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ON THE CARBON ENRICHMENT OF THE INTERSTELLAR MEDIUM

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RESUMEN

Se presenta una evaluación de las contribuciones al enriquecimiento de ^{12}C y ^{13}C en el medio interestelar debidas a novas, estrellas de masa intermedia y estrellas masivas. De dicha evaluación se obtiene que: a) las novas contribuyen de manera significativa a la abundancia de ^{13}C pero no a la de ^{12}C; b) para los modelos de estrellas de masa intermedia, es posible estimar límites para el cociente de la longitud de mezclado sobre la escala de presión, α, y para el parámetro de pérdida de masa, η; c) las estrellas de masa intermedia son las principales enriquecedoras de ^{12}C y ^{13}C en el medio interestelar; d) el cociente ^{12}C/^{13}C para la vecindad solar es más fácilmente explicable que el correspondiente al sistema solar; y e) la masa expulsada por cada explosión de nova tiene que ser $\sim 1 \times 10^{-5}$ $M_\odot$ para poder explicar el cociente ^{12}C/^{13}C en el medio interestelar.

ABSTRACT

The contribution of novae, IMS, and massive stars to the ^{12}C and ^{13}C enrichment of the interstellar medium is evaluated. The following results are obtained: a) novae are not important contributors to the ^{12}C abundance but contribute significantly to ^{13}C, b) limits to the ratio of the mixing length to the pressure scale height, α, and to the mass loss rate paramter, η, are derived for IMS, c) IMS are the main contributors to the ^{12}C and ^{13}C enrichment of the interstellar medium, d) it is easier to explain the solar vicinity ^{12}C/^{13}C ratio than the solar system ratio, e) to explain the ^{12}C/^{13}C ratio in the ISM the mass ejected per nova outburst has to be $\sim 1 \times 10^{-5}$ $M_\odot$

Key words: STARS-NOVAE – GALAXIES-EVOLUTION – INTERSTELLAR-ABUNDANCES

I. INTRODUCTION

The interstellar and the solar C/H and ^{12}C/^{13}C ratios provide important constraints for the study of the chemical evolution of galaxies. It has been suggested in the literature that supernovae of Type II (massive stars, MS), planetary nebulae (intermediate mass stars, IMS), and novae contribute to the interstellar enrichment of ^{12}C and ^{13}C. It is the purpose of this paper to explore the relative importance that these three types of objects have on the enrichment of C in the interstellar medium, ISM.

We did not consider SN of Type I as sources of C production since carbon deflagration models produce very high Fe/C ratios that even if these objects were responsible for all of the Fe in the solar vicinity their contribution to the C abundances would be negligible (Nomoto 1984; Woosley *et al.* 1984; Mallik and Mallik 1985).

In paper I (Peimbert and Sarmiento 1984) we found that novae are about twenty times less important than planetary nebulae (PN) for the ISM enrichment of ^{14}N; moreover we estimated that the mass ejected per nova outburst is $\sim 10^{-5}$ $M_\odot$, this result as well as some of the arguments presented in paper I will be used in this paper.

There are many factors that influence the C enrichment of the ISM and most of them are not well known. For the three types of objects responsible for the C enrichment we need to know their formation rates as well as the mass and chemical composition of their ejecta. In §II we discuss some of the observational data relevant to this paper. In §III we evaluate the ^{12}C/^{13}C value in the ejecta of a generation of IMS. In §IV we evaluate the relative C enrichment of the ISM due to MS and to IMS. In §V we estimate the contribution of novae, IMS and MS to the ^{12}C and ^{13}C values of the ISM. The discussion and conclusions are presented in §VI.

II. OBSERVATIONAL DATA

In Table 1 we present the chemical abundances that will be used as constraints throughout this paper. The value of ^{12}C/^{13}C for the solar system was obtained from meteorites (Boato 1954) and is in very good agreement with the value of 90 ± 15 obtained from CO solar observations (Hall, Noyes, and Ayres 1972).

The ^{12}C/^{13}C value by Hawkins, Jura, and Meyer (1984, 1985) was obtained from visual observations of CH$^+$ and is in good agreement with values derived from radiobservations of other molecules (*e.g.*, Wannier 1980).

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TABLE 1

OBSERVED CHEMICAL ABUNDANCES

Object	$^{12}C/^{13}C^a$	C/H^b	N/H^b	O/H^b	Reference^c
Sun	89 ± 2	8.67	7.99	8.92	1,2
Solar Vicinity	43 ± 5	–	...	...	3
Orion	...	8.52	7.65	8.62	4,5
⟨H II⟩ LMC	...	7.86	7.03	8.34	6,7,8
⟨H II⟩ SMC	...	7.00	6.41	7.89	7,8,9
NGC 2363	...	7.39	6.44	7.92	10
Planetary Nebulae II	...	8.8	8.4	8.7	11
Planetary Nebulae I	...	8.9	9.0	8.8	11
Novae	...	10.1	10.3	10.1	12

a. Given in $N(^{12}C)/N(^{13}C)$;

b. Given in log N(A)/N(H) + 12;

c. References: 1) Boato 1954; 2) Lambert 1978; 3) Hawkins *et al.* 1984, 1985; 4) Peimbert and Torres-Peimbert 1977; 5) Torres-Peimbert, Peimbert, and Daltabuit 1980; 6) Peimbert and Torres-Peimbert 1974; 7) Lequeux *et al.* 1979; 8) Dufour *et al.* 1982; 9) Peimbert and Torres-Peimbert 1976; 10) Peimbert *et al.* 1985; 11) Peimbert 1982; 12) Williams 1982.

The accuracy for the photospheric solar values is about 0.08 dex. Typical errors for the O/H ratio in H II regions and PN are in the 0.04 to 0.1 dex range. Typical errors for the C/H ratio in H II regions and PN are in the 0.1 to 0.2 dex range. The accuracy of the N/H determinations is inbetween those of C/H and O/H. The novae abundances vary considerably from object to object and those presented in Table 1 are an average of six objects.

