Chemo-dynamical Evolution of the ISM in Galaxies

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Abstract. Chemo-dynamical models have been introduced in the late eighties and are a generally accepted tool for understanding galaxy evolution. They have been successfully applied to one-dimensional problems, e.g. the evolution of non-rotating galaxies, and two-dimensional problems, e.g. the evolution of disk galaxies. Recently, also three-dimensional chemo-dynamical models have become available. In these models the dynamics of different components, i.e. dark matter, stars and a multi-phase interstellar medium, are treated in a self-consistent way and several processes allow for an exchange of matter, energy and momentum between the components or different gas phases. Some results of chemo-dynamical models and their comparison with observations of chemical abundances or star formation histories will be reviewed.

Keywords: Galaxies: evolution, Galaxies: ISM

1. Introduction

Disk galaxies consist of complex structures with at least three main components: bulge, halo and disk. These differ in their fraction of ionised, atomic and molecular gas, their dust content and their stellar populations. Since the Milky Way Galaxy (MWG) is the best studied disk galaxy, the observations of its stars and its interstellar medium (ISM) can be used to test galactic evolutionary models in order to answer the addressed fundamental questions concerning the initial conditions, the formation and the evolution of the MWG and of disk galaxies in general, e.g.: When, how and on what time-scales did the galactic components form? Was there any connection between them? Which external influences have affected the structure? Is the solar neighbourhood representative for an "average disk"? These questions are directly related to observational facts, such as the lack of metal-poor G-dwarfs (the well-known G-dwarf problem) or the different observed effective yields in bulge, halo and disk of the MWG (Pagel, 1987). In general, these and other observational indicators, like star formation (SF) and supernova (SN) rates or colour measurements place constraints on galactic models and should be explained in a global scenario.

Another class of objects are dwarf galaxies (DGs) which differ in their structural and chemical properties from those of giant galaxies.

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Because of their low gravitational energies DGs are greatly exposed to energetic influences from processes like stellar winds, SN or even stellar radiation. In addition, low-mass galaxies seem to form at all cosmological epochs and by different processes, which make them ideal laboratories to investigate many of the astrophysical processes relevant for galaxy evolution. Again, the observations of DGs, like SF rates or metal abundances and abundance ratios, should be explained in a global model of galactic evolution.

At present, two major and basically different strategies for modelling galaxy evolution are followed: firstly, dynamical investigations which include hydro-dynamical simulations of isolated galaxy evolution and of proto-galactic 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. Simulating different galactic regions, e.g. by a closed-box model, however, presupposes that these regions are neither energetically nor dynamically coupled. Thus, in this picture a galaxy is only the sum of different isolated subsystems without any connection, despite the initial conditions. Even multi-zone models which include gas exchange between different galactic regions (e.g. Ferrini et al., 1994) are devoid of self-consistent gas dynamics.

Chemo-dynamical models are a different approach to modelling galactic evolution treating self-consistently all important dynamical and energetic processes as well as their dependence on the metallicity. For this, a multi-phase description of the ISM with the inclusion of star-gas interactions is essential. Such models have been applied successfully to spherical symmetric systems (e.g. Theis et al., 1992) and to axisymmetric systems (e.g. Samland et al., 1997, hereafter SHT). More recently with increasing computational power, also 3d chemo-dynamical models have become available (e.g. Samland & Gerhard, 2002). The chemo-dynamical treatment is described in more detail in Sec. 2 and in Sec. 3 some results of two-dimensional models are reviewed.

2. Chemo-dynamical treatment

To approach global models of galaxy evolution which can achieve the structural differences and details, an appropriate treatment of the dynamics of stellar and gaseous components is essential. In addition, at least the following processes should be taken into account: SF, SNe, heating, cooling, stellar mass loss, condensation and evaporation. This includes the treatment of the multi-phase character of the ISM as
Figure 1. A schematic sketch of the chemo-dynamical treatment. The different gaseous and stellar components are connected via mass, momentum and energy exchange. The important interaction processes are shown in this diagram.

well as the star-gas interactions and phase transitions. Since gas and stars evolve dynamically, and because several processes both depend on their metallicities but also influence the element abundances in each component, these models are called chemo-dynamical. The network of chemo-dynamical processes is sketched in Fig. 1 where one can see how the different gaseous and stellar components are connected via mass, momentum and energy exchange. The important processes are: mass from the cloudy medium is transformed into stars by SF; the high and intermediate mass stars return a fraction of this mass, enriched with metals, by SNe and PNe to the ISM; the ISM is also heated by stellar radiation and feedback processes; remnants and low mass stars build the lock-up mass that is no longer available for the galactic cycle of matter; the cloudy medium (CM) and the hot intercloud medium (ICM) are mixed by condensation and evaporation; energy is dissipated by radiative cooling and by cloud-cloud collisions.

