The Astrophysical Journal, 529:L25–L28, 2000 January 20

THE ORIGIN OF EXTREMELY METAL-POOR CARBON STARS AND THE SEARCH FOR POPULATION III

Masayuki Y. Fujimoto and Yasufumi Ikeda
Department of Physics, Hokkaido University, Sapporo, Hokkaido 060-0810, Japan;
fujimoto@phys.hokudai.ac.jp, ikeda@phys.hokudai.ac.jp
and
Icko Iben, Jr.
Departments of Astronomy and Physics, University of Illinois, Urbana-Champaign, IL 61801; icko@astro.uiuc.edu
Received 1999 October 18; accepted 1999 November 23; 1999 December 22

ABSTRACT

The number of known extremely metal-deficient stars has recently increased substantially, stimulating inquiry into the formation and initial chemical evolution of the Milky Way. In order to draw proper inferences from the observations, it is necessary to understand the evolution of these low-mass stars and the modifications in their surface elemental abundances that they have experienced during their long lifetimes. Among the observations to be explained is the fact that the incidence of carbon-enhanced stars increases with decreasing metallicity. We show that low-mass, extremely metal-poor stars evolve into carbon stars along paths that are quite different from those followed by more metal-rich stars of younger populations. This permits us, in principle, to distinguish the brightest survivors of the first generations of stars formed in the universe (Population III carbon stars) from stars belonging to younger populations.

Subject headings: Galaxy: abundances — stars: carbon — stars: evolution — stars: interiors

1. INTRODUCTION

Extremely metal-deficient stars are expected to carry information about the physical conditions of the universe that applies during the early stages of the evolution of galaxies. In particular, the first generation of stars, which were formed from gas completely devoid of carbon and heavier elements, are among the oldest luminous objects (e.g., see Rees 1998). The current survivors of these "Population III" stars, as they are called, can be, if detected, unique probes into the chemical and dynamical conditions in the very early universe.

Owing to a recent survey (hereafter, the HK survey) by Beers, Preston, & Shectman (1992; see also Beers 1999), the number of known extremely metal-poor stars in the Galaxy has substantially increased. At present, more than 100 stars with $[Fe/H] < -3$ are available for careful study, although no star of Population III initial composition has yet been found. Among the most metal-deficient stars discovered to date are a single red giant CD $-38°245$ with $[Fe/H] \simeq -4.2$ (Bessel & Norris 1984) and a binary M dwarf G77−61 with $[Fe/H] \simeq -5.6$ (Gass, Liebert, & Wehrse 1988).

High-dispersion spectroscopic data for these extremely metal-poor stars from new-generation 8–10 m–class telescopes is about to open a new era of inquiry into the initial chemical and dynamical evolution of the Milky Way. For this endeavor to be successful, it is of critical importance to understand the modifications in the surface chemistry that these low-mass survivors may have experienced during their long lifetimes as a consequence of internal nucleosynthesis and mixing as well as from possible accretion from the interstellar medium. Among the observational facts to be explained is that the relative frequency of carbon-enhanced stars increases with decreasing metallicity below $[Fe/H] \sim -2.5$. Rossi, Beers, & Sneden (1999) find that these extremely metal-deficient carbon (EMDC) stars account for ∼25% of the stars in the HK survey for $[Fe/H] \leq -3$. Several of the most metal-poor stars exhibit extremely large carbon enrichments, up to $[C/Fe] \sim 2$ dex. In all of the EMDC stars, nitrogen is also greatly enhanced relative to iron. The *s*-process elements are enriched in some, but not in all, of these stars (Sneden et al. 1996; Norris, Ryan, & Beers 1997a; Barbuy et al. 1997; Bonifacio et al. 1998; Hill et al. 1999). These facts indicate that the predominant mechanism for becoming a carbon star may be different for stars of low metallicity than for stars of high metallicity.

