On the chemical and spectro-photometric evolution of nearby galaxies
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Summary

The chemical enrichment of the interstellar medium (ISM) by successive generations of stars is a key issue in understanding the chemical evolution of galaxies in general, and the formation history and abundance distributions of the stellar populations in our Galaxy in particular. The goal of galactic chemical evolution modelling is to predict reliable abundances in our Galaxy as well as in other galaxies both as a function of time and location. From such modelling, we can learn what processes determine the chemical enrichment history of different galactic regions (e.g. disk, bulge, halo) and deduce how the formation and evolution of galaxies in general may have proceeded according to their chemical properties.

In this thesis, we concentrated on the star formation history and chemical evolution of the Galactic disk. Using a wide range of observational constraints, most of which have become available during the last few years, we aimed at reconstructing the Galactic star formation history by modelling simultaneously various aspects of Galactic chemical evolution. In the second part of this thesis, we investigated the spectro-photometric and chemical evolution of nearby galaxies by means of a photometric evolution model. In particular, this model was applied to the stellar populations of Low Surface Brightness galaxies, a class of very faint galaxies for which a wealth of observational data have recently become available.

We summarize the main results obtained in this thesis as follows:

In Chapter 3, considerable effort was made to discuss and to emphasize the assumptions and uncertainties involved with the current generation of galactic chemical evolution models. In particular, a thorough comparison was made between the two state-of-the-art models for the core-collapse and chemical evolution of massive stars, i.e. the model presented by the group of Woosley, Timmes, and Weaver (1996) on one hand, and that presented by the group of Nomoto, Thielemann, and Hashimoto (1996) on the other. This comparison clearly reveals for the first time the magnitude and origin of the uncertainties and differences between the yields of massive stars predicted by the two groups and allows for a more reliable interpretation of several discrepancies between the actual models and specific observational constraints to the chemical evolution of the Galactic disk.

In Chapter 4, we modelled a large set of observational data related to the chemical evolution of the Galactic disk and halo using a comprehensive and up-to-date galactic evolution model which incorporates metallicity dependent stellar yields, lifetimes, and remnant masses. A new, iterative solution procedure was applied to solve the galactic chemical evolution equations in a self-consistent manner with the freedom to study complex relations between e.g. the IMF and the SFR. We made a distinction between the enrichment contributions by Asymptotic Giant Branch stars, Supernovae Type Ia (SNIa), SNIIb/c, and SNII while using state-of-the-art evolution models for the chemical evolution of these final stages of stellar evolution.

First, we addressed the abundance inhomogeneities observed among similarly aged stars and open clusters in the Galactic disk. We analysed in detail the possibility suggested by e.g. Francois & Matteucci (1993) and Wielen et al. (1996) that stellar orbital diffusion in combination with radial abundance gradients in the disk ISM are the main explanation for these abundance inhomogeneities. We showed that in case of large errors in the derived ages and
Summary

Orbital parameters of the stars in the Edvardsson et al. (1993) sample, orbital diffusion as described by Wielen et al. (1996) can provide an adequate explanation for the majority of the observed stellar abundance variations. However, at the same time, we argued that this requires several specific assumptions which may be unjustified and not appropriate to the chemical evolution of the Galactic disk.

Second, we investigated the sensitivity of the age-metallicity relation (AMR) to specific galactic chemical evolution model assumptions and we selected a set of models that can explain the mean [Fe/H] vs. age relation observed in the local Galactic disk. We studied the sensitivity of the AMR to the main parameters and assumptions involved in our models. We demonstrated that a wide range of enrichment scenarios is consistent with the observed AMR, i.e. there exists no unique model that is in best agreement with the observed AMR. Conversely, the observed AMR alone is found insufficient to constrain tightly Galactic chemical evolution models and additional constraints are needed.

