RevMexAA (Serie de Conferencias), **11**, 171–176 (2001)

A NEW PICTURE FOR THE CHEMICAL EVOLUTION OF THE GALAXY: THE TWO INFALL MODEL

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RESUMEN

Presentamos un modelo de evolución química de la Galaxia, que supone evolución del halo y el disco grueso independiente del disco delgado. La Galaxia se forma por medio de dos colapsos que dan lugar al halo y el disco grueso y al disco delgado, respectivamente. Se predice la evolución de del gas, la tasa de formación estelar, la tasa de formación de supernovas y las abundancias de elementos químicos, como función del tiempo y posición radial en la Galaxia. Nuestros resultados sugieren que el modelo anterior de formación de la Galaxia, en el que gas del halo es el ingrediente principal en la formación del disco delgado, no es válido. Concluímos que se requieren 8×10^9 años para la formación del disco delgado en la vecindad solar. Esto implica que el gas empleado en la formación del disco delgado proviene no sólo del disco grueso, sino principalmente del medio intergaláctico. Podemos establecer algunas restricciones en variaciones de la función inicial de masa, el valor primordial del deuterio y en las fases más tempranas de la evolución de la Galaxia.

ABSTRACT

We present a chemical evolution model for the Galaxy which assumes that the evolution of the halo and thick disk is completely disentangled from the thin disk. The Galaxy formed by two main infall episodes which formed the halo-thick disk and thin disk, respectively. The model predicts the evolution of the gas mass, the star formation rate, the supernova rates and the abundances of 16 chemical elements as functions of time and galactocentric distance. Our results, strongly suggest that the previous picture for the Galaxy formation in which the gas shed from the halo was the main contributor to the thin disk formation, is not valid. We conclude a timescale of 8 Gyr for the thin-disk formation in the solar vicinity is required, implying that the infalling gas forming the thin-disk comes not only from the thick disk but mainly from the intergalactic medium. We constrain the IMF variation, Deuterium primordial value and earliest phases of Galaxy evolution.

Key Words: **GALAXY: CHEMICAL EVOLUTION — ISM: ABUNDANCES — STARS: VERY-METAL POOR STARS**

1. INTRODUCTION

Observational constraints are of fundamental importance to build a realistic chemical evolution model. Model predictions for the chemical evolution of the Galaxy are usually compared with different sets of observables by different authors. A better procedure is to adopt a *minimal set* of observables (Pagel 1997). It is also of fundamental importance to relax the instantaneous recycling approximation (IRA) and to account for the contribution of type Ia supernovae (SNe). This allows us to make a correct comparison between models and observational data, especially because the observed metallicity is usually represented by the iron abundance. Further, as discussed by Tosi (1996) it is important that new models are tested not only on the available observational constraints in the solar vicinity but on the observed radial properties of the disk as well.

With respect to these constraints the last 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 (see Chiappini et al. 1997; hereinafter CMG and Pagel & Tautvaisiene 1995; hereinafter PT for a discussion on this point). New data are now available concerning the age-metallicity relation, the G-dwarf metallicity distribution, the relative abundances of α-elements and iron and the radial abundance gradients and they require the construction of new models. In particular, Gratton et al. (1996) showed that the distribution of the abundances of α-elements to Fe for a large homogeneous sample of stars in the solar neighbourhood seems to indicate a short timescale for the evolution of the halo and thick disk phases and a sudden decrease in the star formation in the epoch preceding the formation of the thin disk. An analogous result was recently found by Bernkopf & Fuhrmann (1998) for the [Mg/Fe] ratio. Moreover, Gratton et al. (1996) identified three kinematically distinct populations: *i)* a population made of halo, thick-disk and perhaps bulge stars originating from the dissipative collapse of the halo, *ii)* a population of thin disk stars originating from the even more dissipative collapse of the disk, and finally *iii)* a population of thick-disk stars the origin of which should be different from the others, namely they should have formed in satellite galaxies and then accreted by the Galaxy during the star formation gap. This last component should contribute negligibly to the total number of stars but it should represent $\sim 50\%$ of the stars with $[Fe/H] < -1.0$. An analogous result was already found by Beers & Sommer-Larsen (1995; hereinafter BSL). These authors have shown that the thick disk population extends to very low metallicities. For instance, according to that work about 30% of metal-deficient stars in their sample, with metallicities $[Fe/H] \leq -1.5$, have kinematic properties typical of a thick disk population. This metal-weak tail of the thick disk population could have its origin in a major accretion episode during the Galaxy evolution (BSL and references therein).