The carbon enhancements observed in stars of Populations I and II are explained in terms of a "third" dredge-up process that occurs during the thermally pulsating asymptotic giant branch (TPAGB) phase (Iben 1975; Fujimoto et al. 1976). The dredge-up process carries to the stellar surface the ^{12}C synthesized in the helium-flash convection zone as well as *s*-process elements synthesized both during the interflash phase and during the flash phase. In close binary systems, changes in the surface abundance may have been imprinted onto the low-mass companions through mass transfer from the TPAGB companions that have long since vanished. This is the accepted mechanism for the formation of Population I Ba stars and Population II CH stars, which have been established observationally to be binary stars in which the erstwhile TPAGB star has evolved to the white dwarf stage (McClure 1983). The less-evolved components in these binary systems all display enhancements of *s*-process elements (see, e.g., Jorissen 1999).

For low-mass model stars of Population III composition, previous investigations of their evolution indicate that another mechanism, triggered by the extension of helium convection through overlying hydrogen-containing layers, can produce carbon-rich surface abundances during the helium core flash (Fujimoto, Iben, & Hollowell 1990; Hollowell, Iben, & Fujimoto 1990). For model stars of younger populations, this type of mixing is prevented by the large entropy barrier formed between the helium-rich zone and the envelope (Iben 1977), except when the envelope mass is very small and hydrogen is not burning (Fujimoto 1977). One of the salient features of Population III and extremely metal-poor models is a very *low* entropy in the hydrogen-burning shell, which reduces the entropy barrier and enables the convection driven by a helium flash to penetrate into the hydrogen-rich envelope. This phenomenon has been found to occur during the core helium flash at the tip of red giant branch (RGB) in 0.8 $M_\odot$ models with metallicities [Fe/H] < −4 (Fujimoto et al. 1995) and during the helium shell flash in 0.8 $M_\odot$ TPAGB models with $\log Z = -10$ (Cassisi, Castellani, & Tornambé 1996).

In this Letter, we extend the calculations to show that the above mechanisms also pertain to extremely metal-poor stars of low and intermediate mass. The present results also provide a new perspective concerning the search for Population III stars.

2. EVOLUTION OF EXTREMELY METAL-POOR STARS

We discuss first how the evolution of a low-mass star depends on its initial metallicity. The evolution of 0.8 $M_\odot$ models is computed from the zero-age main sequence through the TPAGB phase for metallicities $Z = 0$, [Fe/H] = −4, and [Fe/H] = −2. Figure 1 shows the development of the convective zone during an off-center helium core flash or during a helium shell flash.

For the $Z = 0$ case, helium convection during the first off-center helium core flash stretches into the hydrogen-containing layers, as in earlier computations (Fujimoto et al. 1995). We have continued the computation assuming that hydrogen, ingested by the convective zone, is mixed down to a position in which the lifetime of a proton against capture by the $^{12}C(p, \gamma)^{13}N$ reaction is just equal to the timescale of convective mixing. The subsequent evolution is much the same as described in detail by Hollowell et al. (1990), as seen from the top panel of Figure 1. As hydrogen mixing continues, the hydrogen-burning luminosity L_H increases. When the top of the convective zone reaches the point along the hydrogen profile at which $X = 0.023$, L_H exceeds the helium-burning luminosity and causes the convective zone to split into two zones. The upper convective shell (hydrogen convective shell [HCS]) is now driven by a hydrogen flash, while the lower convective shell (helium convective shell [HeCS]) is still driven by the helium flash. As more hydrogen fuel enters the HCS from above, the hydrogen flash develops further. The hydrogen-burning luminosity rapidly climbs to a peak of $L_H^{max} = 2.9 \times 10^{12}\ L_\odot$, and the HCS extends deeply into the hydrogen-rich layer.