III. THE $^{12}C/^{13}C$ RATIO IN IMS

To compare the observations with theoretical predictions we need to adopt an initial mass function, IMF, and a set of stellar evolution models for stars of different masses. The adopted IMF, by mass, is given by (Serrano 1978)

$$\phi = \begin{cases} 0.56\, m^{-2} & 110 \geqslant m \geqslant 1.8\, m_\odot \\ 0.25\, m^{-0.6} & 0.007 \geqslant m \geqslant 1.8\, m_\odot \end{cases} , \tag{1}$$

and has been normalized by

$$\int_{0.007}^{110} \phi(m)\, dm = 1 \quad , \tag{2}$$

where the lower end of the IMF has been chosen according to the work of Low and Lynden-Bell (1976) and Kumar (1972).

To estimate the relative enrichment of ^{12}C and ^{13}C by IMS we will introduce the quantity *b* given by

$$b = \frac{\langle f(^{12}\Delta) \rangle_{IMS}}{\langle f(^{13}C) \rangle_{IMS}} \; ; \tag{3}$$

where $\langle f(^{12}C) \rangle$ is the mass fraction that a generation of stars in the mass interval m_j-m_k ejects as newly formed ^{12}C and is given by

$$\langle f(^{12}C) \rangle = \int_{m_j}^{m_k} f(^{12}C)\, \phi(m)\, dm \quad , \tag{4}$$

and $f(^{12}C)$ is the stellar mass fraction ejected as newly formed ^{12}C. According to the currently accepted mass range for IMS, we have set $m_j = 1\ M_\odot$ and have left m_k as a free parameter in Figure 1.

For IMS we will use the models by Renzini and Voli (1981) which were computed for various values of α and η; α is the ratio of the mixing lenght to the pressure scale height and η gives the mass loss rate during the asymp-

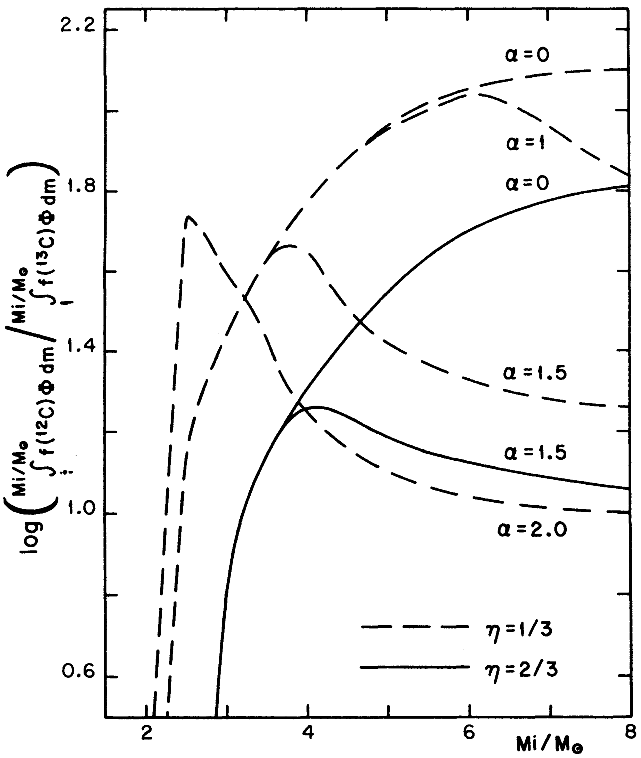

Fig. 1. *b* values due to a generation of stars in the 1 $M_\odot \leqslant M \leqslant M_i$ range as a function of the initial mass M_i and for different values of the mass loss parameter, η, and the ratio of the mixing length to the pressure scale height, α. Values derived from Case A of Renzini and Voli (1981) with Y = 0.28, Z = 0.02; $\alpha = 0$ means no hot-bottom nuclear burning.

totic giant branch when it is multiplied by the Reimers' (1975) rate. By comparing the predicted He/H, C/O and N/O values by Renzini and Voli with the observed values of Type I PN it is found that $1 \leqslant \alpha \leqslant 2$ and that $\eta \gtrsim 1/3$ (*e.g.*, Peimbert 1985).

In Figure 1 we present log *b* as a function of the highest initial mass adopted for IMS from the computations by Renzini and Voli (1981) and Renzini (1984) for different values of α and η and the IMF given by equation (1).

The very large C overabundances observed in halo planetary nebulae (*e.g.*, Torres-Peimbert 1984; Adams *et al.* 1984), planetary nebulae of Types I and II (*e.g.*, Peimbert 1981) and the discussion by Iben and Renzini (1982), arguing that the third dredge up occurs in objects of smaller mass than considered by Renzini and Voli (1981), imply that $\langle f(^{12}C) \rangle_{IMS}$ should be larger than predicted and that the values of *b* presented in Figure 1 probably correspond to lower limits if one assumes that the changes required in the models to produce agreement on ^{12}C abundances with observations do not change the ^{13}C production.

IV. ^{12}C ENRICHMENT BY MS AND IMS

To estimate the ^{12}C relative enrichment due to MS and IMS we will introduce the quantity *d* given by

$$d = \frac{\langle f(^{12}C) \rangle_{MS}}{\langle f(^{12}C) \rangle_{IMS}} \quad , \qquad (5)$$

in what follows we will discuss four determinations of *d*.

a) *The C/O Ratio.*

A representative C/O value for the solar system and the solar vicinity is 0.67 ± 0.15 (see Table 1). Dufour, Shields, and Talbot (1982) have found that for H II regions in the SMC $C/O = 0.13 \pm 0.03$. Alternatively Peimbert, Peña, and Torres-Peimbert (1985) obtained for NGC 2363, a giant H II region in NGC 2366 with similar N/H and O/H values to those of the SMC H II regions, a value of $C/O = 0.30 \pm 0.06$. By assuming that the IMF is the same in the solar vicinity and in NGC 2363, the C/O difference can only be explained as an age effect in the sense that the stellar population in NGC 2363 is younger on the average than that of the solar vicinity and that most of the C enrichment is due to stars with $m_i < 3\ m_\odot$; that is, stars with $m_i > 8\ m_\odot$ produce at most a C/O value of 0.30 and stars with $m_i < 8\ m_\odot$ produce at least the rest of the observed C/O value. From this discussion it follows that $d \leqslant 0.81$. Under the same assumption for the IMF the C/O value of the SMC implies that an even larger fraction of the C/O ratio than estimated above is due to IMS and consequently that *d* is even smaller.