Previous models (Matteucci & François 1989; MF) were based on only one episode of infall during which first the halo formed and then the disk, or (Pardi, Ferrini, & Matteucci 1995) on assuming that halo, thick and thin disk formed simultaneously but at different rates (pure collapse picture). These models, however, are difficult to reconcile with the new results discussed above. We present a chemical evolution model for the Galaxy which assumes two main infall episodes, the first responsible for the formation of the population described in *i)* namely, the one made of that fraction of the halo and thick disk stars which originated from a fast dissipative collapse such as that suggested by Eggen et al. (1962). The second infall episode forms the thin disk component with a timescale much longer than that of the thick disk formation. This model implies that most of the galactic thin disk, if not all, was formed out of accreted extragalactic material. This scenario for the Galaxy formation is not only in agreement with the recent observational results quoted above, but it is also in agreement with dynamical results (Wyse & Gilmore 1992; Ibata & Gilmore 1995). In fact, these last papers have shown that the spheroidal (bulge and halo) and disk (thick and thin disks) components of our Galaxy have substantial different angular momentum distributions. This strongly suggests that the previously adopted picture, where the gas shed from the halo was the main contributor to the thin disk formation, should be revised (PT; Pagel 1997).

2. OBSERVATIONAL CONSTRAINTS

A good model of chemical evolution of the Galaxy should reproduce a number of constraints which is greater than the number of free parameters. Therefore, it is very important to choose a high quality set of observational data to be compared with models predictions. Our set of constraints include: *(i)* The relative number of thin disk and metal-poor stars (halo plus part of thick disk stars) in the solar cylinder;*(ii)* Type I and type II supernova rates at the present time; *(iii)* Solar abundances; *(iv)* Present-day gas fraction; *(v)* Age-Metallicity relation; *(vi)* Present-day infall rate; *(vii)* Metallicity distributions for disk and metal-poor stars; *(viii)* The variation in the relative abundances of the most common chemical elements; *(ix)* Radial profiles for the SFR and gas mass density and *(x)* Radial abundance gradients.

For a detailed discussion on the above constraints see CMG and Pagel (1997). However, for the metalicity gradients the situation changed recently (Matteucci & Chiappini 1999). Observations of H II regions (Shaver et al. 1983) and type II planetary nebulae, good tracers of abundance gradients in the ISM (Maciel & Köppen 1994) show a negative abundance gradient for oxygen of the order of -0.07 dex/kpc. Vilchez & Esteban (1996) found a flattening of O/H, N/H and S/H gradients for $R_{GC} > 12$ kpc suggesting that these gradients present a bimodal behaviour. Kaufer et al. (1994) found that B stars did not exhibit any appreciable gradient but more recent studies (Smartt & Rolleston, 1997) found a gradient of oxygen ~ -0.07 dex kpc^{-1} between 5 and 18 kpc. Friel (1995) found an iron abundance gradient in open clusters of $-0.095\pm$ 0.017 dex kpc^{-1} between 7 and 16 kpc but Friel (1998) showed a more recent determination of the [Fe/H] gradient, shallower than the previous one. Shallower gradients for O/H, of the order of -0.04 dex Kpc^{-1}, are also found by recent determinations for HII regions (Deharveng et al. 2000; Esteban et al. 1999).

