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Chemodynamical Evolution of Dwarf Irregular Galaxies

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Due to their structural and chemical peculiarities dwarf irregular galaxies are of particular interest in astrophysics. Internal and environmental effects which exceed the low gravitational energy of these type of galaxies have a large influence on the evolutions of these low-mass systems. Dwarf irregular galaxies serve a an ideal laboratory for understanding plasmaphysical as well as astrophysical processes.

In order to understand the evolution of this type of galaxies an appropriate description must take large-scale dynamical and smale-scale thermal processes as well as chemical ingredients and their influence on the processes into account. Since the numerical treatment has to adapt properly to the temporal and spatial resolution of these processes and is therefore most time consuming, only in 2d are feasible without loosing insight into smale-scale processes. Here we present numerical simulations of dwarf irregular galaxies performed with our chemo-dynamical galactic evolution code CoDEx. The models not only represent successfully observed signatures but also give an insight into dynamical and physical processes working also in all other kinds of galaxies. By the evolution of a representative dwarf galaxy model we briefly discuss evolutionary phases and typical chemical abundances.

1 Introduction

As the sun is not a unique star, each galaxy like our Milky Way (MWG) is a unicate in the universe. These huge astronomical systems consist of stars and gas with total masses between 10^6 and 10^{12} $\mathrm{M}_\odot$ [a] and show a great variety of morphological types. Their sizes range from around 2 to $40\ kpc$ [b].

Two main parameters to classify galaxies are the total mass and the angular momentum. Massive galaxies with masses above 10^{10} $\mathrm{M}_\odot$ have already been divided by *Edwin Hubble* in the 30s into flattened spiral galaxies (gSs) like our MWG and elliptical systems (gEs). Although, in particular, gSs look very spectacular and complex, also dwarf galaxies (DGs) with masses below 10^{10} $\mathrm{M}_\odot$ are particularly interesting objects. On the one hand, they are the most numerous galaxy type. On the other hand, from cosmological reasons they are expected to serve as the building blocks of galaxy formation, but form at all cosmological epochs, even at present. In addition, dwarf systems are distributed over a wide range of appearances, from dwarf ellipticals with high velocity dispersions and their low-mass end as dwarf spheroidals, to rotationally supported and gas rich dwarf irregular galaxies (dIrr) with a patchy structure due to star formation (SF) sites.

In summary, DGs are most interesting astrophysical objects and serve as an ideal laboratory to investigate processes significant for the chemical and dynamical evolution of galaxies. (See Ferguson & Bingelli[3] for a review about the different morphological types of DGs.)

[a] $\mathrm{M}_\odot$ = *solar masses* is a common astrophysical mass unit; $1\,\mathrm{M}_\odot = 1.99 \cdot 10^{30}\ kg$
[b] $kpc = 1000\ pc$; pc, i.e. $parsec$ is the usual astrophysical length unit and equals to 3.26 $light\ years$; $1\,pc = 3.08 \cdot 10^{16}\ m$

