THE ASTROPHYSICAL JOURNAL, 465:L27–L30, 1996 July 1

ON THE SYNTHESIS OF ^{7}Li AND ^{7}Be IN NOVAE

MARGARITA HERNANZ
Centre d'Estudis Avançats de Blanes (CSIC), Camí de Santa Bàrbara s/n, E-17300 Blanes, Spain
JORDI JOSÉ
Departament de Física i Enginyeria Nuclear, Universitat Politècnica de Catalunya, Avenida Víctor Balaguer s/n, E-08800 Vilanova i la Geltrú, Spain
ALAIN COC
Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, IN2P3-CNRS, Bâtiment 104, F-91405 Orsay Cedex, France
AND
JORDI ISERN
Centre d'Estudis Avançats de Blanes (CSIC), Camí de Santa Bàrbara s/n, E-17300 Blanes, Spain
Received 1996 January 31; accepted 1996 April 15

ABSTRACT

The production of ^{7}Li and ^{7}Be during the explosive hydrogen burning that occurs in nova explosions is computed by means of a hydrodynamic code able to treat both the accretion and the explosion stages. Large overproduction factors with respect to solar abundances are obtained, the exact value depending mainly on the chemical composition of the envelope. Although the final ejected masses are small, these results indicate that novae can contribute to the ^{7}Li enrichment of the interstellar medium. Furthermore, since ^{7}Be decays by emitting a gamma ray (478 keV), with a half-life of 53.3 days, the synthesis of ^{7}Li could be tested during the *INTEGRAL* mission.

Subject headings: gamma rays: theory — novae, cataclysmic variables — nuclear reactions, nucleosynthesis, abundances

1. INTRODUCTION

The origin of lithium and other light elements is still an unsolved problem in astrophysics. It is widely accepted that ^{7}Li isotopes were produced during the big bang and are also produced by "spallation" reactions in the interstellar medium, by galactic cosmic rays or in flares (see Reeves 1993 for a recent review). Standard big bang nucleosynthesis underproduces ^{7}Li with respect to solar abundances by more than an order of magnitude (but see the recent paper by Deliyannis, Boesgaard, & King 1995), whereas spallation reactions due to galactic cosmic rays produce ^{7}Li and ^{6}Li simultaneously, as well as ^{9}Be, ^{10}B, and ^{11}B. These two mechanisms are unable to account alone for the present ^{7}Li abundance (^{7}Li/H $\approx 2 \times 10^{-9}$). Furthermore, they are able to produce neither the high ^{7}Li/^{6}Li isotopic ratio observed in the solar system (^{7}Li/^{6}Li $= 12.5 \pm 0.2$) nor the ^{11}B/^{10}B one ($\approx$4). Recent measurements of the lithium isotopic ratio in the interstellar medium (Lemoine et al. 1993; Meyer, Hawkins, & Wright 1993) have yielded values similar to those found in the solar system, indicating that it has remained nearly constant or even decreased during the last 4.5–5 Gyr. A contribution by a low-energy component of the galactic cosmic rays, confined at the source or by stellar flares (Meneguzzi, Audouze, & Reeves 1971; Canal, Isern, & Sanahuja 1975; Prantzos, Cassé, & Vangioni-Flam 1993), can account for the boron isotopes, but ^{7}Li is still underproduced. Therefore, an extra stellar source able to produce this ^{7}Li without generating ^{6}Li has to be invoked. The interplay of these sources in the galactic evolution of lithium has been extensively studied (D'Antona & Matteuci 1991; Abia, Isern, & Canal 1995).

The synthesis of ^{7}Li by a stellar source requires the formation of ^{7}Be, which transforms into ^{7}Li by an electron capture, the half-life of ^{7}Be being 53.3 days. As ^{7}Li is very easily destroyed, ^{7}Be has to be transported to zones cooler than those where it was formed, with a timescale shorter than its decay time. This *beryllium transport* mechanism, as first suggested by Cameron (1955), requires a dynamic situation like that encountered in asymptotic giant branch (AGB) stars and novae. Another possibility is the production of lithium and boron isotopes by neutrino-induced synthesis during gravitational supernova explosions (Woosley et al. 1990; Woosley & Weaver 1995). The importance of such a mechanism is still a matter of debate (Matteuci, D'Antona, & Timmes 1995).

