Chemical Evolution of the Galaxy

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Standard models for the chemical evolution of the Galaxy are reviewed with particular emphasis on the history of the abundance gradients in the disk. The effects on the disk structure and metallicity of gas accretion are discussed, showing that a significant fraction of the current disk mass has been accreted in the last Gyrs and that the chemical abundances of the infalling gas can be non primordial but should not exceed $\sim 0.3 \, Z_\odot$. The distributions with time and with galactocentric distance of chemical elements are discussed, comparing the observational data with the corresponding theoretical predictions by standard models, which reproduce very well the ISM abundances at various epochs, but not equally well all the features derived from observations of old stellar objects.

1. Introduction

In the last few years a new generation of models for the chemical evolution of the Galaxy has started to appear, in which also the dynamics of the system is taken into account (e.g. Sommer-Larsen & Yoshii 1990, Chamcham & Tayler 1994, Hensler, this volume, and references therein). This new class of models can provide a complete scenario for the evolution of the Milky Way but is still in a rather preliminary phase. The aim of this presentation is then to review the current state of standard models for the chemical evolution of the galactic disk, with particular emphasis on the effect of gas accretion on the element abundances and gradients.

These models are quite successful in accounting for the large scale - long term phenomena taking place in the Galaxy, and reproduce its major observed features, such as the age-metallicity relation and the G-dwarf distribution in the solar neighbourhood, the elemental and isotopic abundances and ratios, the present star formation rate, gas and total mass densities. To avoid misleading conclusions, it is however necessary to test the models by comparing their predictions not only with the observational constraints derived for the solar neighbourhood but also with the data relative to other galactic regions; first of all because the solar neighbourhood is not representative of the whole disk, and secondly because the distribution with galactocentric distance of several quantities provides important information on the history of the Milky Way.

The current rate of star formation (SFR) represents an excellent example of the importance of modeling the whole disk. One of the most popular approximations for the SFR is a linear proportionality with the gas density, and some authors consider it not only a simple and intuitive law, but also a realistic one because it can reproduce several properties observed in the solar neighbourhood objects. Since the observed radial distribution of the gas in the disk is rather flat (see the shaded area in the bottom panel of Fig.2), this approximation inevitably implies a flat radial distribution of the present SFR. However, Lacey & Full (1985) have shown that the current SFR in the disk, derived from a large sample of young objects (pulsars, O-stars, etc.), is actually a steep decreasing function of the galactocentric distance. Thus, the radial distribution predicted by models assuming a SFR linearly proportional to the gas density is totally inconsistent with the observed one. On the contrary, models assuming the SFR proportional to both the gas and the total mass densities (e.g. Tosi 1982 and 1988, Matteucci & François 1989, hereinafter...
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MF) are in agreement with the observed trend, thanks to the steep decrease of the total mass density with galactic radius.

2. Gas infall and abundance gradients

The idea of a long-lasting infall of metal poor gas on the galactic disk was first suggested by Larson (1972) and Lynden-Bell (1975) to solve several inconsistencies of the first simple models: a too rapid gas consumption that prevented to reproduce the amount of gas currently observed in the disk, the unlikelihood of a complete collapse of the whole protogalactic halo in a few $10^8$ yr, and the existence of very few metal poor, long living stars in the solar neighbourhood, compared to the relatively large predicted percentage (the so called G-dwarf problem). Since then, gas accretion has turned out to be necessary to explain most of the characteristics of our disk, and all the chemical evolution models (with or without dynamics) in better agreement with the largest set of observational constraints assume a significant amount of gas infall throughout the disk lifetime.

