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CHEMICAL EVOLUTION OF THE SOLAR NEIGHBORHOOD: YIELDS, BLACK HOLES AND THE AMOUNT OF MASS IN SUBSTELLAR OBJECTS

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RESUMEN

A partir de los modelos de evolución estelar de Maeder y de varias funciones iniciales de masa, FIM, hemos calculado el cociente $\Delta Y/\Delta Z$, el rendimiento de oxígeno, y(O), y el cociente de rendimientos y(O)/y(Z − O), que se esperan para la vecindad solar. Encontramos que los valores calculados concuerdan con los observados únicamente si se adopta la FIM obtenida por Kroupa, Tout, y Gilmore. Este resultado se obtiene sin necesidad de suponer que las estrellas masivas producen hoyos negros. A partir de consideraciones de evolución química encontramos que la densidad de masa en objetos subestelares de la vecindad solar es menor que 0.02 $M_\odot$ pc^{-3}; este valor proporciona una restricción importante a los modelos dinámicos de la vecindad solar.

ABSTRACT

We have computed the $\Delta Y/\Delta Z$ ratio, the oxygen yield, y(O), and the oxygen to other heavy elements yields ratio, y(O)/y(Z − O), expected for the solar neighborhood based on recent stellar evolution computations by Maeder and several initial mass functions, IMFs. We find that the computed values are in good agreement with recent observations only when the IMF derived by Kroupa, Tout, & Gilmore is used. This agreement is obtained without invoking black hole production by massive stars. The implied mass density in substellar objects for the solar neighborhood, derived from chemical evolution considerations, is smaller than 0.02 $M_\odot$ pc^{-3}. This result imposes a strong restriction on dynamical models of the solar neighborhood.

Key words: **GALAXY-ABUNDANCES — GALAXY-EVOLUTION — STARS-EVOLUTION — STARS-LUMINOSITY FUNCTION, MASS FUNCTION**

1. INTRODUCTION

By comparing the observed oxygen yields, y(O), with theoretical ones, several authors find that oxygen is overproduced if all massive stars up to ∼ 100 $M_\odot$ are included in the mass function (Twarog & Wheeler 1982, 1987; Larson 1986; Matteucci 1986; Olive, Thielemann, & Truran 1987). Moreover, by comparing observed helium to heavy element abundance ratios, $\Delta Y/\Delta Z$, with theoretical ones, several authors find that the observed values are larger than the theoretical ones (Mallik & Mallik 1985; Schild & Maeder 1985; Maeder 1992, 1993). These results have led to suggest that stars with initial masses above a critical mass, M(BH), end their evolution as black holes without enriching the interstellar medium with heavy elements. Recent determinations of M(BH) are in the 20–28 $M_\odot$ range (Twarog & Wheeler 1982, 1987; Mallik & Mallik 1985; Maeder 1992, 1993). Alternatively other authors have found that the $\Delta Y/\Delta Z$ restriction does not imply that a large fraction of the massive stars end their lives as black holes (Carigi 1994; Prantzos 1994; Giovagneli & Tosi 1994; Traat 1994). The different results are mainly due to the adopted IMFs and the adopted observational value for $\Delta Y/\Delta Z$.

Another problem, closely related to the previous one, is the implication that the observed oxygen yield has on the IMF for masses smaller than ∼ 0.08 $M_\odot$, and consequently on the total mass of the solar vicinity. While some authors find evidence in favor of dark matter in the solar vicinity, others do not (e.g., Bahcall, Flynn, & Gould 1992, and references therein), moreover if dark matter is present it could be due to substellar objects. From chemical abundance considerations alone it is possible to restrict the amount of dark matter present in the solar vicinity.

To study these problems we have decided to compute yields for helium, oxygen and other heavy elements and to compare them with recent observational data derived for the solar vicinity. In § 2 we present the definition of the "observed" and "net" y(O), $\Delta Y/\Delta Z$, and $y(Z-\mathrm{O})$ values. In § 3 we determine the net y(O), $\Delta Y/\Delta Z$ and $y(\mathrm{O})/y(Z-\mathrm{O})$ values for the solar neighborhood and compare them with the observed ones, in § 4 we present the discussion and in § 5 we present the conclusions.

