Discussion: Between simple and chemodynamical models of galaxies

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1. The arena of galactic evolution models

At first sight, the World of chemical and chemodynamical models might seem to be composed of two camps. But in reality, it is more like a spectrum of possible approaches and tools for modelling and interpreting galactic observations and understanding the evolution of galaxies. In the Table below I roughly sketch the geography of that World, by arranging a selection of studies with respect to the complexity of the local physics and the global complexity indicated by the spatial dimensions. Simplified though this map is, it gives an overview of the modelling tools available to us today.

2. From chemical evolution to chemodynamics: radial abundance gradients

To illustrate the different approaches, properties, and problems of chemical and chemodynamical evolution models, let us consider radial abundance gradients in spiral galaxies: Ever since their discovery in the 1970s, quite a few models have been put forward to explain the typical value of -0.07 dex/kpc. Rather different physical mechanisms have been invoked, among them radial variations of the yields, the SFR, the accretion timescale, and radial gas flows.

When I got first involved, we applied a proper chemical evolution model with detailed nucleosynthesis prescriptions. We quickly realized that a semi-analytical approach gave us a much more efficient way to survey the parameter space for plausible solutions. However, the structures seen on those maps turned out to be surprisingly simple: There must be an even simpler and more fundamental structure behind the models. Direct inspection of the differential equations – they contain

Table I. The arena of chemical evolution models: local complexity increases downward, global complexity towards the right. Numerical models are set in normal type, *analytical models in italics.* Sincere apologies to anybody who could not be named due to space limitations!

	SingleZone	1-D	2-D	3-D
		chemical evolution models		
closed box	*SimpleModel*	./.	./.	./.
gas flows	$\longleftarrow$ *Edmunds, Köppen* $\longrightarrow$			
		Lacey/Fall, ...		
time delay	*Clayton*			
detailed nucleosyn.	Talbot/Arnett	...		
	$\longleftarrow$ Matteucci, Tosi, ... $\longrightarrow$			
		chemodynamic models		
global dynamics	./.	$\longleftarrow$ Larson $\longrightarrow$		(Katz, Navarro) Steinmetz
multi ISM + energetics	$\longleftarrow$ Hensler, Burkert, Theis $\longrightarrow$		Samland97	
	Köppen			
det.stellar dynamics				Samland02 Berczik, ...

all the information about **all** solutions – led us to

$$\begin{aligned}
\frac{\partial}{\partial t}\frac{\partial \ln Z}{\partial r} &= \frac{\mathrm{SFR}}{gZ}\cdot\frac{\mathbf{d\alpha y}}{\mathbf{dr}} && (1)\\
&+ \frac{\alpha y}{Z}\cdot\frac{\mathbf{d}}{\mathbf{dr}}\left(\frac{\mathbf{SFR}}{\mathbf{g}}\right) && (2)\\
&+ \frac{Z_A - Z}{Z}\cdot\frac{\mathbf{d}}{\mathbf{dr}}\left(\frac{\mathbf{ACC}}{\mathbf{g}}\right) && (3)\\
&+ \frac{\mathrm{ACC}}{gZ}\cdot\frac{\mathbf{dZ_A}}{\mathbf{dr}} && (4)\\
&- \frac{\alpha y\,\mathrm{SFR} + Z_A\,\mathrm{ACC}}{gZ}\cdot\frac{\partial \ln Z}{\partial r} &&\\
&- \frac{\partial^2 \ln Z}{\partial r^2}\cdot\mathbf{v_r} - \frac{\partial \ln Z}{\partial r}\cdot\frac{\mathbf{dv_r}}{\mathbf{dr}} && (5)
\end{aligned}$$

which allowed to clearly identify how each physical process would influence the evolution of the gradient(Götz & Köppen, 1992). For example, it now becomes obvious why a linear dependence of the SFR on density may lead to no gradients, because term 2 vanishes. The presence of the gradient itself in term 5 shows that radial flows alone cannot make a gradient, but can modify it in either direction.

