THE CHEMICAL EVOLUTION OF THE GALAXY WITH VARIABLE INITIAL MASS FUNCTIONS

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ABSTRACT

In this work we explore the effects on the chemical evolution of the Galaxy of adopting initial mass functions (IMFs) variable in time. To this end, we adopt a chemical evolution model that assumes two main infall episodes for the formation of the Galaxy that has proved to be successful in reproducing the majority of the observational constraints, at least for the case of a constant IMF. Different variable IMFs are tested with this model, all assuming that massive stars are preferentially formed in ambients of low metallicity. This implies that massive stars are formed preferentially at early times and at large Galactocentric distances. Our numerical results have shown that none of the variable IMFs proposed so far are able to reproduce all the relevant observational constraints in the Galaxy, and that a constant IMF still better reproduces the observations. In particular, variable IMFs of the kind explored here are unable to reproduce the observed abundance gradients, even allowing for changes in other chemical evolution model parameters, such as, for instance, the star formation rate. As a consequence, we conclude that the G-dwarf metallicity distribution is best explained by infall with a large timescale and a constant IMF, since it is possible to find variable IMFs of the kind studied here reproducing the G-dwarf metallicity, but this worsens the agreement with other observational constraints.

Subject headings: Galaxy: abundances — Galaxy: evolution — stars: luminosity function, mass function

1. INTRODUCTION

The initial mass function (IMF) is one of the basic ingredients of chemical evolution models. The IMF is normally derived from the observed present-day mass function (PDMF) in the solar neighborhood and is assumed to be independent of time. The PDMF gives the present number of main-sequence (MS) stars with mass between \( m \) and \( m + dm \) per pc\(^3\) per log \( m \), and is obtained from the observed luminosity function of MS stars (see Scalo 1986).

The derivation of the IMF from the PDMF is a difficult procedure, involving assumptions about the behavior of the star formation rate during the lifetime of the Galaxy (see Tinsley 1980; Scalo 1986). In particular, for stars with lifetimes that are larger than the age of the Galaxy \( (m \lesssim 1 \, M_\odot) \) the IMF is derived by assuming an average star formation rate in the past, whereas for stars with lifetimes that are negligible relative to the age of the Galaxy \( (m \gtrsim 2 \, M_\odot) \), the IMF is derived by assuming a present-time star formation rate and taking into account the stellar lifetimes \( (\tau_m) \). The IMF in the mass range between 1 and 2 \( M_\odot \) is obtained by connecting the two parts of the IMF described above. It is worth noting that in this procedure the main assumption is that the IMF has not varied in time. The IMF is usually approximated by a power law of the form \( \phi(m) \propto m^{-(1+x)} \), with \( m_{\text{lower}} \leq m \leq m_{\text{upper}} \).

This method has often been adopted, and since it cannot generate a precise determination of the IMF slope, different results have been reported. Salpeter (1955), in a pioneering work, found a slope of \( x = 1.35 \) in the mass range 2–10 \( M_\odot \). For the sake of simplicity, this IMF has often been extrapolated to upper and lower masses in order to be used in chemical evolution models. More complex power laws, with different slopes for different mass ranges, have been proposed (Miller & Scalo 1979; Tinsley 1980; Scalo 1986; Kroupa, Tout, & Gilmore 1993). All the IMFs discussed above are constant in time.

However, a variable IMF, which forms relatively more massive stars during the earlier phases of the evolution of the Galaxy compared to the one observed today in the solar vicinity, has often been suggested as one possible solution to the G-dwarf problem (i.e., the deficiency of metal-poor stars in the solar neighborhood compared to the number of such stars predicted by the simple model). Such an IMF would also be physically plausible from the theoretical point of view if the IMF depends on a mass scale such as the Jeans mass. In fact, the Jeans mass is strongly dependent on the temperature, which would have been higher at earlier times (see Larson 1998). Terlevich & Melnick (1983) proposed an IMF in which the slope \( x \) is a strong function of the metallicity. However, the parameterization for this dependence was very uncertain. This IMF was used in a chemical evolution model by Matteucci & Tornambè (1985), who suggested that only an IMF in which the slope is a less strong function of the metallicity could lead to an agreement with the observed properties of our Galaxy. More recent suggestions regarding metallicity-dependent IMFs have been made by Chuevkenov & Gluknov (1995), Silk (1995), and Scully et al. (1996).

Ferrini, Palla, & Penco (1990) investigated the problem of the origin of the IMF by assuming a nonlinear and nonequilibrium dynamics when describing the fragmentation of molecular clouds. In such a system, star formation occurs if an instability criterion is satisfied, giving rise to the mass spectrum of the newly formed stars. Taking into account
different instability criteria when defining the critical mass for fragmentation, these authors have shown that in order to explain the IMF for the solar vicinity, one must assume the more realistic view that the critical mass for fragmentation is determined by a cooperative effect of different forces, namely, gravitational, magnetic, and turbulent. These calculations, however, cannot give any information about the time dependence of the IMF, but only produce an IMF in agreement with that of the solar neighborhood.

