The Chemical Evolution of Galaxy Disks

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Abstract. We discuss the main ingredients necessary to build models of chemical evolution of spiral galaxies and in particular the Milky Way galaxy. These ingredients include: the star formation rate, the initial mass function, the stellar yields and the gas flows. Then we discuss models for the chemical evolution of galaxy disks and compare their predictions with the main observational constraints available for the Milky Way and other spirals. We conclude that it is very likely that the disk of our Galaxy and other spirals formed through an “inside-out” mechanism, where the central parts collapsed much faster than the external ones. This mechanism has important consequences for the appearance of galaxy disks as a function of redshift.

1. Introduction

In order to predict the chemical evolution of galaxy disks one needs to know several fundamental quantities. In particular, to build a model which predicts the evolution of the abundances of the most common chemical elements in the gas as functions of space and time, some assumptions on the following physical processes are required: i) the star formation, ii) the stellar nucleosynthesis, iii) the possible gas flows entering and/or leaving the system. Unfortunately, point i) is still very uncertain since we do not know the physics of star formation and we have to adopt simplifying assumptions about the star formation law. Generally we divide the stellar birthrate into two independent functions, one is the so-called star formation rate (SFR) and is only a function of time, the other is the initial mass function (IMF) and is only a function of the stellar mass. Concerning point ii), the knowledge of stellar evolution and nucleosynthesis is more advanced than that of the star formation process although large uncertainties still exist also in the calculation of the stellar yields; among these there are the treatment of convection, the rates of nuclear reactions and the explosive nucleosynthesis. In particular, the yield of iron from massive stars ($M > 10 M_\odot$) seems to be particularly uncertain owing to the poorly known “mass-cut”, namely how much mass stays in the collapsed remnant and how much is ejected in the supernova event. Finally, point iii) is also highly uncertain since the gas dynamics is a very complex phenomenon and pure chemical evolution models take into account dynamics only in a very simplified manner.

In past years a great deal of theoretical work has appeared concerning the chemical evolution of the disk of the Milky Way and other spirals (Matteucci
and François 1989; Yoshii and Sommer-Larsen, 1990; Burkert et al. 1992; Carigi 1994; Timmes et al. 1995; Tsujimoto et al. 1995; Chiappini et al. 1997, 1999, 2000a,b; Chang et al. 1999; Portinari & Chiosi 1999, 2000, Boissier & Prantzos 1999; Goswami & Prantzos 2000; Prantzos and Boissier, 2000; Romano et al. 2000). Most of the more recent models agree that it is important to assume an “inside-out” formation for disks. This implies that the inner parts of galaxy disks should form on relatively fast timescales whereas the outermost regions might be still forming now.

In this paper we focus on one particular model for the chemical evolution of the Galactic disk, the model of Chiappini et al. (1997, hereafter CMG97) and its more recent development (Chiappini et al. 2000b). This model assumes two main episodes of gas infall of primordial chemical composition. The first episode occurs on a short timescale (∼0.8 Gyr) and contributes to the formation of the halo, the second takes much longer (several Gyrs) and gives rise to the disk. In this picture the formation of most of the disk is disentangled from that of the halo which is assumed to have lost part of its gas to form the bulge. Therefore, the bulge formed on a timescale similar to that of the halo. The formation of the innermost disk regions also occurs on a short timescale whereas the outermost regions form on much longer timescales. From the observational point of view, the distributions of abundances, stars and gas in the disk of our Galaxy are the best studied. In particular, the presence of abundance gradients along the Galactic disk is now well established. Abundance gradients represent an important constraint on the history of the formation of the disk especially if considered together with the distribution of gas, stars and star formation as functions of the Galactocentric distance. Abundance gradients are also measured in other spirals and in some cases the gas distribution is also available. Finally, in the local disk (solar neighbourhood) the abundances in stars of different ages are very well studied. Very good constraints are represented by the G-dwarf metallicity distribution which imposes constraints on the birthrate history of the local disk and the [el/Fe] versus [Fe/H] relations which help us in understanding the stellar nucleosynthesis and supernova (SN) progenitors.