2.1. Interstellar medium abundances

One of the most evident effects of gas infall on galactic evolution concerns the absolute value and the radial distribution of the element abundances. If no gas accretion is assumed after the disk formation, all chemical evolution models with reasonable SFR and initial mass function (IMF) predict too large present abundances and/or inconsistent radial distributions. This problem is apparent in the top panel of Fig.1 where the distribution of the current oxygen abundances predicted by models with exponentially decreasing SFR and Tinsley’s (1980) IMF is compared with that derived by Peimbert (1979) and Shaver et al. (1983) from HII regions observations. The models divide the disk in concentric rings, 1 kpc wide, and assume the sun at 8 kpc. Gas motion can be allowed between consecutive rings, whereas stars are assumed to die in the same region where they were born. If the galactocentric distances of the HII regions are properly rescaled assuming the sun at R=8 kpc, the observational oxygen gradient is $\Delta \log(O/H)/\Delta R = -0.103$ dex kpc$^{-1}$. The long-dashed line corresponds to a model with no infall after the disk formation 13 Gyr ago: it is too flat and lies above the observed range of oxygen abundances. The solid line, instead, fits very well the data and corresponds to a model with SFR e-folding time of 15 Gyr and constant infall of primordial gas with density rate $F = 4 \times 10^{-3} M_\odot kpc^{-2}yr^{-1}$ all over the disk. This uniform density rate implies a larger mass of metal free gas infalling in the outer than in the inner rings and favours the development of negative metallicity gradients as steep as observed. This model reproduces the most important features of the Milky Way and from now on it will be referred to as the reference model. It must be emphasized, however, that other combinations of the SFR and infall parameters may lead to a similarly good agreement with the data, as shown in Fig.1 by the short-dashed line, corresponding to a model assuming a shorter e-folding time for the SFR (5 Gyr) and a lower infall density rate ($F = 2 \times 10^{-3} M_\odot kpc^{-2}yr^{-1}$).

What is generally found is that models in better agreement with the observational constraints assume SFR e-folding times in the range 5-15 Gyr and e-folding times for the gas accretion rate longer than for the SFR. This requirement is not unrealistic, if we consider that according to Sofue’s (1994) models the Magellanic Stream is regularly supplying the Milky Way with gas since 10 Gyr.

If the mass of infalling gas is assumed to increase inwards rather than outwards the model predictions are much less satisfactory. The dotted line corresponds to a model with infall rate proportional to the total mass of each ring, which is then increasing toward the center. As a consequence, there is a larger dilution of the inner interstellar
medium (ISM) resulting in a flat abundance distribution inconsistent with that derived from HII regions.

The above results refer to infalling gas with primordial chemical composition, which would be available at best in the intergalactic medium or in the early halo. If the gas originates from regions already polluted by stellar nucleosynthesis, such as the current halo or the Magellanic Stream, it has most probably a non negligible metal content. The intermediate solid line in the bottom panel of Fig.1 shows that if the metallicity of the infalling gas is 0.5 $Z_\odot$ the predictions of the reference model are at the upper edge of the observed distribution. The top solid line shows that if the infall metallicity is solar the resulting oxygen abundance is definitely outside the observational range. From a large variety of models, Tosi (1988b) has found that to allow for a good agreement with the data the infall metallicity should not exceed 0.3 $Z_\odot$. The same result has been obtained by MF with different models and different assumptions on the relative abundances of the infalling elements. This limit is perfectly consistent with the metal content attributable to both the galactic halo and the Magellanic Clouds.

Depending on the model parameters, the present infall rate for the whole disk ranges between 0.3 and 1.8 $M_\odot$yr$^{-1}$. The lower limit of this range is in agreement with the amount inferred from Very High Velocity Clouds which, with the Magellanic Stream, are the most reliable observational evidence for this phenomenon. If a fraction of High Velocity Clouds could be considered of non disk origin as well (see Danly, this volume), the amount of infalling gas observationally detected would cover all the theoretical range.