Another theoretical approach to the IMF problem has been proposed by Padoan, Nordlund, & Jones (1997; hereafter PNJ). Since random motions are probably ubiquitous in sites of star formation, PNJ suggested describing the formation of protostars as the gravitational collapse of Jeans masses in a density distribution shaped by random supersonic motions. Such flows create a highly nonlinear density field, with density contrasts of a few orders of magnitudes. They show that the probability density function (pdf) of the density field can be well approximated by a log-normal distribution. The weakness of such an IMF is the fact that it predicts that the most massive stars should form where the density is smallest, contrary to what is observed in star-forming regions (see Scalo et al. 1998 for a detailed discussion of this point and further criticism, also on theoretical grounds). The PNJ IMF has already been tested in models of elliptical galaxies by Chiosi et al. (1998), and they concluded that a strongly varying IMF is suitable for such galaxies.

There is at present no clear, direct, empirical evidence that the IMF in the Galaxy has varied with time. A detailed discussion of possible observed variations in the IMF in different environments can be found in the recent review by Scalo (1998), but such variations are comparable with the uncertainties still involved in the IMF determinations. The present uncertainties in the observational results prevent any conclusion against the idea of a universal IMF.

Given the uncertainties on both theoretical and observational grounds, the IMF variations can be treated in a parameterized form, and the proposed IMFs can be tested by means of a detailed chemical evolution model. We chose to rely on the so-called two-infall model (Chiappini, Matteucci, & Gratton 1997; hereafter CMG97), which provided results in good agreement with several observational constraints in the Milky Way. The observational constraints are of fundamental importance to building a realistic chemical evolution model; for this reason the Milky Way is a good starting point, since we have a high number of observational constraints available for our Galaxy. With respect to these constraints, the last few years have been of crucial importance, and in the case of the Milky Way, the new observational data required a revision of the previous chemical evolution models (CMG97; Pagel & Tautvaisiene 1995; Pagel 1997). The results obtained by CMG97 from a careful comparison of model predictions and observational constraints strongly suggest that the previously adopted picture of the formation of the Galaxy, in which the gas shed from the halo was the main contributor to the thin disk formation, is no longer valid.

However, the two-infall model adopted a constant IMF. The aim of this paper is to address the question of what time-dependent IMF properties are allowable while still matching the observational constraints when adopting the two-infall model (CMG97). To this end, we test different IMFs in our chemical evolution code, ranging from those for which the variability is contained on the slope of the power-law taken as a function of the metallicity (Scully et al. 1996; Terlevich & Melnick 1983) to that of PNJ, which also predicts a change in the stellar mass that contributes most to the IMF as a function of time.

In §2 we discuss the characteristics of the IMFs adopted. In the particular case of the PNJ IMF, we show the assumptions necessary to apply this function to the Galactic disk. In §3 we briefly describe the chemical evolution model adopted. In §4 we present the results, and conclusions are drawn in §5.

2. THE VARIABLE IMFS ADOPTED

2.1. PNJ IMF

In the approach adopted by PNJ, the IMF contains a dependence on the average physical parameters (temperature, density, velocity dispersion of gas) of large-scale sites of star formation. The model is based on numerical experiments of highly supersonic random flows (Nordlund & Padoan 1999). In this model, the most probable stellar mass per logarithmic mass interval, that is, the stellar mass that contributes most to the mass function, is defined as \( x(M_{\text{max}}) = 0 \), and is given by

\[
M_{\text{max}} = 0.2 \, M_\odot \left( \frac{n}{1000 \, \text{cm}^{-3}} \right)^{-1/2} \left( \frac{T}{10 \, \text{K}} \right)^{2} \times \left( \frac{\sigma_v}{2.5 \, \text{km} \, \text{s}^{-1}} \right)^{-1},
\]

(1)

As we will see in the next sections, this IMF favors higher mass stars at earlier times when applied to the chemical evolution of the Milky Way. We would like to point out that one possible problem with the equation quoted above is that such an IMF predicts that the most massive stars form in the lowest density and hottest regions, which seems to violate some theoretical expectations. For a careful discussion on this particular point, see Scalo et al. (1998). These authors call attention to the fact that at present there is still no physical basis for such an IMF, and that IMFs other than the one adopted here could be constructed to give similar dependencies.

As is clear from equation (1), in order to use the PNJ IMF, the sites of star formation must be described in terms of the values of the velocity dispersion, temperature, and mean density. Since the chemical evolution model adopted here does not contain the energetics of the ISM, some simplifying hypotheses are needed in order to apply this IMF to the two-infall model. In order to do so, we assume that most of the stars are born in giant molecular cloud complexes, namely, in cold gas at a temperature \( T = 10 \, \text{K} \), mean density \( \langle n \rangle = 50-100 \, \text{cm}^{-3} \), and typical size of 100 pc (Dame et al. 1986). This is almost true at the present time (Myers et al. 1986; Mooney & Solomon 1988; Gerritsen & Ike 1997), but could be a weak hypothesis during the early phases of the formation of the disk.

In fact, the adopted mean cloud temperature could be uncertain even for the present, since it holds only for clouds with virtually no star formation. Moreover, since the temperature of molecular clouds is controlled by the balance between heating by external radiation fields and cooling by line and dust emission, we should expect it to have varied with time. In principle, the effect of changes in temperature
can be compensated for by sufficiently large changes in pressure or gas density (see Larson 1998). However, as discussed by Larson, it is much easier to find reasons to expect higher molecular cloud temperatures at earlier times than important pressure or density variations.

As will be discussed in the next sections, our hypothesis of constant molecular temperature and density throughout the evolution of the Galaxy could be responsible for the mild variation of the PNJ IMF when applied to the two-infall model. In fact, the main effect of such a hypothesis will be to make the IMF variable only in the very early phases of the disk evolution.

