THE CREATION OF LITHIUM IN GIANT STARS

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ABSTRACT. A time-dependent "*convective diffusion*" algorithm for convective transport in the mixing-length framework has been coupled for the first time with a *self-consistent* full evolutionary computation, in order to investigate theoretically the creation of superrich lithium stars on the asymptotic giant branch. For intermediate mass stars in the mass range from 4 to 7 $M_\odot$ with both Population I and II compositions, *hot bottom burning* in the convective envelope was found, with maximum temperatures $T_{\rm ce}$ at the base of the convective envelope ranging from 20 to 100 million K, depending on stellar mass and mass loss rates. For $T_{\rm ce} \geq 40$ million K, *lithium-rich giants* were produced (with $\log \varepsilon(^7{\rm Li}) \gtrsim 1$, i.e., *above* the *normal* observed range in giants). For $T_{\rm ce} \geq 50$ million K, *superrich lithium giants* were created, with $\log \varepsilon(^7{\rm Li}) \gtrsim 3$ (i.e., *larger* than the present *cosmic* ^{7}Li abundance). *Superrich lithium giants* were created for stars in the *approximate mass range from* 4 *to* 7 $M_\odot$ *for both Population I and II*. Peak ^{7}Li abundances were found to lie in the range $4 \lesssim \log \varepsilon(^7{\rm Li}) \lesssim 4.6$, relatively *independent* of mass and chemical composition. We predict a *narrow luminosity range* for superrich lithium stars, namely $-6 \gtrsim M_{\rm bol} \gtrsim -7.2$, i.e., $4.3 \lesssim \log L \lesssim 4.8$. Both the predicted peak ^{7}Li abundances and the predicted luminosity range are in beautiful agreement with the observed values for the Galaxy and the Magellanic Clouds. High ^{7}Li abundances persist for 10^4 to 10^5 years. *Mass loss* in AGB stars *can strongly affect* the ^{7}Li production; it affects the *peak* ^{7}Li *abundance* produced and the *mass of lithium-rich material ejected* into interstellar space, as well as the *timescale and luminosity range* over which the *superrich lithium phenomenon* is observable. For a *modest* mass loss rate (a Reimers' [1975] wind with $\eta = 1.4$), superrich lithium stars are produced from 4 to 7 $M_\odot$. For a more *realistic* intermediate mass loss rate ($\eta = 5$), the 4 $M_\odot$ star was *prevented* from becoming a *superrich lithium star* — it *never even became lithium rich*; for 5 through 7 $M_\odot$, the *peak* ^{7}Li *abundance* is *unaffected* by the increased mass loss, but the *mass of lithium-rich material ejected* into space is *greatly increased*, and thus the total mass of lithium ejected from these stars increases by a factor of 3 over our modest mass loss case. For an *extreme* mass loss rate ($\eta = 14$), even the 5 $M_\odot$ star *barely* reaches superrich lithium abundances ($\log \varepsilon(^7{\rm Li}) \approx 3$), ejecting only *minor amounts of lithium*; on the other hand, the *peak* ^{7}Li *abundance* in 6 and 7 $M_\odot$ stars is *unaffected*, and the amount of lithium ejected by these stars is again increased, by a factor of 3 over the intermediate mass loss case. We conclude that *intermediate mass AGB stars* are *major sources of cosmic lithium*, able to account for $0.5^{-0.25}_{+0.5}$ of the cosmic abundance with our most realistic mass loss rate ($\eta = 5$). With the extreme mass loss case ($\eta = 14$), AGB stars can also provide $0.5^{-0.25}_{+0.5}$ of the cosmic lithium, while the modest mass loss rate ($\eta = 1.4$) can provide $0.2^{-0.1}_{+0.2}$ of the cosmic lithium.

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1. Introduction

Lithium is one of the most easily destroyed elements, burning at only a few million degrees. Therefore the story of lithium is *normally* a story of *destruction.* However, in this paper, we will demonstrate the *creation* of lithium in the envelopes of intermediate mass red giants. We will further demonstrate that these red giants are a prime source of lithium in the interstellar medium.

Lithium is one of the few elements created by the big bang; after hydrogen and helium, it is the most abundant element created. Small amounts of lithium are also created by cosmic ray spallation from heavier elements (Boesgaard & Steigman 1985), and ^{7}Li should also be created in supernovae of Type II (Woosley, Hartman, Hoffman, & Haxton 1990). We will not address these latter lithium sources.

