Abstract

We present our recently developed 3-dimensional chemodynamical code for galaxy evolution. It follows the evolution of all components of a galaxy such as dark matter, stars, molecular clouds and diffuse interstellar matter (ISM). Dark matter and stars are treated as collisionless \( N \)-body systems. The ISM is numerically described by a smoothed particle hydrodynamics (SPH) approach for the diffuse (hot) gas and a sticky particle scheme for the (cool) molecular clouds. Additionally, the galactic components are coupled by several phase transitions like star formation, stellar death or condensation and evaporation processes within the ISM. As an example here we present the dynamical, chemical and photometric evolution of a star forming dwarf galaxy with a total baryonic mass of \( 2 \times 10^9 M_\odot \).

Keywords: computational methods: SPH, chemodynamics – evolution of galaxies: dwarf galaxy evolution

1. Introduction

Since several years smoothed particle hydrodynamics (SPH, Monaghan (1992)) calculations have been applied successfully to study the formation and evolution of galaxies. Its Lagrangian nature as well as its easy implementation together with standard \( N \)-body codes allows for a simultaneous description of complex
dark matter-gas-stellar systems (Navarro & White, 1993; Mihos & Hernquist, 1996). Nevertheless, until now the present codes lack of processes that are based on the coexistence of different phases of the interstellar medium (ISM), mainly dissipative, dynamical and stellar feedback, element distributions, etc. We have therefore developed a 3d chemodynamical code which is based on our single phase galactic evolutionary program (Berczik, 1999, 2000).

This code includes many complex effects such as a multi-phase ISM, cloud-cloud collisions, a drag force between different ISM components, condensation and evaporation of clouds (CE), star formation (SF) and a stellar feedback (FB). The more detailed description of the new code and the full list of the interaction processes between all gaseous and stellar phases will be presented in a more comprehensive paper by Berczik et al. (2002). Here we just briefly describe some basic features and effects.

In our new (multi-phase gas) code we use a two component gas description of the ISM (Theis et al., 1992; Samland et al., 1997). The basic idea is to add a cold ($10^2 - 10^4$ K) cloudy component to the smooth and hot gas ($10^4 - 10^7$ K) described by SPH. The cold clumps are modeled as $N$-body particles with some “viscosity” (Theis & Hensler, 1993) (cloud-cloud collisions and drag force between clouds and hot gas component). The cloudy component interacts with

Figure 1: The radial distribution of the cumulative mass (left) and the surface density (right) for the different components in the central region of the model galaxy after 1 Gyr.
Figure 2: The temporal evolution of the mass (left) and mass exchange rate (right) for the different components of the model galaxy.

the surrounding hot gas also via condensation and evaporation processes (Cowie et al., 1981; Köppen et al., 1998). In the code we introduce also star formation. The “stellar” particles are treated as a dynamically separate (collisionless) N-body component. Only the cloud component forms the stars. During their evolution, these stars return chemically enriched gas material and energy to both gaseous phases.

2. Basic ingredients of the code

For the parametric description of the cold clumps in the code we use the mass vs. radius relation for clouds based mainly on observations and also some theoretical work in this direction (Larson, 1981; Solomon et al., 1987; Maloney, 1990):

\[ h_{cl} \simeq 50 \cdot \sqrt{\frac{m_{cl}}{10^6 \, M_\odot}} \, \text{pc} \]

This parameterization has already successfully been applied for the description of the cloudy medium of the ISM in Theis & Hensler (1993); Samland et al. (1997).

The basic mechanism for the mass exchange between “cold” and “hot” gaseous phases is a condensation vs. evaporation (CE) of the cold cloud clumps.
In our code we follow the prescription of these processes using the model proposed in Cowie et al. (1981); Köppen et al. (1998). In this model the basic parameter controlling the process of CE is $\sigma_0$, which gives the ratio between a typical length scale of electron thermal conduction and the cloud size (compare also McKee & Begelman (1990); Begelman & McKee (1990)). If the cloud is small or the hot gas has a high temperature the conduction length may exceed the cloud size ($\sigma_0 > 1$) and conductive evaporation is limited by saturation. On the other hand, if the temperature of the hot gas becomes very small or the cloud size very large, the cooling length scale becomes shorter than the cloud size and condensation substitutes evaporation. For simplicity and as in Cowie et al. (1981) we just use here $\sigma_0 = 0.03$ as transition value from evaporation to condensation, although a more detailed physical description should invoke the cooling or field length (McKee & Begelman, 1990; Begelman & McKee, 1990).

