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GALACTIC CHEMICAL EVOLUTION AND THE HELIUM ENRICHMENT

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RESUMEN

El cociente de enriquecimiento de helio a elementos pesados, $\Delta Y/\Delta Z$, correspondiente a modelos de evolución química de la vecindad solar se obtuvo adoptando diferentes funciones iniciales de masa y la composición química del material estelar expulsado propuesta por Talbot y Arnett (1974). Todos los valores de $\Delta Y/\Delta Z$ calculados son considerablemente menores que el valor observado. Se presentan soluciones posibles a esta discrepancia entre teoría y observaciones.

ABSTRACT

The helium to heavy element enrichment ratio, $\Delta Y/\Delta Z$, predicted by chemical evolution models of the solar neighborhood, is obtained adopting several initial mass functions and the composition of ejected stellar material suggested by Talbot and Arnett (1974). In all cases the values of $\Delta Y/\Delta Z$ predicted are considerably smaller than the observed one. Possible ways to explain this discrepancy are presented.

Key words: ABUNDANCES—STELLAR EVOLUTION—CHEMICAL EVOLUTION

I. INTRODUCTION

Most of the work on the chemical evolution of our galaxy has been done without considering the change in the helium abundance produced by stellar evolution (*e.g.*, Pagel and Patchett 1975; Trimble 1975; Audouze and Tinsley 1976). From the study of H II regions (Peimbert and Torres-Peimbert 1974, 1976) and of planetary nebulae (D'Odorico, Peimbert and Sabbadin 1976; Torres-Peimbert and Peimbert 1976) it has been found that the overall helium enrichment is proportional to the metal enrichment, the ratio being $\Delta Y/\Delta Z = 2.7 \pm 1.0$ (estimated absolute error). In what follows we will study whether the observed enrichment ratio provides a constraint to the models of chemical evolution of the solar neighborhood that have been proposed in the literature.

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II. DISCUSSION

For our purposes, the following set of equations describes the chemical evolution of the solar neighborhood

$$\frac{dm}{dt} = f \, , \tag{1}$$

$$\frac{dm_g}{dt} = -(1-R)\psi + f \, , \tag{2}$$

$$\frac{d}{dt}(m_g Z) = -Z_*(1-R)\psi + y_Z(1-R)\psi + Z_f \, f \, , \tag{3}$$

and

$$\frac{d}{dt}(m_g Y) = -Y(1-R)\psi + y_Y(1-R)\psi + Y_f \, f \, . \tag{4}$$

In these equations m is the total mass of the system, m_g the mass of the gas; Y and Z are the mean mass fractions of helium and metals of the gas; ψ is the rate at which stars are formed with metal abundance Z_*; f is the rate of mass flow of gas with abundance Y_f and Z_f; R is the mass fraction per stellar generation returned to the gas; $y_Y(1-R)$ and $y_Z(1-R)$ are the fractions of newly synthesized helium and metals per stellar generation; y_Y and y_Z are the helium and heavy element yields, respectively.

General discussions of equations (1) to (3) have been presented by Pagel and Patchett (1975) and by Tinsley (1975).

a) *SIMPLE Model*

We will start by studying the simple standard model, SIMPLE. In this case $f = 0$, $Z(0) = 0$ and $Y(0) = Y_p$, where Y_p is the pregalactic helium abundance. From equations (2) to (4) $dY/dZ = y_Y/y_Z$, and

$$(Y-Y_p)/Z = \Delta Y/\Delta Z = y_Y/y_Z\,. \qquad (5)$$

$$y_Z = -Z/\ln\mu \qquad (6)$$

where $\mu = m_g/m$. In Table 1 we present lower limits for the y_Z value corresponding to the Magellanic Clouds and the solar vicinity, for this model. The Z values for the gas in the Magellanic Clouds were obtained from Peimbert and Torres-Peimbert (1974, 1976), the μ values for the Magellanic Clouds were obtained from Roberts (1969). For the solar neighborhood the Z value and the interstellar atomic hydrogen mass were taken from Pagel and Patchett (1975), while the stellar mass was taken from Schmidt (1965). The y_Z values thus obtained are

TABLE 1

OBSERVED LOWER LIMITS OF THE METAL YIELD

Object	Z	μ	Y_Z
SMC	0.003	0.32	0.0026
LMC	0.01	0.054	0.0034
Solar Neighborhood	0.02	0.063	0.0072

lower limits to the real metal yields because the amount of gas in H_2 molecules has not been considered.