All stars are endowed at birth with lithium. Old, Population II halo stars are observed to have ^{7}Li abundances up to $^7\mathrm{Li/H} \approx 10^{-10}$ (by number), i.e., $\log \varepsilon(^7\mathrm{Li}) \approx 2$ (Spite, Maillard, & Spite 1984), where $\log \varepsilon(^7\mathrm{Li}) \equiv \log(^7\mathrm{Li/H}) + 12$. Young, Population I disk stars are observed to have ^{7}Li abundances up to $^7\mathrm{Li/H} \approx 10^{-9}$ in general, i.e., $\log \varepsilon(^7\mathrm{Li}) = 3.1 \pm 0.2$ (see, e.g., Duncan & Jones 1983; Boesgaard & Steigman 1985; Pilachowski, Booth, & Hobbs 1987; Boesgaard, Budge, & Ramsay 1988). This is inferred to be the present galactic ^{7}Li abundance, usually referred to as the cosmic abundance. Many stars, including our Sun, are observed to be considerably depleted in ^{7}Li; the Sun's abundance is $\log \varepsilon(^7\mathrm{Li}) \approx 1$, i.e., down by two orders of magnitude. This observed main sequence depletion of stars like the Sun is due to lithium being slowly mixed down to interior layers hot enough for lithium burning. This is normally explained by rotation-induced mixing (i.e., turbulent mixing or meridional circulation), although diffusion (and possibly main sequence mass loss) can also lead to lithium reduction. During the red giant phase of evolution, further depletion of lithium takes place due to dilution of the outer (lithium-containing) layers with inner layers where lithium had been burned up. This mixing is due to the deep red giant convective envelope, causing dilution by two orders of magnitude. Together, these two mixing processes result in surface lithium depletions ranging from two to four orders of magnitude, accounting for the observed range of lithium abundances in Population I red giants, namely $-1 \lesssim \log \varepsilon(^7\mathrm{Li}) \lesssim 1$ (Lambert, Dominy, & Sivertsen 1980; Brown, Sneden, Lambert, & Dutchover 1989).

On the other hand, a few decades ago a handful of giant stars were discovered in our galaxy that happened to contain a huge excess of lithium, with $\log \varepsilon(^7\mathrm{Li}) \sim 4$ to 5, one or two orders of magnitude above the cosmic lithium abundance of $\log \varepsilon(^7\mathrm{Li}) \approx 3$, and 3 to 4 orders of magnitude more than the maximum observed in typical giants. These stars were called *superrich lithium giants.* Some of them were *carbon stars*, e.g., WZ Cas (McKellar 1940) with $\log \varepsilon(^7\mathrm{Li}) \sim 4.9$ (Wallerstein & Conti 1969) or WX Cyg (Sanford 1944) with $\log \varepsilon(^7\mathrm{Li}) = 4.7 \pm 0.5$ (Abia, Boffin, Isern, & Rebolo 1991). Others were S stars (*not carbon stars*) e.g., T Sgr (Keenan 1967; Boesgaard 1970) with $\log \varepsilon(^7\mathrm{Li}) = 4.2 \pm 0.5$ (Abia et al. 1991). Recently, Smith & Lambert (1989, 1990) discovered that essentially *all the most luminous AGB stars* in the Magellanic Clouds were lithium-rich.

Cameron (1955) proposed a form of the ^{7}Be-transport mechanism that might create ^{7}Li in stars. Cameron & Fowler (1971) suggested the helium shell flash stage on the asymptotic giant branch (AGB) as the stage where this ^{7}Be-transport mechanism might take place. Scalo & Ulrich (1973) developed a *plume model* to try to account for superrich lithium stars, but this model produced insufficient lithium (log $\varepsilon(^7\mathrm{Li}) \sim 2.3$ in their preferred case) and was based on the hope that the flash-driven intershell convective tongue could penetrate into hydrogen-rich layers, a scenario that no one has ever been able to fulfill in any detailed self-consistent stellar evolution model. Iben (1973) found temperatures high enough for nuclear burning (60 million K) at the bottom of the convective envelope ("*hot bottom burning*") in a $7\,M_\odot$ model, but found *no* ^{7}Li *production* when he used the standard "*instantaneous mixing*" approach for the convective envelope.