The production of lithium in AGB stars has been extensively studied, and these stars represent unique observational evidence of an autogenic stellar origin, since it has been observed in them (Abia et al. 1991; Abia, Isern, & Canal 1993). The huge abundances of lithium found in some AGB stars are clear proof that these stars are currently injecting important quantities of lithium into the interstellar medium. However, it is hard to estimate their total contribution since it depends on the estimated number of such stars, which are buried by their own wind (Abia et al. 1993).

The production of ^{7}Li in explosive hydrogen burning and, in particular, in accreting white dwarfs exploding as classical novae was first studied with a parameterized one-zone model by Arnould & Nørgaard (1975). Later, Starrfield et al. (1978) computed the ^{7}Li yields by means of a hydrodynamic code. This code simulated the explosive stage of novae without considering the accretion phase, i.e., with an initial envelope already in place. The conclusion of their work was that, depending on the initial abundance of ^{3}He and the treatment of convection, ^{7}Li could be formed in substantial amounts during explosive hydrogen burning in novae. This problem was revisited by Boffin et al. (1993). On the basis of an extended nuclear reaction network and updated nuclear reaction rates, but adopting again a parameterized one-zone model, they showed that ^{7}Li could only be produced in significant amounts at peak densities lower than 10^3 g cm^{-3}, which is lower than those predicted by hydrodynamic simulations. They argued that the reason for the discrepancy was the neglect of the ^{8}B$(p,\gamma)^{9}$C reaction in the calculations of Starrfield et al. (1978). However, large overproductions of ^{7}Be were found by Coc et al. (1995) [using the semianalytical model of MacDonald 1983 to obtain the temperature and density profiles and a complete reaction network that included ^{8}B$(p, \gamma)^{9}$C], showing that the origin of the different results was not that reaction. In fact, Boffin et al. (1993) also showed, by means of a two-zone approximation, that the efficiency of mixing by convection is a very critical parameter, and they stressed the need for a detailed hydrodynamic model with which to study ^{7}Li production more accurately.

The purpose of this Letter is to compute the synthesis of ^{7}Li in both carbon-oxygen (CO) and oxygen-neon-magnesium (ONeMg) novae by means of an implicit hydrodynamic code that includes a full reaction network and is able to treat both the hydrostatic accretion phase and the explosion stage. An estimation of the contribution of novae to galactic enrichment is made on the basis of the overproductions and ejected masses obtained. The importance of the initial chemical composition of the envelope is analyzed.

The detection of ^{7}Li in novae would confirm our theoretical prediction. Furthermore, the detection of gamma-ray emission at 478 keV, corresponding to the decay of ^{7}Be to ^{7}Li (half-life 53.3 days) in the early phases of novae by the future mission of the *International Gamma-Ray Astrophysical Laboratory* (*INTEGRAL*) would also confirm the thermonuclear runaway model for novae and the nucleosynthesis related to it.

2. MODEL AND RESULTS

A one-dimensional, Lagrangian, implicit hydrodynamic code has been developed following the techniques described in Kutter & Sparks (1972). The code was built in such a way as to enable the study of both the hydrostatic accretion phase and the fully hydrodynamic explosion. Detailed nucleosynthesis is obtained by means of an extended reaction network, including 100 nuclei ranging from ^{1}H to ^{40}Ca, linked through an up-to-date network that includes more than 370 nuclear reactions (see José 1996 and José et al. 1996 for details). For the reactions involved in ^{7}Be synthesis, rates are taken from the Caughlan & Fowler (1988) compilation, Wagoner (1969), Descouvemont (1989), and Wiescher et al. (1989). Time-dependent convection is included in the code since the hypothesis that the convection timescale is always shorter than the nuclear timescale, inherent to time-independent convection, is not always fulfilled. With this method, partial mixing in the convective region is included.