After the decay of the flash, the HCS still persists as a CN-enhanced convective shell, gradually shifting outward in mass, while the HeCS disappears completely. Then, the base of the surface convective zone penetrates into the layers earlier occupied by the HCS. The penetration (in mass) occurs twice, first owing to the expansion of the region once covered by the erstwhile HCS and second owing to the expansion of the region once covered by the erstwhile HeCS. As a consequence, matter that has experienced helium-burning reactions and that has then been further processed by hydrogen-burning reactions is brought to the surface. At the end of the dredge-up episode, processed material of mass ~0.16 $M_\odot$ is mixed into the surface convective zone, which results in the production of surface abundances (by mass) of CNO elements: $X_C = 0.0040$, $X_N = 0.0046$, and $X_O = 2.5 \times 10^{-6}$.

For the [Fe/H] = −4 case, helium ignites off-center, deeper in the core (at $M_r = 0.334\ M_\odot$) and with a larger core mass (of $M_c = 0.538\ M_\odot$) than in the case of the $Z = 0$ model. The outer edge of the flash-driven convective shell barely touches the hydrogen-containing matter (at a point along the hydrogen profile at which $X = 2.0 \times 10^{-4}$). The amount of hydrogen mixed inward is not enough to cause a hydrogen-burning runaway or to drive further mixing. After the model evolves to the asymptotic giant branch (AGB), helium shell flashes are initiated. During the third flash, the helium convection extends into the hydrogen-containing layer (the middle panel of Fig. 1). The subsequent hydrogen-mixing event proceeds in much the same way as described for the $Z = 0$ model star—the hydrogen-burning luminosity amounts to $L_H^{max} = 2.0 \times 10^{10}\ L_\odot$. After the decay of the flash, the HCS disappears because of the small mass that partakes of the convection. Subsequently, the surface convective zone extends down into the layers formerly occupied by the HCS, which results in surface abundances (by mass) of CNO elements: $X_C = 0.0050$, $X_N = 0.00088$, and $X_O = 1.5 \times 10^{-4}$. The larger C/N ratio for the [Fe/H] = −4 model, in comparison to that for the $Z = 0$ core-flash case, is due to a larger carbon abundance in the helium convection zone ($X_C = 0.18$ as compared to $X_C = 0.04$).

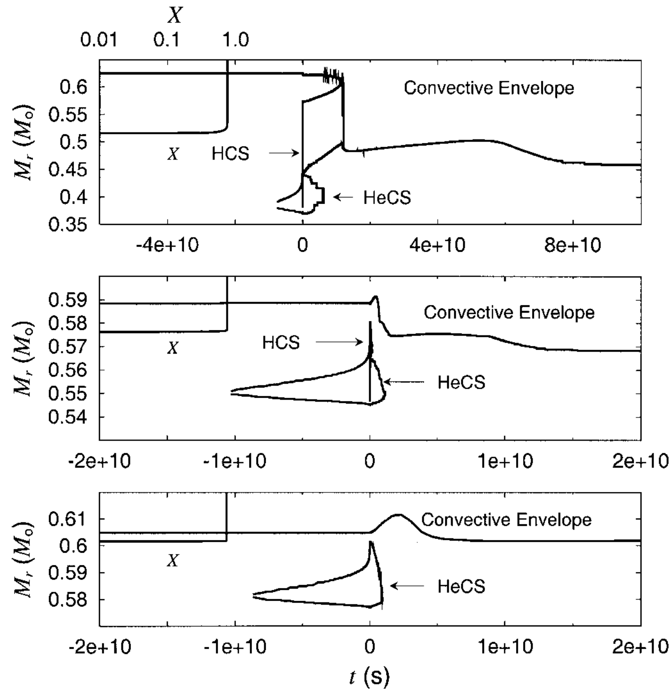

FIG. 1.—Development of convective zones in 0.8 $M_\odot$ model stars during the off-center core helium flash when $Z = 0$ (*top*) and during TPAGB helium shell flashes when [Fe/H] = −4 (*middle*) and [Fe/H] = −2 (*bottom*). The hydrogen profiles are also plotted in the inset at the upper-left corner of each panel.