The work of Smith & Sackmann (1973) and Sackmann, Smith, & Despain (1973, 1974) was the first to model the *time dependence of convective mixing* in deep convective envelopes together with nuclear burning. Rather than assuming instantaneous convective mixing, a *diffusion-type* method was used for *convective transport*, where the local diffusion constant was given by the product of the convective mixing length with the convective velocity (using the framework of the mixing length theory). However, their evolutionary models at that time had not encountered hot bottom burning temperatures, so they simply assumed a temperature $T_{\mathrm{ce}} = 50$ million K at the base of the convective envelope. It turned out that these models were able to create *superrich lithium stars* with *abundances* in the observed range. Scalo, Despain, & Ulrich (1975) borrowed the computer code of Sackmann, Smith, & Despain (1974) for the time-dependent "convective diffusion" and coupled it with their own static envelopes; rather than computing evolutionary tracks, they obtained luminosities for their static envelopes using the Paczyński (1970) core mass–luminosity relationship. This core mass–luminosity relationship has been found to be *invalid* (Lattanzio 1991, 1992; Blöcker & Schönberner 1991; Boothroyd & Sackmann 1992) for the hot bottom burning stars that Scalo, Despain, & Ulrich (1975) were computing. They also used a mixing length parameter $\alpha = 1.5$, somewhat too large for their Cox & Stewart (1970) low-temperature opacities — a value of $\alpha \approx 1.3$ would have been appropriate (Lattanzio 1989; Guenther, Jaffe, & Demarque 1989; see also Sackmann, Boothroyd, & Fowler 1990). Too high a value of α leads to an overestimate of hot bottom burning (Sackmann & Boothroyd 1991).

Nearly two decades later, with the use of *new molecular opacities* and the *nearly doubled* mixing length appropriate to them ($\alpha = 2.1$: see Sackmann, Boothroyd, & Fowler [1990]), Boothroyd & Sackmann (1991) encountered T_{ce} up to 80 million K in *self-consistent, detailed evolutionary models.* Coupling these with the *time-dependent "convective diffusion"* algorithm, Sackmann & Boothroyd (1992) produced *superrich lithium stars* for the first time in *fully self-consistent evolutionary models.* These models turned out to be in beautiful *agreement* not only with the *lithium abundance observations*, but also with the *observed luminosity range* of Magellanic Cloud superrich lithium stars. In the meantime, Lattanzio (1994) has reported that he also has obtained superrich lithium abundances, using a different convective algorithm, namely the "*two streams*" model. This model follows an upward-moving stream and a parallel downward-moving stream, with partial mixing between the two streams at each layer; in the limit of complete mixing between the two streams at each layer, this model approaches the "convective diffusion" approach of Sackmann, Smith, & Despain (1974).

2. The ^{7}Li Production

For the results presented here, we began the stellar evolution in the pre-main sequence Hayashi contraction phase, following a given star through its contraction onto the main sequence, through the main sequence (core hydrogen burning), through the red giant branch (RGB) phase, through the Cepheid loop phase (core helium burning), and through a large number of helium shell flashes (thermal pulses) on the asymptotic giant branch (AGB). For the ^{7}Li nucleosynthesis, we included the time-dependent convective diffusion approach of Sackmann, Smith, & Despain (1974) in the star's convective envelope. For other computational details, see Boothroyd & Sackmann (1988), Sackmann, Boothroyd, & Fowler (1990), Sackmann & Boothroyd (1992), and Boothroyd, Sackmann, & Ahern (1993). It should be noted that all of the work here included mass loss, which tends to fight hot bottom burning and ^{7}Li production. We used a Reimers' (1975) mass loss, namely $\dot{M} = -\eta(4 \times 10^{-13})LR/M$, where the luminosity L, the radius R, and the mass M are in solar units and the mass loss rate $\dot{M}$ is in solar masses per year. From early red giant observations, the mass loss parameter η was observed to be $\eta = 1.4$ (Kudritzki & Reimers 1978). However, a large body of more recent observations indicate that this is too modest for the AGB mass loss (see, e.g., Knapp et al. 1982; de Jong 1983; Weidemann & Koester 1983; Weidemann 1984); we therefore also used an intermediate value about 3 times as large (namely, $\eta = 5$, as reccommended by de Jong [1983]), and also an extreme value 10 times as large (namely, $\eta = 14$).