Complete evolution of the accretion and explosion stages of white dwarfs with masses ranging from 1 to 1.25 $M_{\odot}$, accreting at a rate of 2×10^{-10} $M_{\odot}$ yr^{-1} with initial luminosity 10^{-2} $L_{\odot}$, has been computed. We assume that the infalling material is of solar composition but that some process (diffusion, shear mixing) mixes it with the underlying CO (for $M = 1$ and 1.15 $M_{\odot}$) or ONeMg (for $M = 1.15$ and 1.25 $M_{\odot}$) core. This assumption is based on the current prediction that enhanced CNO (or ONeMg) abundances are required in order to produce a nova outburst and to explain some observed abundances (see Livio 1994 for a recent review and Prialnik & Kovetz 1995 and Politano et al. 1995 for recent calculations of CO and ONeMg novae, respectively). We stress that the problem of the initial composition of nova envelopes is rather complicated and that it is far from being understood in a self-consistent way. Studies of diffusion during accretion onto CO white dwarfs have been carried out (Kovetz & Prialnik 1985; Iben, Fujimoto, & MacDonald 1992), but it is not clear whether enough enhancements of heavy elements are obtained in the ejecta. For the ONeMg white dwarfs, these studies are still lacking. Therefore, a compromise is to adopt some percentage of mixing with core abundances. We have adopted a 50% mixing by mass with core abundances, as was done by Politano et al. (1995).

The chain of reactions leading to the formation of ^{7}Be has been extensively discussed by Boffin et al. (1993). During hydrogen burning, the formation of ^{7}Be proceeds through ^{3}He$(\alpha, \gamma)^{7}$Be from the initial ^{3}He, as (p, γ) reactions cannot bridge the $A = 5$ gap. It is destroyed via ^{7}Be$(p,\gamma)^{8}$B, followed by either ^{8}B$(\beta^{+})2^{4}$He or ^{8}B$(p, \gamma)^{9}$C$(\beta^{+}, p)2^{4}$He. However, at high temperatures the photodisintegration of ^{8}B, i.e., ^{8}B$(\gamma, p)^{7}$Be, becomes faster than proton capture onto ^{7}Be. In these conditions, the effective lifetime of ^{7}Be can become larger than the timescale of the outburst (Boffin et al. 1993). For typical densities at the base of the envelope at the onset of explosion, this would happen only above $T_8 \sim 1$. Below this temperature, destruction by ^{7}Be$(p, \gamma)^{8}$B is efficient. Other destruction mechanisms are ^{7}Be$(\alpha, \gamma)^{11}$C and beta decay to ^{7}Li. Radiative alpha capture on ^{7}Be is always slower than proton capture as long as photodisintegration of ^{8}B is not efficient. The half-life of ^{7}Be (53.3 days) would allow the formation of ^{7}Li long after the outburst, when the cooler envelope would prevent the rapid destruction of this fragile isotope. Since ^{7}Be is more efficiently destroyed than produced below $T_8 \approx 1$ and since it originates only from initial ^{3}He, it can only be formed during the outburst if enough ^{3}He survives the initial phase, when the hydrodynamic timescale is much longer than in the explosive phase.

The ^{3}He found in the envelope originates from the accreted material and from the reaction ^{1}H$(p, e^{-}\nu)^{2}$H followed immediately by ^{2}H$(p,\gamma)^{3}$He, which slightly increases the ^{3}He abundance in the initial phase of accretion. The two major modes of ^{3}He destruction are through ^{3}He$(^{3}$He$, 2p)^{4}$He and ^{3}He$(^{4}$He$,\gamma)^{7}$Be. ^{3}He$(^{4}$He$, \gamma)^{7}$Be is always slower than ^{3}He$(^{3}$He$, 2p)^{4}$He, except at lower ^{3}He abundances. As noted by Boffin et al. (1993), the latter reaction is responsible for the logarithmic dependence of the ^{7}Be yield with respect to the initial ^{3}He abundance above $X(^{3}\mathrm{He})_{\odot}$. This means that hypothetical higher than solar initial ^{3}He abundances, related to enriched secondary star envelopes, do not dramatically alter the final ^{7}Be yields. The results presented in this Letter are little affected by nuclear uncertainties, as the rates of the reactions of ^{3}He destruction are precisely known.