The metallicity gradients predicted by chemical evolution models depend on the ratio between the SFR and the interstellar and infall gas predicted at each epoch and at each galactocentric distance. The top panel of Fig.2 shows the radial distribution of the SFR
and infall rate resulting from the reference model at three different epochs: the dotted line corresponds to the epoch of disk formation (assumed to be 13 Gyr ago), the dashed line to the epoch of sun formation (8.5 Gyr later), and the solid line to the present. Since the infall rate is assumed to be constant, only one line appears in the figure. The bottom panel of Fig. 2 displays the radial distributions of the gas and total mass at the same three epochs. The disk is supposed to evolve from an initial configuration of pure gas with radially decreasing mass (dotted line). The initial SFR is radially decreasing as well, so that in inner regions there is more astration and therefore larger stellar production of metals. However, the amount of ISM gas which must be polluted by these metals is much larger in the inner regions and therefore the efficiency of the ISM enrichment is quite modest. Thus, at early epochs the predicted abundance gradients are either flat or even positive, depending on the model parameters (see also Mollá et al. 1990). After several Gyr, the situation changes significantly, because the larger astration of the inner regions leads to a higher gas consumption which is not totally compensated by infall since the gas accretion is assumed to be increasing outwards. Thus, at a certain time (see for instance the dashed line corresponding to the situation 4.5 Gyr ago) the larger SFR in the inner regions corresponds to a higher efficiency in the metal enrichment of the medium and negative abundance gradients start to develop. Since then, and as long as the star formation activity remains a decreasing function of the galactocentric distance, the slope of the gradients keeps steepening, because the gas radial distribution becomes increasingly flat, the infall dilution is more efficient outside, and the metal enrichment inside. As shown in Fig. 2, the disk of the Galaxy is currently in this phase with a very flat radial distribution of the gas mass, a radially decreasing SFR and a SFR/infall rate
Figure 3. Top panel: Radial distribution of the oxygen abundances 3 Gyr ago derived from the reference model (solid line) and from observations of PNeII (dots). The data are from PP and the dotted line represent their best fit. Bottom panel: same, but for the He abundance.

A steepening with time of the abundance gradients is predicted by most of the models (with or without dynamics) which are able to reproduce the observational features of the Galaxy (e.g. MF, Chamcham & Tayler 1994, Koppen 1994) despite the rather different model characteristics (see, however, Ferrini et al. 1994 for different predictions). It is then important to verify if this predicted trend is indeed consistent with the available observational constraints. Since the gradient derived from data on HII regions is representative of the situation in the current ISM, to test the model predictions older objects must be examined as well.

Planetary Nebulae, specially of Peimbert's (Peimbert & Torres-Peimbert 1983) type II (PNeII), are also very good indicators of the ISM metallicity. PNeII have stellar progenitors with lifetimes in the range 1-5 Gyr and therefore represent the ISM conditions around 3 Gyr ago. Two recent and extensive studies (Pasquali & Perinotto 1993, hereinafter PP, and Maciel & Koppen 1994) show that the abundance gradients derived for several elements in PNeII are systematically flatter than the corresponding gradients derived from HII regions. For instance, the oxygen gradient derived by PP is $\Delta \log (O/H)/\Delta R = -0.03 \pm 0.01$ dex kpc$^{-1}$ and that derived by Maciel & Koppen is $-0.07 \pm 0.01$. The latter authors have also found hints of increasing slopes of the gradients with decreasing age of the PNe (i.e. from type III to type I), in agreement with the model predictions. Fig.3 shows the helium (bottom) and oxygen (top) abundances as derived by PP from PNeII and the corresponding predictions of the reference model. The agreement between the model solid line and the empirical best fit to the data (dotted line) is excellent. This
confirms that in the last few billion years the slope of the abundance gradients in the ISM has actually steepened.

No other gaseous indicators are available to check whether the gradients were increasingly flatter at earlier epochs. Stars and stellar clusters of whatever age are instead visible in a fairly large range of distances and can therefore indicate what was the earlier scenario.

2.2. Stellar abundances

As far as single stars are concerned, the situation is unfortunately rather confuse. Lewis & Freeman (1989) found no significant metallicity gradient in a sample of 600 old K-giants, but more recently Edvardsson et al. (1993) have argued that the radial metallicity distribution derived from a sample of 189 F and G-dwarfs is similar to that derived from HII regions. The major result of this accurate and extensive work is the scatter on the derived abundances which turns out to be much larger than the observational uncertainties and should then be considered an intrinsic feature of the analysed stellar population. Edvardsson et al. therefore avoided to formally derive the slopes of the abundance gradients, but one can obtain them from their table 14 where the analysed stars are divided in different groups according to their age and galactocentric distance and the average [Fe/H] of each group is given. Despite the poorness of the sample in the older and more distant bins, and the corresponding weakness of the statistics, it is interesting to point out that the resulting formal slopes get flatter for increasing age (i.e. toward earlier epochs) and that the oldest bin even shows a positive gradient (derived from two single points, however!), thus giving some further support to the predictions of the chemical evolution models.