Stars are endowed at birth with ^{3}He from the interstellar medium; we used $^3\mathrm{He}/^4\mathrm{He} = 4.0 \times 10^{-4}$, by number (Boesgaard & Steigman 1985). In addition, as was shown long ago by Iben (1967), a ^{3}He pocket is created during the main sequence phase outside the hydrogen burning core, due to low-temperature *p-p* burning; further in, ^{3}He is destroyed. During the RGB phase, when the deep convective envelope swoops down into interior regions (i.e., 1$^{\mathrm{st}}$ dredge-up), the above ^{3}He regions get mixed into the convective envelope; for intermediate mass stars, this results in a slight ($< 40\%$) depletion in envelope ^{3}He. Later, during the early AGB phase, this happens again (i.e., 2$^{\mathrm{nd}}$ dredge-up), resulting in a further slight ($< 3\%$) envelope ^{3}He depletion. Thus a relatively large amount of ^{3}He is contained in the star's envelope on the AGB, namely $\log \varepsilon(^3\mathrm{He}) \approx 7.5$.

The stars are also endowed at birth with ^{7}Li, for which we took a value of $\log \varepsilon(^7\mathrm{Li}) = 3.0$, close to the galactic disk abundance. During the main sequence phase, ^{7}Li is destroyed in the stellar interior. Therefore, as the convective envelope swoops down into these regions, lithium-depleted matter is mixed upwards, and dilution of the envelope ^{7}Li results. This *dilution* is a factor of 100 for 1$^{\mathrm{st}}$ dredge-up, and a factor of nearly 2 for 2$^{\mathrm{nd}}$ dredge-up; note that this dilution surprisingly constant as one proceeds from 4 to $7\,M_\odot$ stars. This dilution could be even larger if one included rotation-induced mixing (as discussed in the Introduction).

During the helium shell flash phase on the AGB, we encountered temperatures T_{ce} at the bottom of the convective envelope up to 100 million K. The actual temperatures reached can be strongly affected by mass loss, as shown in Table 1, which gives the maximum temperatures T_{ce} and their trends at the time when the evolutionary runs were terminated. Note that a "flat" trend in T_{ce} actually refers to the very slow rise in T_{ce} that continues to take place (due to the increase in stellar luminosity) even after

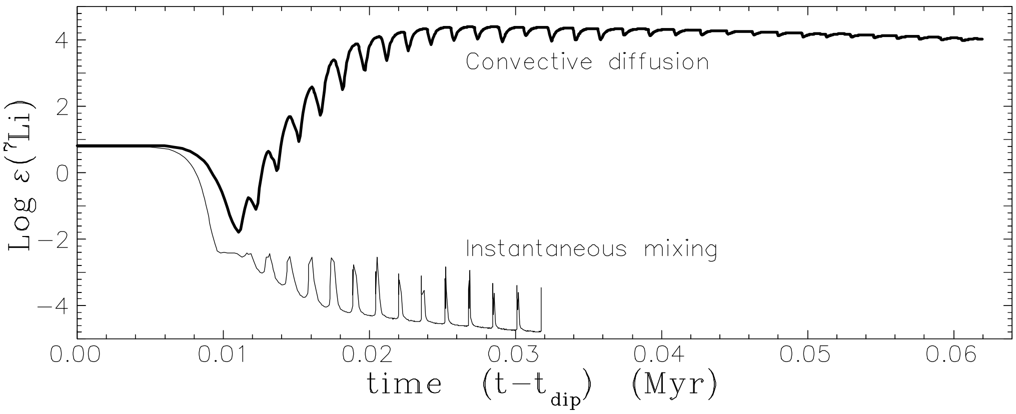

Fig. 1. Lithium production in a $6M_\odot$, $Z = 0.02$ star for the case where the "convective diffusion" approach to the time-dependence of convective transport was employed, and for the case where the usual "instantaneous mixing" approximation was employed.

the entire hydrogen-burning shell has been engulfed by the convective envelope (which corresponds to the maximum possible amount of hot bottom burning).