For the [Fe/H] = −2 case, a hydrogen-mixing event does *not* occur, either during the off-center core helium flash or during helium shell flashes along the TPAGB (Fig. 1, *bottom*). The helium core flash ignites even deeper in the core (at $M_r = 0.274\ M_\odot$ while $M_c = 0.508\ M_\odot$) than in the [Fe/H] = −4 case, and the HeCS misses the hydrogen-containing layer by more than a pressure scale height. During the TPAGB phase, we follow the growth in the strength of shell flashes through the sixth pulse and find that the HeCS reaches only to the edge of the hydrogen profile, where $X = 10^{-7}$. No hydrogen mixing of importance takes place, nor does the classical third dredge-up.

These behaviors are explicable in terms of the difference in the entropy variations within the hydrogen- and helium-burning shells for models of differing initial metal abundance. For a smaller CNO abundance, the temperature in the hydrogen-burning shell becomes larger to partially compensate for the reduction in the number density of CNO catalysts. This results in a smaller entropy, since the effective heat capacity (including the hydrostatic readjustment) is negative in the hydrogen-burning shell. The difference between the off-center core flash and the TPAGB shell flash in the [Fe/H] = −4 model can be ascribed mainly to the difference in the depths of the helium-burning shell. Because of a larger growth rate of the core (i.e., because of higher luminosity), the helium ignites at a lower density for the TPAGB stages. The smaller mass fraction in the HeCS then allows the entropy there to attain higher values before expansion causes the flash to decay. Both of these processes contribute to the reduction in the entropy barrier.

We have also computed the evolution of extremely metal-poor stellar models with other low and intermediate masses. For more massive stars, the temperature in the core is higher at a given core mass because of a larger luminosity and the consequently larger rate of release of gravothermal energy. The $Z = 0$, $M = 0.9\ M_\odot$ model undergoes an off-center core helium flash and experiences the same hydrogen-mixing event at the tip of the RGB as does the $Z = 0$, $M = 0.8\ M_\odot$ model. For the model of mass $M \geq 1.0\ M_\odot$, on the other hand, helium ignites at the center before electrons become degenerate and before plasma neutrino losses become effective enough to cause a temperature inversion in the core. The difference from the results of our earlier computations (Fujimoto et al. 1990) lies in a slightly smaller production of carbon in the hydrogen-burning shell, which may be attributable to finer mass resolution near the base of the hydrogen-burning shell as well as to an improved time resolution in the present computations.

For all $Z = 0$ models of mass $M \geq 1.0$, we have followed the evolution into the TPAGB phase. We find that, for models in the mass range $1.0\ M_\odot \leq M \leq 3\ M_\odot$, the flash-driven convective zone extends sufficiently deep into hydrogen-rich layers to produce the carbon-rich, nitrogen-rich phenomenon. For $M = 2.0\ M_\odot$, we find that the dividing line for the occurrence or absence of deep hydrogen mixing lies in the initial metallicity range $-3 < [\mathrm{Fe/H}] < -2$.

More massive stars enter into the TPAGB phase at a larger core mass and, hence, with greater entropy in the hydrogen-burning shell. The latter impedes the outward extension of the helium flash–driven convective zone. At the same time, helium shell flashes ignite at lower density to be weaker because of the higher temperature in the hydrogen-burning shell and of the larger growth rate of the core. For $M = 4\ M_\odot$, we find that helium flashes are too weak to trigger either the hydrogen-mixing event or the third dredge-up event. For still more massive models, the helium shell burning may even be stabilized, as shown by Chiefi & Tornambé (1984), since helium is consumed before the burning shell attains a high enough density to trigger a thermal runaway (Fujimoto et al. 1984).

3. A GENERAL PICTURE OF THE EVOLUTION TO CARBON STARS

Based on our results, a coherent picture emerges for the evolution of metal-poor stars as a function of stellar mass and metallicity. This picture is conveniently discussed with the help of the mass-metallicity diagram shown in Figure 2.