Third, we confronted the models selected on their ability to fit the observed AMR with observational constraints related to the ISM abundances and stellar content of the disk:

- the present-day stellar mass function (PDMF) and IMF;
- the total number and formation rates of (post) main-sequence stars;
- the gas depletion, infall, and star formation rates in the disk ISM;
- the enrichment history of the Galactic disk as recorded by the abundance-abundance variations (i.e. the variation of the abundance of a given element as a function of the abundance of another element) and the present-day abundances observed. We investigated the impact of: 1) the adopted stellar yields, 2) the star formation history, 3) the IMF, 4) the delay time of SNIa, and 5) the upper mass limit for SNII, on the resulting abundance-abundance variations of the most abundant elements in the disk ISM including C, N, O, Mg, Al, Si, and Fe.
- the luminosity function of white dwarf (WD) remnants;
- the mass distribution of WD remnants;
- the age and metallicity distributions of long-living stars in the local disk (i.e. the classical G-dwarf problem).

By means of this comparison, we attempted to converge to a set of models for the chemical evolution of the Galaxy consistent with the above constraints and we traced back eventual discrepancies between our results and the observations.

In particular, we aimed to deduce the star formation history of the Galaxy both from the abundance-abundance variations observed and other independent observational constraints to the chemical evolution of the Galaxy. As a shortlist of interesting results we like to emphasize the following ones: 1) we found that evolution scenarios in which the SFR gradually increases up to a given maximum in the disk and thereafter decreases exponentially are clearly favoured by the observations. We argue that models which incorporate infall of gas regulating this kind of behaviour of the SFR with age in the Galactic disk are preferred over models which do not incorporate gas infall; 2) we demonstrated that the ejecta of SNIa, associated with stars formed early in the evolution of the Galaxy and with initial masses in the range ~2.5–8 M_☉, need to be delayed over at least 3–5 Gyr after the formation of their WD progenitors in order to fit the observations. Instead of such a time delay, SNIa
may be associated with considerably less massive stars than previously thought, i.e. with masses between \(\sim 1.5\) and \(2\, M_\odot\); and 3) we showed that models in which the upper mass limit of SNII increases as a function of galactic age during early epochs of star formation in the Galaxy are consistent with the observations for variations of \(m_u\) between \(\sim 20\) and \(\sim 30 - 40\, M_\odot\) if these variations occur delayed with respect to the variation of the SFR. Such a behaviour of the upper mass limit of SNII may be supported by the formation of massive stars both in the Galactic disk and in external galaxies.

Fourth, we briefly compared our main results with those presented in several other recent investigations dealing with Galactic chemical evolution. We summarized the type of chemical evolution models that are in best overall agreement with the observations and we discussed what this may imply for the chemical evolution of the Galaxy as a whole. Combined with the detailed description in Chap. 3 of the galactic chemical evolution model assumptions and ingredients involved, the extensive results for a wide range of observations presented in this thesis make that our model is one of the best documented Galactic chemical evolution models currently available.

It's beyond the scope of this summary to list all the results obtained in Chapter 4. Instead, we prefer to highlight some of the results obtained in Sect. 4.3.4 where we modelled the abundances and abundance-abundance relations observed among Galactic disk and halo stars.

- overall, reasonable agreement was found between the predicted and observed abundance-abundance variations for stars in the Galactic disk and halo. In detail, however, none of the SFR models selected on their ability to fit the observed AMR of iron could provide an adequate explanation of the abundance-abundance relations observed, unless additional variations of the element productions by (massive) stars with galactic age are taken into account;

- our results support: 1) a gradual increase of the SFR up to a maximum several Gyr after the onset of star formation in the Galaxy, 2) an exponentially decrease of the SFR past its maximum, and 3) an SFR in the disk ISM regulated by gas infall/accretion of matter. Gas infall onto the Galactic disk seems to be required to explain the stellar abundance-abundance variations observed. Infall time scales between 0.5 and 3 Gyr appear in best agreement with the observations when exponential decaying gas infall is assumed. The agreement of the SFR models above with the observed abundance-abundance variations is very sensitive to the contraction time of the disk ISM before the maximum SFR in the disk ISM is reached;