Serrano and Peimbert (1981) computed chemical evolution models of the solar vicinity based on: i) the IMF by Serrano (1978), ii) the stellar evolution models for helium stars by Arnett (1978) for objects with $m \gtrsim 10\ m_\odot$, iii) the stellar evolution models by Renzini and Voli (1981) for objects with $1 \leqslant m/m_\odot \leqslant 8$, and iv) instant recycling for C and O. In these models O is produced only by stars with $m_i \geqslant 10\ m_\odot$. Serrano and Peimbert obtain that the C produced by stars with $m_i \geqslant 10\ m_\odot$ amounts to a C/O value of 0.25; while the C produced by IMS for $\eta = 1/3$ and α in the 0-2 range amounts to a C/O value in the 0.70-0.28 range, which corresponds to $0.36 \leqslant d \leqslant 0.89$, again a *d* value smaller than one. The result by Serrano and Peimbert depends on the assumed relation between the initial stellar mass M and the mass of the helium core M_α; different C/O values to that of Serrano and Peimbert can be obtained by adopting Arnett's (1978) relation without mass loss which gives $C/O = 0.23$, or by adopting the $M(M_\alpha)$ relation of Chiosi and Caimmi (1979) which gives a somewhat higher value for C/O. However, according to Maeder (1981) the $M(M_\alpha)$ relation undergoes no great change with mass loss when account is taken of the outwards motion of the H-shell during the He-burning phase. This last result favors C/O values around 0.25.

The recent increase in the estimated $^{12}C(\alpha, \gamma)^{16}O$ rate by a factor of five (e.g., Trautvetter *et al.* 1984, Arnett and Thielemann 1984) would reduce the C/O ratio predicted from the models by Arnett (1978) and consequently the C/O value estimated by Serrano and Peimbert (1981) for stars with $m \gtrsim 10\ m_\odot$. Therefore the *d* value determined in the previous paragraph would be reduced accordingly.

From the computations by Arnett and Thielemann (1984) for a single star with an 8 $M_\odot$ He-core, corresponding to a 20-25 $M_\odot$ star, with the $^{12}C(\alpha, \gamma)^{16}O$ reaction rate increased by a factor of five it is found that $C_{MS}/O_{MS} = 0.376\ (C/O)_\odot$, therefore $(C_{IMS} + C_N)/O_{MS} = 0.624\ (C/O)_\odot$ and $C_{MS}/(C_{IMS} + C_N) = 0.376/0.624 = 0.60$; consequently $d > 0.60$, but since $^{12}C_N$ is negligible in comparison with $^{12}C_{IMS}$ (see §V) it follows that $d = 0.6$. This result would apply if the C production by massive stars can be represented by the single model considered by Arnett and Thielemann.

It should be noted that the change in the $^{12}C(\alpha, \gamma)^{16}O$ reaction rate affects the C production by SN but not by novae since in these objects the temperature does not become high enough for this reaction to occur.

b) *The C/H value or the carbon yield.*

It is also possible to determine *d* from the C/H observed value through the carbon yield.

The heavy element yield is defined by

$$p(Z) = \langle f(Z) \rangle / A \quad ; \qquad (6)$$

where $\langle f(Z) \rangle$ is the mass fraction that a generation of stars ejects as newly formed metals and A is the mass fraction of that generation that remains locked in stellar remnants and long-lived stars, where we include the low mass end of the IMF which might comprise objects that do not become stars. A is given by

$$A = \int_{0.007}^{110} (m_r/m)\, \phi(m)\, dm \ , \qquad (7)$$

where m_r is the remnant mass. A similar equation to (6) is

$$p(^{12}C) = \langle f(^{12}C) \rangle / A \ . \qquad (8)$$

From stellar evolution models and a given IMF it is possible to compute $\langle f(^{12}C) \rangle$ and A. Alternatively from models of galactic chemical evolution and the observed C/H ratios in H II regions it is possible to determine $p(^{12}C)$.

To explain the chemical composition of galactic and extragalactic H II regions Peimbert and Serrano (1982) proposed a heavy element yield given by

$$p(Z) = 0.002 + 0.6\, Z \ . \qquad (9)$$

The Z determination was obtained from the O/H values and under the assumption that O constitutes 45% of the Z value; that is, what Peimbert and Serrano really found was that

$$p(^{16}O) = 9 \times 10^{-4} + 0.6\, X_{16} \ , \qquad (10)$$

where X_{16} is the O mass fraction.

From the C abundances presented in Table 1 and following Peimbert and Serrano it can be shown that $p(^{12}C)$ increases with C/H, for simplicity we will assume a relation similar to that for $p(^{16}O)$, i.e.

$$p(^{12}C) = p_0(^{12}C) + 0.6\, X_{12}$$

$$= 2 \times 10^{-4} + 0.6\, X_{12} \ , \qquad (11)$$

where the value of $p_0(^{12}C)$ was estimated from the C/O value in NGC 2363 such that $p(^{12}C)/p(^{16}O) = X_{12}/X_{16}$.

In Table 2 we present $p(^{12}C)$, $p(^{12}C)/p(^{16}O)$ and X_{12}/X_{16} from the C/H and O/H values presented in Table 1 and equations (10) and (11) where it has been assumed that X = 0.70 for Orion and the Sun and X = 0.75 for the SMC, NGC 2363 and the LMC (e.g., Peimbert and Torres-Peimbert 1977; Lequeux *et al.* 1979; Peimbert *et al.* 1985). The increase in the $p(^{12}C)/p(^{16}O)$ ratio with $p(^{12}C)$ could be due to: changes in the IMF or changes in the stellar evolution and mass loss history due to the increased heavy element abundance or to an increase in the average age of the stellar population.