As can be shown and must be emphasized, however, the number of free parameters in the chemo-dynamical scheme is small, because they are either theoretically evaluated (like e.g. condensation and evaporation) or empirically determined (e.g. like stellar winds), or because they force self-regulation in a way that is independent of the parame-
Figure 2. Surface densities and velocities of ICM (left) and CM (right) 7 Gyr after the onset of the galactic collapse. The ICM in the galactic plane has velocities up to 230 km s\(^{-1}\), while the velocities of the infalling CM are less than 60 km s\(^{-1}\). (taken from SHT)

terisation. The latter has been shown for SF by Köppen et al. (1995, 1998). The only free parameters which cannot approach particular "equilibrium values" due to the absence of feedback are the stellar initial mass function (IMF), the momentum transfer by drag and the initial conditions, although the initial density distribution and gas-phase fraction are basically not affecting the model evolution. For a more comprehensive description of the chemo-dynamical treatment the interested reader is referred to Theis et al. (1992) and SHT.

3. Results from chemo-dynamical models

3.1. The Milky Way’s chemo-dynamical evolution

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 \(2 \cdot 10^7 M_\odot \text{pc}^2 \text{Myr}^{-1}\), corresponding to a spin parameter \(\lambda = 0.05\). It is assumed that the protogalaxy consists initially of CM and ICM with a density distribution of Plummer-Kuzmin-type (Satoh, 1980) with 10 kpc scale length. 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. Since almost excellent agreement of the chemo-dynamical model after 15 Gyr is found with the presently observed structure of the MWG, it may be safe to assume that also the evolutionary behaviour of different properties under consideration can be reliable deduced. The 15 Gyr old model
model is e.g. able to reproduce the different metallicity distributions and effective yields of the halo, the bulge and in the solar vicinity (see Fig. 7 in SHT), respectively, and also to solve the G-dwarf problem as an effect of large-scale dynamics of the metal-enriched ICM and its condensation and metal pollution of the CM (Fig. 2). Furthermore, the radial abundance gradients (see Fig. 6 in SHT), abundance ratios like O/Fe versus Fe/H (see Fig. 9 in SHT), mass fractions of the components, SF rate in the disk, etc. fit the observations strikingly. Also interestingly, one can trace the temporal run e.g. of SN and PN rates (see Fig 8. in SHT) and of the SF rates in different MWG regions (Fig. 3) which allow the dating of their formation, showing a delay of disk formation with respect to the halo extinction by almost 4 Gyr and a bulge evolution extended over 5 Gyr with a least two SF episodes.
Figure 4. Star formation history of the $10^9 \text{M}_\odot$ chemo-dynamical dIrr model in units of $\text{M}_\odot \text{Myr}^{-1}$ for different radial zones in the equatorial plane. The absolute values correspond to the differences between two curves. The vertical lines divide the different evolutionary phases as described in the text. (taken from RH)

3.2. A Dwarf Galaxy model

In this model by Rieschick & Hensler (2000, hereafter RH) the initial baryonic mass is about $10^9 \text{M}_\odot$ embedded in a static dark matter halo according to Burkert (1995) with a mass of $10^{10} \text{M}_\odot$. The numerical grid size is 20 kpc x 20 kpc, and the model is aimed to represent a dwarf irregular galaxy (dIrr). In Fig. 4 the SF history is plotted and five distinct dynamical phases of evolution, that can be distinguished from a kinematical analysis of the model, are indicated by vertical lines. In the collapse phase (0 – 0.3 Gyr) the proto-galactic gas distribution cools and collapses with a net gas infall rate of $3.2 \cdot 10^{-1} \text{M}_\odot \text{yr}^{-1}$ leading to a central density increase by a factor of 100. Thus the SF rate rises steeply according to its quadratic dependence on the CM-density to its maximum value of $1.8 \cdot 10^{-2} \text{M}_\odot \text{yr}^{-1}$.