3. THE MODEL

The model of chemical evolution we adopt here is described in detail in the CMG paper. The main assumptions of this model: the Galactic disk is approximated by several independent rings, 2 kpc wide, without exchange of matter between them (MF). Continuous infall of gas ensures the temporal increase of the surface mass density σ_{tot} in each ring. The instantaneous recycling approximation is relaxed. This is of fundamental importance in treating those isotopes, such as ^{14}N and ^{56}Fe, which are mostly produced by long-lived stars.

The two main differences between the present model and the MF model are the rate of mass accretion and the rate of star formation. The prescription for the star formation rate (SFR) is: $\Psi(r,t) \propto \tilde{\nu}\sigma_{tot}^{k_2}\sigma_g^{k_1}$, where σ_{tot} is the total surface mass density, σ_g is the surface gas density, k_1 and k_2 are two constants and $\tilde{\nu}$ is the efficiency of the star formation rate expressed in units of Gyr^{-1} (for a discussion on alternative star formation rates see Matteucci and Chiappini 1999). The k and $\tilde{\nu}$ parameters of the star formation rate are not arbitrarily chosen. For the models to be in agreement with the observational constraints these two parameters must be restricted to a very small range of values (see next section). A threshold in the surface gas density ($\sim 7\ M_{\odot}pc^{-2}$) is also assumed; when the gas density drops below this threshold the star formation stops. The existence of such a threshold has been suggested by star formation studies (Kennicutt 1989) and naturally produces in our model a gap in the star formation rate during the transition between the thick and thin disk phases (as suggested by Gratton et al. 1996) (see figure 4 and 6 of CMG).

This model assumes two distinct infall episodes: the first during which the thick disk is formed and the second, delayed relatively to the first, during which the thin disk forms. The thin disk starts forming roughly at the end of the thick disk phase. In this model, the material accreted by the Galactic thin disk comes mainly from extragalactic sources and this is a fundamental difference between our present model and the one by MF. The extragalactic sources could be, for instance, the Magellanic Stream or a major accretion episode (see BSL) and references therein). Under these hypotheses, the new infall rate is given by:

$$d\,G_i(r,t)_{\rm inf}/dt = (A(r)/\sigma_{tot}(r,t_G))\,(X_i)_{\rm inf}\,e^{-t/\tau_T} + (B(r)/\sigma_{tot}(r,t_G))\,(X_i)_{\rm inf}\,e^{-(t-t_{\rm max})/\tau_D} \qquad (1)$$

where $G_i(r,t)_{\rm inf}$ is the normalized surface gas density of the infalling material in the form of the element i, $(X_i)_{\rm inf}$ gives the composition of the infalling gas, which we assume to be primordial, $t_{\rm max}$ is the time of maximum gas accretion onto the disk, and τ_T and τ_D are the timescales for the mass accretion in the thick disk 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 $t_{\rm max}$ value is chosen to be 2 Gyrs and roughly corresponds to the end of the thick disk 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 neighbourhood (Rana 1991). 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 (inside-out picture - Larson 1976, MF). The adopted radial dependence of τ_D is: $\tau_D(r) = 0.875r - 0.75$. This expression was built in order to obtain a timescale for the bulge formation ($R < 2$ kpc) of 1 Gyr (Matteucci & Brocato 1990), and a timescale of 8 Gyr at the solar neighbourhood, which best reproduces the G-dwarf metallicity distribution (we are adopting $R_{\odot} = 10$ kpc). We assume also that the e-folding time of the thick disk infall rate is $\tau_T = 1$ Gyr, which roughly coincides with the appearance of the first type Ia SNe and which leads to good agreement with the available constraints (see next section). Details on the adopted nucleosynthesis can be found in CMG. For the initial mass function (IMF) we adopt the prescriptions from Scalo (1986) as described in CMG, but we also compute models that adopt the theoretical IMF proposed by Padoan, Nordlund, & Jones (1997) (see Chiappini et al. 1999b). The model predicts abundances of H, D, ^{3}He, ^{4}He, C, O, N, Ne, Mg, S, Si, Ca, Fe, Zn, Cu, gas density, total mass density, star density, rate of type I and type II SNe as functions of time and galactocentric distance.

