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CONVECTIVE MIXING LENGTH AND THE GALACTIC CARBON TO OXYGEN RATIO

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RESUMEN

Hemos desarrollado modelos de evolución química de galaxias, suponiendo reciclaje instantáneo y considerando: a) los efectos de la pérdida de masa, tanto en estrellas masivas como en estrellas de masa intermedia, y b) la función inicial de masa de la vecindad solar (Serrano 1978). De estos modelos hemos derivado los rendimientos del carbono y del oxígeno. Nuestros resultados indican que la condición C/O ~ 0.58 en la vecindad solar sólo puede ser satisfecha si la razón entre la longitud convectiva de mezcla y la escala de presión es $\gtrsim 2$ durante etapas avanzadas de la evolución estelar en estrellas de masa intermedia.

ABSTRACT

We have studied chemical evolution models, assuming instantaneous recycling, and considering: a) the effects of mass loss both in massive stars and in intermediate mass stars, and b) the initial mass function of the solar neighborhood (Serrano 1978). From these models we have derived the yields of carbon and oxygen. It is concluded that the condition C/O ~ 0.58 in the solar neighborhood can only be satisfied if, during advanced stages of stellar evolution of intermediate mass stars, the ratio of the convective mixing length to the pressure scale height is $\gtrsim 2$.

Key words: GALAXIES-CHEMICAL EVOLUTION – GALAXIES-STELLAR CONTENT

I. INTRODUCTION

Serrano and Peimbert (1981*a*, hereinafter Paper I) have discussed the production of helium in chemical evolution models of galaxies. This helium production was found to be sensitive to certain aspects of stellar evolution. Hence, constraints on the stellar models can be imposed by the observed helium to heavy element enrichment ratio, $\Delta Y/\Delta Z$.

An independent observational constraint on models of chemical evolution is the C/O ratio. In this paper, following the same approach as in Paper I, we study the carbon production (§ II) and discuss the constraints imposed by the observed C/O ratio on stellar models (§ III).

II. CARBON PRODUCTION

a) *Massive Stars*

Arnett (1972) finds that, due to the effect of neutrino emission, the size of the carbon-exhausted core in massive stars ($m \gtrsim 10\ M_\odot$) is small. This "core convergence" implies that carbon formed during helium burning is not immediately destroyed and might survive ejection from the star. In this way massive stars are suggested as sources of C and O.

We have adopted, for stars with $m \gtrsim 10\ M_\odot$, Arnett's (1978) results on the evolution of helium stars. From them we have obtained the mass ejected in the form of carbon, $m_c(m_\alpha)$, as a function of the helium core mass, m_α. As discussed by Chiosi *et al.* (1978) and by Chiosi and Caimmi (1979), the effect of mass loss during core hydrogen and helium phases is to decrease the mass of m_α with respect to a star of the same initial mass without mass loss. Lequeux *et al.* (1979) have shown that the heavy element yield derived from observations of irregular and blue compact galaxies implies models of massive stars with large mass loss rates. Consequently, we have adopted the same $m_\alpha(m)$ relationship as in Paper I, which is similar, for $m > 20\ M_\odot$, to that used by Chiosi and Caimmi (1979).

b) *Intermediate Mass Stars*

It is now well established that the intershell region of thermally pulsating stars, where incomplete helium burning has taken place, is an important site of carbon production (Iben 1975; Iben and Truran 1978). Following Iben and Truran's work, Renzini and Voli (1981) have calculated the advanced evolution of intermediate mass stars ($1 \lesssim m/M_\odot \lesssim 8$) taking into account H burning that occurs in the deepest layer of the convective envelope. They find that H burning, and the associated carbon depletion, is strongly sensitive to the ratio a of the convective mixing length, ℓ, to the pressure scale height, H_P:

$$a = \ell/H_P . \quad (1)$$

TABLE 1

COEFFICIENTS OF THE MASS OF NEWLY FORMED CARBON WHICH IS EJECTED, AS DEFINED IN EQUATION (2)

Mass range ($M_\odot$)			Polynomial coefficients				
m_0	m_1	$a = \ell/H_P$	b_0	b_1	b_2	b_3	b_4
0.8	2	0-2	−15.844	51.623	− 55.75	19.972	...
1.5	4.8	0-1					
1.5	4	1.5	81.825	−100.590	20.31	7.818	...
1.5	3.3	2					
4	4.8	1.5	1706.402	−507.377	20.31	7.818	...
3.3	4.8	2	1854.754	−639.399	20.31	7.818	...
4.8	8	0	677.880	104.160	− 10.69	...	...
4.8	8	1	−4207.204	3814.130	−1062.705	132.007	− 6.185
4.8	8	1.5	13401.880	−5439.340	737.98	− 33.389	...
4.8	8	2	2673.280	−1106.940	154.09	− 7.1615	...