2. Observational constraints for the Milky Way Disk

2.1. The Local Disk

- The G-dwarf metallicity distribution (Wyse and Gilmore 1995; Rocha-Pinto and Maciel, 1996), represents the history of the stellar birthrate in the local disk and it can impose strong constraints on the mechanisms of disk formation. In particular, the fit of the G-dwarf [Fe/H] distribution requires that the local disk formed by infall of gas on a time scale of the order of \( \tau_d \sim 6 - 8 \) Gyr, (CMG97; Romano et al. 2000; Boissier and Prantzos 1999).

- The relative abundance ratios as functions of the relative metallicity (relative to the Sun) [X/Fe] vs. [Fe/H] are generally interpreted to be due to the time-delay between Type Ia and II SNe. From these abundance patterns one can infer the timescale for the halo-thick disk formation (\( \tau_h \sim 1.5-2.0 \) Gyr, Matteucci and François, 1989; CMG97).
• Evidence for a hiatus (no longer than 1 Gyr) in the SFR before the formation of the thin disk is suggested by the increase of the \([\text{Fe}/\alpha]\) (with \(\alpha = \text{Mg and O}\)) ratio at a constant \([\alpha/H]\) value, (Gratton et al., 2000; Furlmann, 1998).

• The age-metallicity relation (Edvardsson et al. 1993). This relation is not a strong constraint since it can be fitted by a variety of model assumptions and it shows a very large spread. Part of this spread can be due to the fact that in the local disk we observe also stars which are born elsewhere in the disk and later migrated into the solar vicinity because of orbital diffusion (e.g Wielen et al. 1996).

2.2. The Whole Disk

The main observational constraints for the whole disk are:

• Abundance Gradients: data from various sources (HII regions, PNe, B stars) suggest a standard value for the gradient for oxygen, \(\sim -0.07\) dex/kpc in the galactocentric distance range 4-14 kpc (Maciel and Quireza 1999 and references therein). However, it is not yet clear if the slope is unique or bimodal. Similar gradients are found for N and Fe.

• Gas Distribution: HI is roughly constant over a range of 4-10 kpc whereas \(\text{H}_2\) follows the light. The total gas increases towards the center with a peak at 4-6 kpc.

• SFR Distribution: from various tracers (Lyman-\(\alpha\) continuum, pulsars, SN remnants, molecular clouds) one finds that the SFR increases towards the inner disk regions with a peak at 4-6 kpc similar to that of the gas.

It is worth noting that most of the galactic chemical evolution models suggest, in agreement with Larson (1976), that in order to fit abundance gradients, SFR and gas distribution along the Galactic disk, an inside-out formation of the disk is required, with the timescale for the formation of the disk being a linearly increasing function of the Galactocentric distance, and that the SFR should be a strongly varying function of the Galactocentric distance.

3. Observational constraints on disks of other spirals

• Abundance gradients: if measured in dex/kpc are steeper in smaller disks but the correlation disappears if dex/\(R_d\) is used, namely there is a universal slope per unit scale length (Garnett, 1998). Another important characteristic is that the gradients seem to be flatter in galaxies with central bars (Zaritsky et al. 1994).

• The SFR: is measured mainly from \(H_\alpha\) emission (Kennicutt, 1989; 1998) and shows a well defined correlation with the total surface gas density (\(\text{HI}+\text{H}_2\)).

• Gas distribution: there are differences between field and cluster spirals indicating that these latter have suffered environmental effects (Skillman et al., 1996).
Integrated colors show that a formation inside-out is required (Jimenez et al. 1998; Prantzos and Boissier 2000), in agreement with what is inferred for the Milky Way disk.

4. Different approaches to the chemical evolution of the Galactic disk

The most common approaches to the formation of the Galactic disk and disks in general, from a chemical evolution point of view, are:

- Serial Formation: in this scenario halo, thick and thin disk form in sequence (e.g. Matteucci & François 1989; Burkert et al. 1992). No overlapping in metallicities between the different stellar populations, at variance with observational evidence (Beers and Sommar-Larsen 1995) is predicted.

- Parallel Formation: the various Galactic components start at the same time and from the same gas but evolve at different rates. Within this scenario one predicts overlapping of stars belonging to the different components (e.g. Pardi et al. 1995). However, a problem of this approach, common also to the previous one, is that it is difficult to disentangle the evolution of the halo from that of the disk, at variance with suggestions from the distribution of the angular momentum of stars in the different components (Wyse and Gilmore, 1992), indicating that the gas which formed the stellar halo did not participate in the formation of the disk.

