Chemical Evolution of Galaxies and the Relevance of Gas Processes

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Abstract. Since stellar populations enhance particular element abundances according to the yields and lifetimes of the stellar progenitors, the chemical evolution of galaxies serves as one of the key tools that allows the tracing of galaxy evolution. In order to deduce the evolution of separate galactic regions one has to account for the dynamics of the interstellar medium, because distant regions can interact by means of large-scale dynamics. To be able to interpret the distributions and ratios of the characteristic elements and their relation to e.g. the galactic gas content, an understanding of the dynamical effects combined with small-scale transitions between the gas phases by evaporation and condensation is essential. In this paper, we address various complex signatures of chemical evolution and present in particular two problems of abundance distributions in different types of galaxies: the discrepancies of metallicity distributions and effective yields in the different regions of our Milky Way and the N/O abundance ratio in dwarf galaxies. These can be solved properly, if the chemodynamical prescription is applied to simulations of galaxy evolution.

1. Introduction

For the stellar populations of our Milky Way Galaxy (MWG) - the halo, the bulge, and the disk (thick plus thin disk) - the fundamental questions that have to be addressed are: When, how and on what timescales did the Galactic components form, and was there any connection between them? If yes, simultaneously or sequentially? One possible approach to disentangle the evolutionary scenario is to look for evolutionary signatures in age, dynamics, and chemistry of long-lived stars, in the stellar populations within our MWG. At present, two major and basically different strategies for modelling galaxy evolution can be followed: dynamical investigations which include hydrodynamical simulations of isolated galaxy evolution and of protogalactic interactions reaching from cosmological perturbation scales to direct mergers, and, on the other hand, studies which neglect any dynamical effects but consider either the whole galaxy or particular regions and describe the temporal evolution of mass fractions and element abundances in detail.

For the case of a closed box a linear relation between the time-dependent metallicity $Z(t)$ and the initial-to-temporal gas ratio $\ln[M_{g,0}/M_g(t)]$ follows ana-
lytically, where the slope is determined by the yield $y$, i.e. the metallicity release per stellar population. Deviations from this simple relation are explained by lower “effective” yields $y_{\text{eff}}$ due to outflow of metal-rich gas from the (now open) volume or infall of low-metallicity (presumably primordial) gas. Such dynamical effects can only be properly treated if simulations can account for the energetics, the composition, and the dynamical state of the galactic gas, as well as the relevant interchange processes, in a self-consistent manner. This includes the pollution of the different gas phases with characteristic elements by means of various stellar mass-loss mechanisms, the gas phase transitions, and the self-consistent large-scale streaming motions of hot intercloud gas (ICM) or cool gas (CM) that falls in from a reservoir of protogalactic gas. It follows that galactic regions and components experience mutual dynamical interactions and their evolutions are not decoupled.

Let us consider a number of chemical peculiarities of different kinds of galaxies which justify the use of sophisticated multi-phase dynamical descriptions of the interstellar medium (ISM) in studies of the global scenario of galaxy evolution:

1) In the solar vicinity at least three severe problems arise by considering the metallicity distribution of F or G dwarfs, stars that live sufficiently long to trace the evolution of a galaxy: The age-metallicity relation, $y$ of the metallicity distribution and, finally, the lack of metal-poor G dwarfs (the well-known G-dwarf problem). Various influences on the evolution of the solar neighbourhood have therefore been invoked by different authors and are applied by artificial parametrizations ranging from time-dependent accretion of pristine halo gas to temporal variations of the stellar initial mass function (IMF). Although they lack self-consistency, the results can often provide very helpful basic insights into influences of distinct effects.

2) It is also important to explain the observed differences of $y$ in bulge, disk and halo of the MWG (Pagel 1987).

3) There is now much evidence that metal-absorption line systems (ALS) in QSO spectra arise from the gaseous halos of forming galaxies. In spite of the lack of knowledge of their dynamical properties and their origin, as a working hypothesis it is assumed that the early hot halo gas is produced by supernovae typeII (SNeII), because the observed abundance ratios agree well with SNII yields (Reimers et al. 1992). The metallicity and radial extent of ALS should therefore appear automatically in galaxy models as the result of chemical evolution.

4) Dwarf galaxies (DGs) present a variety of morphological types. Their structural and chemical properties differ from those of giant galaxies. The dwarf irregular galaxies (dIrrs) appear with lower $Z$ at the same gas fraction as gSs. This implies that the metal-enriched gas from SNeII was lost from the galaxy rather than astrated (Larson 1974, Dekel & Silk 1986). Yet many dwarf spheriodals (dSphs) which represent the low-mass end of DGs show not only a significant intermediate-age stellar population, but also more recent SF events (Smecker-Hane et al. 1994, Han et al. 1997) with increasing metallicity, indicating that gas was kept in the system.

5) gSs and DGs differ significantly in their N/O ratios. A fundamental explanation is needed to explain why gSs like the MWG reach higher ratios at larger
O abundances than DGs, while N/O is almost restricted to around -1.5 for DGs over a wide range in O (see fig.3).