Once these values of temperature and mean density are adopted, the IMF depends on the particular value of the velocity dispersion of the large-scale site of star formation. As an estimate of the velocity dispersion of the cold gas, we use the vertical velocity dispersion (perpendicular to the plane of the Galactic disk), under the assumption that the gaseous disk (cold molecular gas) is supported in the vertical direction by the velocity dispersion of molecular clouds. In fact, the vertical velocity dispersion is expected to be comparable to the internal velocity dispersion of giant molecular cloud complexes, since, according to Larson (1981), the velocity dispersion of gas generally scales as the square root of the linear dimension of the considered region, and the giant molecular cloud complexes have a linear extension comparable to the scale height of the disk.

Following Bahcall & Casertano (1984), we can relate the total surface mass density \( \sigma_{\text{tot}} \), the scale height \( h \), and the vertical velocity dispersion \( \sigma_v \) as

\[
\sigma_v^2 \approx 2n_G h \sigma_{\text{tot}}. \tag{2}
\]

This is a good approximation in the early evolution of the disk, when the gravitational potential is dominated by the gas, while it is a rough approximation toward the end of the disk evolution, when the stellar component contributes significantly to the gravitational potential and its scale height can grow larger than the scale height of the cold gas. N-body simulations by Gerritsen & Icke (1997) show that the star formation can only occur in the midplane of a spiral galaxy, where the gas is dense enough to cool, and that for this gas the scale height is lower than that of the other components, namely, old stars or warm gas.

To be able to predict the vertical velocity dispersion of the clouds, we assume that (1) the disk surface density has a radial distribution and a time evolution determined by an infall law, where the radial distribution is exponential (see CMG97), and that (2) the scale height of the molecular clouds in the disk is constant with time and radius, \( h = 100 \text{ pc} \).

The second of the two hypotheses above is based on a mixture of theoretical assumptions and observational evidence. We assume \( h \) to be constant in time, because its time evolution during the disk formation process is poorly known. However, the vertical velocity dispersion grows only as the square root of \( h \), so even if the scale height were initially 4 times larger, the velocity dispersion would be only twice as large as assumed here. We have verified that the results of the present work are not significantly affected by such a time variation of the velocity dispersion. We also assume \( h \) to be constant along the radius, because a number of observational results in our Galaxy and in external edge-on late-type galaxies have shown that the scale height is approximately constant in the molecular gas (Solomon, Sanders, & Scoville 1978; Sanders, Solomon, & Scoville 1984; Garcia-Burillo, Dahlem, & Guélin 1991; Heiles 1991), in the atomic gas (Dickey & Lockman 1990; Heiles 1991; Ferrara 1993, 1996), and in the stellar disk (de Grijs & Peletier 1997). By approximately constant we mean that the variation of the scale height is small compared to the exponential radial variation of the column density. However, all of these considerations refer mostly to the region inside 10 kpc from the Galactic center, since in the outer disk both the molecular and the atomic gas components flare to large scale heights (Grabelsky et al. 1987). Therefore, our assumption weakens outside the region of 10 Kpc.

Once \( h \) is assumed to be constant, the velocity dispersion of the molecular clouds grows toward the center of the disk according to equation (2).

Since the total surface mass density of the disk is assumed to have an exponential dependence on the Galactocentric distance and to increase with time (see § 3), the vertical velocity dispersion depends on the Galactocentric distance, \( r \), and time, \( t \):

\[
\sigma_v(r, t) \approx (3.8 \text{ km s}^{-1}) \sqrt{h_{\text{pc}} \sigma_{\text{tot}}(r, t)}, \tag{3}
\]

where \( h_{\text{pc}} \) is the scale height of the (cold gas) disk in kpc, and \( \sigma_{\text{tot}}(r, t) \) is the total (gas plus stars) surface mass density of the disk, measured in \( M_\odot \text{ pc}^{-2} \).

Under these assumptions, the IMF in the Galactic disk can be determined.

From equation (1), the typical stellar mass is inversely proportional to the velocity dispersion of the star-forming gas. Since the surface density has an exponential distribution (at least approximately in the present model), the velocity dispersion also depends exponentially on the Galactocentric distance, with a scale length equal to twice the value for the disk mass density, and the typical stellar mass grows exponentially with Galactocentric distance, with the same scale length as the velocity dispersion.

Given the mild variation of the PNJ IMF when applied to the two-infall model, due to our assumptions of constant molecular temperature and density, we will explore cases of more strongly variable IMFs in a parameterized form in the next sections. In fact, in order to follow the evolution of the gas temperature, we would need a hydrodynamical model, which is beyond the scope of this paper.

2.2. IMFs with a Variable Slope

Following a suggestion by Terlevich & Melnick (1983), Matteucci & Tornambé (1985) adopted a parameterized variable IMF, assuming its slope \( x \) to be a function of the metal content of the interstellar medium, \( x = \log Z + 0.45 \) for \( Z > 0.002 \), while for \( Z \leq 0.001 \) a Salpeter IMF was adopted. This IMF was tested in a model that formed the disk in a much smaller timescale than the one adopted in the present two-infall model.

The third IMF we adopt is the one proposed by Scully et al. (1986). This IMF also has a slope that is a function of metallicity, parameterized as a function of oxygen instead of the global total metal content. The following parameterization is adopted: \( x = 1.25 + O/\text{O}_0 \).