4. RESULTS

Model predictions versus Observational Constraints

We ran a large number of models for the solar vicinity and the whole disk, varying the star formation rate parameters (k, ν) and timescales for the thick and thin disk formation (τ_T, τ_D). Surprisingly only very few combinations of parameters lead to an agreement with the observational constraints. Parameters for our best model are: $\nu_T = 2.0, \nu_D = 1.0, k_T = 1.5, k_D = 1.5, \tau_T = 1.0, \tau_D = 8.0$. Subscripts T and D refer to thick and thin disk, respectively. Is is worth noting that the higher k value adopted by CMG together with the longer timescale for the thin disk formation (8 Gyrs for the solar vicinity) relative to those of MF, ensures a good fit of the reviewed G-dwarf metallicity distribution (Rocha-Pinto & Maciel 1996). Moreover, this choice for the star formation exponent agrees with recent estimates of the star formation rate in spirals (Kennicutt 1998).

It is clear from our models that in order to obtain a reasonable number of metal poor stars and simultaneously fit the metallicity distribution of the solar vicinity it is necessary to decouple the evolution of the (halo)-thick-disk from that of the thin disk. In fact, this was a long standing problem for chemical evolution models (see Matteucci et al. 1990 for a discussion). Moreover, as already pointed out in section 1, this decoupling is also required from the observational point of view (Wyse & Gilmore 1992; BSL; Pagel 1997; PT). Our best model predicts a fraction of low metallicity stars in the range $6 - 10\%$, the exact value depending on the assumed duration of the thick disk phase (1 to 2 Gyrs). This is in good agreement with the observed value of 10% as estimated by Matteucci et al. (1990) (see CMG). A very good agreement is obtained between the predictions of our model and the new data for the metallicity distribution of disk stars in the solar vicinity (Figure 7 of CMG). The observed metallicity includes the thin disk stars as well as part of the thick disk stars, since the halo stars and the metal weak tail of the thick disk were excluded from the data by using an abundance criterion (all stars with [Fe/H] < -1.2). The same criterion has been used in the model predictions.

The predicted ratio of supernovae rates SNII/SNI is 2.7, well in agreement with the results by Capellaro & Turatto (1996) of ~ 2.4. Other predictions are (where the values inside parentesis are the observed values): $\Psi(R_\odot, t_{now}) = 2.64\ M_\odot\ \mathrm{pc}^{-2}\ \mathrm{Gyr}^{-1}$ (2-10) ; $\sigma_g(R_\odot, t_{now}) = 7.0\ M_\odot\ \mathrm{pc}^{-2}$ (6.6 $\pm$ 2.5); $\sigma_g/\sigma_T(R_\odot, t_{now}) =$ 0.14 (0.05–0.20); $\dot{\sigma}_{inf}(R_\odot, t_{now}) = 1.05\ M_\odot\ \mathrm{pc}^{-2}\ \mathrm{Gyr}^{-1}$ (1.0) and $\Delta Y/\Delta Z = 1.63$ (3.5 $\pm$ 0.7 although recent results give lower values); $\Psi(R_\odot, t_{now})/\langle\Psi\rangle = \sim 0.7$ (0.18–3.0) (for the references see CMG).

The solar abundances (by mass) predicted by the best model are compared with the observed ones (Anders & Grevesse 1989) in Table 3 of CMG. These abundances represent the composition of the interstellar medium at the time of the formation of the sun, i.e., 4.5 Gyrs ago. Since we assume a Galactic lifetime of 15 Gyrs this time corresponds to 10.5 Gyrs after the Big Bang. Given the uncertainties involved in observed determinations we can consider that the model is in agreement with the observed value within a factor 2 difference. Only for two elements, namely ^{3}He and Mg the model predictions fail (see CMG and Chiappini et al. 1999a).