2. The Chemodynamical Treatment

For systems and sites of low potential energy we know from empirical studies and theoretical investigations that the ISM is on average held in balance by counteracting processes like heating and cooling, turbulence and dissipation (Burkert & Hensler 1989, Hensler et al. 1998b). Since these processes are non-linearly coupled, the effect of neglecting one of them will alter the evolution completely. A number of studies of self-regulated SF exist with particular attention to the influences of stellar radiation, supernova explosions, and the evaporation/condensation balance between the two chemically and dynamically distinct gas phases, the cloudy medium (CM) and the hot intercloud medium (ICM) (Franco & Cox 1983, Ikeuchi et al. 1984, McKee 1989, Bertoldi & McKee 1995, Köppen et al. 1995,1998). The evolution of DGs is self-regulated and determined by large-scale outflows (Hensler et al. 1993,1998a). External effects like extended DM halos, the IGM pressure, etc. (Vilchez 1995) could cause the morphological differences of DGs by regulating the otherwise unbound hot gas that can be held in the galactic halo. The gas could then either be stripped off, or it cools and recollapses, igniting subsequent SF.

Self-regulation with SNII energy deposition can also characterise the structure and evolution of galactic disks which reach a lower effective gravitational potential in rotational equilibrium (Firmani & Tutukov 1992; Burkert et al. 1992, Rosen & Bregman 1995).

To approach global models of galaxy evolution which yield the structural differences and details, adequate treatment of the dynamics of stellar and gaseous components is essential. At least the following processes have to be taken into account: SN, SF, heating, cooling, stellar mass loss, condensation and evaporation. This includes the treatment of the multi-phase character of the ISM as well as the star-gas interactions and phase transitions. Since gas and stars evolve dynamically, and because several processes both depend on their metallicities and also influence the element abundances in each component, these models are called chemodynamical (cd).

It must be emphasized, however, that the number of free parameters in the cd scheme is not large but actually smaller than in multi-zone models. The allowed ranges of parameter values are strongly constrained, either because they are theoretically evaluated (like e.g. evaporation and condensation), empirically determined (like e.g. stellar winds), or because they force self-regulation in a way that is independent of the parameterization. Because of limited space we refer the interested reader to more comprehensive descriptions of the cd treatment and to different applications (non-rotating galaxies: Theis, Burkert & Hensler 1992, Hensler, Burkert & Theis 1993, Hensler, Gallagher & Theis 1998a; vertical settling of the galactic disk: Burkert, Truran & Hensler 1992; disk galaxies: Samland & Hensler 1996; the MWG: Samland, Hensler & Theis 1997 (SHT97), Samland 1998; dwarf galaxies: Hensler & Rieschick 1998, also section 5).
Figure 1. Differential iron distribution of stars in the halo, K giants in the bulge, and G dwarfs in the solar neighbourhood in comparison with observations. The dashed lines show the results of simple one zone models with effective yields of $0.025 \ Z_\odot$ (halo), $1.9 \ Z_\odot$ (bulge) and $0.5 \ Z_\odot$ (disk)(from SHT97).

3. The Milky Way's Chemical Evolution

As a striking success of the $cd$ treatment we will first briefly present some of the results from a published model (SHT97) which can be compared to the observational features of the MWG. The model starts from an isolated spheroidal, rotating but purely gaseous cloud with a mass of $3.7 \cdot 10^{11} \ M_\odot$, a radius of 50 kpc, and an angular momentum of about $2 \cdot 10^7 \ M_\odot \ pc^2 \ Myrs^{-1}$, corresponding to a spin parameter $\lambda=0.05$. We assume that the protogalaxy consists initially of CM and ICM with a density distribution of Plummer-Kuzmin-type (Satoh 1980) with 10 kpc scalelength. The initial CM/ICM mass division (99%/1%) does not affect the later collapse, because the onset of SF determines the physical state within less than $10^7$ years.

While the evolutionary phases are described in detail in SHT97, here we wish to emphasize the striking agreement of the $cd$ model after 15 Gyrs with
first the metallicity distributions of the halo, the bulge, and the solar vicinity (fig.1), and secondly the radial oxygen gradient within the disk (fig.2). Convincingly one single cd model reproduces the different (otherwise implausible) $y_{\text{eff}}$ in the different regions and demonstrates that they result simply from large-scale streaming effects of the hot gas. The ICM is produced by SNeII in overpressure to its surrounding ISM and expands until its cooling leads to condensation, i.e. the phase transition to the CM. In addition, the model shows agreement with the MWG structure, i.e. gas-star content, baryonic mass distributions, velocity distributions, PN and SN rates. From this agreement it may be safe to assume that the temporal evolution of the model is reliable, e.g. the formation epochs of the components and the temporal variation of the radial metallicity gradient (see SHT97).