Another interesting feature of the Edvardsson et al. data is the different distribution of metallicity with age for stars at different galactic locations. As pointed out by Pagel (1994) and shown in Fig.4, if one divides their stars into three groups according to their mean galactocentric distances (inner objects, solar ring objects, and outer ones), one finds that the outer stars show a much flatter age-metallicity distribution, with average abundances in the last ten billion years (i.e. over most of the disk lifetime) systematically lower that those of the other objects. As already mentioned above, the data show a large
Figure 5. Radial distribution of open clusters metallicity as derived from Friel & Janes (1993) and Thogersen et al. (1993) samples. The clusters have been divided in age bins and the linear best fit for each bin is shown (dotted line for the oldest bin, long-dashed for the 4-5 Gyr bin, short-dashed for the 2-4 Gyr bin, and solid line for the youngest one.

intrinsic scatter in the derived metallicities of stars of any age and this scatter cannot be directly reproduced by standard chemical evolution models like the reference one which assumes both the SFR and the gas accretion in a sort of steady-state. However, the age-metallicity relations predicted for the three ranges of galactocentric distances are consistent with each of the corresponding average empirical distributions. Notice that the relations predicted for the solar (solid line) and the outer (dotted line) rings flatten off at recent epochs, whereas the relation predicted for the inner ring (dashed line) keeps increasing up to the present time, as already shown by MF. Besides, François & Matteucci (1993) have argued that even the spread of the observed age-metallicity distribution can be accounted for by standard models, once the different birthplaces of the sample stars are considered.

The major problem of single stars analyses is the uncertainty in the derived R, age and metallicity of objects beyond a limited distance from the sun as confirmed by the Edvardsson’s et al. survey. From this point of view, open clusters are in principle safer indicators. There are, however, several problems affecting also the determination of the cluster parameters, such as the non homogeneity of most age estimates and the uncertainty on the cluster original birthplace, the cluster disruption due to disk friction which can alter the original distributions, etc. (see, however, Carraro & Chiosi 1994).

Several years ago, young open clusters have been suggested to indicate steeper abundance gradients than old open clusters (Mayor 1976, Panagia & Tosi 1981). However, more recent and extensive studies (Friel & Janes 1993, Thogersen et al. 1993) do not seem to support this hypothesis. The metallicity gradient derived by Janes and collaborators is $\Delta[Fe/H]/\Delta R = -0.09 \pm 0.02$ dex kpc$^{-1}$ for the whole sample of clusters of any age, and does not seem to depend on the cluster age. Bearing in mind that for field stars in the disk oxygen has been empirically found to follow the relation $[O/Fe] \simeq -0.3[Fe/H]$ (e.g. Edvardsson et al. 1993), and assuming that this relation applies to open clusters as well, the iron gradient corresponds to an oxygen gradient $\Delta\log(O/H)/\Delta R = -0.06$, flatter indeed than that derived from HII regions and more similar to that of objects (as the PNeII discussed above) a few Gyr old.

The most striking feature of Friel & Janes’ sample is that at each galactic radius the oldest clusters are also the most metal rich (see Fig.5). It is true that the published clusters in the oldest age bin ($\geq 8$ Gyr) are only four and the corresponding statistics
is therefore too poor; however two additional clusters of roughly the same age have been found (Friel 1994, private communication) with less extreme metal abundances but still higher than average. It is of crucial importance to verify this result with a larger sample of old clusters and with more accurate and homogeneous methods to derive their ages, chemical abundances and galactic original locations. It might well be, in fact, that this anomaly is fictitious and resulting from the uncertainty in the metallicity and/or, more probably, age determination. However, if confirmed, this phenomenon would have remarkable implications on our understanding of the Galaxy evolution, because it is opposite to any intuitive age-metallicity relation derivable from steady-state scenarios where old stars are inevitably more metal poor than young objects and may result from short, intense phenomena not considered in our models.