- our models suggest that the ejecta of SNIa associated with intermediate mass stars formed at early epochs in the evolution of the Galaxy have been delayed over at least 3–5 Gyr after the formation of their WD progenitors. It is difficult to extract information about the detailed SNIa delay time profile from the observed abundance-abundance variations. However, a substantial delay of a large number of SNIa over at least several Gyr after the major period of star formation is needed to strongly affect the slope of the \([O/Fe]\) vs. \([Fe/H]\) variation at values of \([Fe/H]\) \(\gtrsim -1\). The WD delay time effect on the iron enrichment by SNIa leads to an underestimate of the iron abundance at early epochs in the evolution of the Galaxy. Although there are several ways out to compensate for this effect, we favour the possibility that the ages of stars in the Edvardsson et al. (1993) sample are systematically too large by at least 3–4 Gyr;
• if the time delay of SNIa would not be the primary cause for the change in slope of the variation of [O/Fe] with [Fe/H], it appears difficult to explain the observed abundance-abundance trends for these elements unless different processes have initiated and regulated the star formation history in the Galactic halo and disk ISM. This may involve corresponding differences in e.g. the IMF, lower stellar mass limit, and/or upper mass limit for SNII;

• our models combined with the Geneva/Nomoto yields are unable to explain adequately the [O/Fe] and [C/O] ratios observed in Galactic halo stars. This conclusion is independent of the SFR and IMF model used and is insensitive to the parameter values assumed;

• we have argued that the amount of carbon produced during the SNII explosion of massive stars as predicted both by the Geneva/Nomoto and Woosley/Weaver yield sets is considerably too large. This may be e.g. related to the $^{12}$C($\alpha$, $\gamma$) rates adopted;

• we find that nitrogen is overproduced in our models by $\sim$0.3–0.4 dex. This suggests that: 1) too many stars reach the AGB, and/or 2) the effect of hot bottom burning is too large in our models. This result needs further investigation;

• in general, an IMF distinct from the Salpeter IMF results in a shift of the abundance-abundance variations predicted, while the shape of these variations is predominantly determined by the underlying star formation (and infall) history;

• the agreement with the observations for oxygen and the $\alpha$–elements is improved when IMFs are considered that flatten towards low-mass stars as compared to the Salpeter IMF. However, elements such as C and N formed in intermediate mass AGB stars, probably are overproduced in case of such flat IMFs. Therefore, such flat IMFs are excluded by the observed abundance-abundance variations unless the formation rate of intermediate mass AGB stars is suppressed at the same time. Alternatively, the carbon and nitrogen yields of stars with metallicities $Z \lesssim 0.001$ may be substantially in error;

• no observational support is found for large variations of the stellar lower mass limit at birth over the lifetime of the Galaxy. If such variations did occur, episodes of relatively massive star formation must have been very short with respect to the lifetime of the Galaxy and/or simultaneous variations in the enrichment contributions by massive stars must have occurred to prevent overproduction of heavy elements in the disk ISM;

• models for which the stellar upper mass limit at birth increases substantially with the SFR are not supported by the observations (unless e.g. simultaneous variations in the lower stellar mass limit at birth did occur);

• models for which the upper mass limit of SNII increases as a function of galactic age during early epochs of star formation in the Galaxy are consistent with the observations for variations of $m_u$ with between $\sim$20 and $\sim$30–40 $M_\odot$, if these variations occur delayed with respect to the variation in the SFR with age. We emphasize, however, that the precise value and variation of $m_u^{\text{SNII}}$ favoured by the observed abundance-abundance variations is rather sensitive to e.g. the IMF, and the contribution by SNIa to the iron enrichment;

• the Dopita SFR (e.g. Dopita 1989; Dopita & Ryder 1994) and Salpeter IMF models are found in best agreement with the observed stellar abundance-abundance variations in the Galaxy for values of $m_u^{\text{SNII}}$ between 20 and 25 $M_\odot$ at the early epoch of
star formation in the Galaxy, a SNII fraction $F_{\text{SNII}} \sim 0.2$ for stars with masses between $\sim 8 \, \text{M}_\odot$ and $m_{\text{g}}^{\text{SNII}}$, a SNIa fraction $F_{\text{SNIa}}$ between 0.01 and 0.02 for stars with masses between $\sim 2.5$ and $\sim 8 \, \text{M}_\odot$, and a SNIa delay time after formation of the WD progenitor of $\sim 3$–5 Gyr;

- for these models, we find that AGB stars roughly account for $\sim 40\%$ of the present-day stellar consumption rate of hydrogen, and contribute $\sim 50\%$ and $\sim 90\%$ to the present-day ejection rates of newly synthesized helium and nitrogen, respectively. SNIII are found to contribute $\sim 80\%$ to the current stellar ejection rate of newly synthesized oxygen. When oxygen initially present in stars at time of their formation is included in the total stellar ejection rate of oxygen, we find that the contribution by SNIII is reduced to $\sim 50\%$ and that AGB stars contribute $\sim 35\%$ to this rate;