TABLE 2

CARBON YIELDS AND X_{12}/X_{16} RATIOS

Object	$p(^{12}C)$	$p(^{12}C)/p(^{16}O)$	X_{12}/X_{16}
SMC	2.54×10^{-4}	0.17	0.096
NGC 2363	3.33×10^{-4}	0.22	0.22
LMC	5.91×10^{-4}	0.24	0.25
Orion	1.87×10^{-3}	0.51	0.59
Sun	2.56×10^{-3}	0.40	0.42

Renzini and Voli (1981) carried out extensive computations for IMS with Z = 0.02 which is representative of the solar vicinity. We will consider as a representative $p(^{12}C)$ value of the solar vicinity the average of the values for Orion and the Sun i.e. $p(^{12}C) = 2.22 \times 10^{-3}$. We will compare the ^{12}C yield with the computations by Renzini and Voli under the assumption of instant recycling. Equation (8) can be expressed as

$$A\, p(^{12}C) = \int_{1}^{8} f(^{12}C)\, \phi(m)\, dm +$$

$$+ \int_{8}^{110} f(^{12}C)\, \phi(m)\, dm$$

$$= \langle f(^{12}C) \rangle_{IMS} + \langle f(^{12}C) \rangle_{MS} \ ; \qquad (12)$$

where it has been assumed that stars with masses smaller than one solar mass do no contribute to $\langle f(^{12}C) \rangle$. From equation (5) and (12) we obtain

$$d = \frac{A\, p(^{12}C) - \langle f(^{12}C) \rangle_{IMS}}{\langle f(^{12}C) \rangle_{IMS}} \ , \qquad (13)$$

therefore it is possible to estimate *d* without directly evaluating the contribution by MS to the ^{12}C enrichment.

To compute A from equation (7) we can divide the integration in three parts: i) from 0.007 to 1 $m_\odot$ we will assume that the stars have not had time to leave the main sequence and that they have not lost mass, i.e. $m_r/m = 1$, these objects contribute to A with 0.54; ii) from 1 to 8 $m_\odot$ we will assume the m_r/m relationship by Renzini and Voli (1981), these stars contribute to A with 0.16, iii) finally the fraction of the mass that goes into stars more massive than 8 $m_\odot$ is only 0.06; it is not well known which is the fraction that remains in black holes and neutron stars but in any case this mass interval contributes very little to A. From the previous discussion it follows that A $\sim$ 0.72. If the lower end of the IMF is set equal to 0.1 (e.g., as in the IMF by Miller and Scalo 1979) the value of A decreases to 0.67 which does not significantly affect the previous discussion.

The value of A together with the adopted value for $p(^{12}C)$ for the solar vicinity yield $A\,p(^{12}C) = 1.6 \times 10^{-3}$.

In Figure 2 we present $\langle f(^{12}C)\rangle_{IMS}$ from the computations by Renzini and Voli (1981) as a function of the maximum initial mass for IMS. From Figure 2, $A\,p(^{12}C) = 1.6 \times 10^{-3}$ and $m_i(\text{maximum}) = 8\ m_\odot$, the values for *d* given by equation (13) are presented in Table 3.

As mentioned in §III the $\langle f(^{12}C)\rangle_{IMS}$ values predicted by Renzini and Voli (1981) are a lower limit to the real value, therefore the *d* values presented in Table 3 correspond to upper limits.

TABLE 3

d VALUES FOR THE SOLAR VICINITY

	α			
η	0	1	1.5	2
1/3	0	0	0.57	1.25
2/3	0.52	...	2.08	...

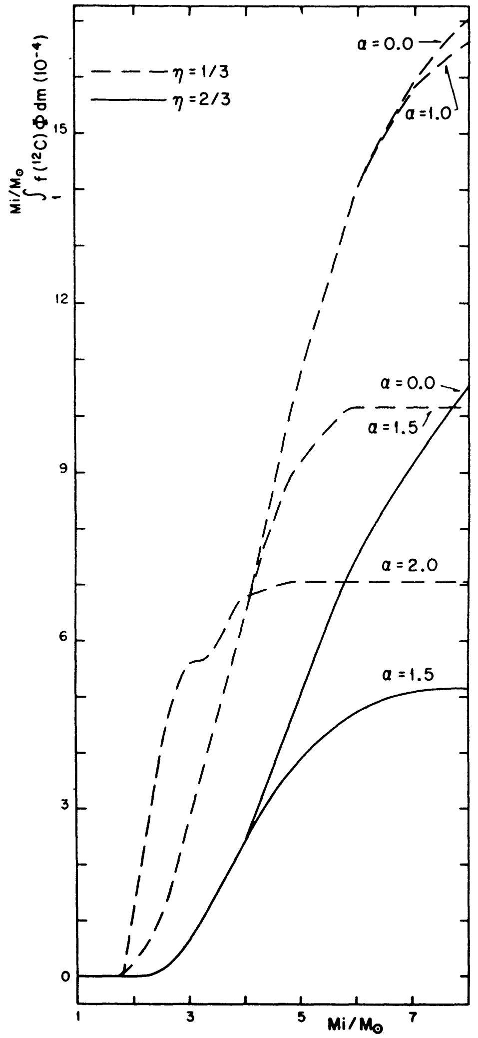

Fig. 2. Mass fraction ejected by IMS as newly formed ^{12}C per generation of stars in the $1\ M_\odot \leqslant M \leqslant M_i$ range as a function of the initial mass M_i and for different values of η and α. Values derived from Case A of Renzini and Voli (1981) with Y = 0.28, Z = 0.02.