Another characteristic of old open clusters is that all of them are located beyond 7-7.5 kpc from the galactic center, contrary to younger clusters which are likely to be equally distributed everywhere in the disk (Janes & Phelps 1994). On the one hand, the external location of the older clusters in the observed sample might not reflect an odd distribution of all the clusters formed several Gyr ago and be the result of a more efficient disruption in the inner than in the outer regions. On the other hand, it may instead correspond to a non homogeneous star formation activity, perhaps related to external phenomena like the first impact on the disk of the Magellanic Stream (Sofue 1994). The latter scenario might also provide an explanation to the large metallicity of the oldest clusters, in terms of a transitory metal enhancement of the ISM due to the larger SFR triggered by the sudden event and later smeared out during the following steady-state evolution.

3. Summary

In conclusion, the comparison between the abundance distributions in the galactic disk predicted by standard chemical evolution models and derived from observational data can be summarized as follows:

a) Abundance distributions derived from observations of gaseous objects of various ages (HII regions and PNe) are very well reproduced by steady-state models with slowly decreasing SFR and large - long lasting infall of metal poor gas.

b) Average abundance distributions derived from stars are also reproduced. These standard models, however, do not reproduce the observed spread in the metallicity distribution of field stars and the anomalously high [Fe/H] of the oldest open clusters.

We must bear in mind, however, that old stars can have quite eccentric orbits and can therefore have formed in galactic regions different from those where they are observed now. According to François & Matteucci this might explain most of the abundance spread in the Edvardsson’s et al. sample. On the other hand, Carraro & Chiosi (1994) have suggested that the same argument cannot apply to the case of old open clusters, for which other explanations are thus needed, unless all the inconsistencies with the model predictions can be attributed to observational errors.

A possible reason for the different agreement found for gas and stellar objects is that the gas mixes rapidly, compared to the timescales for galactic evolution, therefore forgets local perturbations occurred in the past and follows the steady-state scenario. Stars, instead, keep memory of the local perturbations occurring at, or just before, their birth and therefore deviate more from that scenario, showing intrinsic large scatter and anomalous behaviours. To interpret in detail their observed features more sophisticated models taking into account also the small scale, short term phenomena are therefore required.
I wish to thank Francesca Matteucci for always being ready to discuss and compare the results and the different approaches of our models: a praiseworthy attitude rather unusual among theoreticians.

REFERENCES

Carraro, G. & Chiosi, C. 1994 A.A. 287, 761
Chamcham, K. & Tayler, R.J. 1994 M.N.R.A.S. 266 282
Danly, L. 1994 this volume
Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D.L., Nissen, P.E., Tomkin, J. 1993, A.A. 275, 101
Ferrini, F., Molla, M., Pardi, C., Díaz, A.I. 1994, Ap.J. 427, 745
Friel, E.D. & Janes, K.A. 1993 A.A. 267, 75
François P. & Matteucci, F. 1993 A.A. 280, 136
Hensler, G. 1994 this volume
Janes, K.A. & Phelps, R.L. 1994 A.J. in press
Koppen W. E. 1994 A.A. 281, 26
Lacey, C.G. & Fall, S.M. 1985 Ap.J. 290, 154
Larson, R.B. 1972 Nature 236, 21.
Lewis, J.R. & Freeman, K.C. 1989 A.J. 97, 139
Lynden-Bell, D. 1975 Vistas in Astr. 97, 139
Maciel, W.J. & Koppen, W.E. 1994 A.A. 282, 436
Matteucci, F. & François, P. 1989 M.N.R.A.S. 239, 885, MF
Mayor, M. 1976 A.A. 48, 301
Molla, M., Díaz, A.I. & Tosi, M. 1990 in Chemical and Dynamical Evolution of Galaxies , F.Ferrini, J.Franco and F.Matteucci eds (ETS Pisa, Italy), p.577
Pagel, B.E.J. 1994 in Galaxy Formation and Evolution, C.Munoz-Turon ed. (CUP, UK), in press
Panagia P. & Tosi, M. 1981 A.A. 96, 306
Pasquali A. & Perinotto, M. 1993 A.A. 280, 581
Peimbert M. 1979, in The Large Scale Characteristics of the Galaxy W.B.Burton ed. (Reidel, Dordrecht Holand), p.307
Peimbert M. & Torres-Peimbert S. 1983, in Planetary Nebulae , IAU Symp 103, (Reidel, Dordrecht Holland), p.233
Shaver, P.A., McGee, R.X., Newton, L.M., Danks, A.C., Pottasch, S.R. 1983 M.N.R.A.S. 204, 53
Sofue 1994 P.A.S.J. , in press
Sommer-Larsen, J. & Yoshii, J. 1990 M.N.R.A.S. 243, 468
Thogersen, E.N., Friel, E.N., Fallon, B.V. 1993 P.A.S.P. 105, 1253
Tinsley, B.M. 1980 Fund.Cosmic Phys. 5, 287
Tosi, M. 1982 Ap.J. 254, 699
Tosi, M. 1988a A.A. 197, 33
Tosi, M. 1988b A.A. 197, 47
Wilson, T.L. & Matteucci, F. 1992, A.A.R. 4, 1
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**Discussion**