In total the rate with which “cold” clouds evaporate to the surrounding “hot” gas their own material or acquire mass by condensation from the surrounding gas is

$$\frac{dm_{cl}}{dt} = \begin{cases} 
0.825 \cdot T_{hot}^{5/2} \rho_{cl} \sigma_0^{-1} & \sigma_0 < 0.03 \\
-27.5 \cdot T_{hot}^{5/2} \rho_{cl} \Phi & 0.03 \leq \sigma_0 \leq 1.0 \\
-27.5 \cdot T_{hot}^{5/2} \rho_{cl} \Phi \sigma_0^{-5/8} & \sigma_0 > 1.0
\end{cases}$$

where we have used $\Phi = 1$ (no inhibition of evaporation by magnetic fields) and

$$\sigma_0 = \left( \frac{T_{hot}(K)}{1.54 \cdot 10^7} \right) \left( \frac{1}{\Phi \rho_{hot}(cm^{-3}) h_{cl}(pc)} \right)^{2/5}$$

In our model the first important dynamical effect in the list of interaction between the two gaseous phases is a cloud dragging (DRAG). For this reason we use the prescription proposed in the papers Shu et al. (1972); Bisnovat’i-Kogan & S’un’aev (1972). The drag coefficient $C_{DRAG}$ represents the ratio of the effective cross section of the cloud to its geometrical one $\pi h_{cl}^2$ and is set to 0.5. A value of order unity for $C_{DRAG}$ has the physically correct order of magnitude for the forces exerted by a pressure difference before and after a supersonic shock wave (Courant & Friedrichs, 1998). The second important dynamical effect in the evolution of the cloudy medium is a cloud vs. cloud collisions (COLL). These processes also can significantly
reduce the kinetic energy of the cloudy system. As a first approach for these processes we assume that in each collision the colliding clouds loss only 10% of its kinetic energy.

Stars inject a lot of mass, momentum and energy (both mechanical and thermal) in the galactic system through Super Novae (SN) explosions, Planetary Nebula (PN) events and Stellar Wind (SW). The gas dynamics is then strongly depend on the star formation (SF) and a feedback (FB) processes.

Stars are supposed to be formed from collapsing and fragmenting cold gaseous clouds. Some possible SF criteria in numerical simulation have been examined (Katz, 1993; Navarro & White, 1993; Friedli & Benz, 1995). In our code we use the "standard" Jeans instability criterion inside the cloud particle, with randomized efficiency for SF. As a first step we select the cloud particles with:

\[ h_{cl} > \lambda_J \equiv \frac{c_{cl}}{\sqrt{G \rho_{cl}}} \]

After, we calculate the maximum SFR using the idea, what the whole Jeans mass \( M_J \) from the cloud convert to star particle during the \( \tau_{J_{cl}}^{ff} \) time inside the Jeans volume \( V_J \):

\[ \frac{d\rho_s^{\text{max}}}{dt} = \frac{M_J}{\tau_{J_{cl}}^{ff} V_J} = \frac{4}{3} \sqrt{\frac{6 G}{\pi}} \cdot \rho_{cl}^{3/2} \]

where: \( \tau_{J_{cl}}^{ff} \equiv \sqrt{\frac{3}{2 G \rho_{cl}}} \). The actual SFR in the each current act of SF we set by randomized these maximum SFR:

\[ \frac{d\rho_s}{dt} = \text{RAND} (0.1 \div 1.0) \cdot \frac{d\rho_s^{\text{max}}}{dt} \]

Every new "star" particle in our SF scheme represents a separate, gravitationally bound star formation macro region i.e. Single Stellar Population (SSP). The "star" particle is characterized its own time of birth \( t_{SF} \) which is set equal to the moment of particle formation. We assume that in the moment of creation the "star" particle, the individual stars inside our macro "star" particle distributed accordingly the Kroupa et al. (1993) Initial Mass Function (IMF).

During the evolution, these "star" particles return the chemically enriched gas to surrounding "gas" particles due to SNII, SNIa, PN events. As a first approach, we consider only the production of \(^{16}\text{O}\) and \(^{56}\text{Fe}\). The "star" particles return to ISM also the energy due to the SW, SNII, SNIa, PN processes. The total energy released by "star" particles calculated at each time step and
Figure 3: Temporal evolution of the metallicities (left) and their radial distribution after 1 Gyr (right). Individual metallicities of newly born stars are marked by dots.

distributed (in the form of thermal energy) between the neighbor \((N_B = 50)\) “gas” particles.