V. CONTRIBUTIONS BY NOVAE, IMS AND MS TO THE ^{12}C AND ^{13}C VALUES OF THE ISM

Spatial distributions of novae and PN appear to be very similar in spiral galaxies and in the Magellanic Clouds (Williams 1982 and references therein; Graham 1984); this implies that the mass of their progenitors is similar and that time delays, producing a differential enrichment between novae and PN, can be neglected to a first approximation. Consequently the global ratios of the mass ejection rates for novae and PN should be representative of their local values within galaxies at the present time and should be equal to the mass fraction ratios, i.e.,

$$\frac{\dot{M}(^{12}C)_{PN} + \dot{M}(^{13}C)_{PN}}{\dot{M}(^{12}C)_{N} + \dot{M}(^{13}C)_{N}} = \frac{\langle f(^{12}C)\rangle_{IMS} + \langle f(^{13}C)\rangle_{IMS}}{\langle f(^{12}C)\rangle_{N} + \langle f(^{13}C)\rangle_{N}} \ . \qquad (14)$$

From the observed N/H and C/H ratios in novae ejecta (Williams 1982) and in PN (Peimbert 1981), equation (14) can be rewritten as

$$\frac{\langle f(^{12}C)\rangle_{IMS} + \langle f(^{13}C)\rangle_{IMS}}{\langle f(^{12}C)\rangle_{N} + \langle f(^{13}C)\rangle_{N}} = \frac{(C/N)_{PN}\,\dot{M}(N)_{PN}}{(C/N)_{N}\,\dot{M}(N)_{N}} = \frac{5.87 \times 10^{-4}\ M_\odot}{M_{ej}(M_\odot)} \ , \qquad (15)$$

where $\dot{M}(N)_{PN}$ and $\dot{M}(N)_{N}$ denote the mass ejection rates of nitrogen by planetary nebulae and novae respectively,

M_{ej} denotes the ejected mass per nova outburst in solar units, and equation (4.2) of paper I has been used for the last equality (see also Table 1 of paper I).

To explore the relative importance that each of the three types of objects under consideration has on the C enrichment of the ISM, let us express the $^{12}C/^{13}C$ mass ratio as

$$\frac{X_{12}}{X_{13}} = \\ = \frac{\langle f(^{12}C)\rangle_N + \langle f(^{12}C)\rangle_{IMS} + \langle f(^{12}C)\rangle_{MS}}{\langle f(^{13}C)\rangle_N + \langle f(^{13}C)\rangle_{IMS}} = \gamma \ , \qquad (16)$$

where it has been assumed that the ^{13}C production by MS is negligible (e.g., Maeder 1983). We will study two cases: $\gamma = 82.2$ and $\gamma = 39.7$, which correspond to the solar system and the solar neighborhood respectively (see Table 1).

From equations (15) and (16) we obtain

$$5.87 \times 10^{-4}\ M_\odot\ (1 + a)\,[b(1 + d) - \gamma] = \\ = M_{ej}\,(1 + b)\,(\gamma - a) \ , \qquad (17)$$

where b, d, and γ are given by equations (3), (5) and (16) respectively and a is given by

$$a = \frac{\langle f(^{12}C)\rangle_N}{\langle f(^{13}C)\rangle_N} \qquad (18)$$

Equation (17) can be used to obtain a, b or d as a function of: the other two, M_{ej}, and the observed parameter γ.

The value of a, given by equation (18), may be obtained from the models by Starrfield *et al.* (1972, 1974, 1978). By considering only those models which predict reasonable $^{14}N/^{15}N$ ratios (paper I), the derived values for a vary from 0.43 to 0.76 (broken horizontal lines in Figures 3 and 4). From §III and §IV it follows that $10 \lesssim b \lesssim 50$ and $0.25 \lesssim d \lesssim 0.75$.

Most determinations of M_{ej} are rms masses that do not consider the filling factor inside the ejected shell; it can be shown that due to the possible filamentary and clumpy structure of the ejected material these masses, that cluster around $1 \times 10^{-4}\ M_\odot$, are upper limits to the real mass (e.g., paper I). Other determinations of M_{ej}, which take into account the filling factor, are those by Snijders *et al.* (1984) for Nova Aquilae 1982 and by Peimbert and Sarmiento (1984) for Nova Cygni 1978, where the obtained value is $\sim 10^{-5}\ M_\odot$. Cohen and Rosenthal (1983) have determined the hydrogen mass of five novae shells taking into account the filling factor, their results for four of them indicate total shell masses smaller than $5 \times 10^{-5}\ M_\odot$; we prefer the results by Snijders *et al.* (1984) and Peimbert and Sarmiento (1984) because they compute the filling factor while Cohen and Rosenthal (1983) assume it. From the previous discussion we consider that $M_{ej} \sim 10^{-5}\ M_\odot$ is representative of the observed values.

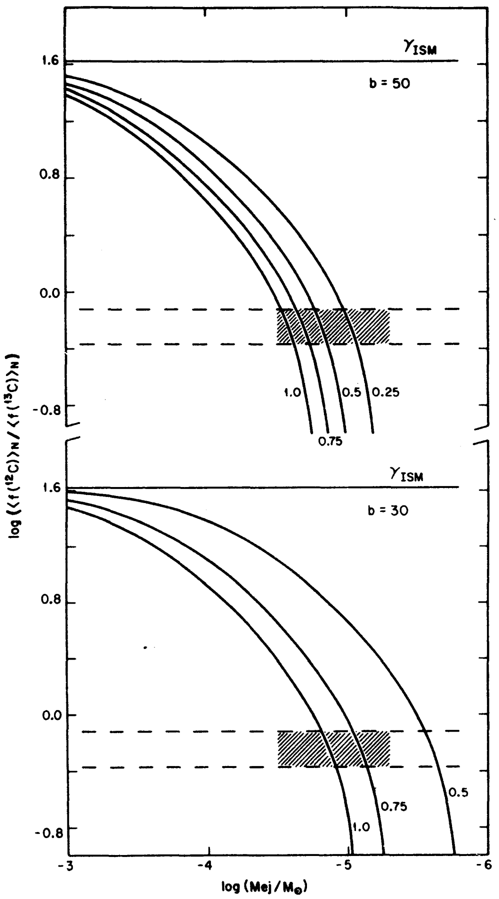

Fig. 3. a versus M_{ej} for $\gamma = \gamma_{ISM} = 39.7$, the solar vicinity value. The curves correspond to different d values. The region between the horizontal broken lines indicates the allowed a range. The upper frame has been calculated for b = 50 and the lower one for b = 30. Shaded areas show the maximum probability regions according to present astrophysical ideas (see text).