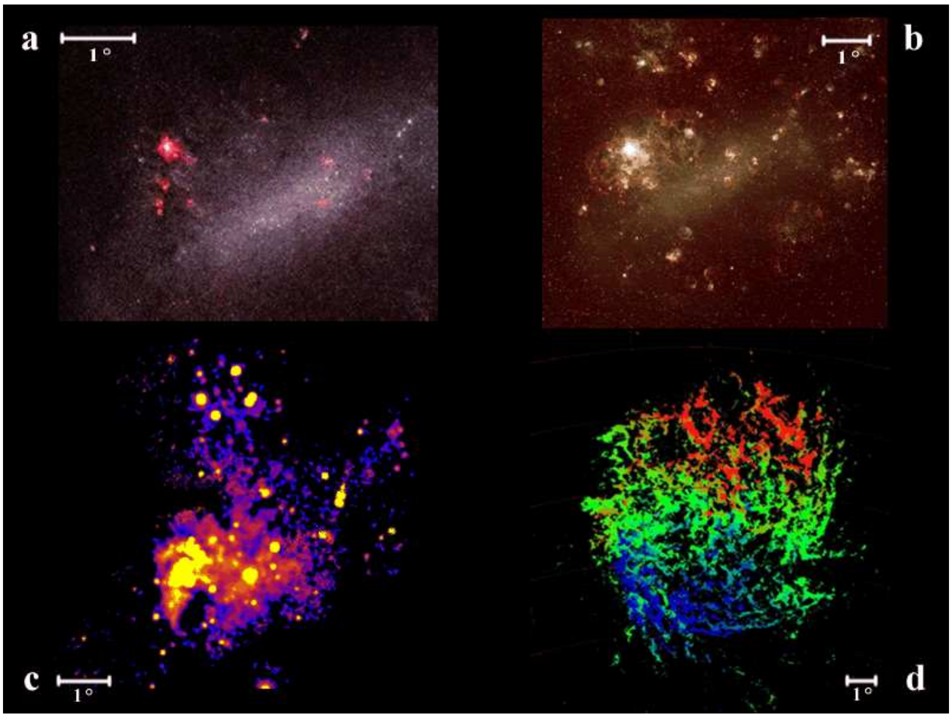

Figure 1. The dwarf irregular galaxy *Large Magellanic Cloud* (LMC) at different wavelengths: a) optical image showing stars and luminous interstellar gas; b) $H\alpha$ image pronouncing star forming regions; c) X-ray here traces hot supernova expelled gas; d) large-scale neutral hydrogen gas structures in the 21 cm radio line. Please note the different scales of the four images.

1.1 Irregular Dwarf Galaxies

A typical example of an dIrr galaxy is the Large Magellanic Cloud (LMC) on the southern sky, being a small companion to our MWG, 20-40 times lighter and around 5 times smaller. Fig. 1 shows four images of the LMC at different wavelengths. As a typical feature of dIrrs, the visible stellar bar of the LMC is deeply embedded in a large HI disk. While the gas fraction in the MWG is about 10 % of the baryonic mass, in dIrrs sometimes not more than 60 % of the initial gas mass is transformed into stars yet by means of star forming processes. According to their lower gas mass also their SF rate amounts to 10^{-3} to 10^{-1} $\mathrm{M}_{\odot}/yr$ only compared to 2.0 $\mathrm{M}_{\odot}/yr$ in the MWG. The old stellar population is usually widely distributed, while the current SF regions show a patchy structure as in Fig. 1.

Because of their lower binding energy internal energetical processe like supernova (SN) explosions, stellar winds and stellar radiation strongly influence the evolution of dIrrs and make their figure irregular. They are also strongly affected by external influences like infall of intergalactic gas and encounters with nearby galaxies. Most dIrrs have undergone various epochs of enhanced SF. Some galaxies with very bright, blue and compact SF centers are in an extreme state of SF, a so called *starburst* (SB), probably triggered e.g. by gas infall.

Due to the low gravitation of these low-mass galaxies a continuous mass outflow driven by SNe has to be assumed. To keep the baryonic matter gravitationally bound an additional *dark matter* component is required, whose nature is still unknown. Remarkably, dIrrs have low chemical element abundances (always lower than the sun and sometimes down to $1/100$ of the solar value) with a large scatter. Often abundance peculiarities are observed.

1.2 Problems in Understanding Chemical Evolution

Our universe started from the *primordial* gas mixture consisting mainly of hydrogen and helium with tiny portions of other light elements (Li, B, Be). All heavier chemical elements have been produced by nucleosynthesis processes in the hot interior of stars.

The element mixture blown back into the galactic gas at stellar death [c] depends mainly on stellar masses but also on individual conditions, like e.g. initial chemical composition or the interaction with a companion in a *binary star* system.

All chemical elements heavier than helium are referred to by astronomers as *metals*. This *metallicity* has increased from zero to the solar value of 2 % in mass or even higher values in some galaxies. It traces the evolution of galaxies. Analytically, in a simple model of an isolated system the metallicity increases with the logarithm of gas consumption by SF. This simple picture is to some extent not fulfilled in dIrrs with respect to the existence of underlying old stellar populations but still low metallicites.