When $T_{\rm ce}$ reaches about 15 million K, the envelope ^{7}Li begins to burn significantly on timescales of 10^4 - 10^3 years, fast enough for large ^{7}Li depletion in 4 - 7 $M_\odot$ AGB stars. When $T_{\rm ce}$ reaches about 25 million K, ^{7}Li creation via the Cameron-Fowler mechanism takes over; as $T_{\rm ce}$ continues to increase, the ^{7}Li abundance also increases. For $T_{\rm ce} \gtrsim$ 40 million K, the stars become *lithium-rich giants*, with log $\varepsilon(^7\rm Li) \gtrsim 1$, i.e., above the normal observed range in giants; for $T_{\rm ce} \gtrsim$ 50 million K, the stars became *superrich lithium giants*, with log $\varepsilon(^7\rm Li) \gtrsim 3$, i.e., above the present cosmic lithium abundance.

TABLE I

Temperatures $T_{\rm ce}$ at the Bottom of the Convective Envelope

Stellar	$\eta = 1.4$		$\eta = 5.0$		$\eta = 14.0$	
Mass ($M_\odot$)	Max $T_{\rm ce}$ (10^6 K)	Trend[a] of $T_{\rm ce}$	Max $T_{\rm ce}$ (10^6 K)	Trend[a] of $T_{\rm ce}$	Max $T_{\rm ce}$ (10^6 K)	Trend[a] of $T_{\rm ce}$
4	55	rising	30	falling	20	falling
5	80	flat	75	flat	50	falling
6	90	flat	85	flat	80	flat
7	100	flat				

[a] Trend of $T_{\rm ce}$ at the termination of the computational runs.

For a 6 $M_\odot$ star of solar composition, Figure 1 presents our results of the growth of the surface ^{7}Li abundances with time as $T_{\rm ce}$ increases during the AGB evolution; the wiggles in the diagram show the effect of the successive helium shell flashes, which temporarily reduce $T_{\rm ce}$. Also illustrated are the results obtained by us when we used the instantaneous mixing approach (as was customarily done in the past). One sees that the

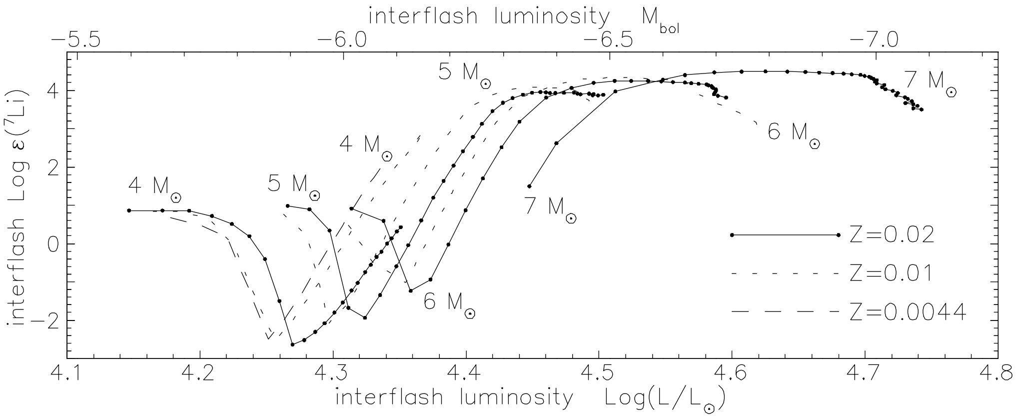

Fig. 2. Lithium abundances in hot bottom burning stars as a function of stellar mass and luminosity, for solar composition ($Z = 0.02$), and for Large and Small Magellanic Cloud compositions ($Z = 0.01$ and 0.0044, respectively).

instantaneous mixing approach results in 9 *orders of magnitude less* ^{7}Li at the star's surface.

