^{7}Li Creation and ^{3}He Destruction in Low Mass Stars

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In low mass stars ($< 2.5M_\odot$), the ^{12}C/^{13}C ratio on the upper red giant branch (RGB) is lower than expected from first dredge-up in standard stellar models; this has been attributed to "extra mixing" induced by rotation, and resulting partial CNO processing of material in the stellar envelope. A simple circulation model of such extra mixing has been constructed; it is shown that ^{7}Li-rich low-mass RGB stars can result. Also, considerable ^{3}He destruction is predicted, counteracting the enrichment from first dredge-up. An estimate of the final ^{3}He abundance as a function of stellar mass and metallicity indicates that stars are net destroyers of ^{3}He. A slight increase is thereby permitted in the inferred upper bound on the primordial (D+^{3}He)/H ratio, yielding a slight reduction in the lower bound on the cosmic baryon density Ω_b from big bang nucleosynthesis calculations.

1. INTRODUCTION

A few subgiants and red giants have recently been observed to have lithium abundances far in excess of the standard predictions [1–3], occasionally having abundances much higher than the present interstellar medium abundance [4–6]. These stars have not yet reached the asymptotic giant branch (AGB), and at least some are observed to be low mass stars; thus they cannot have experienced ^{7}Li creation via hot bottom burning.

Deuterium and ^{3}He are created in the Big Bang; stars burn their initial deuterium to ^{3}He before the main sequence. Low mass stars create ^{3}He pockets in their interior during main sequence burning [7–9], which are subsequently dredged up to the surface on the red giant branch (RGB), and injected into the interstellar medium. This contradicts a requirement of galactic chemical evolution models, namely, that low mass stars must create little or no ^{3}He [9]. Hogan [10] suggested that ^{3}He depletion in low mass stars might result from the *extra deep mixing* below the conventional convective envelope on the RGB, which is generally invoked to explain the anomalously low ^{12}C/^{13}C ratios observed in low mass stars (below the ^{12}C/^{13}C values resulting from first dredge-up).

The following results were obtained in collaboration with I.-Juliana Sackmann (Caltech) and Robert A. Malaney (CITA).

2. RESULTS

Models of "cool bottom processing" (CBP) using a "conveyor-belt" circulation model were computed, guided by stellar evolution models along the RGB [8,11,12]. The depth of circulation (in terms of temperature) was normalized by requiring the ^{12}C/^{13}C ratio