It is more likely to assume scenarios of very low SF rates and sporadic events like SB under which conditions metal-rich gas can be expelled from the galaxy. The infall of primordial intergalactic gas clouds could additionally dilute the dIrr's gas mixture. Huge halos of neutral gas observed around many dIrrs could serve as a reservoir of pristine gas.

Additionally to the metallicity the ratio of chemical element abundances is of special interest, in particular, nitrogen (N) and oxygen (O) are well observable even in distant and faint galaxies. N is mainly released by intermediate mass stars[d] to the warm cloudy interstellar gas (CM), while the high-mass stars produce O and expel it into the hot intercloud medium (ICM). These two gas phases are dynamically decoupled but exchange matter due to evaporation and condensation processes on the surfaces of gas clouds. Only a detailed comparison of both dynamical and mixing timescales can provide an insight into the amount of stellar nucleosysthesis products exchanged between the gas components. The following processes are interesting with respect to their influence on chemical abundances:

- Oxygen is lost from the galaxy by means of galactic winds if not mixed into the warm gas phase before. This leads to a lower O and higher N/O value.
- Short-living massive stars in SBs decrease the N/O-rate by O release, until long-living intermediate mass stars dominate the metal production and release.
- Infall of pristine gas leaves the N/O-ratio unchanged but leads to generally lower metallicities.

Detailed comparisons with observations and, even more important, a close look on the detailed effects of astropysical processes and their timescales are necessary to decide about

[c] by supernova explosion in the case of massive stars or by the formation of *planetary nebulae* for stars with masses below ca. $10\ \mathrm{M}_\odot$

[d] with masses between $1\ \mathrm{M}_\odot$ and nearly $10\ \mathrm{M}_\odot$

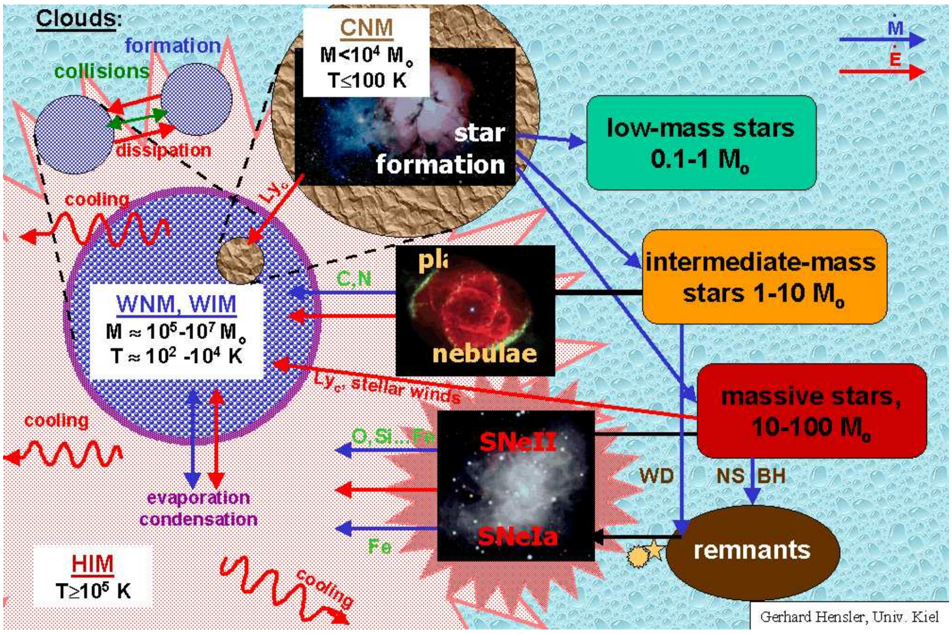

Figure 2. The scheme of components included in the chemo-dynamical treatment and their materialistic and energetic interaction processes. The abbreviations are: CNM: cold neutral medium, WNM: warm neutral medium, WIM: warm interstellar medium, HIM: hot interstellar medium, WD: white dwarfs, NS: neutron stars, BH: black holes. Red arrows denote energetical, blue arrows materialistic transitions between the components.

their importance for the galactic evolution. Significant processes which affect the evolution of these galaxies are:

- large-scale streaming motions,
- local gas-phase mixing processes,
- long cooling timescales due to low mass densities,
- starbust-trigger events which also fuel the dIrr with pristine gas,
- star-gas interactions with a large energetic input relative to the energy content of the whole dIrr,
- loss of metals due to galactic winds and the resulting change of chemical abundances.