4. Small and Large-scale Mixing Effects between the Interstellar Gas Phases and what can Abundance Ratios tell us about?

The enormous energy release by massive stars from their combined wind, radiation and SNIa explosion leads to violently expanding hot gas bubbles. They act dynamically on the ambient ISM by sweeping it up and squeezing it into dense shells, which break up due to dynamical instabilities. Since massive stars have peeled off their unprocessed shell material during the H-main sequence lifetime, they expel their nucleosynthesized products before and during their Wolf-Rayet phase and even more intensely by SNII explosion. Due to its rapid expansion the hot gas engulfs the denser cool clumps and clouds. The effect is twofold: First, as it passes the clouds the ICM significantly perturbs their shape and surface (Elmegreen, this volume). Secondly, the contact interface between CM and ICM
Figure 3. Evolutionary tracks of 2d chemodynamical models for $10^9 M_\odot$ galaxies with (long full dotted curve) and without DM halos (open circles) in comparison with N/O vs. O/H measurements of irregular galaxies and two chemical evolutionary models by Matteucci & Tosi (1985) (upper lines) and a simple model (arrows; see Garnett, 1990).

is blown up by heat conduction. If the cloud is able to get rid of the diffused energy, hot gas can condense onto its surface; if not, the cloudy material evaporates from the surface and immigrates into the ICM. Reasonably, this mass exchange by means of evaporation/condensation is a self-regulated process in static media (Köppen et al. 1998). Streaming motions, however, can alter this picture and can lead to runaway behaviour in either direction. Certainly this mechanism causes a highly efficient small-scale mixing between the gas phases and by this homogenizes abundances on the local scales of massive star associations.

Indeed, Kobulnicky (this volume) reports the non-detection of any sizable O, N, and He anomalies from HII regions in the vicinity of young super starclusters in starburst DGs with one exception, NGC 5253, which reveals a central N overabundance.

While C and N are mainly contributed to the CM by PNe from intermediate-mass stars, O and Fe are the dominant tracers of SNII and SNIa ejecta, respectively. Since the mixture of e.g. N and O can only result from phase transitions between CM and ICM, the N/O ratio allows to make qualitative deductions about the mixing direction and its temporal efficiency. Additionally, its radial distribution provides an insight into dynamical effects of the ISM. As mentioned in the introduction (point 5) the N/O ratio is smaller in DGs than in gSs by
almost 0.7 dex, while O is lower by one order of magnitude. The averaged N/O value for DGs (see fig.3) at -1.46 (Garnett 1990) lies only 0.2 dex below the ratio determined from metal-dependent yields (Woosley & Weaver 1995) for Z⊙ and integrated over a Salpeter IMF. The almost linear dependence of the nitrogen production on Z allows for even smaller N/O in DGs because of the generally lower Z, which explains the observed scatter to even smaller ratios.

In order to study and compare abundances and structural signatures in cd models of DGs, we have performed 2d simulations of rotating gaseous protogalactic clouds for a large range of initial masses with and without dark matter halos. The density distribution is again of the Plummer-Kuzmin-type with the same spin parameter as the above-mentioned MWG model. Here we discuss 10⁹ M⊙ DG models starting with a 2 kpc scalelength. Fig.3 presents a diagram for the N/O vs. O/H ratios of DGs and gSs (also the solar value) compared with evolutionary tracks by different authors. In contrast to the other models shown (see Garnett 1990) which begin and partly remain at too large N/O ranges, both our cd models commence at very low values due to the delayed nitrogen release by PNe and the lower N production in massive stars at low metallicities. The most evolved track (10⁹ M⊙ with DM) rises rapidly and reaches N/O of -1.8 after 1 Gyr and -1.6 after 2 Gyr, respectively. This small value results numerically as the yield ratio, but as N and O enrich different gas phases, an almost ideal mixing of CM and ICM is required. Since the hot material cannot fully condense onto the clouds, an almost total evaporation of the CM in the vicinity of the SF and SNII explosion sites must be invoked. Reasonably, the N mixes perfectly in this case with O in the ICM to an almost constant abundance ratio and expands over larger distances within the DG. Due to its cooling the ICM forms new condensations of CM where the abundances are observed in HII regions at a constant value (Kobulnicki, this volume). In the case of phase transition by means of condensation, only parts of the ICM (and therefore of the O content) is incorporated into the CM, which leads to higher N/O ratios, but also reveals inhomogeneous N/O distributions. Larger gravitational potentials and resulting mass densities in more massive galaxies lead to a faster cooling of the ICM and significantly higher condensation rates which produces a larger N/O. With the same differential mixing processes the observed C/O tendency of DGs (Garnett et al. 1995) can also be explained (Rieschick & Hensler, in preparation).

5. Conclusion

Because of limited space here, we could only briefly demonstrate that various structural and chemical agreement with observations can be achieved self-consistently by global evolutionary cd models. If the cd prescription is applied, important physical processes like large-scale coupling of different galactic regions by dynamical interactions as well as small-scale mixing effects between the gas phases are adequately taken into account, and this substantially fixes the element abundances. Abundances can serve as reliable diagnostic tools of galaxy evolution and provide a chance to deconvolve it in detail, if studies couple the above-mentioned gas processes with the dynamics of gas and stars as well as with their mutual interactions.
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