Case I: $[\mathrm{Fe/H}] < -4$ *and* $M < 1.0\ M_\odot$.—Model stars in this range of parameter space evolve to become nitrogen-rich carbon stars at the tip of the RGB. The enhancement of CN elements at the surface can be as large as $Z_{\mathrm{CN}} \simeq 0.01$ for $M = 0.8\ M_\odot$. During subsequent evolution, these models mimic the evolution of Population I and Population II stars.

For such low-mass stars, the occurrence of the third dredge-up has been a subject of concern for some time (Iben & Renzini 1982; Boothroyd & Sackmann 1988; Lattanzio 1989; see also the references in Marigo, Giraardi, & Bressan 1999). Theoretically, it has been shown to be possible, but it is true that the results depend sensitively on the treatment of the dredge-up process and on the input physics (Wood 1981; Frost & Lattanzio 1996). Bessel, Wood, & Evans (1983) infer, from comparisons with observations of carbon stars in the Magellanic Clouds and the Milky Way, that the third dredge-up does not produce single carbon stars with mass $M \lesssim 1.3$ and $M \lesssim 0.9\ M_\odot$ for $[\mathrm{Fe/H}] \simeq 0$ and $\simeq -1$, respectively. Because of the large CN enhancement, therefore, we may well assume that the stars of case I will spend the rest of their (luminous) lives as nitrogen- (and ^{13}C-) rich carbon stars both on the horizontal branch (HB) and AGB.

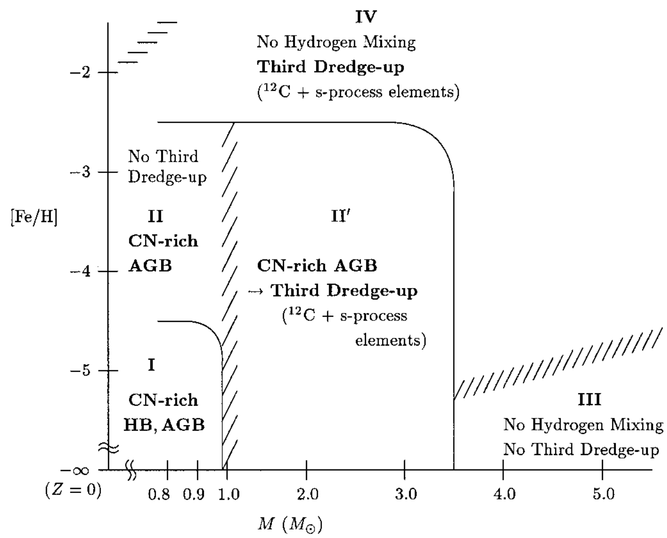

FIG. 2.—Schematic describing evolutionary paths in the initial mass-metallicity plane.

Cases II and II′: $-4 \leq [\mathrm{Fe/H}] < -2$ *and* $M \lesssim 1.0\ M_\odot$ *and* $[\mathrm{Fe/H}] < -2$ *and* $1.0\ M_\odot \lesssim M \leq 3\ M_\odot$, respectively.—Model stars in these ranges evolve into nitrogen-rich carbon stars when helium shell flashes begin near the base of the AGB. The two cases may be separated by the absence or occurrence of the third dredge-up, whose boundary is assumed to lie at $M \sim 1.0\ M_\odot$. These carbon stars may be distinguished from those arising from case I by a larger C/N ratio, reflecting the larger carbon abundance in the helium convective zone. Because of a larger core mass, more ^{13}C is produced relative to ^{14}N because CN cycling is stalled at ^{13}N at high temperatures during the flash. The stars of case II′ later enrich their surfaces with ^{12}C and *s*-process elements owing to the third dredge-up. These carbon stars may be distinguished from the carbon stars of case II by the presence of *s*-process elements in their surface.