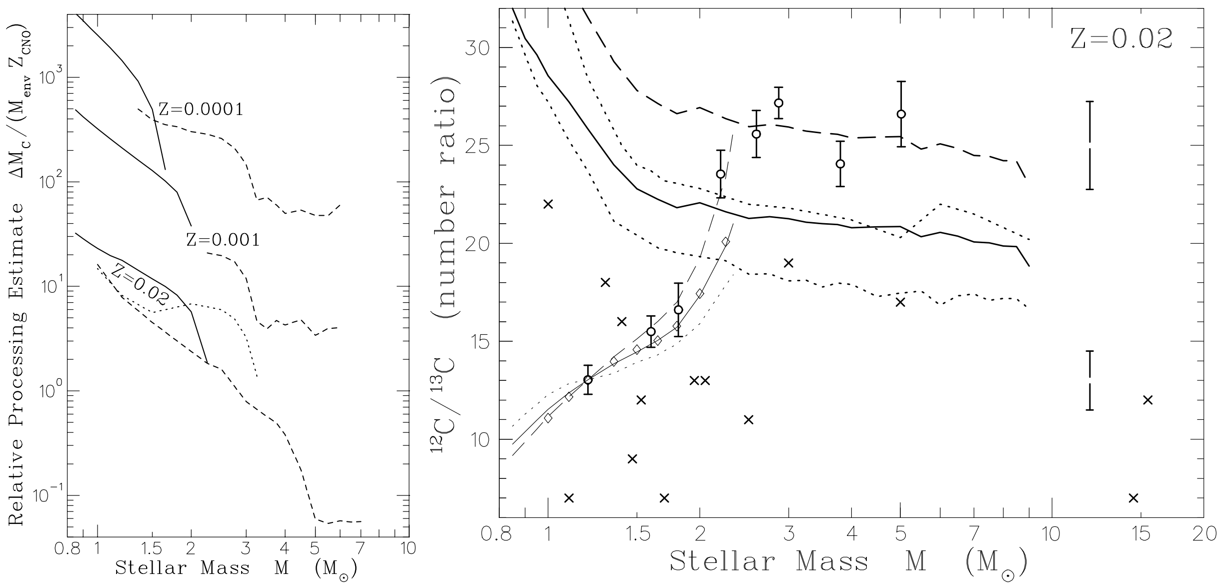

Figure 1. (a) Estimate of relative amounts of CNO cool bottom processing. *Solid lines*: RGB cool bottom processing, *dashed lines*: early AGB, *dotted line*: helium shell flash stage on the AGB (this could be estimated only for the $Z = 0.02$ case).
(b) $^{12}C/^{13}C$ in red giants with $Z = 0.02$. *Open circles*: cluster observations [13], showing uncertainty in the mean from internal dispersion (empty errorbars at right show typical observational uncertainties). *Crosses*: observations of isolated stars [14,15], with stellar masses uncertain by a factor of ~ 2. *Heavy solid line*: theory of first dredge-up (present work); *dotted lines* give approximate range of theoretical predictions (see [11]). A better match to observations for masses $> 2.5\,M_\odot$ would be obtained if the ^{13}C pocket were slightly smaller than theory predicts (*heavy dashed line*). *Light solid*, *dashed*, and *dotted* lines indicate predicted CBP results, using the relative estimate of (a) and normalizing by the observations at $1.2\,M_\odot$; for the solid line, *diamonds* show full CBP model results.

to match the mean observed value at $1.2\,M_\odot$; the speed of circulation was given by the mass flow rate $\dot{M}_P$ (in $M_\odot$/yr), various reasonable values being used. A case where the downward flow was narrow and fast relative to the upward flow was also tested (ratio $f = 9$, rather than unity); this affects only ^{7}Li.

Figure 1a shows an estimate of the relative extent of CBP for CNO isotopes during the RGB and AGB, as a function of stellar mass and metallicity; this should be proportional to the advance ΔM_C of the core mass (which gives the amount of hydrogen burned) multiplied by the amount of CNO isotopes relative to hydrogen (roughly, $1/Z$) and divided by the envelope mass $M_{\rm env}$ (giving the amount of dilution of processed material) [12]. Figure 1b shows the $^{12}C/^{13}C$ from first and second dredge-up, and from CBP due to extra mixing, with the extent of CBP normalized by the observations for $1.2\,M_\odot$ stars. The trend of the observations is relatively well fitted by the CBP models, and the above CBP estimate is not much less accurate than the full CBP models.

Figure 2 shows the evolution of relevant isotopes on the RGB for the $1\,M_\odot$ full CBP