The fundamental result is that the best model predicts a timescale for the thick and thin disk formation of, respectively, ≤ 1 Gyr and 8 Gyr. The τ_T value cannot be much less than 1 Gyr because in such a case the model would predict a metallicity distribution for metal-poor stars which is shifted towards a metallicity higher than the observed one, as a consequence of the faster evolution of the thick disk. On the other hand, a value greater than 1 Gyr, would produce a model which does not agree with the observed behaviour of the oxygen to iron ratio (i.e. the long plateau in [O/Fe]) and which also predicts too many metal poor stars in the disk (G-dwarf problem). Concerning the timescale for the thin disk formation, the high value for τ_D is necessary to fit the new observed G-dwarf distribution for disk stars which shows a much more pronounced peak for intermediate metallicities than the previous one. Models with $\tau_D \leq 6$ Gyr lead to a poor agreement with the metallicity distribution by Rocha-Pinto & Maciel (1996). This explains the larger timescale obtained by the present model compared with that found by MF, which was 3-4 Gyrs, and also the higher exponent k of the star formation rate. A longer timescale for the thin disk formation was also found recently by Prantzos & Silk (1998). A timescale for the thin disk formation much longer than that of the formation of the halo/thick disk implies that the thin disk (at least at the solar vicinity and beyond) was built from halo gas but mainly by extragalactic gas. This conclusion is in good agreement with the suggestion by PT that the thin disk formation starts almost from a zero metallicity gas without previous enrichment from the halo gas.

We predict bimodal gradients along the Galactic disk, in the sense that the gradients are flatter in the outermost regions and steeper in the inner ones ($R < 10$ kpc), in agreement with Vilchez & Esteban (1996). In particular, the gradients, in the range 4–14 kpc, are: -0.032 dex kpc^{-1} in the inner region and -0.018 dex kpc^{-1} in the outer region for oxygen, and -0.04 dex kpc^{-1} in the inner region and -0.017 dex kpc^{-1} in the outer region for iron (for further results see table 4 in CMG). The gradients are all flatter than predicted by MF and also flatter than indicated by observations of H II regions and PN. The adopted threshold in the star formation process acts mostly in the external regions where the amount of gas is almost always close to the threshold. However, the two-infall model presented here predicts a gas distribution along the disk (see Figure 15 of CMG) in better agreement than that predicted by MF and this is also due to the assumed threshold in the star formation rate. Another important prediction of this model is that the gradients steepen with time.

A variable IMF

We explored the effects of adopting an IMF variable in time on the chemical evolution of the Galaxy (Chiappini et al. 1999b). In order to do that we adopted the two-infall model discussed above, and a new IMF derived by Padoan, Nordlund, & Jones (1997). The new IMF when applied the the two-infall model showed only a small variation of the IMF slope during most of the disk lifetime, being biased towards massive stars only in the early phases of the Galactic evolution. As a consequence, this model is also in agreement with the available observational constraints of the Galaxy and with the present day mass function. The abundance gradients along the galactic disk are flatter when adopting the above IMF, but still marginally consistent with the observed ones. However it was clear from these calculations that an IMF strongly time-dependent will not lead to good agreement with the observational constraints, suggesting that any variation of the IMF should have been small.