In Figure 1 we present for the SIMPLE model the dependence on Z of the ratio of gas mass to total mass. The values of μ assigned to the solar neighborhood are in the 0.062 to 0.2 range.

In Table 2 we present the yields derived from the chemical composition of ejected material predicted by Talbot and Arnett (1974, Fig. 1), for a power law initial mass function, IMF, with $\alpha = 1.55$, where the number of stars between M and M + dM is proportional to $M^{-\alpha-1}$. A minimum stellar mass of 0.09 $M_\odot$ and an upper cutoff mass, M_c, of 95 $M_\odot$ were used. To compute y_Y we assumed an initial value of helium of 0.23. The ratio of yields derived is $y_Y/y_Z = 0.41$. This value is at least a factor of 6 smaller than the observed $\Delta Y/\Delta Z$.

TABLE 2

METAL AND HELIUM YIELDS

α	$M_c/M_\odot$	y_Z	y_Y	y_Y/y_Y	y^*_Y/y_Z
1.35	95	.029	.0092	.32	1.15
	40	.013	.0092	.69	1.15
	25	.006	.0079	1.4	1.18
	15	.0008	.0051	6.1	1.27
1.55	95	.011	.0044	.41	1.22
	40	.006	.0044	.78	1.22
	25	.002	.0038	1.6	1.25
	15	.0004	.0026	6.5	1.37
1.80	95	.0032	.0017	.53	1.35
	40	.0018	.0017	.94	1.35
	25	.0009	.0015	1.8	1.39
	15	.0002	.0011	7.0	1.54

From Talbot and Arnett (1974) it can be seen that the metal enrichment is due to the most massive stars, $M \geq 10\,M_\odot$, while the helium enrichment is mostly due to stars in the $4\ M_\odot \leq M \leq 10\ M_\odot$ range; therefore without modifying the chemical composition of ejected material predicted by Talbot and Arnett it is possible to increase $\Delta Y/\Delta Z$ by adopting steeper IMF (higher α) or by adopting a mass cutoff lower than 95 $M_\odot$. In Table 2 we also present yield values for $\alpha = 1.35$ and 1.80, and for M_c from 15 $M_\odot$ to 95 $M_\odot$. It is valid to consider