- Two-infall Formation: the evolution of the halo and thin disk are independent and they form out of two separate infall episodes (overlapping in metallicity of different stellar populations is also predicted) (e.g. CMG97; Chang et al. 1999).

5. Basic Ingredients for Galaxy Evolution

5.1. The Star Formation Rate

Given the poor knowledge of the physical processes determining star formation we are forced to parametrize the SFR. Various parametrizations have been proposed, in particular:

- Exponentially decreasing with time: \( SFR = \nu e^{-t/\tau_s} \), with \( \tau_s = 5 - 15 \) Gyr (Tosi, 1988) in order to give good agreement with the present time gas and SFR in the solar neighbourhood.

- The Schmidt law, namely depending on a power between 1 and 2 of the volume or surface gas density: \( SFR = \nu \rho_{gas}^k \) or \( SFR = \nu \sigma_{gas}^k \).

- A law which includes the total surface mass density: \( SFR = \nu \sigma_{tot}^k \sigma_{gas}^k \), where \( \sigma_{tot} \) is the total surface mass density and accounts for the feedback mechanism between star formation and heating of the interstellar medium (ISM), due to supernovae and stellar winds. Observational evidence for such a law is provided by Dopita and Ryder (1994).
• A function of the surface gas density and the angular rotation speed of the gas: 
  \[ SFR = 0.017\Omega_{\text{gas}}\sigma_{\text{gas}} \propto R^{-1}\sigma_{\text{gas}}, \]
  with \( \Omega_{\text{gas}} \) being the angular rotation speed of the gas. This law was suggested by Kennicutt (1998) as a good fit of the SFR measured from the \( H\alpha \) emission in spirals and starburst galaxies. Kennicutt has also suggested the existence of a threshold gas density for star formation of few \( \text{M}_\odot \text{pc}^{-2} \), below which the star formation cannot occur. CMG97 have adopted such a threshold in their model and have shown that this naturally produces a hiatus in the star formation rate between the thick and thin disk formation as observed in the plots \([\text{Fe/Mg}] \) vs. \([\text{Mg/H}] \) and \([\text{Fe/O}] \) vs. \([\text{O/H}] \) (Fuhrmann 1998; Gratton et al. 2000).

All of these SFRs have to be calibrated in order to reproduce the present time SFR in the solar vicinity and this is done by means of the parameter \( \nu \) which is the efficiency of star formation and is a free parameter.

The local disk SFR, measured from the tracers mentioned above and by assuming a specific IMF, is in the range \( \text{SFR} = 2-10 \text{M}_\odot \text{pc}^{-2} \text{Gyr}^{-1} \) (Timmes et al. 1995).

5.2. The Initial Mass Function

The IMF is normally parametrized as a power law of the type: 
  \[ \phi(m) \propto m^{-(x+1)}, \]
defined over a mass range of 0.1-100\( \text{M}_\odot \). There is a general agreement that the Salpeter IMF with \( x = 1.35 \) does not work well for the disk of the Galaxy and that IMFs with steeper slopes in the range of massive stars have to be preferred (e.g. Scalo, 1986). On the other hand, it seems that in elliptical galaxies a Salpeter or even flatter IMF gives better results elaborating the evolution of these galaxies and the intra-cluster medium (see Matteucci 1996).

5.3. The Infall Rate

The importance of the gas infall in the formation of the Galactic disk is originally due to the best fit that it provides for the G-dwarf metallicity distribution in the solar neighbourhood. A biased gas infall (inside-out formation) also provides a very good explanation for the main properties of the disk (abundance gradients, gas and star formation) as functions of the Galactocentric distance.

There are various parametrizations of the infall rate:

• Constant in space and time.

• Variable in space and time: 
  \[ IR = A(R)e^{-t/\tau(R)}, \]
  with \( \tau(R) \) constant or varying along the disk. The quantity \( A(R) \) is derived by fitting the actual surface mass density distribution along the disk: 
  \[ \sigma_{\text{tot}}(R) = \sigma_0 e^{-R/R_d}. \]

• CMG97 adopted a double law for the halo-thick disk and thin-disk: 
  \[ IR = A(R)e^{-t/\tau_H} + B(R)e^{-\frac{(t-t_{\text{max}})}{\tau_D(R)}}, \]
  where \( \tau_H \) and \( \tau_D(R) \) are the timescales for the halo-thick and thin-disk formation, respectively. The dependence of \( \tau_D \) on the Galactocentric distance is a linear function (see CMG97).
5.4.Radial Flows
Observationally, it is not clear whether radial flows along the Galactic disk and disks in general really exist. In a recent study, Portinari and Chiosi (2000) analysed in detail the effects of radial flows and concluded that they are important in connection with the peak observed in the gas in the Galactic disk at 4-6 kpc.