After passing a post-collapse, a transitional and a turbulent phase (see RH for details) the galaxy reaches its final irregular phase after 6.2 Gyr, when a global quasi-equilibrium seems to be established. At this stage the disk is balancing itself in the sense of keeping the gas mass constant. This can be seen in Fig. 5 where the mass flows between the different components averaged between 6.2 - 10.0 Gyr over a cylinder with $r = 2 \text{kpc}$ and $z = 1 \text{kpc}$ are analyzed. From the mass flow rates one can distinguish between an outer and an inner cycle. The outer
one is produced by infall of CM. The CM-reservoir in the galaxy is consumed by means of SF. The SF rate amounts to about 24% of the infall rate and 10% of this matter is almost instantaneously reejected by high mass stars (HMS). The inner cycle represents SF and stellar evolution and, therefore, contains different time-scales.

The production of a minor fraction of hot ICM by SNe II leads to evaporation of remaining CM and escapes from the galactic body as outflow as a consequence of its high energy content. Significantly, almost 80% of the infall is immediately converted into outflow by only 3% of gas that has gone through the stellar cycle and is puffed up by stellar energy release. The full evaporation rate can exceed the infall rate because shell sweep-up leads to fragmentation and cloud formation in addition to a small amount of condensation. It should be emphasized that even though a large amount of the outflowing gas is gravitationally unbound and leaves the galactic body, the metals produced in HMS are for the most part kept in the outer gas flow cycle by mixing ICM with continuously infalling clouds. As a result of this mechanism only...
a few percent of the metals leave the gravitational field of the galaxy with the outflowing ICM. While this mixing itself happens on a time-scale of about 20 Myr, the complete cycle of metal enrichment takes almost 1 Gyr because of the low infall velocity at later evolutionary stages. In contrary, the inner cycle leads to an efficient self-enrichment of SF regions within 10 Myr (see also Skillman et al., 1998). The outer enrichment time-scale would be reduced significantly, however, in a scenario of a rapidly infalling intergalactic gas cloud.

4. Summary and outlook

Chemo-dynamical models of the MWG and dIrrs have been reviewed. Results demonstrate both the agreement of one single global model with numerous detailed and regional observations as well as with the global structures. The necessity of the full but complex chemo-dynamical treatment of the galaxy components is justified. Several observational features like abundance distributions and ratios can only be understood in a self-consistent global evolutionary scenario if one is taking the dynamics of the components and their relevant interaction processes into account. It has been shown that a large-scale coupling of different galactic regions by dynamical effects as well as the small-scale mixing between the gas phases due to condensation/evaporation affect the observational signatures. As long as the long-range streaming with inherent small-scale interactions under the inclusion of a two-phase ISM with their small-scale spatial resolution cannot be treated in other numerical simulations, e.g. in present SPH models, they miss self-consistency and cannot reproduce the observations in their global extent.

One has to emphasize that a reliable chemo-dynamical model has to reproduce the complete set of observational features on different galactic scales, i.e. for all existing components and observed variables as the whole. It is not sufficient for an understanding of the global galactic evolution to fit single particular observed properties. The time dependence of element abundances and their ratios can serve as reliable diagnostic tools of galaxy evolution and the physical state of the ISM. Their combination provides a new chance for a detailed deconvolution. While the chemo-dynamical models also provide element abundances in the hot ICM, their observational validation is still a problem.

The here applied grid code is still limited to two dimensions because of the numerically expensive treatment of complex processes and spatial resolution. It has already been mentioned, that recently also three-dimensional models were published (e.g. Samland & Gerhard, 2002;
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Harfst et al., 2002; Harfst et al., 2003; see also Samland, this volume). Most approaches are based on N-body simulation and a multi-phase description of the ISM is achieved by combining a SPH algorithm, to describe the hot ICM, with a sticky particle scheme, to describe the cloudy medium. With three-dimensional models infall of gas clouds or small satellites can be studied as well as the merging of giant spiral galaxies. This should help to explain e.g. the question on how and to what extend SF is triggered by such events. Nevertheless, one has to keep in mind, that even the two-dimensional chemo-dynamical investigations present a giant leap with respect to non-dynamical chemical or purely gas-dynamical studies.

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