- models in best agreement with the observations and computed with the Woosley/Weaver stellar yields, the Salpeter IMF, and parameters as listed hereabove imply typical contributions by AGB stars, SNIa, SNII, and SNIb/c, to the total present-day stellar ejection rates of C, O, and Fe as follows (normalized to one):

<table>
<thead>
<tr>
<th>El</th>
<th>AGB</th>
<th>SNIa</th>
<th>SNII</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.45</td>
<td>–</td>
<td>0.30</td>
</tr>
<tr>
<td>O</td>
<td>0.35</td>
<td>–</td>
<td>0.15</td>
</tr>
<tr>
<td>Fe</td>
<td>0.25</td>
<td>0.50</td>
<td>0.10</td>
</tr>
</tbody>
</table>

- the present-day abundances observed in the Galactic disk ISM are not suited to distinguish between different SFR models. However, the interstellar abundances for a large number of elements at distinct epochs in the evolution of the Galaxy may provide the most stringent constraint to models for the star formation history and chemical evolution of the Galaxy. A first confrontation of this kind was made in Sect. 4.3.4.

- unfortunately, the present-day abundances predicted by our models deviate strongly from the mean abundances observed in HII regions in the SNBH and in Canopus. We propose that the abundances of young objects in the solar vicinity are not representative for the mean present-day abundances in Galactic disk stars;

- the possibility that the enrichment in the Galaxy proceeded at a relatively rapid rate during the transition phase in the [O/Fe] vs. [Fe/H] relation may imply that the formation of massive stars during this phase has not been accompanied by a corresponding enhancement in the formation of low and intermediate mass stars (i.e. not many of such stars are nowadays observed). This may point to a difference in the IMF of stars formed before and after the transition phase as compared to the bulk of disk stars nowadays observed;

- we suggest that the large spread in abundances observed among Galactic halo stars is related to small-scale spatial variations in the nucleosynthesis of intermediate mass stars ($m = 2$–$8 \, \text{M}_\odot$) which do not produce both at the same time iron and e.g. oxygen in substantial amounts. These abundance variations may be primarily due to the local enrichment of the halo ISM by SNIa.

In Chapter 5, we investigated in detail the origin of the abundance variations observed among similarly aged F and G dwarfs in the local Galactic disk. We argued that orbital diffusion of stars in combination with radial abundance gradients is probably insufficient to explain these variations. We showed that episodic and local infall of metal-deficient gas can
provide an adequate explanation for iron and oxygen variations as large as $\Delta[M/H] \sim 0.6$ dex among stars formed at a given age in the solar neighbourhood (SNBH). However, such models appear inconsistent with the observations because they: 1) result in current disk ISM abundances that are too high compared to the observations, 2) predict stellar abundance variations to increase with the lifetime of the disk, and 3) do not show substantial scatter in the $[\text{Fe}/\text{H}]$ vs. $[\text{O}/\text{H}]$ relation. Notwithstanding, our results do suggest that metal-deficient gas infall plays an important role in regulating the chemical evolution of the Galactic disk. We demonstrated that sequential enrichment by successive stellar generations within individual gas clouds can account for substantial abundance variations as well. However, such models are inconsistent with the observations because they: 1) are unable to account for the full magnitude of the observed variations, in particular for $[\text{Fe}/\text{H}]$, 2) predict stellar abundance variations to decrease with the lifetime of the disk, and 3) result in current abundances far below the typical abundances observed in the local disk ISM.

We presented arguments in support of combined infall of metal-deficient gas and sequential enrichment by successive stellar generations in the local Galactic disk ISM. We showed that galactic chemical evolution models which take into account these processes simultaneously are consistent with both the observed abundance variations among similarly aged F and G dwarfs in the SNBH and the abundances observed in the local disk ISM. For reasonable choices of parameters, these models can reproduce $\Delta[M/H]$ for individual elements $M = C, O, \text{Fe}, \text{Mg}, \text{Al}, \text{and} \text{Si}$ as well as the scatter observed in abundance-abundance relations like $[\text{O}/\text{Fe}]$. For the same models, the contribution of sequential stellar enrichment to the magnitude of the observed abundance variations can be as large as $\sim 50\%$. We discussed the impact of sequential stellar enrichment and episodic infall of metal-deficient gas on the inhomogeneous chemical evolution of the Galactic disk.