2 Numerical Models

Astrophysics is unique among all physical disciplines since it has to suffer from the impossibility of hand-made experiments. Astronomical observations, even with enormous and sophisticated instruments, like e.g. the Hubble Space Telescope or the European Very Large Telescope, offer always a 'snapshot' of the extremely long-lasting astrophysical evolutionary progression. The evolution of galaxies is counted in billion years and begins soon

- two dimensions, cylindrical symmetry
- staggered grid, logarithmically stretched
- explicit/implicit code
- spatial resolution $40 - 50$ pc
- total grid size 20 kpc
- operation splitting, van Leer advection scheme
- 5 component: 3 stellar, 2 gaseous
- differential equations for each component
- 7 variables per component (hot gas: 5)
- 22 materialistic and energetic transition rates

Table 1. Numerical characteristics of the *cd* galactic evolution code CoDEx

after the 'birth' of our universe, the Big Bang, around 15 billion years ago. Evolutionary simulations of galaxies try to reproduce the history of galaxies in order to explain individual signatures of galaxies and to study the influences of evolutionary effects.

One approach to treat the dynamical evolution are N-body simulations where the galactic components are represented by thousands of mass points. These calculations can properly deal with 3d structures, like e.g. bars or external perturbations by means of galactic encounters, and are at present in progress to handle the chemo-dynamical interaction scheme (Berczik et al.[1]). Nevertheless, they lack of sufficient spatial resolution for small-scale effects, although the particles concentrate where mass is accumulating.

The main purpose of hydrodynamical grid codes is the proper treatment of gas dynamics in galaxies even on smaller scales. If interaction processes, however, are treated on small scales, they are limited yet to 2d. Chemical evolution calculations are trying to trace the metallicity and chemical abundance ratios.

The *chemodynamical* (cd) evolutionary description applied in our models are the most complex and sophisticated numerical calculations concerning the entire galaxy. A 2d hydrodynamical grid code is combined with a complete set of plasmaphysical and astrophysical processes as shown in Fig. 2. The chemical evolution is taken into account during the lives of stars by means of by means of a treatment simulating the nucleosynthesis of chemical elements inside stars. Since dynamical and chemical processes are closely coupled only these *cd* simulations allow to get a self-consistent picture of the SF history and also the chemical evolution of galaxies. The restriction to two dimensions due to the complexity of these calculations does not falsify the results as comparisons with less complex and resolved 3d simulations show.

Table 1 shows an overview of the numerical characteristics of the *cd* galactic evolution code CoDEx. This modeling of galactic evolution is properly treated by the *cd* prescription. Its formulation in 1d and 2d dynamics with the "materialistic" and "energetic" equations can be found for interested readers e.g. in Theis et al.[8] and Samland et al.[6], respectively.

2.1 A Representative Dwarf Irregular Galaxy Model

The model galaxy presented here starts with a gaseous mass of 10^9 $\mathrm{M}_\odot$ within the total numerical grid size of $20{\times}20$ kpc^2. The matter is distributed according to a Kuzmin-