2. YIELDS AND $\Delta Y/\Delta Z$

The heavy element yield is defined by

$$y(Z) = M(Z)/M_* \ , \tag{1}$$

where $M(Z)$ is the mass that a generation of stars ejects as newly formed heavy elements to the interstellar medium and M_* is the mass of the same generation that remains locked into stellar remnants and long lived stars, where the low mass end of the IMF which might comprise objects that do not become stars has been included. Similarly the oxygen yield is defined by

$$y(\mathrm{O}) = M(\mathrm{O})/M_* \ . \tag{2}$$

The yields in equations (1) and (2), hereafter net yields, have been also defined as true yields or real yields (e.g., Peimbert 1985; Pagel 1987, and references therein).

It is possible to derive net yields and net $\Delta Y/\Delta Z$ values based on: a) an IMF, b) a set of stellar evolution models, and c) an M(BH) value. The $\Delta Y/\Delta Z$ value does not depend on the IMF for masses smaller than 1 $M_\odot$ nor on the presence of non baryonic matter. Alternatively the $\Delta Y/\Delta Z$ ratio depends on the slope of the IMF because helium and heavy elements are produced in different amounts by stars of different masses.

Most of the heavy elements are formed by stars more massive than 8 $M_\odot$, those that produce supernovae of type II; for these elements the instantaneous recycling approximation, IRA, works very well. It is known that the IRA is poor for the fraction of Fe that is produced by SNe of type Ia, but the total amount of Fe produced by SNe of types II and Ia comprises only 6% of the total $Z_\odot$ value (Grevesse & Anders 1989; Grevesse et al. 1990; Biémont et al. 1991; Holweger et al. 1991; Hannaford et al. 1992). Serrano & Peimbert (1981) have shown that the IRA is also valid for helium in systems with a star formation rate, SFR, of the order of 10^{-10} M_{gal} yr^{-1}; a restriction which is satisfied by the solar neighborhood and by normal galaxies. On the other hand for galaxies with a strong burst of star formation, i.e., SFR in the 10^{-8} to 10^{-9} M_{gal} yr^{-1} range, the IRA for helium is only a fair approximation.

It is possible to determine an observed $\Delta Y/\Delta Z$ value from observations of H II regions adopting a value for the pregalactic helium abundance by mass, Y_p. For the simple model the observed $\Delta Y/\Delta Z$ value should be equal to the net value. Similarly for infall models with $Y = Y_p$ and $Z = 0$, ΔY and ΔZ become equally diluted without affecting the $\Delta Y/\Delta Z$ value. There are two cases where the observed value could be different from the computed one: a) in the presence of selective loss of Z-rich material in outflow models, or b) in the presence of inhomogeneous mixing of the interstellar medium by a generation of stars which could be due to selective enrichment of Y or Z by massive stars inside the observed H II region.

We will assume that the ratio of net yields $y(\mathrm{O})/y(Z-\mathrm{O})$ is equal to the observed ratio of abundances $Z(\mathrm{O})/[Z - Z(\mathrm{O})]$. This assumption is correct if the IRA applies, which is a good assumption for this case, since most of the heavy elements are formed by stars more massive than 8 $M_\odot$.

3. SOLAR NEIGHBORHOOD

In what follows we will compute yields and compare them with observations of the solar neighborhood because we have more information for it than for any other system. For example the solar vicinity has: a) the best IMF, $\Delta Y/\Delta Z$ and $Z(\mathrm{O})/[Z - Z(\mathrm{O})]$ values available, b) a relatively small amount of non-baryonic matter, and c) several detailed chemical evolution models.

3.1. IMF

A recent determination of the IMF for the solar neighborhood is that by Kroupa, Tout, & Gilmore (1993) hereafter KTG.