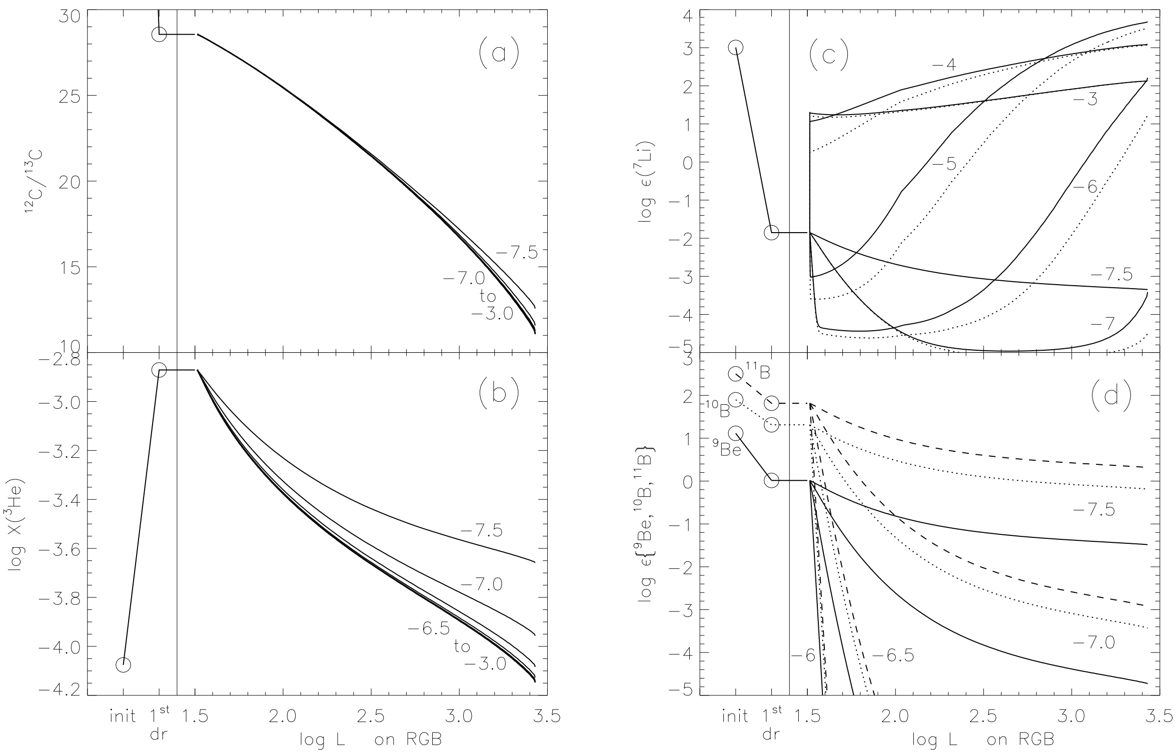

Figure 2. 1 $M_\odot$ cool bottom processing models as a function of luminosity on the RGB, for (a) ^{12}C/^{13}C, (b) ^{3}He, (c) ^{7}Li (*dotted lines* have geometry factor $f = 9$), and (d) ^{9}Be (*solid*), ^{10}B (*dotted*), and ^{10}B (*dashed*). Initial and first-dredge-up values are shown by circles at left in each case. The log of the mass mixing rate $\dot{M}_P$ (in $M_\odot$/yr) is indicated next to the curves.

models. Evolution of the CNO isotopes and ^{3}He is almost independent of the mass mixing rate $\dot{M}_P$, except at the very lowest mixing rates; the ^{3}He enhancement from first dredge-up is destroyed again by CBP. The ^{9}Be, ^{10}B, and ^{11}B isotopes are destroyed almost immediately, except at very low mixing rates. Very large ^{7}Li abundances can be generated via the Cameron-Fowler mechanism, but the results depend very strongly on the mixing rate; variation in the mixing rate, or episodic mixing, could yield brief periods of high ^{7}Li abundances [8], as expected from observations.

Figure 3 shows the ^{3}He abundances expected from CBP as a function of stellar mass and metallicity, and some chemical evolution models of (D + ^{3}He), similar to those of Vangioni-Flam et al. [16], that fit observational constraints from other isotopes [17]. The maximum allowed primordial (D + ^{3}He)/H ~ 0.00012 is less than a factor of 3 larger than its present value; using models with more extensive CBP yields relatively little change in this. At most, the primordial (D + ^{3}He)/H value may be about 20% higher than the value assumed in most recent chemical evolution models (where the ad hoc assumption is generally made that low mass stars neither create nor destroy ^{3}He [9,17]).

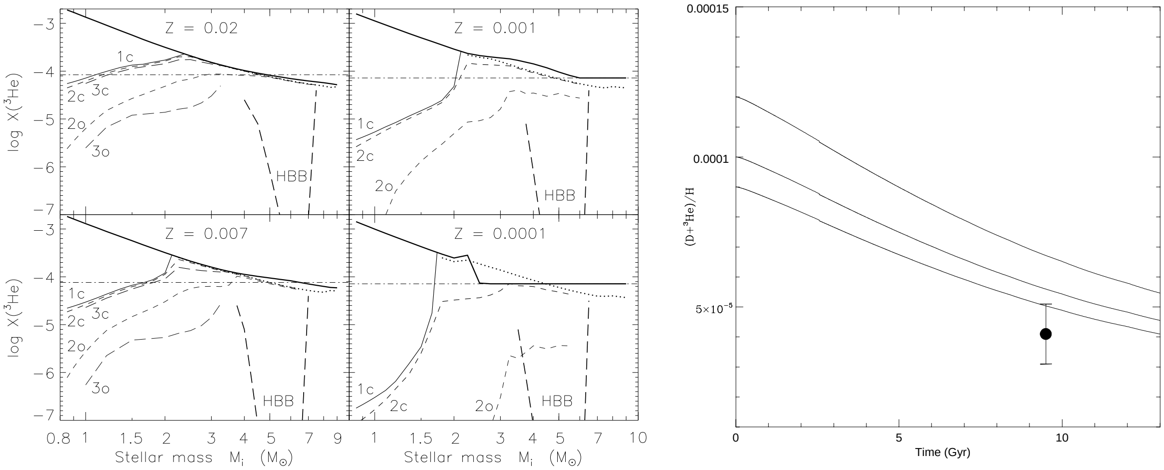

Figure 3. (a) Predicted ^{3}He abundances. *Heavy solid* and *dotted lines*: first and second dredge-up; *lines* 1c, 2c, and 3c: from CBP on the RGB, early AGB, and the shell flash stage of the AGB (normalization from observed RGB ^{12}C/^{13}C); *lines* 2o and 3o: same as 2c and 3c, but normalized by observed ^{18}O depletion on the AGB; line HBB: effects of hot bottom burning on the AGB. *Dotdashed line*: initial ^{3}He abundance.
(b) Galactic chemical evolution models of (D + ^{3}He), using ^{3}He depletion factors lying between curves 2c and 2o of (a), starting from primordial (D + ^{3}He)/H = 0.00012, 0.0001, and 0.00009. The point with (1-σ) errorbars is the solar system value.

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