For the ONeMg model with $M = 1.15$ $M_{\odot}$ (hereafter the "ONe model," since magnesium is almost absent; see Domínguez, Tornambé, & Isern 1993; Ritossa, García-Berro & Iben 1996), we show the profiles of ^{3}He and ^{7}Be abundances along the envelope for different times starting at the beginning of the accretion phase in Figure 1. The corresponding temperatures at the base of the envelope are 10^7, 2×10^7, 3×10^7, 5×10^7, and 10^8 K and the maximum temperature (2×10^8 K). An additional model, for which a considerable expansion has already occurred ($R_{\mathrm{wd}} > 10^{11}$ cm), is also shown. Our

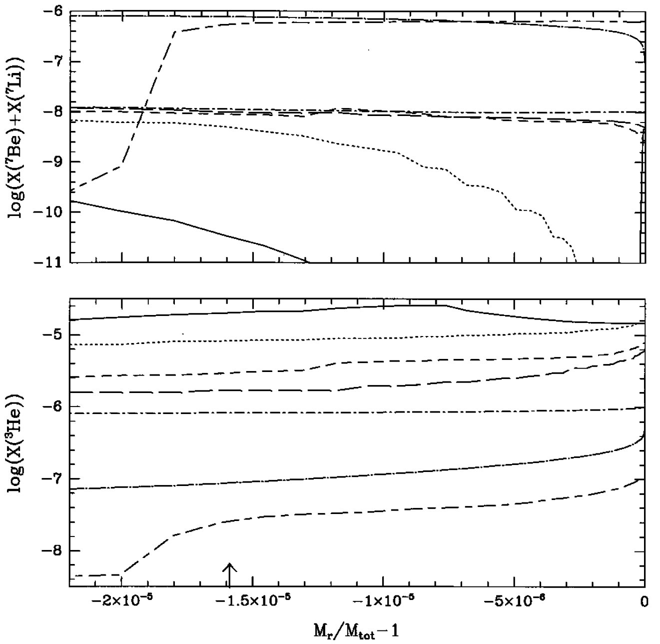

FIG. 1.—Profiles of ^{7}Be (*top*) and ^{3}He (*bottom*) abundances along the envelope for different times from the beginning of accretion up to the ejection of the envelope, for a 1.15 $M_\odot$ ONe novae accreting at a rate $\dot{M} = 2 \times 10^{-10}$ $M_\odot$ yr^{-1}. The successive models correspond to temperatures at the base of the envelope of 2×10^7 (*solid lines*), 3×10^7 (*dotted lines*), 5×10^7 (*short-dashed lines*), 7×10^7 (*long-dashed lines*), 10^8 (*dot–short-dashed lines*), and 2×10^8 K (T_{max}; *dot–long-dashed lines*) plus an additional case, for which a considerable expansion has already occurred, $R_{wd} > 10^{11}$ cm (*short-dash–long-dashed lines*). The arrow indicates the base of the ejected shells.