Figure 3 shows a from equation (17) as a function of M_{ej} for different values of d and for b equal to 50 and 30; the horizontal lines represent $\gamma_{ISM} = 39.7$ (solid line) and the allowed interval according to model predictions (broken lines). From this figure, for $0.43 < a < 0.76$, $0.25 < d < 1$ and $30 < b < 50$ it follows that $2 \times 10^{-6} < M_{ej} < 3 \times 10^{-5}\ M_\odot$; while for $a = 0.6$, $d = 0.5$ and $b < 50$ it follows that $M_{ej} < 1.5 \times 10^{-5}\ M_\odot$.

Figure 4 shows the values derived from equation (17) for a as a function of b for different values of d, M_{ej} and

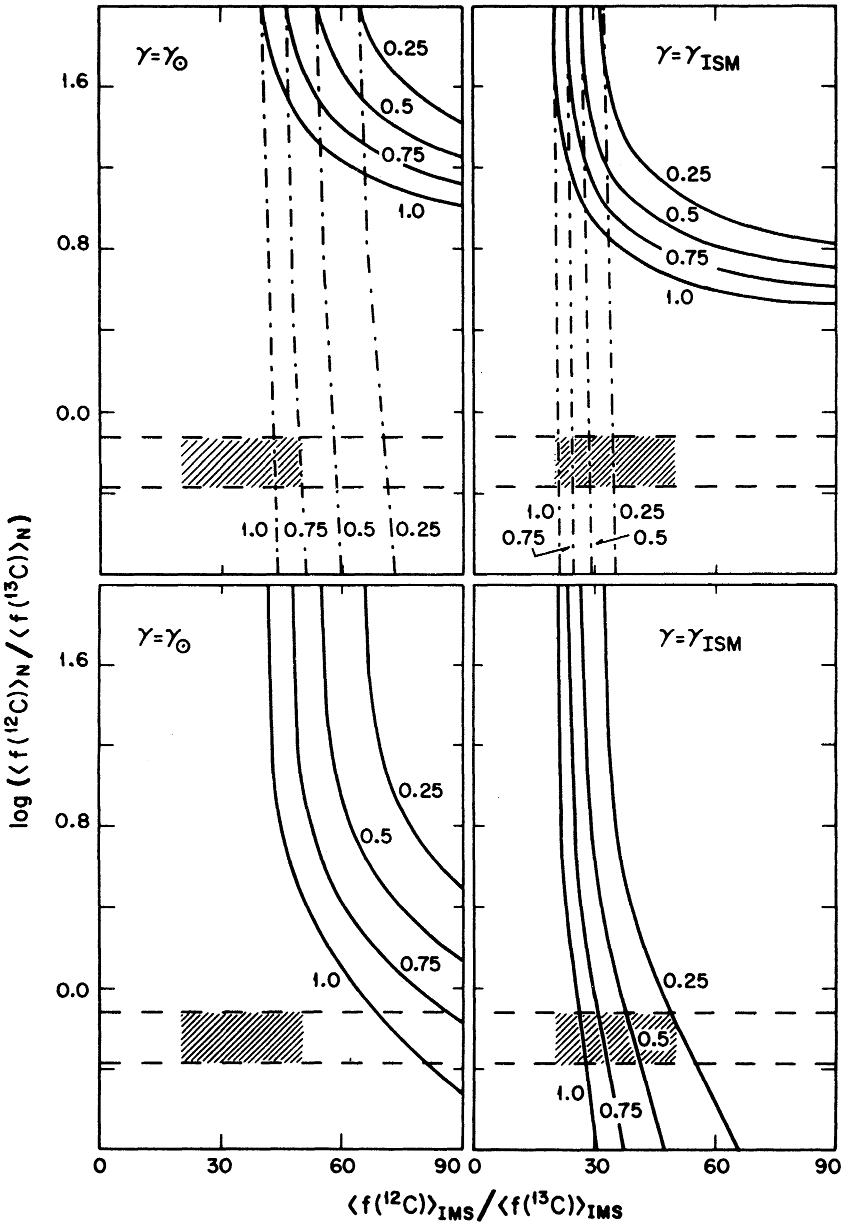

Fig. 4. a versus b. The curves correspond to different d values. The region between horizontal broken lines indicates the allowed a range. Upper frames are for $M_{ej} = 10^{-4}$ $M_\odot$ (solid lines) and $M_{ej} = 10^{-6}$ $M_\odot$ (vertical broken lines). Lower frames are for $M_{ej} = 10^{-5}$ $M_\odot$. Left hand frames are for $\gamma = \gamma_\odot = 82.2$ (solar system) while right hand frames are for $\gamma = \gamma_{ISM} = 39.7$ (solar vicinity). Shaded areas show the maximum probability regions according to present astrophysical ideas (see text).

γ. The left hand frames are for $\gamma_\odot = 82.2$ and the right hand frames for $\gamma_{ISM} = 39.7$. Figures 3 and 4 rule out values for $M_{ej} \geqslant 10^{-4}$ $M_\odot$ because for expected b and d values, they would predict a values considerably higher than those given by the novae models. It is also clear from Figure 4 that for $M_{ej} = 10^{-5}$ $M_\odot$ the restrictions given by equation (17) for the allowed values of a, b and d are only compatible in the $\gamma_{ISM} = 39.7$ case (right hand frames in Figure 4) but not in the $\gamma_\odot = 82.2$ case.

Table 4 has been produced from equation (17) for $M_{ej} = 1 \times 10^{-5}$ $M_\odot$. Column 3 gives the fraction of ^{13}C in the ISM produced by novae for different values of a and b; for a given set of a, b and M_{ej} values the ^{13}C fraction is independent of γ which can be easily adjusted by varying d. Table 4 also shows the d values for $\gamma_{ISM} = 39.7$ and $\gamma_\odot = 82.2$ and different a and b values. For all the cases presented in Table 4 the fraction of ^{12}C in the ISM due to novae is smaller than one percent.