Case III: $[\mathrm{Fe/H}] \lesssim -5$ *and* $M \geq 4\ M_\odot$.—For the $Z = 0$ models of mass in this range, neither the hydrogen-mixing event nor the third dredge-up takes place. There exists a critical metallicity in the envelope, Z_e^*, below which the characteristics of the hydrogen-burning shell are insensitive to the stellar abundance (Fujimoto et al. 1984). Therefore, for $Z < Z_e^*$, these higher mass stars will *not* experience a change in their surface chemical compositions, as in the $Z = 0$ models, and finish their lives as white dwarfs, after mass loss as TPAGB stars, or as carbon-deflagration supernovae.

For the rest of the parameter space, which we label case

IV, model stars are predicted to undergo similar evolution with time as Populations I and II stars.

4. CONCLUSIONS AND DISCUSSION

Models of extremely metal-poor stars have been shown to develop carbon enhancements at an earlier stage of evolution, and with a smaller core mass, than do Populations I and II stars. The mass in the flash-driven convective zone for these stars is larger, so that a greater enhancement of carbon can result from only one hydrogen-mixing event. These facts explain both the observed increase in the incidence of carbon-enrichment and the observed tendency for the degree of carbon enrichment to increase as metallicity decreases. The large nitrogen enrichments (up to $[N/Fe] \simeq 2$) and small $^{12}C/^{13}C$ ratios (several times larger than the equilibrium value) that are observed in all the EMDC stars can be understood in the context of our hydrogen-mixing formation mechanism.

EMDC stars that have been studied at high spectral resolution using present-generation telescopes, such as CS 22892−052 ($[Fe/H] = -3.0$; Sneden et al. 1996; Norris et al. 1997a) and CS 22957−027 ($[Fe/H] = -3.4$; Bonifacio et al. 1998; Norris, Ryan, & Beers 1997b), do not exhibit enhancements of *s*-process elements. For these two giants, their carbon enhancements may be interpreted in terms of mass transfer from companion stars that have undergone case II evolution. For those EMDC stars which DO exhibit *s*-process element enrichment (these include giants, subgiants, and even dwarfs), their surface abundances are consistent with case II′ evolution. For some EMDC stars, such as the subgiant LP 625−44 (Norris et al. 1997a), observed radial velocity variations are consistent with the binary hypothesis and, for others, radial velocity variations are yet to be monitored. The star that is claimed to be *the* most metal-deficient one known, G77−61, may also be understood in terms of case II′ evolution, although the ratio $^{12}C/^{13}C$ that has been derived ($\simeq 4$; Gass et al. 1988) seems rather small in comparison with a large C/N ($\simeq 20$) ratio. The presence or lack of *s*-process enhancements in this star has yet to be explored.

For the EMDC stars in binaries, a determination of the mass of the white dwarf companion would establish an upper limit on the initial mass of the primary. Furthermore, a determination of the surface temperature of the white dwarf would impose a lower limit on the age of the system and, hence, on the age of the universe. Such observations should be pursued in the near future.

The general picture of the evolution of extremely metal-poor stars shows qualitative agreement with the observed surface chemistry of stars in the HK survey that have been studied to date. Since we have employed a limited reaction network and a crude procedure to follow mixing, investigations with appropriate nuclear networks and with better treatment of the mixing process are necessary to explore modifications in surface characteristics more precisely. In particular, some hydrogen, captured by ^{12}C, is carried down to the helium-burning region before the initial convective shell splits into two parts. It is therefore important to follow their consequence and to compare the predicted results with observed abundances of *s*- and *r*-process elements at the surfaces of the EMDC stars.

Finally, we discuss the relevance of the present results to the search for the first generations of stars in our universe. Stars that are presently in advanced evolutionary stages and hence have larger luminosities are expected to be the most suitable targets. By searching for them at the most remote distances possible (or, equivalently, targeting stars with orbits which never take them into the plane of the Galaxy), contamination of surface layers by accretion of metal-rich gas in the Galactic disk can be minimized. Taking advantage of their evolutionary peculiarity, we may seek Population III stars among the nitrogen-rich carbon stars. These stars are distinguishable from their counterparts among the EMDC stars that have undergone cases II and II′ evolutions on the basis of their C/N and $^{13}C/N$ ratios and also from the absence of *s*-process elements. The time has arrived to develop new methods of detecting stars that are entirely devoid of pristine metals as well as methods that are more sensitive to redder stars than can be analyzed using the Ca II K line.