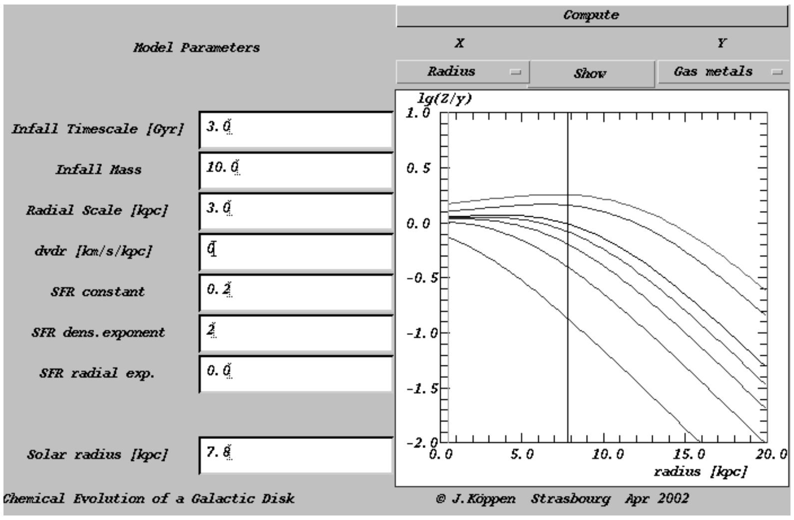

Figure 1. The evolution of the radial metallicity profile in an infall model with quadratic SFR law, computed with the Java applet available on the Web at `http://astro.u-strasbg.fr/~koppen/galdisk/Galdisk.html`

The essential structure of the problem can be preserved in these somewhat simplified equations which is easily solved numerically, even interactively (cf. Fig. 1), so that one realizes that the temporal evolution gives essential clues to distinguish models of the various scenarios (Köppen 1994). Fig. 2 shows that the form of the SFR determines the initial gradient which then may be modified by radial gas flows. Obviously, there are many different ways to explain the present gradients observed with the H II regions. One only wishes that one could accurately determine the abundance gradient in the past. But even then, a unique interpretation might still escape us!

This **non–uniqueness** illustrates one limitation of modelling the chemical evolution with by adjusting parameterized recipes. The other classical example is the notorious G dwarf "Problem" (cf. Pagel, 1997), though there is now a general agreement that the most likely explanation lies with the fact that the solar vicinity is not a closed box, and that stellar metallicity distributions present powerful constraints for models.

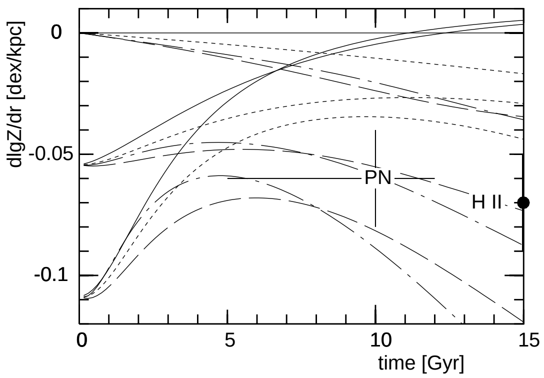

Figure 2. The time evolution of the Galactic radial metallicity gradient from models with SFR exponent 1, 1.5, 2 (top to bottom) and exponential infall with radial scale of 4 kpc and time scale of 5 Gyrs. Full lines are without radial gas flows; linearly increasing inflow velocities of 1 km/s (long dashes) and 0.5 km/s (short dashes); the dash-dotted curves are with 1 km/s but an infall time scale of 2.5 Gyrs.

Another limitation is linked with the **physical meaning** of a parameter value derived by fitting the model to the observations: For instance, what is the physical reason for the star formation time scale to be about 3 Gyrs in the solar neighbourhood? Why is the infall time scale about 5 Gyrs, or has a particular radial variation (inside–out formation recipe)? Why are the apparent yields in the Bulge, Disk, and Halo obtained from stellar metallicity distributions so different (Pagel, 1989). If this is due to gas infall, why are the infall rates so tuned to give the yields of about 1.8, 0.4, and 0.025, respectively? All these questions are outside the scope of chemical modelling. We know that these limitations exist, and we should be conscious of them! Nonetheless, chemical evolution models are very useful and efficient tools.

3. The Realm of Chemodynamics

3.1. Assumptions

The philosophy of chemodynamics is to model galactic evolution based on a description with a set of physical processes as complete as possible today. The essential ingredients are

- **global dynamics**: initially we used Larson's approach of moment equations, but including the ICM as a hot gas; more recently, the stellar dynamics is treated more appropriately in detail via n-body approach
- **multiphase ISM**: exchange of mass, metals, (angular) momentum, thermal and kinetic energy, also with stellar component
- **gas-star interactions**: stellar nucleosynthesis with time delays similar to chemical evolution models, i.e. star formation, supernovae (II and Ia), planetary nebulae, stellar winds, et al.

All prescriptions and rate coefficients are taken either from theoretical models of that physical process, or from empirical evidence or observations of the local ISM. In this way, the only free parameters that remain are the truely physical ones, such as the initial mass and angular momentum of the protogalactic gas cloud.