In previous works, both of these IMFs where tested only in the solar vicinity. In the next sections we will also see the predicted gradients for the abundance of oxygen and the gas in the disk of the Milky Way when such IMFs are applied to the two-infall model.
3. THE MODEL

The two-infall model assumes two major gas infall episodes. The first one is responsible for the formation of the halo and part of the thick disk. The second infall episode, delayed with respect to the first, forms the thin disk. One of the basic results of CMG97 is that in order to reproduce simultaneously all the constraints in our Galaxy, one should disentangle the evolution of the halo/thick disk from that of the thin disk. This implies that most of the thin disk was formed by accretion of extragalactic primordial material and not just from gas lost from the halo, as previously thought. The timescales suggested for the formation of the halo/thick disk and the thin disk are 1 and 8 Gyr, respectively.

As in Matteucci & Francois (1989), the Galactic disk is approximated by several independent rings, 2 kpc wide, without exchange of matter between them. We chose not to include radial flows, since it is known that they cannot originate an abundance gradient by themselves (Edmunds & Greenhow 1995). In our model, the abundance gradient for a constant IMF arises as a consequence of the assumed inside-out formation of the Galactic disk. The basic equations are the same as in Matteucci & Francois (1989), except for the expression adopted for the rate of mass accretion in each shell, which is given by

\[ \frac{dG(r, t)}{dt} = \frac{A(r)}{\sigma(r, t)} (X)_{\text{inf}} e^{-t/\tau_H} + \frac{B(r)}{\sigma(r, t)} (X)_{\text{inf}} e^{-t/\tau_D}, \]

where \(G(r, t)\) is the normalized surface gas density of the infalling material in the form of the element \(i\), \((X)_{\text{inf}}\) gives the composition of the infalling gas, which we assume to be primordial, \(\tau_{\text{max}}\) is the time of maximum gas accretion onto the disk, and \(\tau_H\) and \(\tau_D\) are the timescales for the mass accretion in the halo and thin disk components, respectively. These are the two really free parameters of our model and are constrained mainly by comparison with the observed metallicity distribution in the solar vicinity. The \(\tau_{\text{max}}\) value is chosen to be 2 Gyr and roughly corresponds to the end of the halo phase. The quantities \(A(r)\) and \(B(r)\) are derived by the condition of reproducing the current total surface mass density distribution in the solar neighborhood. The current total surface mass distribution is taken from Rana (1991), whereas the surface gas density distribution is predicted by the model. For the thin disk, we assume a radially varying \(\tau_D(r)\), which implies that the inner parts of the thin disk are built much more rapidly than the outer ones. In other words, we are dealing with an inside-out picture, as suggested by dynamical models (Larson 1976). The adopted radial dependence of \(\tau_D\) is

\[ \tau_D(r) = 0.875r - 0.75. \]

As discussed in CMG97, the above expression was generated in order to obtain a timescale for the bulge formation \((R < 2 \text{ kpc})\) of 1 Gyr, in agreement with the results of Matteucci & Brocato (1990), and a timescale of 8 Gyr at the solar neighborhood, which best reproduces the G-dwarf metallicity distribution (we are adopting \(R_{\odot} = 10 \text{ kpc}\)).

The star formation rate (SFR) adopted here is the same as in CMG97, and it was chosen in order to give the best agreement with the observed constraints. It is assumed to be proportional both to the surface gas density and to the total surface mass density, with an exponent \(k_H = 1.5\) and a SFR efficiencies of \(v_H = 2.0 \text{ Gyr}^{-1}\) and \(v_D = 1.0 \text{ Gyr}^{-1}\) (see CMG97 for details). Note that the surface mass density exponent of 1.5 obtained from the best model of CMG97 is in very good agreement with the recent observational results of Kennicutt (1998). An exponent of this order is also suggested by the N-body simulations of Gerritsen & Icke (1997).

Our adopted SFR has the form

\[ \Psi(r, t) \propto v(r) \sigma_{\text{tot}}^{-1}, \]

were \(\sigma_{\text{gas}}\) and \(\sigma_{\text{tot}}\) are the gas and total surface mass density, respectively. We also adopted a threshold in the star formation process in which the star formation stops when the surface gas density drops below 7 M\(_{\odot}\) pc\(^{-2}\). Such a threshold has been suggested by star formation studies (Kennicutt 1989; McGaugh & Blok 1996) and naturally produces a gap in the star formation between the first and second infall episode, as suggested by observational results discussed in Gratton et al. (1997; see CMG97 for a discussion).

The threshold surface gas density of 7 M\(_{\odot}\) pc\(^{-2}\) used in the model is not directly related to the mean density of molecular clouds. Nevertheless, it is interesting to note that the existence of this threshold for star formation and our assumption that stars are formed in molecular clouds are strongly related to each other. In fact, 7 M\(_{\odot}\) pc\(^{-2}\) is approximately the column density necessary for the gas to shield from UV radiation and form molecules: if the disk column density is significantly below this value, molecular clouds can hardly be formed, and no star formation will occur (if stars are assumed to be formed in molecular clouds).

The adopted nucleosynthesis prescriptions are (1) for low- and intermediate-mass stars, the yields from Renzini & Voli (1981) with \(\alpha = 1.5, \eta = 0.33\); (2) for Type Ia super-
novae, the yields from Thielemann, Nomoto, & Hashimoto (1993); (3) for massive stars, yields from Woosley & Weaver (1995); and (4) $^3$He yields from Dearborn, Steigman, & Tosi (1996).