The code also includes the photometric evolution of each “star” particle, based on the idea of the SSP (Bressan et al., 1994; Fantalo et al., 1996). At each time-step, absolute magnitudes: \(M_U, M_B, M_V, M_R, M_I, M_K, M_{bol}\) are defined separately for each “star” particle. The spectro-photometric evolution of the overall ensemble of “star” particles forms the Spectral Energy Distribution (SED) of the galaxy.

3. Initial conditions

As a test of our new code, we calculate the evolution of an isolated star forming dwarf galaxy. The initial total gas content of our dwarf galaxy is \(2 \times 10^9 M_\odot\) (80% “COLD” + 20% “HOT” which is placed inside a fixed dark matter halo with parameters \(r_0 = 2 \text{ kpc} \) and \(\rho_0 = 0.075 \text{ M}_\odot/\text{pc}^3\) (Burkert, 1995). With these parameters the dark matter mass inside the initial distribution of gas (20 kpc) is \(\approx 2 \times 10^{10} M_\odot\). The initial temperatures for the cold gas we set \(10^3 \text{ K}\), for the hot gas \(10^5 \text{ K}\). For the initial gas distribution we use a Plummer-Kuzmin disk with parameters \(a = 0.1 \text{ kpc}\) and \(b = 2 \text{ kpc}\) (Miyamoto & Nagai, 1975).
The gas initially rotates in centrifugal equilibrium around the z-axis.

We choose the dwarf galaxy as an appropriate object for our code, because in this case even with a relatively “small” number of cold “clouds” (∼ 10⁴) we achieve the required physical resolution for a realistic description of individual molecular clouds (∼ 10⁵ M⊙) as a separate “COLD” particle. In the simulation we use N_{hot} = 10⁴ SPH and N_{cold} = 10⁴ “COLD” particles. After 1 Gyr more then 10⁵ additional stellar particles are created.

4. First results

After a moderate collapse phase the stars and the molecular clouds follow an exponential radial distribution, whereas the diffuse gas shows a central depression as a result of stellar feedback Fig. 1. The metallicities of the galactic components behave quite differently with respect to their temporal evolution as well as their radial distribution Fig. 2. Especially, the ISM is at no stage well mixed.

In Fig. 2 we present the mass and surface density distribution of the different components in the central region of the model after 1 Gyr of evolution. In the region up to ≈ 2 kpc the baryonic matter dominates over the DM. The surface density of the stars can be well approximated by an exponential disk with a scale length of 0.55 kpc. In the distribution of hot gas, we see a central “hole” (∼
1 kpc), as a result of gas blow-out from the center mainly due to SN explosions but not for the cold gas. This result disagrees with the model by Mori et al. (1999) where a density hole occurs caused by their single gas-phase treatment.

In Fig. 2, we present the evolution of the mass and the mass exchange rate of the different components. The SFR (i.e. dM_{\text{STAR}}/dt) peaks to a value of 1 M_{\odot} yr^{-1} after 200 Myrs. Afterwards it drops down to 0.2 M_{\odot} yr^{-1} within several hundred Myrs. I.e. that after 1 Gyrs the stellar mass has already reached $5 \times 10^8$ M_{\odot}. Another interesting feature is the behaviour of the hot gas phase mass exchange. After the initial violent phase of condensation an equilibrium is established which gives a hot gas fraction of about 10% of the total gas mass.

The metal content of the diffuse gas and the clouds differs significantly over the whole integration time (Fig. 3). Due to SNII and SNIa events the metallicity of the hot phase exceeds that of the clouds by almost one order of magnitude. The clouds mainly get their metals by condensation of the hot phase. The central metallicity plateau (up to 1 kpc) of the cold component is explained by the fact, that condensation of metal-enriched material does not work efficiently in that region. This signature agrees well with the observed abundance homogeneity in dIrrs over up to 1 kpc (e.g. in I Zw 18: Izotov (1999)). Moreover, the conditions in the center lead mainly to evaporation of clouds which also prevents the mixing with the metal enriched hot gas.

In the Fig. 4, we present the evolution of the model galaxy magnitudes in different spectral branch and also the color indexes.

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