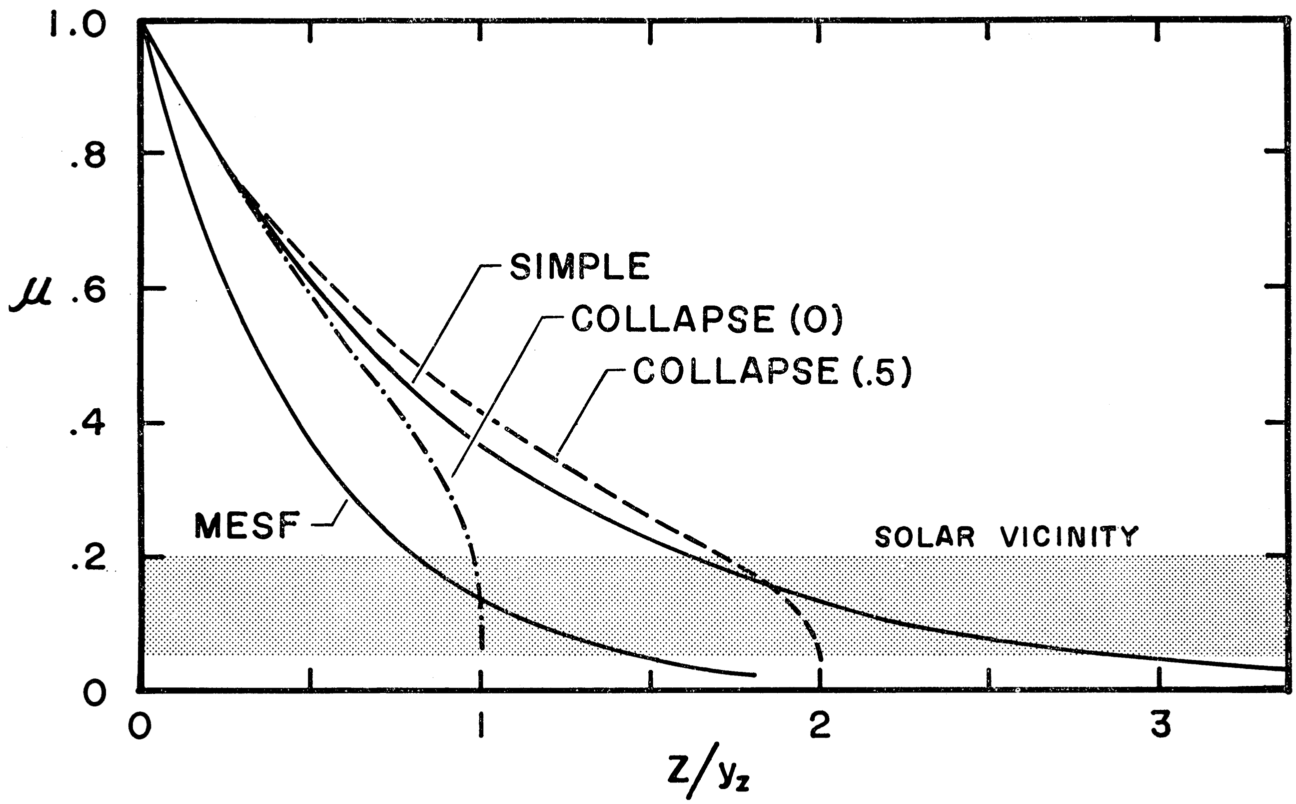

FIG. 1. The relationship between the ratio of gas mass to total mass and the metal abundance is shown for each of the models. Also marked are the observed limits for the solar neighborhood, $0.06 \leq \mu \leq 0.2$. The relationship for PIE models would shift the curves to the right by Z_0/y_Z.

values of M_c lower than 95 $M_\odot$, because even if stars as massive as 95 $M_\odot$ are formed, it is likely that they lose a considerable fraction of their mass before reaching very advanced stages of evolution and exploding as supernovae. From Table 2 it follows that higher α or lower M_c values produce higher y_Y/y_Z ratios; however this result is achieved by lowering y_Z considerably below the observed lower limits in the Magellanic Clouds and the solar neighborhood. Moreover, if a value as low as $y_Z = 0.007$ is adopted, it can be found from Table 2 that the y_Y/y_Z ratio is 1.2 for $\alpha = 1.35$, which corresponds to $M_c \simeq 27$ $M_\odot$.

Another modification that can be attempted is to consider the contribution to helium enrichment due to objects in the 1 $M_\odot$ to 4 $M_\odot$ range (which for convenience we will call planetary nebulae). This contribution is small and was not considered by Talbot and Arnett. Stellar evolution models predict that the outer convective envelope of the star must be enriched by $Y_{env} - Y_{initial} \simeq 0.01$ (Torres-Peimbert and Peimbert 1971; Demarque 1975). In Table 2 we also present y^*_Y, the total helium yield that includes the contribution from massive stars and planetary nebulae. To compute y^*_Y it was assumed that 0.01 of the material ejected from stars between 1 $M_\odot$ and 4 $M_\odot$ is newly formed helium. From Table 2 it can be seen that, in this case, there is only a modest increase in the helium yield and that it is not large enough to account for the observed values.

For the SIMPLE model the relation $\Delta Y/\Delta Z = y_Y/y_Z$ was derived under the assumption of instant recycling. It is clear that for planetary nebulae this simplification is no longer valid, therefore $y_Y/y_Z \leq \Delta Y/\Delta Z \leq y^*_Y/y_Z$.