We have approximated Renzini and Voli's (1981) results on carbon production by polynomials of the form

$$m_c = \sum_{i=0} b_i \, m^i \tag{2}$$

The coefficients b_i, for various values of a and different mass ranges, are presented in Table 1. It must be stressed that m_c in equation (2) is partly ejected in the stellar wind during the asymptotic giant branch evolution, and partly ejected in a rapid ejection phase of the stellar envelope, like the planetary nebulae formation.

To get an idea of the efficiency of the third dredge-up and of the effects of varying a for carbon production, we present in Figure 1, for each initial mass m, the fraction of the star ejected as newly formed carbon:

$$f_c = m_c/m \tag{3}$$

Notice that if hot-bottom burning is not present, stars with $\simeq 5\, M_\odot$ are the most efficient carbon producers with $\sim 2\%$ of the stellar mass in the form of carbon. Increasing a, the temperature at the base of the convective envelope increases and hot-botton burning becomes important. This shows up in Figure 1 by a decrease of f_c for the higher masses as a increases.

III. DISCUSSION

It can easily be shown (see e.g., Paper I) that, assuming instantaneous recycling, the carbon to oxygen ratio by mass is given by

$$X_c/X_o = \left\{ \langle f_c(1\text{-}8) \rangle + \langle f_c(>8) \rangle \right\} / \langle f_o \rangle , \tag{4}$$

where

$$\langle f_c \rangle = \int f_c \, \Phi \, dm \quad . \tag{5}$$

In this case $\langle f_c\ (1\text{-}8) \rangle$ and $\langle f_c\ (>8) \rangle$ represent the carbon contribution due to intermediate mass and massive stars, respectively, f_o corresponds to oxygen, $\Phi(m)$ is the initial mass function by mass (IMF), usually expressed as

$$\Phi \propto m^{-x} , \tag{6}$$

which obeys the normalization condition

$$\int \Phi \, dm = 1 \ . \tag{7}$$

Very often Salpeter's (1955) IMF, with $x \simeq 1.35$, has been used. However, recent determinations of the IMF in the solar neighborhood (Serrano 1978; Lequeux 1979; Miller and Scalo 1979) indicate a steeper IMF in the large mass range with $x \simeq 2$. Thus, as in Paper I, we have adopted Serrano's (1978) IMF

$$\Phi = \begin{cases} 0.56 \, m^{-2} , & m > 1.8\, M_\odot \\ 0.25 \ m^{-0.6} , & m < 1.8\, M_\odot \ . \end{cases} \tag{8}$$

In Figure 1, we present the carbon fractions, f_c, for different masses and for various values of a. In Figure 2 we present the carbon fraction weighted by the IMF, $f_c\Phi$. The area under the curve in Figure 2 directly represents the fraction of an average stellar mass, per generation of stars, ejected as newly formed carbon, in the $1 < m/M_\odot < 8$ range, $\langle f_c\ (1\text{-}8) \rangle$.

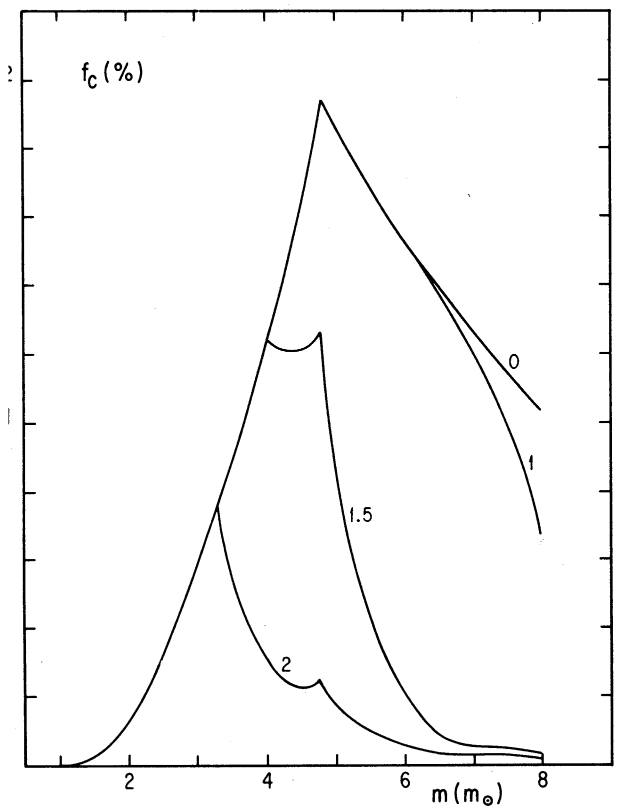

Fig. 1. Fraction, f_c, of the mass of a star which is ejected as newly formed carbon as a function of initial stellar mass. Curves are labeled by the ratio of the mixing length to the pressure scale height.