TABLE 4

FRACTION OF ^{13}C IN THE ISM DUE TO NOVAE AND d VALUES FOR $\gamma_{ISM} = 39.7$ AND $\gamma_{\odot} = 82.2$[a]

a	b	$13F_N$[b]	$d(39.7)$	$d(82.2)$
0.25	20	0.22	1.55	4.28
0.25	30	0.30	0.88	2.89
0.25	40	0.36	0.54	2.20
0.25	50	0.41	0.34	1.78
0.50	20	0.19	1.45	4.08
0.50	30	0.26	0.78	2.70
0.50	40	0.32	0.45	2.01
0.50	50	0.37	0.25	1.59
0.75	20	0.17	1.38	3.94
0.75	30	0.23	0.72	2.56
0.75	40	0.29	0.38	1.87
0.75	50	0.33	0.18	1.45
1.00	20	0.15	1.33	3.84
1.00	30	0.21	0.66	2.45
1.00	40	0.26	0.33	1.76
1.00	50	0.30	0.13	1.35

a. For ejected novae shell mass of 10^{-5} M$_{\odot}$

b. $^{13}F_N \equiv {}^{13}C_N / ({}^{13}C_N + {}^{13}C_{IMS})$

Similar tables to Table 4 can be computed for other values of M$_{ej}$. For $M_{ej} = 1 \times 10^{-4}$ M$_{\odot}$ and the same range of values for a and b given in Table 4 it is obtained that $3.16 < d < 6.63$ for $\gamma_{ISM} = 39.7$ and $7.70 < d < 14.84$ for $\gamma_{\odot} = 82.2$.

VI. DISCUSSION AND CONCLUSIONS

As mentioned before this paper should be regarded as a first approximation to the problem of the C enrichment of the ISM. We need new IMS models for different α and η values extending the third dredge up mechanism to masses smaller than those considered by Renzini and Voli (1981), these models would increase the ^{12}C production; even without the expected ^{12}C increase the models by Renzini and Voli for $\eta = 1/3$ with $\alpha = 0$ and $\alpha = 1$ can be ruled out because they would overproduce ^{12}C. We also need a set of models, with the new value for the $^{12}C(\alpha, \gamma)^{16}O$ reaction rate, to reevaluate the ^{12}C production by MS.

From the computations by Renzini and Voli (1981) most of the C production due to IMS is produced by objects in the 3-8 M$_{\odot}$ range; for this mass range and for the characteristic times involved (about 5 Gyr for the solar system and about 10 Gyr for the solar vicinity) the instant recycling approximation, IRA, for C production is good enough, but as mentioned before stars in the 1-3 M$_{\odot}$ range also contribute to the C enrichment and when new models for IMS become available the IRA has to be dropped. Nevertheless we consider that the main results of this paper will not be substantially affected.

Tinsley (1978) made a chemical evolution model of the solar vicinity without IRA and making the following assumptions: i) $d = 1$, ii) stars with masses smaller than 5 M$_{\odot}$ become PN and iii) the models by Arnett (1978) for MS. She found that the model is consistent with the idea that PN are a major additional source of C.

The solar vicinity $^{12}C/^{13}C$ ratio is consistent with reasonable values for a, b, d and M$_{ej}$. On the other hand it is not possible to explain the solar system $^{12}C/^{13}C$ ratio without changing one or more of the assumptions made in this paper. If a large fraction of ^{12}C is produced by MS and all of ^{13}C is produced by IMS the $^{12}C/^{13}C$ ratio should diminish with time, in agreement with the observations, for the solar system and the solar vicinity; but the C/O ratio, which is similar for the solar system and for the Orion nebula, seems to imply that the relative importance of MS and IMS has not changed considerably in the solar vicinity since the formation of the solar system (e.g., Tinsley 1978). A possible explanation for the high $^{12}C/^{13}C$ value of the solar system is that the solar nebula was made from material recently exposed to a SN explosion and consequently rich in ^{12}C.

Four independent determinations of d were discussed: i) from galactic and extragalactic H II regions it is obtained that $d \leqslant 0.8$, ii) from stellar evolution models by Arnett (1978) for MS and by Renzini and Voli (1981) for IMS it is obtained that $0.36 \leqslant d \leqslant 0.89$, iii) from a single model for a star of about 20-25 M$_{\odot}$ and taking into account an increase of a factor of five in the $^{12}C(\alpha, \gamma)^{16}O$ reaction rate a value of $d = 0.60$ is obtained, and iv) from the C yields and the models by Renzini and Voli for $\eta = 1/3$ and $\alpha = 1.5$ it is obtained that $d = 0.57$. Each of these results is based on different assumptions but all of them are consistent with $0.25 \lesssim d \lesssim 0.75$. The conclusion that d is smaller than unity has also been reached by Mallik and Mallik (1985), based on similar arguments to those of Serrano and Peimbert (1981) as well as the increase in the $^{12}C(\alpha, \gamma)^{16}O$ reaction rate, and by Dufour (1984, 1985*a*, *b*), based on the observed C/O ratio in galactic and extragalactic H II regions.

The mass ejected per nova outburst, M$_{ej}$, cannot be substantially greater than 10^{-5} M$_{\odot}$, otherwise novae would overproduce ^{13}C and it would not be possible to explain the observed $^{12}C/^{13}C$ ratio in the solar vicinity for d values smaller than 1. This result is in agreement with the M$_{ej}$ values of $\sim 10^{-5}$ M$_{\odot}$ determined by Snijders *et al.* (1984) and in paper I as well as with the $^{14}N/^{15}N$ ratio of the ISM (see paper I).

It is found that IMS are the main contributors to the ^{12}C and ^{13}C abundance of the ISM.

Novae produce a substantial fraction of the ISM ^{13}C, between 15% and 41%, alternatively the contribution of novae to ^{12}C is negligible, less than one per cent of the ISM ^{12}C.