5.5. Stellar Nucleosynthesis
We briefly recall here the element production by stars of all masses, as suggested by the most recent nucleosynthesis calculations. In particular these calculations are: Woosley and Weaver (1995) and Thielemann et al. (1996) for massive stars, Marigo et al. (1996) and van den Hoeck and Groenewegen (1997) for low and intermediate mass stars.

- Massive stars: \( M > 10M_\odot \): produce the bulk of O and \( \alpha \)-elements (Mg, Si, Ca, Ti) and some Fe (very uncertain). They die as Type II SNe.

- Low and Intermediate Mass Stars \( 0.8 \leq M/M_\odot \leq 6 \ldots 8 \): i) single stars produce C, N and some s-process elements, they die as C-O white dwarfs (WDs). ii) Carbon-oxygen white dwarfs in binary systems give origin to Type Ia SNe when they accrete enough matter from the companion to reach the Chandrasekhar mass limit. At this point a C-deflagration is initiated with a consequent explosion (Type Ia SN), and the WD is transformed into Fe and traces of elements from C to Si. They are responsible for the production of the bulk of Fe in galaxies, unless a very unusual IMF is adopted.

6. Model Results
As an example of a model which can satisfactorily fit the properties of the Galactic disk we show the results of Chiappini et al. (2000b) and Chiappini et al. (this conference). The model is basically that of CMG97 except that here we considered a more realistic density profile decreasing outwards for the stellar halo rather than constant as in CMG97. The nucleosynthesis prescriptions are the most recent ones and the nucleosynthesis of novae is also included. In figure 1 we show the predicted oxygen abundance gradient at the present time, the distribution of the \( SFR/SFR_\odot \) ratio, the total surface gas density and the stellar density distributions.

The model reproduces all the four constraints except for the peak of the gas and SFR at 4-6 kpc which is probably the result of the dynamical effects of the central bar, as discussed in Portinari and Chiosi (2000).

7. Conclusions
The comparison between observations and models suggests that:

- The disk of the Galaxy formed mostly by infall of primordial or very metal poor gas accumulating faster in the inner than in the outer regions (inside-out scenario).
Figure 1. Predictions (thin lines) from the best model of Chiappini et al. (2000b). In the upper left panel is shown the oxygen gradient compared to the data, in the upper right panel the distribution of the SFR, in the lower left panel the distribution of the total surface gas density and in the lower right panel the distribution of stars. The thick lines enclose the areas where the observations lie (see Chiappini et al., 2000b for references).
• In the framework of the inside-out scenario the SFR should be a strongly varying function of the galactocentric distance. This can be achieved by assuming a dependence of the SFR either on the total surface mass density (feedback mechanism) or on the angular circular velocity of gas (both are supported by observations), besides the dependence upon the surface gas density.

• Radial flows probably are not the main cause of gradients but can help in reproducing the gas profile.

• An IMF constant in space and time should be preferred, as shown by several numerical experiments (e.g. Chiappini et al. 2000a).

• The disks of other spirals also indicate an inside-out formation, as shown by Prantzos and Boissier (2000) who described the galaxy disks by means of scaling laws, taken from semianalytical models of galaxy formation (Mo et al. 1998), calibrated on the Galaxy.

• Dynamical processes such as the formation of a central bar can influence the evolution of disks and deserve more attention in the future.

• Abundance ratios (e.g. [$\alpha$/Fe]) in stars at large galactocentric distances can provide clues for understanding the formation of the disk and the halo (inside-out or outside-in) (see Chiappini et al., 2000b).

• The predictions of chemical evolution models can be tested in a cosmological context by studying galaxy surface brightness and size evolution as a function of redshift. Roche et al. (1998) concluded that a size-luminosity evolution, as predicted by the inside-out model of CMG97, represents a good fit to the observations.

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