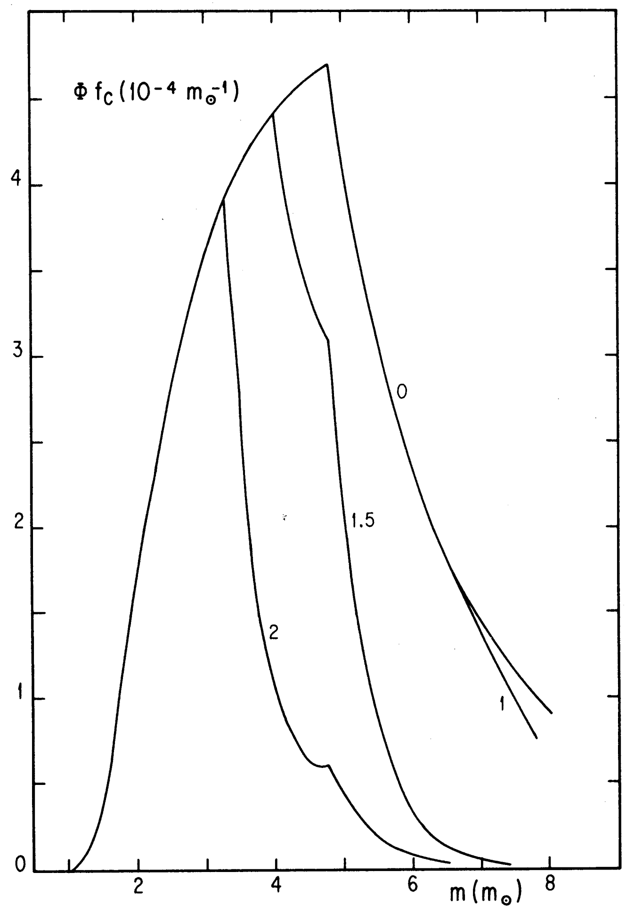

Fig. 2. Weighted fraction of the newly formed carbon, $f_c \Phi$, as a function of initial stellar mass. The area under the curve gives the fraction of an average stellar mass, in a generation of stars, which is ejected as newly formed carbon, in the $1 \leq m/M_\odot \leq 8$ range, $\langle f_c (1\text{-}8) \rangle$. Curves are labeled as in Figure 1.

We have computed the $\langle f \rangle$ values from the IMF given in equation (8); for $\langle f_c (1\text{-}8) \rangle$ we have used m_c and the coefficients b_i from Table 1, while for $\langle f_c(>8) \rangle$ and $\langle f_o \rangle$ we have used Arnett's results. In Table 2 we present the derived values of C/O (by number).

If we compare the values in Table 2 with the observed value

$$(C/O)_{obs} \cong 0.58$$

TABLE 2

MODEL C/O FOR DIFFERENT VALUES OF a

$a = \ell/H_P$	C/O*
0	0.95
1	0.95
1.5	0.71
2	0.53

* Total C/O ratio by number. The contribution of C (> 8)/O is 0.25 in these units.

of the Orion Nebula and the Sun (Peimbert and Torres-Peimbert 1977; Lambert 1978), it is quite clear that there is overproduction of Carbon with respect to Oxygen unless the mixing length ℓ is greater than twice the pressure scale height, H_p.

An independent argument in this direction comes from an analysis of the relation between N/O and He/H ratios in planetary nebulae. Peimbert and Serrano (1980) have argued that planetary nebulae of Type I (those with $|N/O|>0$ and He/H $\gtrsim 0.125$) come from stars with initial masses greater than $\sim 2.5\ M_\odot$. In Table 3 we present the minimum mass giving rise to planetary nebulae of Type I, taken from Renzini and Voli's models (their Figure 10). Again, a value of $a \gtrsim 2$ is needed for consistency with observations.

The results presented here are based on a large number of uncertain assumptions and there may be other alternatives to avoid overproduction of carbon. A more detailed analysis of this problem, without the instanta-

TABLE 3

MINIMUM MASS REQUIRED TO PRODUCE PLANETARY NEBULAE OF TYPE I*

$a = \ell/H_p$	m_{min} ($M_\odot$)
0	...
1	7.4
1.5	4.3
2	3.4

* From models by Renzini and Voli (1981).

neous recycling approximation and considering also the abundances of N and Ne, will be given elsewhere (Serrano and Peimbert 1981*b*).

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