**Palous.** As you have shown, SFR(R) is a function of both $\sigma_{\text{gas}}$ and $\sigma_{\text{tot}}$: $\text{SFR} = \psi(\sigma_{\text{gas}}, \sigma_{\text{tot}}) \ e^{-t/\tau}$. In the model of propagating SF, recently published by Palous, Tenorio-Tagle & Franco (1994, M.N.R.A.S.) the SFR $\propto [\sigma_{\text{gas}}, \text{sheer}(R)]$. Sheer follows the total mass distribution and is decreasing with R. It seems then that the propagating SF model reaches conclusions similar to yours.

**Chernin.** Do I understand you correctly that there might be two characteristic time scales of the chemical evolution of the galactic disk, 15 and 5 Gyr, and that the available observational data do not enable us to make a choice between them? And, by the way, is there any room for dark matter in your models, whatever its physical nature may be?

**Tosi.** Yes, with a proper combination of the other parameters, both a SFR with e-folding time 15 Gyr and one with 5 Gyr provide results consistent with the disk observational data. I haven’t included dark matter in my models.

**Tenorio-Tagle.** Would you comment about outflows?

**Tosi.** Outflows haven’t been introduced yet in standard chemical evolution models, because we don’t have enough observational constraints on their chemical composition, on the significance of the phenomenon or on the final fate of the ejected gas (does it eventually escape from the system or falls back, and where?). In absence of such information, too many free parameters should be assumed in the models to allow for a safe interpretation of the results.

**Serrano.** What would be the effect on the standard model of outflows larger at small R and smaller at large R?

**Tosi.** If the ejected gas is lost for ever, it should lead to a reduction of the inner abundances and therefore to a flattening of the radial gradient of the outflowing chemical elements. If the wind is made only of the gas ejected by SNe, the effect will be restricted to the elements, like oxygen, synthesized by their progenitors, otherwise it will be on all the metals.

**Martin.** In your models you need a total amount of infalling gas mass comparable to the mass of the disk. So much infall cannot come from the Magellanic Clouds: where from do you think it’s coming?

**Tosi.** The infalling gas has presumably a composite origin: at early epochs it must have been mostly collapsing halo material, with a small component of extragalactic gas; nowadays it is most probably due to external gas. The sum of these components can easily account for the required $\sim 10^{10} M_\odot$.

**Andersen.** I am still somewhat concerned about the amount and age of data on which some crucial features of the models depend rather critically. Edvardsson et al. did not discuss possible radial gradients from their data, simply because we did not have a fair sample of the stars originally inside or outside the solar circle.

**Tosi.** I mentioned indeed that the statistics on the older and more distant bins is quite poor. With this caveat in mind, I think however that it is useful to check whether or not the model predictions are consistent with such a large and good sample of data.