The basic input parameters ($v_H, v_D, k_H, k_D, \tau_H, \tau_D$, and the adopted IMF) are summarized in Table 1. The subscripts $H$ and $D$ refer to the halo and thin disk, respectively.

4. RESULTS

The two-infall chemical evolution model published by CMG97 (hereafter model A) has been modified to test the IMF proposed by PNJ (hereafter models B and C) and the other two IMFs (models D and E). All those models are essentially the same as model A, but with different IMFs.

4.1. Solar Vicinity

The PNJ IMF predicts a higher number of massive stars in the early phases of the Galaxy evolution, with a progressive increase of low-mass stars in time. Figure 1 shows the behavior of the PNJ IMF at different epochs of Galactic evolution. From this figure we can see that at the beginning such an IMF presents a peak at a mass of almost $1 M_\odot$, and this peak mass shifts very soon (most of the variation occurs in the time interval 0.02–0.06 Gyr) toward lower values, leading to an IMF of the kind observed in the solar vicinity.

Figures 2 and 3 show the behavior of the Matteucci & Tornambé (1985) and Scully et al. (1996) IMFs, respectively (models D and E). As can be seen, those IMFs vary during the entire Galactic lifetime, since they are functions of the interstellar metal content. Both IMFs predict a higher number of massive stars at early times. Only in the very beginning does the Matteucci & Tornambé (1985) IMF predict a lower number of massive stars, as a result of the assumption that the IMF is a Salpeter one until the metal abundance in the interstellar medium has reached a value of 0.002.

Figure 4 shows the effect of the adopted mean density of the star-forming gas on the G-dwarf metallicity distribution in model B. It can be seen that a rather good fit of the G-dwarf metallicity distribution is obtained in model B, especially when the value $n = 50 \text{ cm}^{-3}$ is adopted for the mean density of the giant molecular clouds.

Figures 5 and 6 compare the model B (with $\langle n \rangle = 50 \text{ cm}^{-3}$) and model A predictions for the G-dwarf metallicity distribution and the $[O/Fe]$ versus $[Fe/H]$ relation. It can be seen that model B gives essentially the same results as model A. As discussed in CMG97, the G-dwarf metallicity distribution constitutes the tightest constraint for chemical
The G-dwarf metallicity distribution is representative of the history of the chemical enrichment of the Galaxy, since these stars have lifetimes larger than or equal to the age of the Galaxy.

Model B is also in agreement with the other available constraints in the solar vicinity. In Table 2 we present the results of model B compared with the observational constraints and with the model A predictions. It can be seen that model B results do not differ much from those of model A with regard to the observed quantities reported in Table 2. There are some differences in the predicted ratio of metal-poor and metal-rich stars and in the $\frac{\nu_\odot}{\nu_T}$ ratio. Model B predictions are in better agreement for both, although $\frac{\Delta Y}{\Delta Z}$ is still lower than the observed value (Pagel et al. 1992; Chiappini & Maciel 1994). Model B also predicts a value for the relative number of disk and halo stars that is in better agreement with the observed value of 3% suggested by Pagel & Patchett (1975). A higher value (~10%) was suggested by Matteucci et al. (1990), who estimated that the number of stars contained in a cylinder around the solar neighborhood with a practically infinite height above the Galactic plane, which is the actual quantity predicted by the chemical evolution models, could be a factor of 3–4 larger than the estimate by Pagel & Patchett (1975). The range in model predictions for this constraint is due to different assumptions of the halo phase duration (1 or 0.8 Gyr). Model B, however, predicts a ratio between the Type II and Type I supernova rates that is lower than the observed one. One of the consequences of this can be seen in Table 3. This table shows the solar abundances (by mass) predicted by both models at the time of formation of the Sun, e.g., 4.5 Gyr ago, and the observed solar values. Note that model B predicts systematically lower values for the products of massive star nucleosynthesis (O, Ne, Si, and Mg) and higher ones for the elements that are mainly produced by low- and intermediate-mass stars (Fe, N, and C) when compared with model A results. This is a consequence of the fact that the IMF adopted here slightly underestimates the number of massive stars.

As is well known, the oxygen abundance in the interstellar medium and young stars in the Orion nebula seems

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**TABLE 2**

**CURRENT PREDICTED AND OBSERVED QUANTITIES FOR THE SOLAR NEIGHBORHOOD FOR MODELS A AND B**

| Parameter | Model A | Model B | Observations* |
|-----------|---------|---------|---------------|
| Metal-poor/total stars (%) | 6–13 | 2–4 | 2–10 |
| SN II/SN I | 2.7 | 1.4 | 2.4 |
| $\Psi(R_p,t_{saw})$ (M$_\odot$ pc$^{-2}$ Gyr$^{-1}$) | 2.64 | 2.65 | 2–10 |
| $\sigma_j$ (R$_p$, t$_{saw}$) (M$_\odot$ pc$^{-2}$) | 7.0 | 7.0 | 6.6 $\pm$ 2.5 |
| $\sigma_j/\sigma_T$ (R$_p$, t$_{saw}$) | 0.14 | 0.14 | 0.05–0.20 |
| $\delta_{\nu \nu}$ (R$_p$, t$_{saw}$) (M$_\odot$ pc$^{-2}$ Gyr$^{-1}$) | 1.05 | 1.05 | 1.0 |
| $\Delta Y/\Delta Z$ | 1.63 | 1.96 | 3.5 $\pm$ 0.7 |
| $\Psi(R_p,t_{saw})/\langle \Psi \rangle$ | $\sim$0.7 | $\sim$0.7 | 0.18–3.0 |
| $X_j(P)/X_j$(now) | 1.51 | 1.82 | 1.4–11.9* |

*a* See CMG97 for references.