The KTG IMF is given by

$$\xi(m) = \begin{cases} 0.035\ m^{-1.3} & \text{if } 0.08 \le m < 0.5\ , \\ 0.019\ m^{-2.2} & \text{if } 0.5\ \le m < 1.0\ , \\ 0.019\ m^{-2.7} & \text{if } 1.0\ \le m < 120\ , \end{cases} \tag{3}$$

where m is the stellar mass in solar units and $\xi(m)dm$ is the number of stars in the mass interval from m to $m + dm$. For the $0.08 \le m < 0.5$ mass range the exponent at the 95 percent confidence interval is in the -0.70 to -1.85 range and the center is given by -1.3. We will define three IMFs: Ka, Kb and Kc that are obtained by extrapolating the KTG IMF to $m = 0$ and adopting the center and the two extremes of the 95% confidence interval the corresponding IMFs are given by

$$\xi_a(m) = 0.051m^{-0.7} , \quad (4)$$

$$\xi_b(m) = 0.035m^{-1.3} , \quad (5)$$

$$\xi_c(m) = 0.025m^{-1.85} , \quad (6)$$

for $0 \leq m < 0.5$, while for $m \geq 0.5$ we have adopted equation (3). The K IMFs have the same slope for $m \geq 1$ than the Scalo (1986) IMF and the slope only differs for $m < 1$ values.

Since the Salpeter IMF has been frequently used in the literature for $m \geq 1$ we will use it for comparison purposes. For $1.0 \leq m < 120$ we will adopt an IMF, with the Salpeter exponent, given by

$$\xi(m) = 0.019\, m^{-2.35}, \quad (7)$$

while for the $0.5 \leq m < 1$ range we will adopt equation (3) and for the $0 \leq m < 0.5$ range we will adopt equations (4–6). We will call these three IMFs: Sa, Sb and Sc, respectively.

3.2. Net y(O)

To compute the net yield it is necessary to evaluate the enrichment of the ISM by different stellar generations taking into account its variations with Z from zero to the present value. We have computed y(O) for the solar neighborhood based on: a) the six IMFs defined in § 3.1, b) the stellar evolution computations by Maeder (1992) for $Z = 0.001$ and $Z = 0.02$, where for $Z = 0.02$ we used the recommended high $\dot{M}$ case, c) the assumption of a linear relationship for the behaviour of y(O) with Z, and d) the IRA, which for oxygen is excellent because it is produced by stars with $m > 8$. Objects with $m \leq 1$ do not enrich the interstellar medium but affect M_* in equation (2). The M(BH) is left as a free parameter. The results are presented in Figure 1, where we plot y(O) as a function of the critical mass for black hole formation for six different IMFs.

3.3. Observed y(O)

The $Z(\mathrm{O})_\odot$ value is often used to determine y(O). Sometimes the Z(O) value of H II regions is used (e.g., Peimbert & Serrano 1982). The Z(O) value for H II regions depends on their temperature structure; it is often assumed that the mean square temperature fluctuation, t^2, is zero, and in this case the derived Z(O) is two or three times smaller than $Z(\mathrm{O})_\odot$. Recent results indicate that $t^2 \approx 0.04$ for H II regions in the solar neighborhood (Peimbert, Torres-Peimbert, & Ruiz 1992; Peimbert, Storey, & Torres-Peimbert 1993a; Peimbert, Torres-Peimbert, & Dufour 1993b) which increases the Z(O) of H II

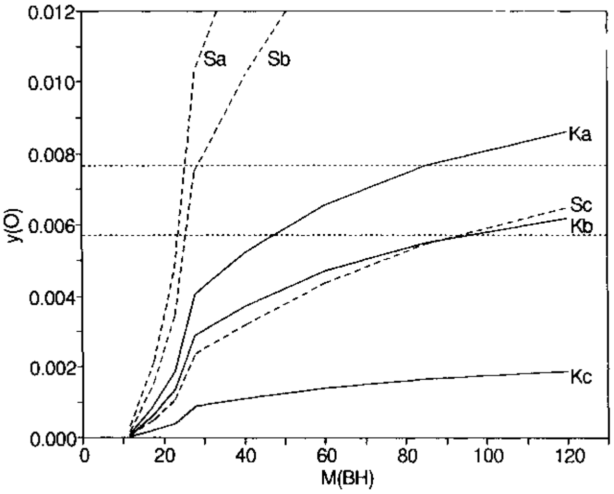

Fig. 1. y(O) versus M(BH) diagram for six IMFs. K stands for KTG and S for Salpeter, and the horizontal band indicates the observed y(O) values.

regions to values very similar to $Z(\mathrm{O})_\odot$ (see Table 1). In Table 1 we have taken into account the fraction of oxygen tied up in dust grains and corrected the interstellar gaseous oxygen abundance by 0.08 dex (Meyer 1985). In what follows we will adopt $Z(\mathrm{O})_\odot$ as representative of the solar vicinity.