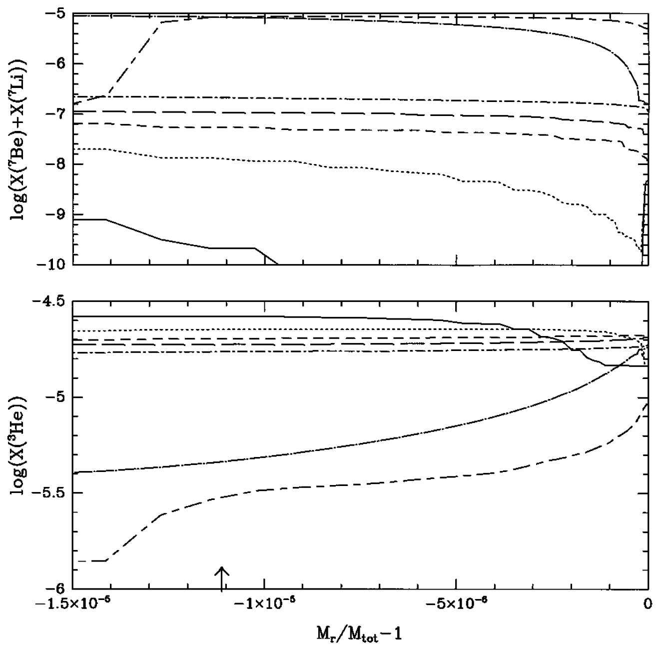

FIG. 2.—Same as Fig. 1, but for a CO nova

results indicate that ^{3}He is destroyed down to abundances between 10^{-6} and 10^{-7} by mass at the end of the accretion phase. More specifically, these abundances correspond to the phase during which temperatures are around 10^8 K, allowing the photodisintegration of ^{8}B to prevent ^{7}Be destruction (see discussion above). Therefore, the final ^{7}Be abundances are similar to the ^{3}He ones at this critical phase. It is important to note that these values are much higher than those at the burning shell (~10^{-9} by mass; see Fig. 1), indicating that one-zone models are unable to provide correct yields. The average mass fraction of ^{7}Be in the shells that will be ejected and thus will contribute to interstellar medium enrichment is ~10^{-6}. Since all the ^{7}Li finally produced comes from the decay of ^{7}Be, and as the temperatures of our last model are low enough to prevent ^{7}Li destruction, the final ^{7}Li yield corresponds to the addition of ^{7}Be and ^{7}Li mass fractions in the ejected shells. The final ejected mass is 1.9×10^{-5} $M_\odot$, with a mean abundance of ^{7}Li by mass of 6.0×10^{-7}. Thus 1.1×10^{-11} $M_\odot$ of ^{7}Li would be ejected (see Table 1).

Concerning the CO cases, ^{3}He destruction is less pronounced at the same critical phase, and this allows the synthesis of a larger amount of ^{7}Be. The corresponding profiles of ^{3}He and ^{7}Be are shown in Figure 2 for the $M = 1.15$ $M_\odot$ case. The mean mass fraction of ^{7}Li is 8.2×10^{-6} (the ejected mass of ^{7}Li is 1.1×10^{-10} $M_\odot$, and the total ejected mass is 1.3×10^{-5} $M_\odot$). The main reason for the different nucleosynthesis in the two cases is that for CO novae the presence of ^{12}C implies that the fast reaction $^{12}C(p, \gamma)^{13}N(\beta^+)^{13}C$ is dominant during the late accretion phase (whereas the energy production through this reaction is lower in ONe novae, as they almost lack from ^{12}C). Consequently, the duration of the phase prior to maximum temperature is shorter in CO novae, preventing efficient ^{3}He destruction and thus leading to a larger final amount of synthesized ^{7}Be.

To summarize our results (see Table 1, where additional cases are shown), overproductions of ^{7}Li, with respect to solar abundances, between 100 and 2000 are obtained, depending mainly on the chemical composition of the envelope, which is related to that of the underlying core. It is hard to estimate its real contribution to the ^{7}Li enrichment in the galaxy, since theoretical models systematically produce ejected masses smaller than are observed. For instance, our models typically eject ~10^{-5} $M_\odot$ while the estimated mass of QU Vul 1984 (which has been invoked as a true "neon nova") is ~10^{-3} $M_\odot$