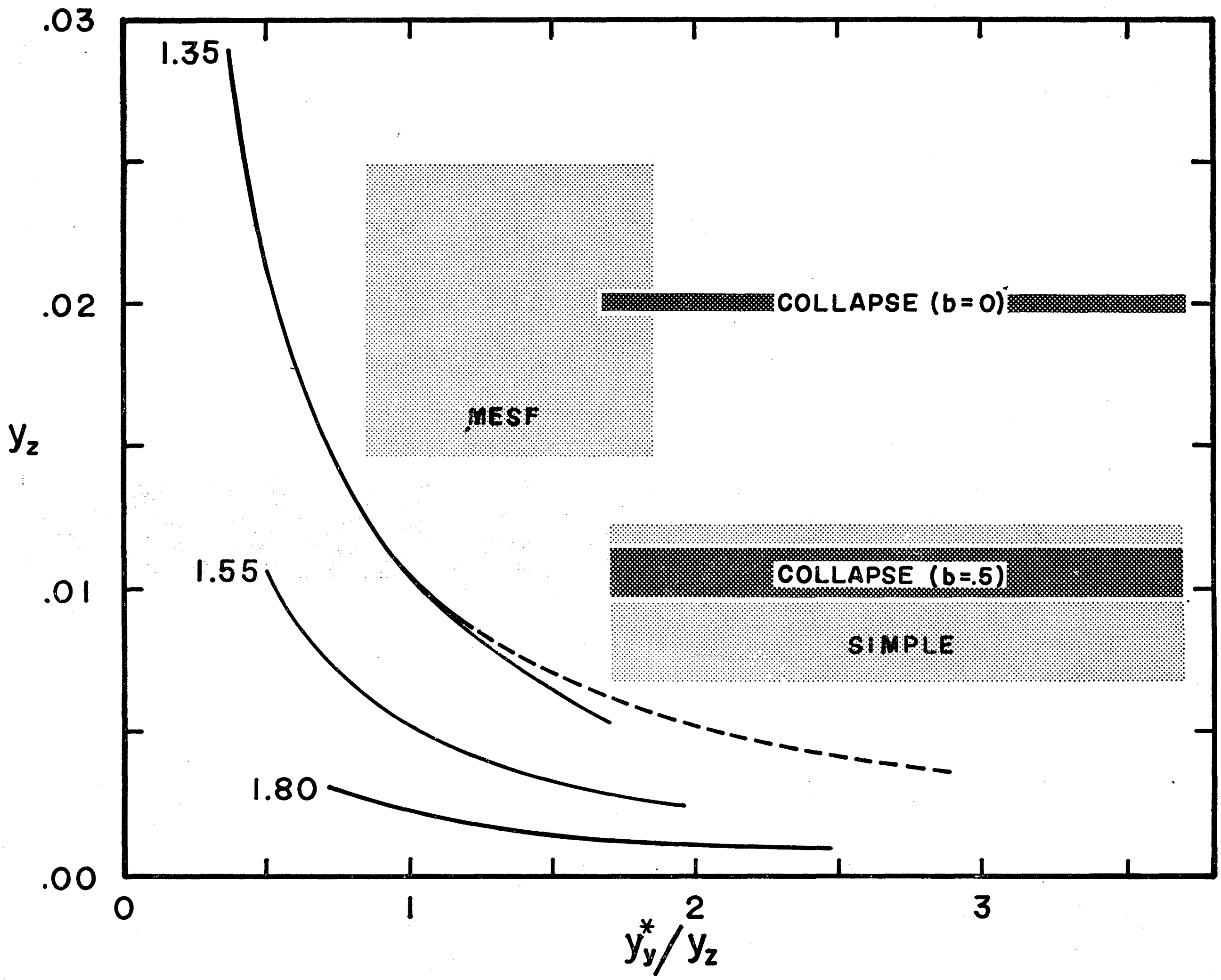

Fig. 2. The relation between y_Z and y_Y/y_Z is exhibited as solid lines for each of the IMFs adopted. The lowest points on the lines correspond to $M_\text{C} = 25\ M_\odot$ and the highest points to $M_\text{C} = 95\ M_\odot$. Included in this figure are the restrictions that the observed gas mass to total mass ratio imposes on y_Z [assuming that Z (solar neigborhood) = 0.02] as well as that imposed by the restriction $\Delta Y/\Delta Z = 2.7 \pm 1.0$. The dashed line corresponds to the case where the stellar remnants are larger than $1.4\ M_\odot$ retaining the newly synthesized metals but not the newly synthesized helium.

In Figure 2 we present the y_Z *vs.* y_Y^*/y_Z diagram. In this figure the theoretical yields derived from the values by Talbot and Arnett corresponding to different slopes of the IMF and to mass cutoffs varying from 95 $M_\odot$ to 25 $M_\odot$ are shown. The observations would be compatible with the SIMPLE model only for a range of values $0.007 \leq y_Z \leq 0.012$ arising from the restriction $0.06 \leq \mu \leq 0.2$, and $1.7 \leq y_Y/y_Z \leq 3.7$ from the value $\Delta Y/\Delta Z = 2.7 \pm 1.0$. This region does not overlap with the theoretical predictions. From this figure and Table 2 it follows that for $y_Z = 0.007$ the maximum attainable value of y_Y^*/y_Z, is 1.4 for $\alpha = 1.35$. For larger values of α the difference is even larger.