M. Y. F. is grateful for valuable discussions with T. C. Beers and S. Rossi. This work was supported by the Grant-in-Aid for Scientific Research of the Japanese Ministry of Education, Science, and Culture (09640308, 10147201).

REFERENCES

Barbuy, B., Cayrel, R., Spite, M., Beers, T. C., Spite, F., Nordstroem, B., & Nissen, P. E. 1997, A&A, 317, L63
Bessel, M. S., & Norris, J. 1984, ApJ, 285, 622
Bessel, M. S., Wood, P. R., & Evans, T. L. 1983, MNRAS, 202, 59
Beers, T. C. 1999, in ASP Conf. Ser. 165, The Third Stromlo Symposium: The Galactic Halo, ed. B. K. Gibson, T. S. Axelrod, & M. E. Putman (San Francisco: ASP), 206
Beers, T. C., Preston, G. W., & Shectman, A. 1992, AJ, 103, 1987
Bonifacio, P., et al. 1998, A&A, 332, 672
Boothroyd, A. I., & Sackmann, I.-J. 1988, ApJ, 328, 671
Cassisi, S., Castellani, V., & Tornambé, A. 1996, ApJ, 459, 298
Chiefi, A., & Tornambé, A. 1984, ApJ, 287, 745
Frost, C. A., & Lattanzio, J. C. 1996, ApJ, 473, 383
Fujimoto, M. Y. 1977, PASJ, 29, 331
Fujimoto, M. Y., Iben, I., Jr., Chiefi, A., & Tornambé, A. 1984, ApJ, 287, 749
Fujimoto, M. Y., Iben, I., Jr., & Hollowell, D. 1990, ApJ, 349, 580
Fujimoto, M. Y., Nomoto, K., & Sugimoto, D. 1976, PASJ, 28, 89
Fujimoto, M. Y., Sugiyama, K., Iben, I., Jr., & Hollowell, D. 1995, ApJ, 444, 175
Gass, H., Liebert, J., & Wehrse, R. 1988, A&A, 189, 194
Hill, V., et al. 1999, A&A, in press
Hollowell, D., Iben, I., Jr., & Fujimoto, M. Y. 1990, ApJ, 351, 245
Iben, I., Jr. 1975, ApJ, 196, 525
———. 1977, ApJ, 217, 788
Iben, I., Jr., & Renzini, A. 1982, ApJ, 263, L23
Jorissen, A. 1999, in IAU Symp. 191, Asymtotic Giant Branch Stars, ed. T. Le Bertre, A. Lèbre, & C. Waelkens (San Francisco: ASP), 437
Lattanzio, J. C. 1989, ApJ, 344, L25
Marigo, P., Giraardi, L., & Bressan, A. 1999, A&A, 344, 123
McClure, R. B. 1983, ApJ, 268, 264
Norris, J. E., Ryan, S. G., & Beers, T. C. 1997a, ApJ, 488, 350
———. 1997b, ApJ, 489, L169
Rees, M. 1998, Space Sci. Rev., 84, 43
Rossi, S., Beers, T. C., & Sneden, C. 1999, in ASP Conf. Ser. 165, The Third Stromlo Symposium: The Galactic Halo, ed. B. K. Gibson, T. S. Axelrod, & M. E. Putman (San Francisco: ASP), 264
Sneden, C., et al. 1996, ApJ, 467, 819
Wood, P. R. 1981, in Physical Process in Red Giants, ed. I. Iben, Jr. & A. Renzini (Dordrecht: Reidel), 135