TABLE 1

^{7}Li YIELDS AND EJECTED MASSES FOR SOME NOVA MODELS

Composition	M_{wd} ($M_\odot$)	$\dot{M}$ ($M_\odot$ yr^{-1})	$\bar{X}$ (^{7}Li)	$N(^7Li/H) / N(^7Li/H)_\odot$	M^{ej}_{tot} ($M_\odot$)	$M^{ej}_{^7Li}$ ($M_\odot$)
CO............	1.0	2×10^{-10}	3.1×10^{-6}	742	2.3×10^{-5}	7.1×10^{-11}
CO............	1.15	2×10^{-10}	8.2×10^{-6}	1952	1.3×10^{-5}	1.1×10^{-10}
ONe	1.15	2×10^{-10}	6.0×10^{-7}	143	1.9×10^{-5}	1.1×10^{-11}
ONe	1.25	2×10^{-10}	6.5×10^{-7}	155	1.8×10^{-5}	1.2×10^{-11}
ONe	1.25	2×10^{-8}	7.9×10^{-7}	187	8.3×10^{-6}	6.7×10^{-12}

(Saizar et al. 1992). For an overproduction factor as large as 2000 and a total ejected mass of $\sim 10^{-5}$ $M_\odot$ (2 orders of magnitude lower than observed for QU Vul 1984), a nova event would produce $\sim 10^{-10}$ $M_\odot$ of ^{7}Li. If we adopt the galactic nova rate of Della Valle & Livio (1994) (20 yr^{-1}) and an age for the galaxy of $\sim 10^{10}$ yr, novae should produce at least 20 $M_\odot$ of ^{7}Li. This quantity is clearly smaller than the estimated present content of ^{7}Li in the galaxy, ~ 150 $M_\odot$, but given the uncertainties in the ejected mass per event, the contribution of novae to the galactic content of ^{7}Li cannot be ruled out yet. A complete analysis of ^{7}Li yields by novae and their inclusion in a model of galactic evolution is beyond the scope of this Letter and will be presented elsewhere.

3. DISCUSSION AND CONCLUSIONS

Our results confirm that nova explosions can produce significant amounts of ^{7}Li. Overproduction factors as large as 2000 are obtained. Our results are quite different from those obtained from one-zone models (Boffin et al. 1993), as the most important contribution to ^{7}Li enrichment comes from the external shells, where this element has been transported by convection from the burning shell.

Comparison with the results of Coc et al. (1995) and Politano et al. (1995) shows that the behavior of ^{7}Be abundances can be correctly predicted only if the evolution of ^{3}He during the accretion phase is accurately followed. We also stress that the final results strongly depend on the chemical composition at the onset of the explosion. If the underlying white dwarf is a CO one, the ^{7}Li abundances are ~ 1 order of magnitude larger than if the white dwarf is an ONe one.

Since the decay of ^{7}Be to ^{7}Li emits a photon with energy 478 keV, during a phase in which the envelope is very transparent, this transition could be detected by the future *INTEGRAL* mission (with a sensitivity of $\sim 6 \times 10^{-6}$ at this energy). The flux of the ^{7}Be decay line is

$$F = 2.2 \times 10^{-6} \frac{X(^7\mathrm{Be})}{10^{-6}} \frac{M_{\mathrm{ej}}}{10^{-4}\ M_\odot} \times \frac{1}{[D\ (\mathrm{kpc})]^2} e^{-t/76d} \text{ counts s}^{-1}\text{ cm}^{-2} .$$

For an ejected mass of 10^{-5} $M_\odot$, with an abundance by mass of $X(^7\mathrm{Be}) = 8 \times 10^{-6}$, the ^{7}Be decay line would be detectable just after the outburst only for a nova closer than 0.5 kpc. But for an ejected mass of 10^{-4} or 10^{-3} $M_\odot$, more in accordance with observations, the lower limit for the distance would be 1.7 or 5.4 kpc, respectively. Such a detection would provide a confirmation of the theoretical models of novae and also ensure that ^{7}Li is produced in these scenarios, encouraging a deep search for this element in novae.