3.2. Results

In the 2-D full chemodynamical model by Samland et al. (1997) for the Galaxy one obtains:

- The radial gradient for the oxygen abundance in the cloudy medium in the solar neighbourhood is -0.07 dex/kpc (Fig. 6 of Samland et al., 1997). The principal mechanism appears to be the strong outflow of metal-rich hot gas from the centre of the Galaxy due to the initial phase of intense star formation, followed in the gaseous halo by condensation into the cloudy medium
- The distribution functions of the stellar iron abundances computed with the same (true) yields in the Bulge, Solar neighbourhood, and Halo reproduce well the observed distributions (Fig. 7 of Samland et al., 1997). Thus the different effective yields are consistently explained as the consequence of the global gas flows.

It is worth emphasizing that in this comparison, not a single parameter in the network of the gas–star interactions was adjusted to fit the data!

3.3. How does chemodynamics work?

The inner workings of chemodynamical models can be elucidated by single zone models. A very important aspect is the existence of a self-regulation of the SFR, via a balance between heating of gas due to UV radiation and stellar winds emitted by massive stars and radiative cooling. The analytical and numerical studies by Köppen et al.

(1995) revealed that under normal galactic conditions a model quickly enters a stable equilibrium which is quite robust against details in the description. The resultant self–regulated SFR is proportional to the square of the gas density, irrespective of what form of the stellar birth law is assumed, as shown in Fig. 3. Comparison with the complete 2-D models by Samland et al. (1997) showed that almost all the volume elements are found in this self–regulated mode during most of the time. Thus, this SFR is one **characteristic property of chemodynamical models**.

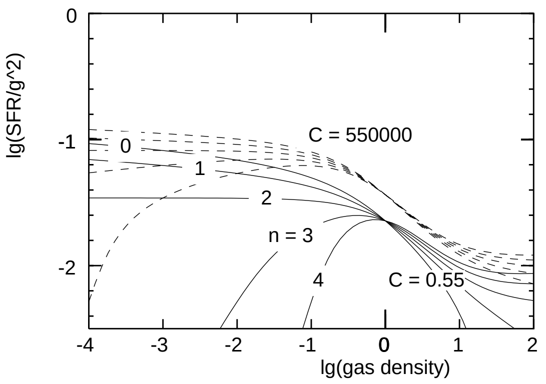

Figure 3. The self-regulated star formation rate in single zone chemodynamical models, for various values of the exponent n and the factor C of the stellar birth function $\Psi = C\rho^n$ (Units: time in Gyrs, density in $M_\odot/\mathrm{pc}^3$, 1 atom/cm3 corresponds to 0.02 $M_\odot/\mathrm{pc}^3$)

One important ingredient is the multi–phase structure of the ISM. The theoretically predicted evaporation and condensation rates between clouds and ICM gas imply the presence of another, slower equilibrium (Köppen et al., 1998). This results in the ICM mass density to remain fixed at about 0.001 to 0.01 of the CM density, and gives a sufficiently high degree of mixing, so that the closed–box chemodynamical model behaves very closely to the Simple Model (Fig. 4). Again, this **characteristic equilibrium** is present in the more complete models (Samland, Rieschick). In summary, the apparently complicated network of interactions between the gas phases and stars evolves in a rather simple fashion, a hierarchy of separated equilibria working at different time scales. Ongoing studies indicate that this behaviour of the local model is also essential in determining the behaviour models which include the global dynamics of gas and stars.

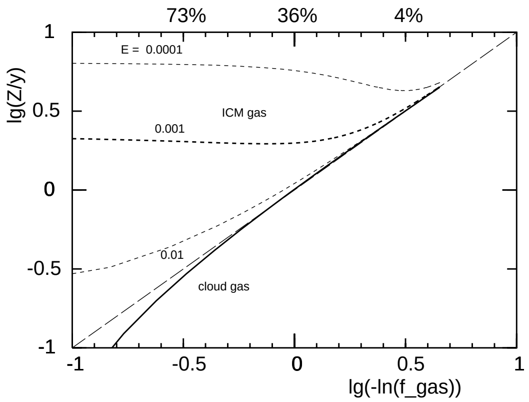

Figure 4. The relation between gas fraction and metallicity in single zone chemodynamical models follows the Simple Model (dashed diagonal) closely, though the metallicity of the ICM, which amount to a small mass fraction only, may be as high as the metallicity of the SN ejecta. Thick lines refer to models consistent with Samland et al. (1997)

3.4. Another explanation

The more cosmologically–minded model by Steinmetz & Müller (1995) shows that the evolution of star forming gas which is gravitationally ruled by dark matter also leads to galaxies whose spatial, dynamical, and chemical properties resemble well the observations. Their model gives a radial metallicity gradient in the disk of -0.05 dex/kpc. Though the model is differs from a genuine chemodynamical one, e.g. it lacks the hot ICM gas, and also predicts too many metal-poor stars in the disk, it does come up with most reasonable values for the radial abundance gradients in disk and bulge. The fact that physics–based models of two different types are able to explain the gradients wants to tell us something about the origin of abundance gradients ...