The yields were obtained under the assumption that, for $M > 4\ M_\odot$, the mass of the remnant is $1.4\ M_\odot$, while for $1\ M_\odot < M < 4\ M_\odot$ the mass of the remnant is that proposed by Thuan, Hart and Ostriker (1975). If the masses of the remnants for objects with $M > 4\ M_\odot$ are larger than $1.4\ M_\odot$ the

y_Z value would be reduced, thus increasing the $\Delta Y/\Delta Z$ enrichment ratio. There is observational evidence supporting the existence of such massive ($M > 1.4\ M_\odot$) remnants as neutron stars (*e.g.,* van Paradijs *et al.* 1976) and even black holes (*e.g.,* Bolton 1975). Therefore the possibility of remnants more massive than 1.4 $M_\odot$ will be studied further.

The most extreme assumption that can be made to increase the theoretical y_Y/y_Z ratio is that the stellar remnant retains only heavy elements and that the newly produced helium is able to abandon the remnant. In Figure 2 we have included (dashed line) the solutions arising from this assumption for the most favorable case with $M_c = 95\ M_\odot$ and $\alpha = 1.35$, and assuming that the fraction of the metals locked up in stellar remnants increases. It can be seen that even if this hypothesis produces large y_Y/y_Z values, it does so by decreasing y_Z below the values derived from observations.

It is well known that the SIMPLE model cannot explain the observed lack of stars of very low metallicity in the solar neighborhood (van den Bergh 1962; Schmidt 1963). To overcome this deficiency several other models have been proposed. In what follows we will examine whether these models can explain the observed $\Delta Y/\Delta Z$ values.

b) *COLLAPSE Models*

Models have been advanced in which material is falling into the solar neighborhood (*e.g.,* Larson 1974; Quirk and Tinsley 1973). They can be simplified by assuming that the infalling external material compensates the rate of star formation, which implies m_g = constant. For these models $m(0) = m_g$, $Z(0) = 0$, $Z_f = bZ$ and $Y_f = Y_p + b'\ (Y - Y_p)$. From equations (1) to (3)

$$\frac{1-\mu}{\mu} = -\frac{1}{1-b}\ \ln\left[1 - \frac{Z}{y_Z}(1-b)\right], \quad (8)$$

and the relation between the enrichment of helium and that of metals is given by the following expression

$$\left[1 - \frac{\Delta Y}{y_Y}\ (1-b')\right]^{1-b} = \left[1 - \frac{\Delta Z}{y_Z}\ (1-b)\right]^{1-b'} . \quad (9)$$

i) inflow of unprocessed material

In this case $b = b' = 0$. The gas mass to total mass ratio for different Z has been plotted in Figure 1, from equation (8). The enrichment ratio is $\Delta Y/\Delta Z = y_Y/y_Z$ for $y_Z \geq Z$. The restrictions imposed on the yields by observations for this model are indicated in Figure 2.

ii) inhomogeneous collapse

The enrichment ratio depends on the adopted helium enrichment for the net flux of material. In the case where the infalling material and the local gas are enriched by the same type of objects $b = b'$. Under these assumptions, equation (9) reduces to $\Delta Y/\Delta Z = y_Y/y_Z$, for $y_Z \geq Z(1-b)$. In Figure 1 we have plotted $\mu(Z)$ from equation (8), and in Figure 2 we present the range of values of y_Z and y_Y/y_Z compatible with observations for the inhomogeneous collapse model, for $b = 0.5$.

c) *PIE Model*

In the prompt initial enrichment model (PIE), it is assumed that a first generation of very massive stars rapidly increased the Z content of the disk, that is, $Z(0) = Z_0$. As mentioned before, the helium enrichment is mainly produced by intermediate mass stars, therefore the PIE model with very massive stars gives a larger discrepancy in the $\Delta Y/\Delta Z$ ratio than the SIMPLE model. As an example of the expected initial values of helium, we find from the models of 70, 36 and 22 $M_\odot$ by Arnett and Schramm (1973) that $Y(0) - Y_p$ would lie in the range of $-0.01\ Z_0$ to $0.4\ Z_0$, where a pregalactic value of $Y_p = 0.23$ was adopted. The most massive stars can produce a net negative output of helium, since the ejected material may contain less helium than it contained at the time the star formed.