This research was partially supported by the CICYT (ESP95-0091), the DGICYT (PB94-0827-C02-02), the CIRIT (GRQ94-8001), the AIHF (95-335), and the Human Capital and Mobility Programme (CHGE-CT92-0009) "Access to Supercomputing Facilities for European Researchers" established between the European Community and CESCA/CEPBA.

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
———. 1995, A&A, 298, 465
Arnould, M., & Nørgaard, H. 1975, A&A, 42, 55
Boffin, H. M. J., Paulus, G., Arnould, M., & Mowlavi, N. 1993, A&A, 279, 173
Cameron, A. G. W. 1955, ApJ, 212, 144
Canal, R., Isern, J., & Sanahuja, B. 1975, ApJ, 200, 646
Caughlan, G. R., & Fowler, W. A. 1988, At. Data Nucl. Data Tables, 40, 283
Coc, A., Mochkovitch, R., Oberto, Y., Thibaud, J. P., & Vangioni-Flam, E. 1995, A&A, 299, 479
D'Antona, F., & Matteuci, F. 1991, A&A, 248, 62
Deliyannis, C. P., Boesgaard, A. M., & King, J. R. 1995, ApJ, 452, L13
Della Valle, M., & Livio, M. 1994, A&A, 286, 786
Descouvemont, P. 1989, Thèse d'Aggrégation, Univ. Libre Bruxelles
Domínguez, I., Tornambé, A., & Isern, J. 1993, ApJ, 419, 268
Iben, I., Jr., Fujimoto, M. Y., & MacDonald, J. 1992, ApJ, 388, 521
José, J. 1996, Ph.D. thesis, Univ. Barcelona
José, J., et al. 1996, in preparation
Kovetz, A., & Prialnik, D. 1985, ApJ, 291, 812
Kutter, G. S., & Sparks, W. M. 1972, ApJ, 175, 407
Lemoine, M., Ferlet, R., Vidal-Madjar, A., Emerich, C., & Bertin, P. 1993, A&A, 269, 469
Livio, M. 1994, in Interacting Binaries, ed. H. Nussbaumer & A. Orr (Berlin: Springer), 135
MacDonald, J. 1983, ApJ, 267, 732
Matteuci, F., D'Antona, F., & Timmes, F. X. 1995, A&A, 303, 460
Meneguzzi, M., Audouze, J., & Reeves, H. 1971, A&A, 15, 337
Meyer, D. M., Hawkins, I., & Wright, E. L. 1993, ApJ, 409, L61
Politano, M., Starrfield, S., Truran, J. W., Weiss, A., & Sparks, W. M. 1995, ApJ, 448, 807
Prantzos, N., Cassé, M., & Vangioni-Flam, E. 1993, in Origin and Evolution of the Elements, ed. N. Prantzos, E. Vangioni-Flam, & M. Cassé (Cambridge: Cambridge Univ. Press), 156
Prialnik, D., & Kovetz, A. 1995, ApJ, 445, 789
Reeves, H. 1993, in Origin and Evolution of the Elements, ed. N. Prantzos, E. Vangioni-Flam, & M. Cassé (Cambridge: Cambridge Univ. Press), 168
Ritossa, C., García-Berro, E., & Iben, I., Jr. 1996, ApJ, 460, 489
Saizar, P., et al. 1992, ApJ, 398, 651
Starrfield, S., Truran, J. W., Sparks, W. M., & Arnould, M. 1978, ApJ, 222, 600
Wagoner, R. W. 1969, ApJS, 18, 247
Wiescher, M., Görres, J., Graff, S., Buchmann, L., & Thielemann, F. K. 1989, ApJ, 343, 352
Woosley, S. E., Hartmann, D. H., Hoffman, R. D., & Haxton, W. C. 1990, ApJ, 356, 272
Woosley, S. E., & Weaver, T. A. 1995, ApJS, 101, 181