4. Inheritance of properties

How much information about the physical processes can be extracted from a model depends on how sensitive the model is to that particular effect. In the Table below I indicate how the well known relations of the analytical Simple Model remain intact when one considers more complicated models. There are what seem to be trivialities, such as that in all chemical and chemodynamical models the abundance ratio of elements produced undelayed and with constant yield is simply the ratio of their yields. Thus, in order to explain the abundance ratios of O, Ne, S, and Ar in emission line objects (Henry & Worthey 1999), there is no need to resort to any complicated evolution model. On the other hand, this offers clear constraint for the stellar nucleosynthesis. The reason for such a behaviour is that the relevant differential equations remain *linear* with respect to the abundance.

Table II. Inheritance of properties of the Simple Model solution to more complex models

	abund. of prim.elmt. $Z = -y \ln f$	abund.ratio prim.elmts. $P_1/P_2 = y_1/y_2$	sec./prim. abund.ratio $S/P \propto P$	stellar metal. distr.fctn. $\frac{ds}{dZ} \propto \exp(-Z/y)$
Single zone models				
with inflow	$\approx$	yes	yes	no: *fixes Gdwarfs*
inhomogeous	yes	yes	no	yes
chemodynamics	yes	yes	yes	yes
1-D models				
chemical evol.	$\approx$	yes	yes	no: *like infall*
Larson	no	yes	yes	yes
Larson + ICM	$\approx$	yes	yes	no
2-D models				
chemodynamics (Samland97)	no	yes	yes	no: *bulge/disk/halo*

Inflow of gas changes the relation between metallicity and gas fraction somewhat, and the stellar metallicity distributions sufficiently as to give an explanation for the G dwarf problem. While the spatially averaged abundances in models that permit *spatial chemical inhomogeneities* (White & Audouze, 1983; Wilmes & Köppen, 1994) evolve just as in the Simple Model, the relation between secondary and primary abundances at any time is much different.

Single zone *chemodynamical* models share the same properties as the Simple Model, but they add relations characteristic for the interactions with the multi–phase ISM: the self-regulated star formation rate which depends quadratically on gas density, and the density ratio of cloudy and intercloud medium. These characteristics we have also found in the complete chemodynamical models.

Larson's (1973) *spherical collapse* models show a diverse deviation from the simple relation of metallicity and gas fraction, but they have the same stellar metallicity distribution as the Simple Model (cf. Köppen, this volume). Inclusion of the hot ICM gas modifies this substantially. The full chemodynamical models (Samland et al. 1997) give different distributions for stars of the Bulge, Disk, and Halo, in agreement with the Milky Way data.

5. The relation between chemical and chemodynamical models

The region between the two "camps" of galactic modelling can be made into a mutually fruitful interface to improve our understanding of physics in galaxies:

- Chemodynamical models should **provide physical explanations** for the parameter values found by chemical evolution models, such as: the temporal and spatial form of the gas infall into the disk as a function of fundamental galactic parameters (mass, ...)

- Conversely, chemical models could provide constraints not only on parameter values in certain types of galaxies, but also on acceptable forms for the parameterizations, for example by reverse modelling (Meusinger, 1992; Prantzos, this volume).

- Chemodynamical models are merely chemical evolution models with **built-in physics**. This should limit the solutions in a characteristic way. In which aspects does that differ from chemical models? They should offer less freedom in modelling an object than conventional chemical evolution models. How much do they offer? Perhaps it shows up as a "conspiration of parameters". Any such knowledge would permit to predict the behaviour of chemodynamical models ("back-of-the-envelope chemodynamics") and allow to feed more physics into the parameterizations useful for chemical modelling

- What **verifyable predictions** can chemodynamical models make that go beyond the chemical models? Examples could be: Relations between kinematical and chemical properties of stars, Radial gas flows, Abundances in the hot phase of the ICM, Ejection rates of gas and metals into intergalactic space

- Because chemodynamical models are a special subset of chemical evolution models, their behaviour has to follow any general laws that one can derive from general models of chemical evolution.
- The **nonlinear ingredients** in the formulations are likely to cause the emergence of structures of the solutions, some of which may be typical for chemodynamics
- As this conference has shown, there are now a **variety of chemodynamical models** in a broader sense, and with a variety of descriptions for the ISM and the gas-star interactions. Both their similarities and their differences will be useful to understand better the complex physics involved. How narrow or how wide is the range of their behaviours? We should profit from a careful intercomparison.
- Finally, we like to note that in both chemical and chemodynamical modelling we usually assume that there are no small-scale chemical inhomogeneities. Though it might be interesting to address the implications for either type of model, chemodynamics is already quite complex!

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