There have been several detailed chemical evolution models of the solar neighborhood. It is beyond the scope of this paper to select one of these models or to produce a new one; nevertheless we will select a value of y(O) compatible with them. From chemical evolution models of the solar neighborhood the following values have been obtained: $y(Z) = 0.7\ Z_\odot$ (Twarog 1980 a,b), $y(\mathrm{O}) = 0.8\ Z(\mathrm{O})_\odot$ (Pagel 1989), $y(\mathrm{O}) = 0.6\ Z(\mathrm{O})_\odot$ (Meusinger & Stecklum 1992) and $y(Z) = 0.72\ Z_\odot$ (Malinie et al. 1993). Since y(O) is proportional to $y(Z)$ we will adopt $y(\mathrm{O}) = (0.7 \pm 0.1)Z(\mathrm{O})_\odot$ as a representative value for the solar vicinity, and from $Z(\mathrm{O})_\odot$ in Table 1 we obtain $y(\mathrm{O}) = 0.0067 \pm 0.001$. This y(O) value is presented in Figure 1.

From Figure 1 it can be seen that the Salpeter IMFs produce higher y(O) values than the KTG IMFs due to their higher exponent for $m > 1$. Furthermore the larger the amount of mass in objects with $m < 0.5$, the smaller the y(O) value. From this figure it is clear that Kc is incompatible with the observations for any value of M(BH).

3.4. Net $\Delta Y/\Delta Z$

We present the $\Delta Y/\Delta Z$ values in Figure 2, based on the same assumptions as for the y(O) computations, where again M(BH) has been left as a free parameter. The IRA is a good approximation for the solar neighborhood because the SFR is of the order of $10^{-10} M_{sn}$ yr^{-1}, where M_{sn} is a rep-

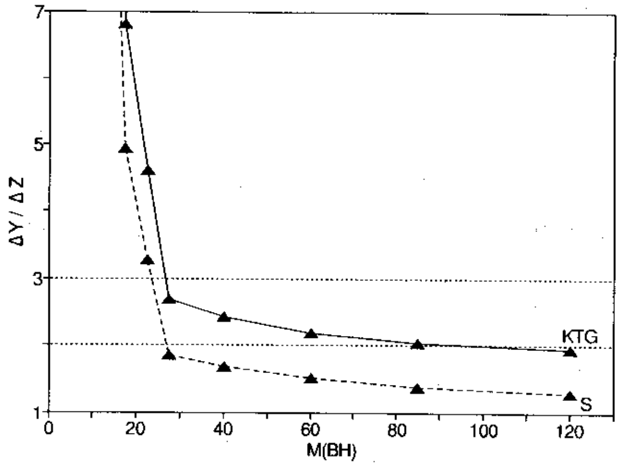

Fig. 2. $\Delta Y/\Delta Z$ versus M(BH) diagram for the K and S IMFs. $\Delta Y/\Delta Z$ depends only on the IMF for $m > 1$ and consequently there are no differences among cases a, b and c. The permitted $\Delta Y/\Delta Z$ band corresponds to the M17 observed value.

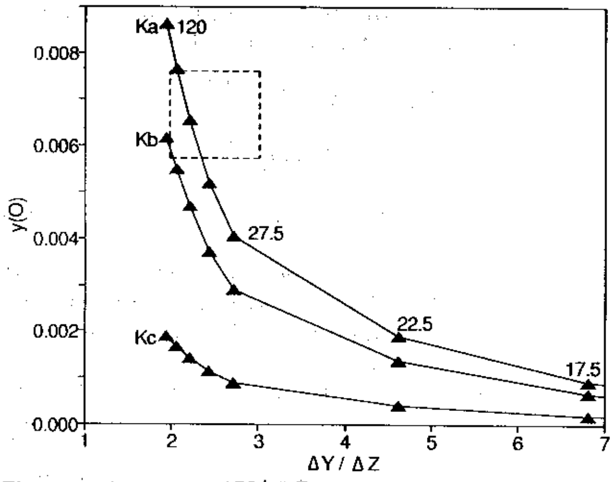

Fig. 3. y(O) versus $\Delta Y/\Delta Z$ values for the K IMFs. The region limited by observations is shown as a box. For a given $\Delta Y/\Delta Z$ the same M(BH) applies to the three IMFs. M(BH) increases to the left and the unmarked triangles in the top line correspond to 40, 60 and 85 $M_\odot$.

resentative mass of the solar neighborhood (e.g., Miller & Scalo 1979). The $\Delta Y/\Delta Z$ values are independent of the behaviour of the IMF for $m < 1$.