*b* See Tosi et al. 1998.
to be smaller by a factor of 2 than the solar value. Thus, it is not clear whether the solar composition should be considered as representative of the local ISM 4.5 Gyr ago. In fact, as suggested by Wielen & Wilson (1997), the Sun could have been born at a Galactocentric distance that is roughly 2 kpc smaller than its present position. Given the uncertainties involved, we can consider that observations and model predictions are in agreement inside a factor of 2 difference. This is the case for almost all the elements listed in Table 3 for models A and B. However, neither model predicts the abundances of $^3$He and Mg very well. As discussed in CMG97, $^3$He is a problem for almost all the chemical evolution models (see Tosi 1996). For Mg, this can be attributed to the lower yield predicted for this element by Woosley & Weaver (1995; see Chiappini et al. 1999).

The good agreement between model B and the observed properties of the Milky Way at the solar vicinity is due to the fact that the PNJ IMF, when applied to our Galaxy, does not vary much over most of the Galactic lifetime, as a consequence of our assumptions of constant molecular cloud temperature during the Galactic evolution. If in fact the cloud temperature and density have varied strongly over the history of the Galaxy, the predicted IMF will also vary more, and this would certainly worsen the agreement with the observational constraints considered here.

On the other hand, the other two IMFs (models D and E) vary substantially over the entire Galactic evolution. As a consequence, these IMFs do not give a good agreement with the solar-vicinity observational constraints. Figure 7 shows the predicted G-dwarf metallicity distribution for models D and E compared with models A and B. Those

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**Table 3**

| Element | Model A | Model B | Model D | Model E | Observations |
|---------|---------|---------|---------|---------|--------------|
| H       | 0.731   | 0.730   | 0.736   | 0.758   | 0.702        |
| D       | 4.63 (-5) | 4.10 (-5) | 5.27 (-5) | 5.72 (-5) | 4.80 (-5)   |
| $^3$He  | 10.05 (-5) | 14.0 (-5) | 5.48 (-5) | 5.31 (-5) | 2.93 (-5)   |
| $^4$He  | 2.55 (-1) | 2.57 (-1) | 2.50 (-1) | 2.37 (-1) | 2.75 (-1)   |
| $^{12}$C | 1.83 (-3) | 2.59 (-3) | 1.17 (-3) | 0.49 (-3) | 3.03 (-3)   |
| $^{16}$O | 7.29 (-3) | 4.39 (-3) | 8.26 (-3) | 2.45 (-3) | 9.59 (-3)   |
| $^{16}$Ne | 1.39 (-3) | 1.79 (-3) | 0.96 (-3) | 0.27 (-3) | 1.11 (-3)   |
| $^{13}$C | 4.76 (-5) | 7.40 (-5) | 2.51 (-5) | 0.99 (-5) | 3.65 (-5)   |
| Ne      | 0.94 (-3) | 0.53 (-3) | 1.12 (-3) | 0.32 (-3) | 1.62 (-3)   |
| Mg      | 2.48 (-4) | 1.55 (-4) | 2.76 (-4) | 0.83 (-4) | 5.15 (-4)   |
| Si      | 7.04 (-4) | 6.71 (-4) | 6.00 (-4) | 2.15 (-4) | 7.11 (-4)   |
| S       | 3.07 (-4) | 3.11 (-4) | 2.51 (-4) | 0.93 (-4) | 4.18 (-4)   |
| Ca      | 3.95 (-5) | 4.16 (-5) | 3.13 (-5) | 1.18 (-5) | 6.20 (-5)   |
| Fe      | 1.37 (-3) | 1.79 (-3) | 0.92 (-3) | 0.39 (-3) | 1.27 (-3)   |
| Cu      | 8.20 (-7) | 9.29 (-7) | 5.96 (-7) | 1.58 (-7) | 8.40 (-7)   |
| Zn      | 2.45 (-6) | 2.93 (-6) | 1.71 (-6) | 0.58 (-6) | 2.09 (-6)   |
| Z       | 1.43 (-2) | 1.26 (-2) | 1.37 (-2) | 0.44 (-2) | 1.89 (-2)   |

* From Anders & Grevesse 1989.
models predict too few metal-poor stars and a higher solar metallicity peak than that observed. The predicted solar abundances are also not in agreement with the observed ones (see Table 3). It is worth noting that here we adopt a long timescale for the formation of the solar vicinity (8 Gyr) and that a better agreement with the G-dwarf observed metallicity distribution could in principle be achieved by adopting these variable IMFs in a closed-box model scenario. However, as already shown by Scully et al. (1986) and Matteucci & Tornambe (1985), models that adopt a shorter infall timescale for the solar vicinity formation do not give good agreement with all the other observed properties. Moreover, in a closed-box model, the predicted gradients along the disk would be essentially flat.

From a comparison with the solar vicinity observational constraints, we can confirm the result of Matteucci & Tornambe (1985) that only a constant IMF or an IMF that varies only at early times can be in agreement with the solar vicinity properties.