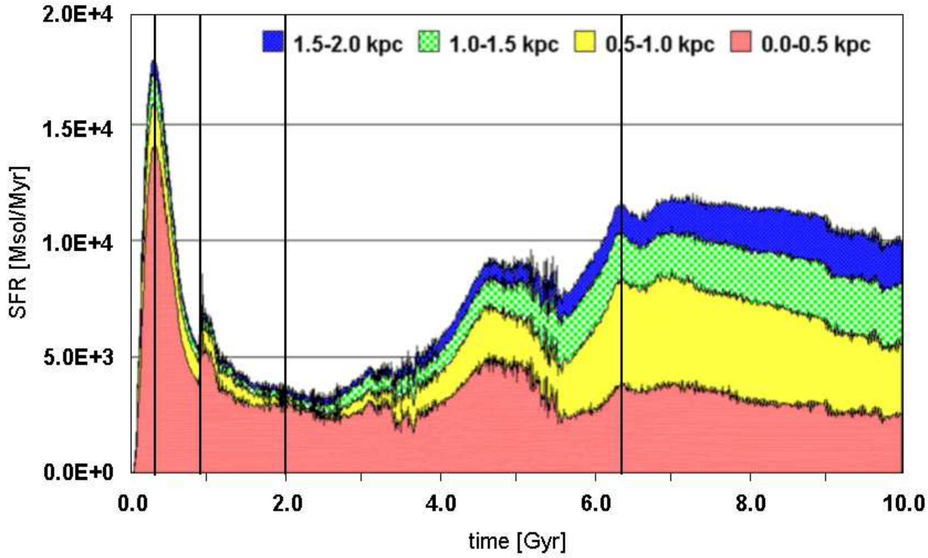

Figure 3. SF history of the dIrr model in units of $\mathrm{M}_\odot/Myr$ for different radial zones in the equatorial plane. The absolute values correspond to the differences between two curves. The vertical lines devide the different evolutionary phases described in the text.

Plummer-model (Satoh[7]) and is thereby in virial equilibrium until a collapse of this protogalactic cloud is initiated by dissipative processes like radiative cooling or cloud-cloud collisions. Even after the collapse is finished most of the initially given matter remains in the form of CM gas and envelopes the galaxy as a gas reservoir for later infall. Merely $10^8\ \mathrm{M}_\odot$ form the core region of the galaxy where most of the SF takes place. Additionally to the gas matter a static dark matter halo with a total mass of $10^{10}\ \mathrm{M}_\odot$ ($10^9\ \mathrm{M}_\odot$ in the core region) is given with a density distribution according to Burkert[2].

3 Results

3.1 Evolutionary Phases

The evolutionary history of the model galaxy (as shown in Fig. 3) is traced for a time intervall of $10\ Gyr$ since the beginning of the collapse and in characterized by five destinct epochs which differ with regard to the dynamics of the two gas phases and the SF history as well as to the morphological structure. (See Rieschick & Hensler[5] for details.) The phases are:

- Collapse phase ($0 - 0.3\ Gyr$): collapse of protogalactic cloud; increasing SF activity,
- Post-collapse phase ($0.3 - 0.8\ Gyr$): reduction of SF rate due to self-regulation and reexpansion,
- Transitional phase ($0.8 - 2.0\ Gyr$): formation of final galactic structure: center and thick disk,
- Turbulent phase ($2.0 - 5.8\ Gyr$): strong variation in SF rate, galaxy grows slightly,

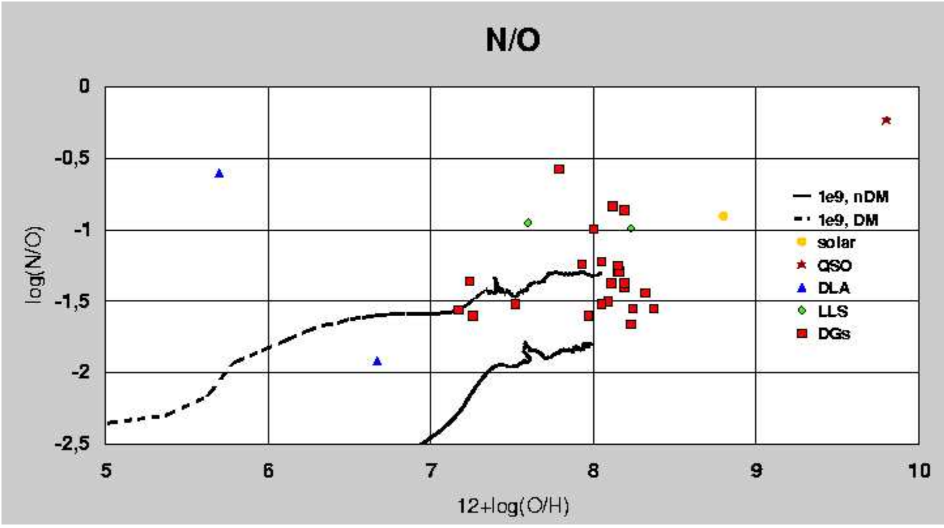

Figure 4. Evolutionary tracks of 2d *cd* models for 10^9 $M_\odot$ galaxies with (upper dashed curve) and without DM halo (lower full line) in comparison with N/O vs. O/H measurements of SF regions in different objects. The symbols are: yellow filled circle: the solar value, stars: quasi-stellar objects (QSOs), blue triangles: damped Lyman alpha galaxies (DLAs), green diamonds: Lyman limit systems (LLS), red squares: dwarf galaxies (DGs).