d) *HALO Model*

In this model by Ostriker and Thuan (1975) the astrated gas present in the disk comes from two sources: mass loss from disk stars and mass loss from halo stars. It is assumed that half of the material ejected by very massive halo stars, rich in heavy elements, leaves the Galaxy, while all the material ejected in more recent times by less massive stars reaches the plane of the Galaxy. Thus, averaging over the whole lifetime of the Galaxy, the ratio $(Y - Y_p)/Z$ expected for the halo material is larger than that of the disk. HALO models with most of the mass originally in halo stars predict values of $\Delta Y/\Delta Z$ larger by as much as a factor of 2 than those predicted by the SIMPLE model. However Schmidt (1975) estimates that the mass of the halo is 6% of the mass of the Galaxy, and therefore it is unlikely that enrichment from the halo has affected significantly the disk evolution.

e) *MESF Model*

For the metal enhanced star formation model, MESF, (Talbot and Arnett 1973) it is assumed that stars are born with $Z_* = Z + a$, where a can be estimated from the dispersion of the metallicity inhomogeneities. We will assume that there is no star formation associated preferentially with helium inhomogeneities. This consideration is valid since not much helium is expected to be on dust grains. In this case $f = 0$, $Z(0) = 0$, $Y(0) = Y_p$ and the solution of equations (3) and (4) is

$$\Delta Y/\Delta Z = y_Y/(y_Z - a).$$

Moreover if we adopt $a = y_Z/2$, which is a reasonable value for the solar neighborhood, the $\Delta Y/\Delta Z$ predicted is twice as large as that predicted by the SIMPLE model. However, since $\ln \mu = -Z/(y_Z - a)$, given the same μ and Z conditions the metal yield required is twice as large as for the SIMPLE model (see Figure 1). Furthermore, larger values of a might be ruled out by the large y_Z implied. The yield values compatible with observations for MESF models of $a = y_Z/2$ are presented in Figure 2.

III. CONCLUSIONS

Different models for the chemical evolution of the solar neighborhood predict different $\Delta Y/\Delta Z$ values for our galaxy. While PIE models with very massive stars predict a smaller value than SIMPLE and COLLAPSE models, MESF and HALO models predict larger ones.

The observed Z and $\Delta Y/\Delta Z$ values, together with their estimated errors, provide us with constraints on y_Z and y_Y/y_Z for different models of evolution of the solar neighborhood. It is found that the yields predicted from the work on stellar evolution by Talbot and Arnett (1974) do not agree with the permitted values obtained from observations. We considered four possible modifications, that do not solve the discrepancy. Namely: a) a small increase in the helium production by stars in the 1 $M_\odot$ to 4 $M_\odot$ range, b) different slopes of the IMF, c) different values of the upper mass cutoff of the IMF, and d) more massive stellar remnants than 1.4 $M_\odot$ which would trap the newly synthesized metals but not the newly synthesized helium.

Agreement may be reached between the predicted values and the observed ones if any of the following quantities differs by at least a factor of 2 from the values considered in this paper:

a) higher helium production in stars,
b) a lower observed $\Delta Y/\Delta Z$,
c) lower gas mass to total mass ratio in the solar neighborhood, and
d) lower Z (solar neighborhood).

The first two possibilities would improve the agreement between all the models discussed here and observations; while the last two possibilities would do so for the MESF model.

In this work only simple models of stellar evolution have been considered. There is a possibility, however, that the agreement between the theoretical and observed values of $\Delta Y/\Delta Z$ might be improved if one considers more sophisticated (and realistic) models of stellar evolution that would lead to a substantial helium production. In particular, one could take into account the occurrence of stellar instabilities in the evolution of individual massive stars (Ledoux 1974).

The values given in Table 2 are specified with more significant numbers than permitted from any presently known nucleosynthesis theory. As for the IMF, it is still poorly known, particularly for $M < 1\ M_\odot$.

A better knowledge of the value of μ is also needed to study this problem; therefore it is necessary to estimate the amount of H_2 present in the solar neighborhood. In the case of the Magellanic Clouds, indirect determinations based on the abundances of other molecules will be particularly useful.

It is clear that accurate $\Delta Y/\Delta Z$ determinations combined with theoretical predictions of y_Y/y_Z will provide strong constraints on models of the chemical evolution of the Galaxy.

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