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REFERENCES

Adams, S., Seaton, M.J., Howarth, I.D., Auriere, M., and Walsh, J.R. 1984, *M.N.R.A.S.*, **207**, 471.

Arnett, W.D. 1978, *Ap. J.*, **219**, 1008.

Arnett, W.D. and Thielemann, F.K. 1984, in *Stellar Nucleosynthesis*, eds. C. Chiosi and A. Renzini (Dordrecht: D. Reidel), p. 145.

Boato, G. 1954, *Geochim. Cosmochim. Acta*, **6**, 209.

Chiosi, C. and Caimmi, R. 1979, *Astr. and Ap.*, **80**, 234.

Cohen, J.G. and Rosenthal, A.J. 1983, *Ap. J.*, **268**, 689.

Dufour, R.J. 1984, *Bull. AAS*, **16**, 888.

Dufour, R.J. 1985*a*, private communication.

Dufour, R.J. 1985*b*, in *Future of Ultraviolet Astronomy based on Six Years of IUE Research*, NASA CP 2349, eds. J.M. Mead, R.D. Chapman, and Y. Kondo, p. 107.

Dufour, R.J., Shields, G.A., and Talbot, R.J., Jr. 1982, *Ap. J.*, **252**, 461.

Graham, J.A. 1984, in *IAU Symposium No. 108, Structure and Evolution of the Magellanic Clouds*, eds. S. van den Bergh and K.S. de Boer (Dordrecht: D. Reidel), p. 374.

Hall, D.N.B., Noyes, R.W., and Ayres, T.R. 1972, *Ap. J.*, **171**, 615.

Hawkins, I., Jura, M., and Meyer, D.M. 1984, *Bull. AAS*, **16**, 878.

Hawkins, I., Jura, M., and Meyer, D.M. 1985, preprint.

Iben, I., Jr. and Renzini, A. 1982, *Ap. J. (Letters)*, **263**, L23.

Kumar, S.S. 1972, *Ap. and Space Sci.*, **17**, 219.

Lambert, D.L. 1978, *M.N.R.A.S.*, **182**, 249.

Lequeux, J., Peimbert, M., Rayo, J.F., Serrano, A., and Torres-Peimbert, S. 1979, *Astr. and Ap.*, **80**, 155.

Low, C. and Lynden-Bell, D. 1976, *M.N.R.A.S.*, **176**, 367.

Maeder, A. 1981, *Astr. and Ap.*, **101**, 385.

Maeder, A. 1983, *Astr. and Ap.*, **120**, 113.

Mallik, D.C.V. and Mallik, S.V. 1985, *J. Astrophys. Astr.*, in press.

Miller, G.E. and Scalo, J.M. 1979, *Ap. J. Suppl.*, **41**, 513.

Nomoto, K. 1984, in *Stellar Nucleosynthesis*, eds. C. Chiosi and A. Renzini (Dordrecht: D. Reidel), p. 205.

Peimbert, M. 1981, in *Physical Processes in Red Giants*, eds. I. Iben Jr. and A. Renzini (Dordrecht: D. Reidel), p. 409.

Peimbert, M. 1985, *Rev. Mexicana Astron. Astrof.*, **10**, 125.

Peimbert, M. and Sarmiento, A. 1984, *Astr. Express*, **1**, 97, paper I.

Peimbert, M. and Serrano, A. 1982, *M.N.R.A.S.*, **198**, 563.

Peimbert. M. and Torres-Peimbert, S. 1974, *Ap. J.*, **193**, 327.

Peimbert, M. and Torres-Peimbert, S. 1976, *Ap. J.*, **203**, 581.

Peimbert, M. and Torres-Peimbert, S. 1977, *M.N.R.A.S.*, **179**, 217.

Peimbert, M., Peña, M., and Torres-Peimbert, S. 1985, *Astr. and Ap.*, submitted.

Reimers, D. 1975, *Mem. Soc. Roy. Sci. Liege*, 6^{e} Ser., 8, 369.

Renzini, A. 1984, in *Stellar Nucleosynthesis*, eds. C. Chiosi and A. Renzini (Dordrecht: D. Reidel), p. 99.

Renzini, A. and Voli, M. 1981, *Astr. and Ap.*, **94**, 175.

Serrano, A. 1978, D. Ph. Thesis, University of Sussex, U.K.

Serrano, A. and Peimbert, M. 1981, *Rev. Mexicana Astron. Astrof.*, **6**, 41.

Snijders, M.A.J., Batt, T.J., Seaton, M.J., Blades, J.C., and Morton, D.C. 1984, *M.N.R.A.S.*, **211**, 7 p.

Starrfield, S., Sparks, W.M., and Truran, J.W. 1974, *Ap. J. Suppl.*, **28**, 247.

Starrfield, S., Truran, J.W., and Sparks, W.M. 1978, *Ap. J.*, **226**, 186.

Starrfield, S., Truran, J.W., Sparks, W.M., and Kutter, G.S. 1972, *Ap. J.*, **176**, 169.

Tinsley, B.M. 1978, in *IAU Symposium No. 76, Planetary Nebulae*, ed. Y. Terzian (Dordrecht: D. Reidel), p. 341.

Torres-Peimbert, S. 1984, in *Stellar Nucleosynthesis*, eds. C. Chiosi and A. Renzini (Dordrecht: D. Reidel), p. 3.

Torres-Peimbert, S., Peimbert, M., and Daltabuit, E. 1980, *Ap. J.*, **238**, 133.

Trautvetter, H.P., Görres, J., Kettner, K.U., and Rolfs, C. 1984, in *Stellar Nucleosynthesis*, eds. C. Chiosi and A. Renzini (Dordrecht: D. Reidel), p. 79.

Wannier, P.G. 1980, *Ann. Rev. Astr. and Ap.*, **18**, 399.

Williams, R.E. 1982, *Ap. J.*, **261**, L77.

Woosley, S.E., Axelrod, T.S., and Weaver, T.A. 1984, in *Stellar Nucleosynthesis*, eds. C. Chiosi and A. Renzini (Dordrecht: D. Reidel), p. 263.

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