3.5. *Observed* $\Delta Y/\Delta Z$

We present in Table 1 the $\Delta Y/\Delta Z$ values for the sun and for H II regions of the solar neighborhood. For these determinations a Y_p value of 0.23 was adopted (Pagel et al. 1992; Torres-Peimbert, Peimbert, & Fierro 1989). We consider the M17 value to be the best and we have used it in Figure 2 to compare with the net values. As can be seen from this figure the Salpeter IMF is in agreement with the observations for M(BH) ~ 24–27 $M_\odot$ while the KTG IMF is in agreement with the observations for $M(\text{BH}) \geq 27\ M_\odot$.

In Figure 3 we have combined the two observational restrictions, y(O) and $\Delta Y/\Delta Z$, with the predictions from the K IMFs. From this figure it can be seen that: a) Ka agrees with the restriction for M(BH) in the 47 to 85 $M_\odot$ range, b) Kb agrees with the restriction for $95 \leq M(\text{BH}) \leq 110\ M_\odot$, and c) Kc does not agree with the restrictions.

Similarly in Figure 4 we have presented the predictions using the Salpeter IMFs and we find that Sa and Sb agree with the restrictions for M(BH) ~ 23–26 $M_\odot$ and 25–27 $M_\odot$, respectively, while Sc does not agree.

Similar results regarding M(BH) are obtained by using ΔZ(O) instead of ΔZ in Figures 2, 3, and 4.

3.6. $y(\text{O})/y(Z-\text{O})$

We present in Figure 5 the net $y(\text{O})/y(Z-\text{O})$ values based on the same assumption as for the y(O) computations. The $y(\text{O})/y(Z-\text{O})$ value varies strongly with M(BH) because O is preferentially formed by stars in the high-mass end of the 8–120 $M_\odot$ range while the other heavy elements are preferentially formed in the low-mass end of the 8–120 $M_\odot$ range.

TABLE 1

OXYGEN, HELIUM AND HEAVY ELEMENT ABUNDANCES BY MASS

Object	$\Delta Y/\Delta Z$	Z(O)	$Z(\text{O})/[Z-Z(\text{O})]$	Ref.[a]
Sun	2.31 ± 0.85	0.0096 ± 0.0009	0.97 ± 0.10	1
Orion($t^2 = 0.04$)	3.19 ± 0.85	0.0078 ± 0.0011	0.95 ± 0.12	2,3
M8 ($t^2 = 0.046$)	3.27 ± 1.00	0.0074 ± 0.0011	0.91 ± 0.14	2,4
M17 ($t^2 = 0.04$)	2.50 ± 0.50	0.0087 ± 0.0012	0.77 ± 0.11	2,3,5

[a] References: (1) Grevesse & Anders 1989; Grevesse et al. 1990; Biémont et al. 1991; Holweger et al. 1991; Hannaford et al. 1992. (2) Peimbert 1993. (3) Peimbert et al. 1993a. (4) Peimbert et al. 1993b. (5) Peimbert et al. 1992.

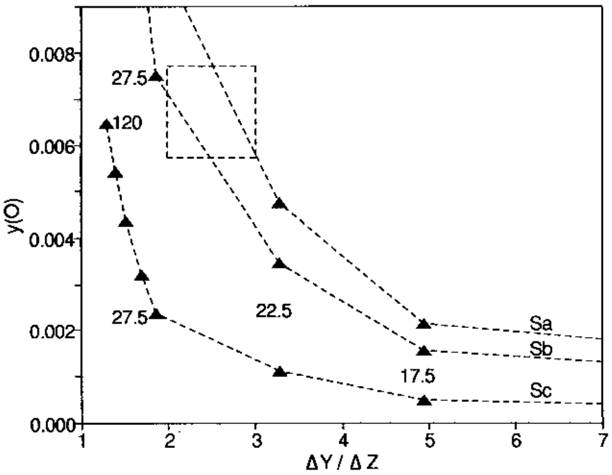

Fig. 4. Same as Figure 3 but for the Salpeter IMFs.