In Chapter 6, we investigated the star formation history and chemical evolution of low surface brightness (LSB) disk galaxies by means of their observed spectro-photometric and chemical properties. To this end, we used a galactic chemical and spectro-photometric evolution model incorporating a detailed metallicity dependent set of up-to-date stellar input data covering all relevant stages of stellar evolution. Comparison of our model results with the observations confirms the idea that LSB galaxies are relatively unevolved systems.

Based on extensive modelling, we found that for the majority of the LSB galaxies in our sample, observed Johnson-Cousin $UBVR\text{I}$ magnitudes, $[\text{O}/\text{H}]$ abundances, gas masses and fractions, and $\text{H}i$ mass-to-light ratios, are best explained by galactic evolution models incorporating an exponentially decreasing global star formation rate (SFR) ending at a present-day gas-to-total mass ratio of $\mu_1 = 0.5$ for a galaxy age of 14 Gyr. About 35 $\%$ of the LSB galaxies in our sample exhibit properties that cannot be explained by exponentially decreasing SFRs alone. We argued that most of these systems experienced recent episodes of enhanced star formation superimposed on exponentially decreasing global SFR models. Only a small fraction ($\sim 10-15\%$) of the LSB galaxies have properties consistent with those resulting from linearly decreasing or constant SFR models.

We found evidence, from model point of view, for recent and ongoing star formation in the disks of LSB galaxies at rates of $\sim 0.1 \text{ M}_\odot \text{ yr}^{-1}$. In particular, we demonstrated that the occurrence of small amplitude star formation bursts in LSB galaxies is required to explain the contribution of the young (5-50 Myr old) stellar population to the galaxy integrated luminosity. This result suggests that star formation in LSB galaxies has proceeded in a
stochastic manner from the moment star formation started in their disks. On the basis of this result, we argued that sporadic star formation in LSB galaxies is probably associated with local accretion and/or infall of matter.

The presence of an old stellar population in many late-type LSB galaxies, as confirmed by our results, suggests that LSB galaxies roughly follow the same evolutionary history as HSB galaxies, except at a much lower rate. In particular, our results imply that LSB galaxies do not form late, or have a delayed onset of star formation, but evolve slowly. We showed that the observed color differences between LSB and HSB galaxies can be interpreted almost entirely in terms of the relatively low extinction and metallicity in LSB galaxies. We proposed that LSB galaxies are in an early stage of disk formation and probably are still in the accumulation phase of gas during which their current amount of star formation and chemical enrichment is regulated. In particular, the gas reservoir at the time of onset of main star formation in LSB galaxies may have been substantially less than that estimated from their present-day amounts of gas since accretion of matter is still very important in these systems.

The low evolutionary state of LSB galaxies relative to HSB galaxies suggests that LSB galaxies are just HSB galaxies in the making (except on time scales much longer than a Hubble time). We discussed our results in the context of the evolutionary history of LSB galaxies compared to that of HSB and dwarf irregular galaxies.

Apart from the results presented in this thesis, I have been and/or am currently working on: evolutionary population synthesis models for the stellar contents in the nuclei of elliptical galaxies (in cooperation with Paul Goudfrooij, Pascale Jablonka, and Danielle Alloin), the star formation history and chemical evolution of the Magellanic Clouds (with Martin Groenewegen and Ken’ichi Nomoto), the luminosity function of AGB stars in the Galactic disk and Magellanic Clouds (with Martin Groenewegen), the formation and evolution of interstellar dust grains in the Galactic disk and Magellanic Clouds (with Teije de Jong), and the radial distribution of the stellar content in spiral galaxies with high and low central surface brightnesses (with Roelof de Jong and Erwin de Blok). Part of the results of these investigations will be presented elsewhere.

The road to wisdom?
Well, it’s plain and simple to express
Err, err, and err again
but less, and less, and less

Piet Hein
Niemand kijkt naar wat zich voor zijn/haar voeten bevindt.
We staren allemaal naar de sterren ...

Quintus Ennius