The Deuterium Problem

Galactic destruction of primordial deuterium is inevitably linked through star formation to the chemical evolution of the Galaxy. The relatively high present gas content and low metallicity suggest only modest D-destruction. In concert with deuterium abundances derived from solar system and/or interstellar observations this suggests a primordial deuterium abundance in possible conflict with data from some high-redshift, low-metallicity QSO absorbers (Tosi et al. 1998). We have explored a variety of chemical evolution models including infall of processed material and early, supernovae-driven winds with the aim of identifying models with large D-destruction which are consistent with the observations of stellar-produced heavy elements. When such models are confronted with data we reconfirm that only modest destruction of deuterium (less than a factor of 3) is permitted. When combined with solar system and interstellar data, these results favor the low deuterium abundances derived for QSO absorbers (Tytler et al 1996), with a 2 σ upper bound of: $(D/H)_P \leq 5.0 \times 10^{-5}$.

The earliest phases of Galaxy evolution

We also studied (Chiappini et al. 1999a) the very early phases of the evolution of our Galaxy by means of a comparison between the two-infall model predictions for the abundance ratios and the abundances measured in very-metal poor stars. We have restricted our analysis to the solar neighborhood and present the predicted abundances of several elements over an extended range of metallicities [Fe/H] $= -4.0$ to [Fe/H] $= 0.0$ compared to previous models. We adopted the most recent yield calculations for massive stars taken from different authors (Woosley & Weaver 1995; Thielemann, Nomoto & Hashimoto 1996) and compared the results with a very large sample of data, one of the largest ever used for this purpose. We have achieved this by selecting the most recent and higher quality abundance data from a number of sources and renormalizing them to the same solar abundances. Our analysis shows that the "plateau" observed for the [α/Fe] ratios at low metallicities ($-3.0 < [Fe/H] < -1.0$) is not perfectly constant but it shows a slope, especially for oxygen. This slope is very well reproduced by our model with both sets of yields (see Figures 1 and 2 of Chiappini et al. 1999a). This is not surprising since realistic chemical evolution models, taking into account in detail stellar lifetimes, never predicted a completely flat plateau. This is due either to the fact that massive stars of different mass produce a slightly different O/Fe ratio or to the often forgotten fact that supernovae of type Ia, originating from white dwarfs, start appearing already at a galactic age of 30 million years and reach their maximum at 1 Gyr. For lower metallicities ($-4.0 < [Fe/H] < -3.0$) the two sets of adopted yields differ, especially for iron. In this range the "plateau" is almost constant since at such low metallicities there is little contribution from type Ia supernovae. However, there are not enough data in this domain to significantly test this point. Finally, we show the evolution with redshift of the [O/Fe] ratio for different cosmologies and conclude that a sharp rise of this ratio should be observed at high redshift, *irrespective* of the adopted yields. Future measurements of either [α/Fe] or [α/Zn] ratios in very metal poor stars will be very useful to infer the nature and the age of high-redshift objects.

5. SUMMARY

The two-infall model is in very good agreement with most of the observational constraints. In particular, a very good fit of the G-dwarf metallicity distribution is obtained implying a timescale for disk formation much longer than that for the formation of the halo (0.5-1 Gyr for the inner halo and 8 Gyrs for the thin disk at the solar circle). We predict that the radial abundance gradients in the inner regions of the disk ($R < R_{\odot}$) are steeper than in the outer regions, a result confirmed by recent abundance determinations, and that the inner ones steepen in time during the Galactic lifetime. The IMF may be a function of time, but such a time variation is important only in the early phases of Galactic evolution; in these early phases the IMF could have been biased towards massive stars. We derived a 2 σ upper bound of: $(D/H)_P \leq 5.0 \times 10^{-5}$. Clearly, this inferred upper bound to primordial deuterium is in conflict with the high D/H values claimed for some QSO absorbers (Rugers & Hogan 1996) but is entirely consistent with the low values derived by Tytler et al (1996). From the adopted data sample we found that the so-called "plateau" for the $[\alpha/Fe]$ ratio at low metallicities is not perfectly flat but it presents a slight slope, especially for oxygen and that this slope is in very good agreement with the two-infall model predictions. This is an important fact that had been not noticed before since the number of data at low metallicities used to compare with chemical evolution models was always small.

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