4.2. The Galactic Disk

As stressed by Tosi (1996), it is of fundamental importance to apply the chemical evolution models not only to the solar vicinity but also to the whole Galaxy. She showed that it is possible to find models in good agreement with the solar vicinity constraints that do not fit the radial profiles observed in the Galactic disk, namely, the abundance gradients and the radial gas distribution, and that the main differences between the various models in the literature concern the predictions for the abundance gradient evolution. These can be seen as the most promising constraints to Galactic chemical evolution models.

Figure 8 shows the behavior of the model B IMF at different Galactocentric distances. This figure shows that the radial variation of the adopted IMF in model B is important only for low-mass stars (M ≤ 0.5 M☉), and predicts a higher number of them toward the Galactic center, where the metallicity is higher. A direct consequence of this fact is the predicted flatter gradient with respect to those presented by CMG97 (model A). Figure 9 shows the oxygen abundance gradient for three different models: model A (CMG97), model B (adopting the PNJ IMF), and model C (same as B, but with star formation efficiency increasing with decreasing Galactocentric distance). Model B predicts a flat gradient between 6 and 10 kpc, and a small negative one in the inner part of the Galaxy (R < 6 kpc). Model C, which adopts an increasing star formation efficiency νD toward the Galactic center, predicts a steeper gradient inside the solar circle. In this case, a bimodal abundance gradient steeper in the inner part and flatter outside, similar to the one found by CMG97, is recovered. However, as can be seen in Figure 10, a model with a higher star formation efficiency in the central parts (model C) consumes the gas very rapidly, thus reaching the threshold density value very soon. As a consequence, model C predicts a flat gas density radial profile, at variance with observations, whereas model B predicts a gas density distribution very similar to the one predicted by model A and in better agreement with observations.

Figure 10 also shows model D and E predictions for the radial gas profile. From this figure it can be seen that the only two models in good agreement with the observed radial profile are models A and B. However, as shown above (see Fig. 9), model B predicts even flatter abundance gradients than model A. Models D and E predict a radial gas profile that is flatter than the observed one, but in better agreement with the observations than the one predicted by model C. Moreover, the oxygen abundance gradient predicted by models D and E (see Fig. 11) has a slope similar to the one obtained with model A. In any case, those two models do not give predictions in agreement with the solar vicinity constraint, as shown in § 4.1.

This is a very important result, showing that only model A, with a constant IMF, is in agreement simultaneously...
Fig. 10.—Total surface gas density distribution given by Rana (1991) \((\text{thick solid lines})\). The predictions from all models of Table 1 are also shown.

Fig. 11.—Oxygen abundance gradient predicted by models A, D, and E.

with the solar vicinity and the disk observational constraints. The abundance gradients predicted by model A, although slightly flatter than the observed one, are steeper inside than in the outer parts of the Galactic disk and also steepen with time, in agreement with the recent results of Maciel & Quireza (1999).

Figure 12 shows the oxygen gradient evolution in time for model B. The present model \((B)\), with a variable IMF, predicts a more complex evolution for the radial abundance gradients than model A (see Fig. 13). In this case, although the general behavior is the same as in A (a gradient that becomes more negative in the inner parts and is roughly constant in the outer ones), there is an intermediate region in which the gradient is zero today and was positive at early epochs.

Another approach was recently proposed by Carigi (1996). She adopted a simple parameterized IMF that depends on the metallicity, taking into account the suggestion by Silk (1995) that at low metallicities the IMF should be more biased toward the formation of low-mass stars than the Scalo one. This is exactly the opposite of the IMFs presented here. She took the IMF from Kroupa et al. (1993) and adopted a metallicity dependence on the slope of their IMF for low-mass stars \((M \leq 0.5 \, M_\odot)\). Her IMF contains
an explicit dependence on the oxygen abundance and predicts that the number of very low mass stars decreases as oxygen increases. She applies this IMF to her chemical evolution model (one infall episode) and shows that such a model produces radial abundance gradients that steepen with time (at variance with her previous models but in agreement with the CMG97 model) but fails, as expected, to reproduce the G-dwarf metallicity distribution, predicting too many low-metallicity stars (the G-dwarf problem).

5. DISCUSSION AND CONCLUSIONS

In this work we adopt a new IMF proposed by PNJ and applied it to the two-infall chemical evolution model (CMG97) and two other strongly variable IMFs already suggested in the literature (Matteucci & Tornambé 1985; Scully et al. 1996). Those IMFs all predict a higher number of massive stars at the beginning of the Galaxy evolution and in the outermost regions of the Galactic disk.

The two-infall model coupled with the PNJ IMF reproduces most observational constraints for the solar vicinity, namely, the G-dwarf metallicity distribution, the $\alpha$/Fe versus [Fe/H] behavior, the solar abundances, the gas density, etc., as a consequence of the mild variation of such an IMF when applied to our chemical evolution model under the hypothesis of constant molecular cloud temperature and density, allowing only for a variation in the velocity of dispersion throughout the Galaxy evolution.

However, the gradient predicted when adopting this IMF (model B) is flatter than that obtained with a constant IMF, at variance with observations. This is due to the fact that the peak mass of the PNJ IMF is shifted toward higher mass values during the early phases of Galaxy evolution. This, combined with an inside-out picture for the thin-disk formation, leads to a flat abundance gradient. In this scenario, the outer parts of the thin disk are less evolved than the central ones, and hence there the IMF is biased toward higher mass stars. In order to obtain a steeper gradient, a stronger dependence of the star formation rate on the Galactocentric distance should be invoked. This, however, leads to a flat gas density profile, at variance with observations.