Our work showed that the only stars that can create ^{7}Li are in the mass range from ~ 4 to $\sim 7\ M_\odot$; the exact boundaries depend on the chemical composition and the mass loss rate. Figure 2 presents the abunances and the luminosities for our superrich lithium stars. The peak predicted ^{7}Li abundances are $\log \varepsilon(^7\text{Li}) \sim 4$ to 4.6, which is in excellent agreement with the most extreme superrich lithium stars observed (e.g., T Sgr: 4.2 ± 0.5; WX Cyg: 4.7 ± 0.5 [Abia et al. 1991]). The compositions selected for Figure 2 were solar ($Z = 0.02$), Large Magellanic Cloud ($Z = 0.01$), and Small Magellanic Cloud ($Z = 0.0044$). We predict a *narrow luminosity range* in which *superrich lithium stars* can occur, $4.3 \lesssim \log L \lesssim 4.8$, i.e., $-6 \gtrsim M_{\text{bol}} \gtrsim -7.2$. This is in *excellent agreement with the observations* of Smith & Lambert (1989, 1990), who found in the Magellanic Clouds that *all* red giants in the luminosity range $-6 \gtrsim M_{\text{bol}} \gtrsim -7$ are "Li-strong", while *all* red giants in the luminosity range $-5 \gtrsim M_{\text{bol}} \gtrsim -5.5$ and $-7 \gtrsim M_{\text{bol}} \gtrsim -9$ show *no* lithium features. Note that the *peak* ^{7}Li abundance attained is *almost independent of mass and chemical composition*; the timescale for a star to be super lithium rich (i.e., $\log \varepsilon(^7\text{Li}) \gtrsim 3$) is of the order of 10^5 yr for solar composition ($Z = 0.02$), and of the order of a few times 10^4 yr for Population II stars ($Z = 0.001$).

After reaching its peak, the ^{7}Li abundance declines slowly as the ^{3}He fuel is burned up; if hot bottom burning continues long enough, the ^{7}Li abundance approaches a plateau value of $\log \varepsilon(^7\text{Li}) \sim -1.5$, due to reaching nuclear equilibrium of ^{3}He production and destruction at the hot bottom temperature (Boothroyd, Sackmann, & Wasserburg 1994). However, hot bottom burning and the associated ^{7}Li production can also be terminated by mass loss, as discussed below.

3. Mass Loss and Enrichment of the Interstellar Medium

Figure 3*a-c* illustrates the effect of different mass loss rates on ^{7}Li production in 4, 5, and 6 $M_\odot$ stars of solar composition. The abscissa $M_{\rm star}$ decreases monotonically with time (due to the star's mass loss). The wiggles are again due to successive helium shell flashes. We chose this abscissa to illustrate the amount of ^{7}Li-rich matter that is ejected into the interstellar medium.

Figure 3*a* shows that a *modest loss rate* allowed a 4 $M_\odot$ star to become a *superrich lithium star*, but *intermediate* or *extreme* mass loss rates totally *prevented* a 4 $M_\odot$ star from becoming lithium rich. Figures 3*b* and 4*c* demonstrate that stars of mass $\gtrsim 5\,M_\odot$ will *always become superrich lithium stars, independent of the mass loss rate.*

Figure 3 allows one to estimate the ^{7}Li-enrichment of the interstellar medium resulting from hot bottom burning. One must integrate the ^{7}Li abundance as a function of mass lost from the star, which is precisely what Figure 3 provides. The 5 and 6 $M_\odot$ runs have all progressed far enough to provide a reasonably accurate estimate of the amount of ^{7}Li produced (i.e., with an uncertainty of less than a factor of 2). For the 4 $M_\odot$ cases, ^{7}Li is not produced at all except for the standard ($\eta = 1.4$) mass loss rate, where the amount of ^{7}Li produced cannot be estimated with any accuracy; therefore, the 4$M_\odot$ case is not included in Table 2. Results from Boothroyd, Sackmann, & Wasserburg (1994) allow estimation of the ^{7}Li production in a 7 $M_\odot$ star. Note that values of $\eta = 1.4$, 5.0, and 14.0 led to mass loss rates of 3×10^{-6}, 1×10^{-5}, and 3×10^{-5} $M_\odot$/yr, respectively, at the time where the runs were terminated.

TABLE II

^{7}Li Production In Hot Bottom Burning AGB Stars

	η	=	1.4	η	=	5.0	η	=	14.0
Stellar Mass ($M_\odot$)	Peak log ε(Li)	Mean log ε(Li)	$M_{\rm Li}$ (10^{-8} $M_\odot$)	Peak log ε(Li)	Mean log ε(Li)	$M_{\rm Li}$ (10^{-8} $M_\odot$)	Peak log ε(Li)	Mean log ε(Li)	$M_{\rm Li}$ (10^{-8} $M_\odot$)
4	> 3.3	?	?	-1	-0.1[a]	~ 0	-1.5	-0.1[a]	~ 0
5	4.0	3.0	2	4.0	3.7	8	3.0	2.0	0.2
6	4.4	2.7	1.4	4.4	3.2	4	4.35	3.6	10
7	4.5	2.6	1.2	4.5	~ 3.1	~ 3	4.5	~ 3.55	~ 10

[a] For non-lithium-producing cases, the mean AGB ^{7}Li abundance is larger than the peak hot bottom burning ^{7}Li abundance because the mean includes matter lost prior to lithium burning.