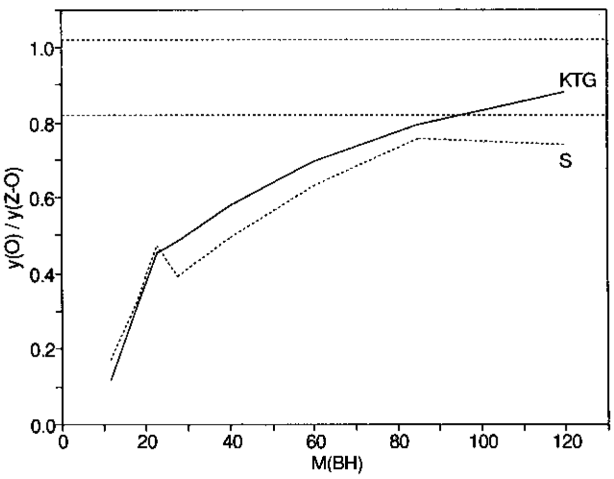

Fig. 5. $y(\mathrm{O})/y(Z-\mathrm{O})$ versus $M(\mathrm{BH})$ diagram for the IMFs by KTG and Salpeter. The yields ratio depends only on the IMF for $m > 1$, consequently there are no differences among cases a, b and c. The permitted band corresponds to the $Z(\mathrm{O})/[Z - Z(\mathrm{O})]$ observed value.

By giving equal weight to the solar value and the average value of the H II regions from Table 1 we obtain that $Z(\mathrm{O})/[Z - Z(\mathrm{O})] = 0.92 \pm 0.10$ for the solar neighborhood, this observational restriction is presented in Figure 5.

From Figure 5 it is seen that an excellent agreement between the net and the observed values is obtained for the KTG IMF; alternatively the S IMF predicts smaller values than observed, particularly for $M(\mathrm{BH}) < 45\ M_\odot$.

4. DISCUSSION

The observational constraints with 1σ errors are: $y(\mathrm{O}) = 0.0067 \pm 0.001$, $\Delta Y/\Delta Z = 2.5 \pm 0.5$ and $Z(\mathrm{O})/[Z - Z(\mathrm{O})] = 0.92 \pm 0.1$.

Of the three observational restrictions Sa and Sb satisfy $y(\mathrm{O})$ and $\Delta Y/\Delta Z$ for $M(\mathrm{BH}) \sim 23$–$27\ M_\odot$, but fail at these $M(\mathrm{BH})$ values by 4.0σ to satisfy the $Z(\mathrm{O})/[Z - Z(\mathrm{O})]$ restriction. Sc satisfies $y(\mathrm{O})$ for $M(\mathrm{BH}) \geq 103\ M_\odot$ but fails to satisfy the other two observational restrictions at these $M(\mathrm{BH})$ values by about 2σ. Furthermore, Scalo (1986) had already found that the Salpeter IMF exponent for $m > 1$ does not apply to the solar neighborhood.

On the other hand for the K IMFs we find that: a) Ka satisfies the $y(\mathrm{O})$ and $\Delta Y/\Delta Z$ restrictions for $M(\mathrm{BH})$ in the 47 to 85 $M_\odot$ range, but for these $M(\mathrm{BH})$ values fails to satisfy the $Z(\mathrm{O})/[Z - Z(\mathrm{O})]$ restriction by more than 1σ. b) Kb satisfies the $y(\mathrm{O})$ and $\Delta Y/\Delta Z$ restrictions for $95 \leq M(\mathrm{BH}) \leq 110\ M_\odot$ and it agrees with the $Z(\mathrm{O})/[Z - Z(\mathrm{O})]$ restriction for $M(\mathrm{BH}) \geq 95\ M_\odot$. Consequently Kb is concordant with the observations without the need to invoke black holes at the 1σ level. It is important to recall that the Kb exponent for $m < 0.5$ is in the center of the confidence interval of the KTG IMF. c) Kc in the most favorable case, without black holes, fails at the 4.8σ level to explain the observed $y(\mathrm{O})$; the observed restriction is $y(\mathrm{O}) = 0.0067 \pm 0.001$ while the net value with Kc is $y(\mathrm{O}) = 0.0019$.