This fact suggests that models assuming a star formation rate that is a strong function of the radial Galactocentric distance (e.g., Prantzos & Aubert 1995) must also be confronted with the observed radial density profile and the abundance gradients. A strong radial variation for the star formation rate was adopted by Prantzos & Aubert (1995), but they also adopted a mild dependence of the SFR on the gas density, namely, a smaller $k$-value than the one adopted here. In this case, even with a SFR that is a strong function of the Galactocentric distance, they could obtain a gas density profile that strongly decreases outside the solar circle. In fact, as discussed by Matteucci & François (1989), the total surface gas density along the Galactic disk crucially depends on the exponent of the star formation law, $k$, and on the parameter $\tau_{\text{sf}}(r)$. The best value for $k$, as shown by CMG97, who obtained a good fit to the recent observed G-dwarf metallicity distribution (Rocha-Pinto & Maciel 1996), is larger than that used by Prantzos & Aubert (see Matteucci 1996 for a discussion) and is coupled with a timescale for the thin disk formation, at solar vicinity, of 8 Gyr. These are the two most important parameters of the models and are constrained into a very narrow range of values (see CMG97).

When adopting strongly variable IMFs along with the two-infall model, we obtain better gradients but a worse agreement with other observational constraints in the solar vicinity and the radial gas profile. Recently, Martinelli & Matteucci (1999) proposed a method to solve the G-dwarf problem in a closed-box model with a time-dependent IMF. They concluded that an IMF similar to the one proposed by Larson (1998) fails to reproduce the [O/Fe] versus [Fe/H] relation observed in the solar vicinity, even if it gives a good fit to the G-dwarf metallicity distribution, because of the strong time dependence of the number of Type II supernovae at early times. Their study also showed that a better fit to the abundance ratios is obtained when a constant IMF is adopted.
Contrary to the suggestion by Larson (1998) that it now appears that most of the known intergalactic gas has been heated and enriched in heavy elements by the effects of early star formation in galaxies, we do not think that this was the case at least for galaxies such as the Milky Way. For the Milky Way, in fact, a model with a constant IMF and a long timescale for the formation of the solar vicinity is still the best way to solve the G-dwarf problem.

It is interesting to note that not only can we conclude from theoretical considerations that models with a longer timescale for Galactic disk formation are better at reproducing the observational constraints, but also there is now observational evidence for infall. In a recent paper, Blitz et al. (1999) suggest that the high-velocity clouds (HVCs) represent infall of intergalactic medium onto the Local Group, and that those clouds could also represent the building blocks from which the Local Group was assembled, continuing to fuel the star formation on the disk of the Milky Way (see also Braun & Burton 1999). From a simulation of the dynamics of the HVCs, the authors estimate that the accretion of HVCs by the Milky Way was rapid early on, reaching a peak of about 30 times the current rate (estimated as being of the order of 7.5 $M_\odot$ yr$^{-1}$) within the first 1 Gyr after the beginning of the simulation, and that half of the mass accreted by the Milky Way falls onto it during the first 2 Gyr. The authors also show that the few available measurements from absorption lines give metallicities much lower than solar, in agreement with the idea that those clouds do not represent gas that left the disk through Galactic fountains, as has often been suggested in the literature (Bregman 1980). Those simulations are still very uncertain, mainly because of the uncertainty of the distance to HVCs. Better data on HVCs are fundamental to confirming or discarding the existence of infall onto the Milky Way.

Another argument in favor of models that adopt infall for the formation of the disk of the Milky Way is offered by Roche et al. (1998). Those authors estimate that galaxies at $2 < z < 3.5$ show a brightness evolution relative to those at $z < 0.35$, which is significantly larger than the luminosity evolution over this redshift range. They suggest that this can be explained by a size and luminosity evolution model in which the outer regions of spiral galaxies form later and with a longer timescale than the inner regions, causing the half-light radius to increase with time. To create this kind of model, those authors adopted the $\tau_d(r)$ proposed by CMG97 as corresponding to the SFR timescales at different radii of a spiral galaxy.

To summarize, the main results of the present paper are:

1. We tested the IMF proposed by PNJ in a model for the chemical evolution of the Milky Way (CMG97), and we showed that this IMF gives good agreement with the observed properties of the solar vicinity.

2. We concluded that such an agreement is due to the fact that this IMF, when applied to the two-infall model, shows a time variation that is important only in the early phases of Galactic evolution. This in turn is due to the simplifying assumptions adopted here, such as neglecting the dependence of the IMF on the gas temperature, which would produce a more sharply varying IMF. In these early phases, the IMF is biased toward massive stars.

3. The PNJ IMF combined with the inside-out picture for the thin disk formation predicts a gradient flatter than the one predicted by a model that adopts a constant IMF. This situation cannot be reversed by changing the SFR, because in this case the abundance gradient is recovered, but the gas density profile is destroyed. To better constrain the radial dependence of some of the adopted parameters, such as $\tau(r)$ or $\tau_d(r)$, more reliable observations are needed, especially for the gas, star formation, and abundance radial profile.

4. Models that adopt IMFs that are strongly dependent on metallicity, thus also simulating a dependence on the gas temperature, are not in agreement with the most important observational constraints of the solar vicinity and predict radial gas profiles at variance with observations; therefore, they should be rejected.

5. We conclude that a constant IMF and the assumption of a continuous infall onto the Galactic disk is still the best way to explain the observational constraints in the Milky Way, including the G-dwarf metallicity distribution.

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