We may use the same simple "closed box" model of interstellar ^{7}Li enrichment that was used by Smith & Lambert (1990), to estimate the cosmic ^{7}Li abundance that could result from this AGB ^{7}Li production. Under the assumption that hot bottom burning is the only source of ^{7}Li enrichment (i.e., that all other stars eject only lithium-depleted material), they estimate that the interstellar medium ^{7}Li abundance approaches a lim-

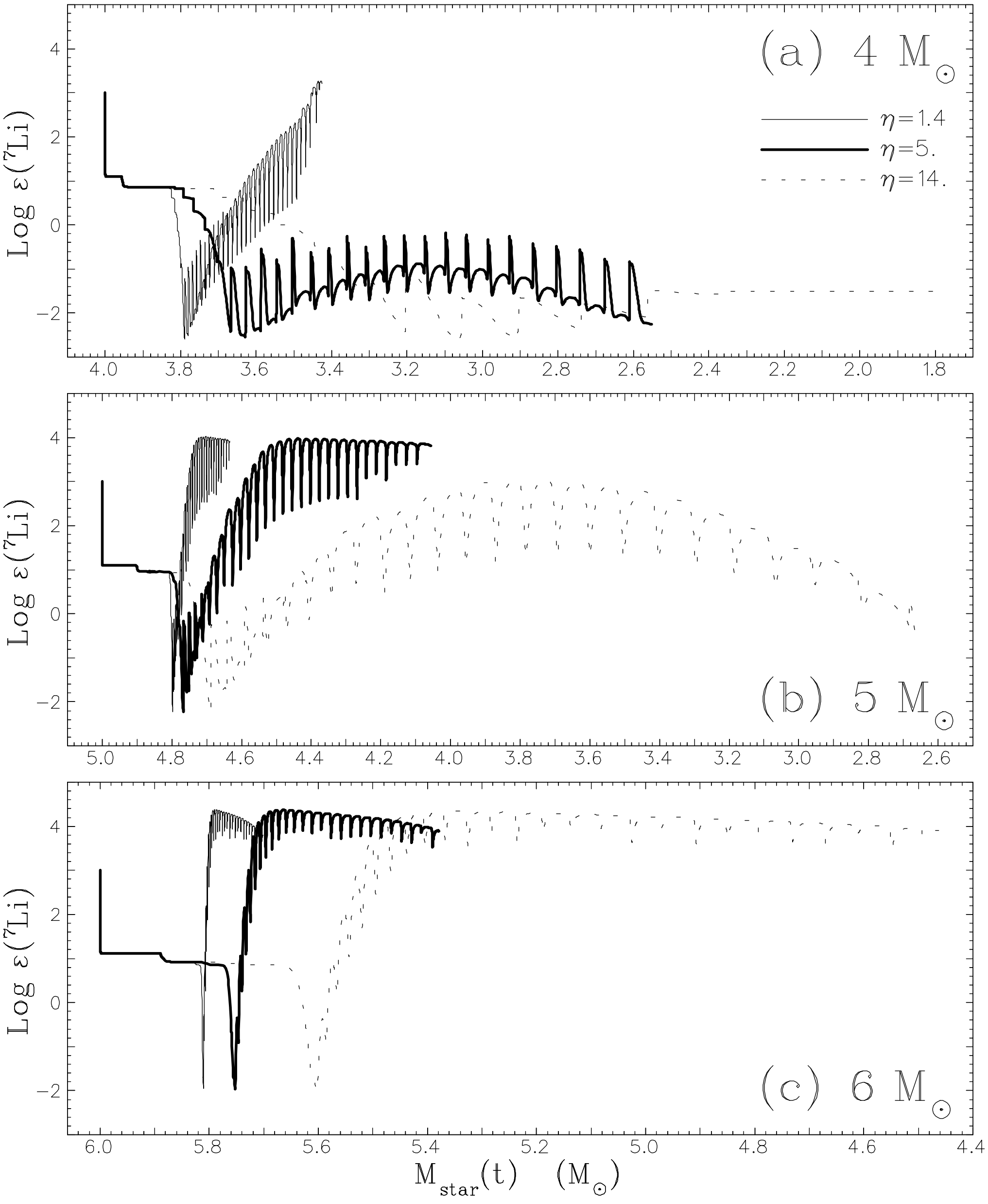

Fig. 3. The effect of different mass loss rates on lithium production in stars of solar metallicity. Three mass loss rates are presented: the standard mass loss rate ($\eta = 1.4$), the intermediate mass loss rate ($\eta = 5$, which may be more appropriate for these stars), and the extreme mass loss rate ($\eta = 14$). Abundances are plotted as a function of the star's mass $M_{\rm star}(t)$, which is being reduced by mass loss, in order to show the amount of lithium-rich material lost by the star. (*a*) For a $4\,M_\odot$ star, intermediate or high mass loss rates prevent lithium production. (*b*) For a $5M_\odot$ star, the extreme mass loss rate turns off lithium production shortly after the star becomes super lithium rich. (*c*) For a $6\,M_\odot$ star, lithium production is essentially independent of the mass loss rate; higher mass loss rates result in larger amounts of lithium-rich material being ejected into the interstellar medium.

iting value given by

$$\varepsilon(^7\mathrm{Li})_{\mathrm{lim}} = 0.25 \frac{\int_{M_{\mathrm{low}}}^{M_{\mathrm{up}}} \varepsilon(^7\mathrm{Li})_{\mathrm{AGB}}(m - w_m)\phi(m)dm}{\int_{4\,M_\odot}^{8\,M_\odot}(m - w_m)\phi(m)dm} ,$$