The fit of the K IMFs has important consequences for the total mass in substellar objects of the solar vicinity. The mass density in substellar objects for Ka, Kb and Kc is obtained by integrating equations (4–6) in the $0 \leq m \leq 0.08$ range and is equal to $1.5 \times 10^{-3} M_\odot\ \mathrm{pc}^{-3}$, $8.5 \times 10^{-3} M_\odot\ \mathrm{pc}^{-3}$ and $0.114\ M_\odot\ \mathrm{pc}^{-3}$ respectively. As a consequence of the net $y(\mathrm{O})$ value for Kc, mentioned above, the $0.114\ M_\odot\ \mathrm{pc}^{-3}$ value is ruled out at the 4.8σ level.

We will derive the maximum mass density for substellar objects compatible with the observed yield at the 2σ level based on a K IMF. We will define Kd by

$$\xi_d(m) = 0.030 m^{-1.54} , \qquad (8)$$

for $0 \leq m < 0.5$, and by equation (3) for $m \geq 0.5$. The Kd exponent for $m < 0.5$ is inside the 95% confidence interval of the KTG IMF. For Kd without black holes, we obtain a net $y(\mathrm{O}) = 0.0047$ and by integrating (8) a mass density of substellar objects of $0.02\ M_\odot\ \mathrm{pc}^{-3}$.

Substellar objects, those with $m \leq 0.08$, have been proposed as candidates to solve the problem of the unobserved mass in the solar vicinity (e.g., Oort 1932, 1960; Bahcall 1984). Bahcall (1984) and Bahcall, Flynn, & Gould (1992) estimate that the unobserved mass amounts to 0.1 $M_\odot$ pc^{-3}. Alternatively Kuijken & Gilmore (1989) and Kuijken (1991) estimate that the unobserved mass is smaller than $0.02\ M_\odot\ \mathrm{pc}^{-3}$ (see also Ashman 1992 and references therein). From Kd and the observed $y(\mathrm{O})$ value we find that the mass density of substellar objects at the 2σ level has to be smaller than 0.02 $M_\odot$

pc^{-3}. Moreover, if Kd is adopted for $0.08 \leq m < 0.5$, then the y(O) restriction implies that the mass density of substellar objects has to be smaller than 0.02 $M_{\odot}$ pc^{-3} regardless of the behavior of the IMF as a function of mass for $m < 0.08$. Therefore if the missing mass amounts to 0.1 $M_{\odot}$ pc^{-3} then our result implies that it is not due to substellar objects and that it should be of the type that does not participate in the chemical evolution process.

5. CONCLUSIONS

We have found that by combining the stellar evolution models by Maeder (1992) with the IMF by Kroupa et al. (1993) and by comparing the predictions of this combination with the best observational restrictions, the need for the production of black holes by massive stars is ruled out. This result is mainly based on the Z(O)/[$Z - Z$(O)] constraint; the $\Delta Y/\Delta Z$ constraint alone is not yet strong enough to decide this issue. Carigi (1994) also rules out the presence of black holes based on the Scalo IMF and an elaborate model of the solar vicinity that does not assume IRA. Moreover, Peimbert, Colín, & Sarmiento (1994) also find that black holes are not necessary to account for the observed Z(O), $\Delta Y/\Delta Z$, and Z(O)/[$Z - Z$(O)] values in dwarf irregular galaxies.

We also find that the IMF by Kroupa et al. (1993) is in agreement with the observed $\Delta Y/\Delta Z$, Z(O), Z(O)/[$Z - Z$(O)] values, while the Salpeter IMF is not.

We have found from chemical evolution considerations, mainly based on the comparison of Z(O) with y(O), that the mass of substellar objects in the solar vicinity is smaller than 0.02 $M_{\odot}$ pc^{-3} (2σ). This result rules out the possibility that the dark mass derived from dynamical considerations by Bahcall (1984) and Bahcall et al. (1992) could be due to substellar objects.

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