1983, *Ap. J.*, **272**, 99 (WBF).
Wood, P. R., and Zarro, D. M. 1981, *Ap. J.*, **247**, 247.

David L. Lambert and Verne V. Smith: Department of Astronomy, University of Texas, Austin, TX 78712