- Irregular phase ($> 5.8\ Gyr$): equilibrium is reached; short-scale fluctuations dominate.

3.2 Gas Mixing Cycles

During the whole evolution matter is exchanged between the gaseous components leading to a mixing of matter and especially to a redistribution of the metals produced by stars on different cycles. About 90% of the metals released in PNe and $25\ \%$ of the SN products stay in a small-scale *local cycle*. On the other hand, gas is blown out from the galactic body with high initial velocities of about $100\ km/s$ and reaches typical distances from the galactic center of $5\ kpc$. Although this velocity exceeds the graviational binding, due to energy losses by expansion, interaction with clouds and work against external pressure the gas returns to the inner parts of the galaxy as CM infall. This forms a second, so called *galactic cycle*.

On even longer ranges a *global cycle* occurs where the galactic gas mixes with the intergalactic medium. This metal-enriched gas can, since it is not longer gravitationally bound, only fall back in the case of external infall events. Only the minor part of metals leaves the galactic gravitation. From classical simulations only the local and the global cycle are known. *Cd* simulations show that rather the galactic mixing cycle which includes the gas reservoir, is the most important one.

3.3 Reproduction of Observed N/O Chemical Abundences

Fig. 4 shows different evolutionary tracks up to a galactic age of $3 \cdot 10^9\ yr$. In contrast to the metal enrichment in classical chemical evolutionary models, here the evolutionary track in the N/O-O diagram does not circumvent the regime of the observed values for dIrrs along a horizontal track at almost solar N/O ratios, but passes from low N/O and O/H values through the regime of dIrr observations. At higher ages the tracks would leave the regime of the observed values to larger O value, unless sporadic infall of primodial or sparsely enriched gas would reduce the metallicity again.

The interested reader is referred to Hensler et al.[4] for further details about chemical implications from *cd* models without assuming artificial mixing and outflow processes.

4 Conclusions

As a great success the *cd* models reproduce already convincingly the observed abundance peculiarities of dIrr in a self-consistent way. Since the *cd* treatment is appropriate for sensitively balanced systems of low gravitational potential energy like the disks of spiral galaxies or, in this case, dIrrs, its models can provide a fundamental insight into interaction processes of small-scale energetics and large-scale dynamics.

Contrary to the often used assumption in chemical evolutionary simulations, the *cd* calculations show only a small selective outflow of metal-enriched SN expelled gas. A small fraction of metals is mixed locally, while the larger part enters the long-range galactic cycle coupled to the enveloping neutral gas reservoir. While some scenario assume that the time needed by the metals to return to the inner regions of the galaxy is determined by the dynamics of the hot gas, the *cd* models show that the timescale depends solely on the infall velocity of the cold CM onto which the metals condense in shorter times. The mixing process will change if infall of large amounts of intergalactic matter, gravitational interaction with a nearby galaxy or even mergers are assumed, that drive gas from the reservoir into the galactic body. In this case the deposited metals flow into the SF regions instantanously and thereby would be accessible to observations.

The *cd* models indicate that instead of gaseous outflows infall events of pristine material lead to the reduction of metals. By this infall also the SF history with current peaks and ancient episodes, determined from underlying old stellar components can be explained. *Cd* models suggest that infall events are essential to explain the trigger of enhanced SF, since the usually self-regulated SF does not permit large variations of the stellar populations.

We have shown that only self-consistent, and hence, numerically expensive simulations which take all coupled non-linear processes into account, can provide a detailed picture about the mixing processes and the metal enrichment of galaxies.

Up to now the models are calculated with a program version optimized for vector computers. Because of the large fraction of time consuming local processes parallization of the code seems to be reasonable. Programming and first testing activities concerning this item are in progress now.

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