where $\varepsilon(^7\mathrm{Li})_{\mathrm{AGB}}$ is the average ^{7}Li abundance in the matter lost from a hot bottom burning star, M_{low} and M_{up} give the mass range of stars that encounter hot bottom burning, w_m is the remnant (white dwarf) mass left behind by these stars at the end of their AGB evolution, and $\phi(m)$ is the initial mass function (IMF) giving the relative number of stars that are formed, as a function of stellar mass m. Note that the IMF is a fairly steeply descending function of mass: e.g., one may approximate $\phi(m) \propto m^{-s}$ with $s \sim 2.3$ to 2.5 (Salpeter 1955); thus the upper limit M_{up} (which our models indicate lies somewhere between 7 and 8 $M_\odot$) is less crucial than the lower limit M_{low}, which is a function of the mass loss rate.

For the standard ($\eta = 1.4$) mass loss case, we may estimate $M_{\mathrm{low}} \approx 4 M_\odot$; this results in a value of $\log \varepsilon(^7\mathrm{Li})_{\mathrm{lim}} \sim 2.4 \pm 0.3$, which represents $0.2^{-0.1}_{+0.2}$ of the present cosmic abundance of $\log \varepsilon(^7\mathrm{Li}) \sim 3.1$. (Note that Woosley, Hartman, Hoffman, & Haxton [1990] predict that supernovae are the other major source of ^{7}Li.) For the intermediate mass loss case ($\eta = 5$), which is probably more appropriate to intermediate mass stars, $M_{\mathrm{low}} \sim 4.5\,M_\odot$, but the larger masses of lithium-rich material ejected more than compensate for this, yielding $\log \varepsilon(^7\mathrm{Li})_{\mathrm{lim}} \sim 2.8 \pm 0.3$, which is $0.5^{-0.25}_{+0.5}$ of the present cosmic abundance. Similarly, for the extreme mass loss ($\eta = 14$) case, $M_{\mathrm{low}} \sim 5.5\,M_\odot$ yields $\log \varepsilon(^7\mathrm{Li})_{\mathrm{lim}} \sim 2.8 \pm 0.3$, which again is $0.5^{-0.25}_{+0.5}$ of the cosmic lithium abundance. We thus conclude that a major fraction of the present lithium content of the interstellar medium is the consequence of hot bottom burning and mass loss in intermediate mass AGB stars from ~ 4 to $\sim 7\,M_\odot$.

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