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Modelling Galaxies with a 3D Multi-Phase ISM

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Abstract: We present a modified TREE-SPH code to model galaxies in three dimensions. The model includes a multi-phase description of the interstellar medium which combines two numerical techniques. A diffuse warm/hot gas phase is modelled by SPH, whereas a cloudy medium is represented by a sticky particle scheme. Interaction processes (such as star formation and feedback), cooling, and mixing by condensation and evaporation, are taken into account. Here we apply our model to the evolution of a Milky Way type galaxy. After an initial stage, a quasi-equilibrium state is reached. It is characterised by a star formation rate of $\sim 1\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$. Condensation and evaporation rates are in balance at 0.1–$1\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$.

Keywords: galaxies: ISM, evolution — ISM: evolution; kinematics and dynamics — methods: N-body simulations

1 Introduction

In most 3D models of galaxies the interstellar medium (ISM) is described as a single phase: either as a diffuse gas e.g. using smoothed particle hydrodynamics (SPH) (Lucy 1977; Gingold & Monaghan 1977) or as a clumpy phase e.g. by sticky particles (Theis & Hensler 1993). Single-phase models have been successfully applied in the context of cosmological simulations (Steinmetz & Müller 1994, 1995; Navarro, Frenk, & White 1997) as well as in simulations of isolated galaxies (Friedli & Benz 1995; Raiteri, Villata, & Navarro 1996; Berczik 1999). A problem in these simulation can be the so-called overcooling (White & Frenk 1991; Cole et al. 1994) leading to an overproduction of dwarf galaxies. More recent models use a multi-phase ISM. This allows a more realistic description of star formation (SF) and feedback processes which could be a solution to this problem.

A multi-phase ISM can be accomplished by modifying the SPH algorithm (Hultman & Pharasyn 1999; Ritchie & Thomas 2001; Springel & Hernquist 2003). We follow a different approach and combine both treatments of a one-phase model in a particle based code: the hot, diffuse gas phase is described by a SPH formalism, whereas the cold molecular clouds are represented by sticky particles. In this model, the two gas phases are dynamically independent. The coupling between the gaseous phases is achieved by condensation/evaporation (C/E) and by a drag force due to ram pressure. Energy is dissipated by cloud–cloud collisions or by radiative cooling. Furthermore, stars are formed in clouds and the stars return mass and energy to the gas by feedback processes (through supernovae (SNe) and planetary nebulae (PNe)). A similar concept is followed by Semelin & Combes (2002) and Berczik et al. (2003).

In SPH codes, SF is usually based on the Schmidt law, i.e. the SF rate depends on gas density to some power and a characteristic time scale. For sticky particles the SF can be coupled to cloud–cloud collisions, or a single cloud forms stars with a constant SF efficiency. Here, a SF scheme using a different approach is presented: the process of SF is treated individually for each cloud. The SF efficiency depends on local properties of the ISM and the star forming clouds, thereby enabling self-regulation of SF by feedback.

In Section 2 the code is described in more detail, in Section 3 a model of a Milky Way type galaxy is presented, and a short summary and future prospects are given in Section 4.

2 Numerical Treatment

We use a particle code to model the evolution of galaxies. In our code, different components of a galaxy are distinguished by means of particle types. These particle types are stars, clouds, (diffuse) gas, and dark matter particles. The gravitational force for all particles is calculated with a new, very fast TREE algorithm proposed by Dehnen (2002). An additional external potential can act as a static dark matter halo. A standard SPH formalism is used to compute the hydrodynamics of the diffuse gas. A description of the SPH method can be found in Monaghan (1992). Furthermore, the code includes the sticky particle scheme of Theis & Hensler (1993) to describe the collisional cloud dynamics. The integration of the system is done with a

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leapfrog scheme. Individual time steps are used for each particle.

The drag force and the mass exchange rates for C/E are calculated according to Cowie et al. (1981). We apply a mass–radius relation for the clouds based on observations (e.g. Rivolo & Solomon 1988). Effects of both processes are individually determined for each cloud using the local density, temperature, and velocity of the hot gas. Energy can be dissipated by inelastic cloud–cloud collisions (Theis & Hensler 1993) or by radiative cooling. The cooling function is taken from Böhringer & Hensler (1989).

In Figure 1 the process of SF is drawn schematically. The general idea is that stars are formed in clouds and the cloud is fragmented in the process. Each cloud (or fragment from a previous SF process) is inactive for a given time $T_{\rm ia}$ (t_0). The time $T_{\rm ia}$ represents a global SF time scale which is typically of the order of a few 100 Myr. The time scale of the SF process itself is neglected as recent observations suggest that SF occurs on the much faster local crossing time scale (Elmegreen 2000). Because not all the gas in clouds is dense or unstable enough for SF, $T_{\rm ia}$ is the time scale on which clouds provide the matter that is able to form stars.

Once the SF process has started, an embedded star cluster is formed (t_1) with the SF efficiency ϵ being a function of cloud mass and gas pressure according to Elmegreen & Efremov (1997). The energy released by SNe (type II) is calculated using a multi-power law IMF (Kroupa et al. 1993) with stellar lifetimes taken into account (Rateri et al. 1996). This energy injection disrupts the cloud into smaller fragments (t_2) leaving a new star particle. The time for disruption $T_{\rm dis}$ ($t_2 - t_1$ in Figure 1) is determined from the energy input: a self-similar solution is used to calculate the SN shell expansion. It is assumed that the cloud disrupts when the shell radius equals the cloud radius. The fragments are then placed symmetrically on the shell with velocities corresponding to the expansion velocity at $T_{\rm dis}$. The energy not consumed by cloud disruption and kinetic energy of the ejecta is returned to the hot gas phase (SPH particles). Additionally, the mass returned by PNe is added to surrounding cloud particles also taking stellar lifetimes into account.

3 The Model and Results

Initially, a galaxy similar to the Milky Way was set up using the galaxy building package described by Kuijken & Dubinski (1995). We chose their model A and some parameters of the initial model are listed in Table 1. A cloudy gas phase is added by treating every fifth particle from the stellar disk as a cloud. The total mass in clouds is $M_{\rm cl,tot} \approx 6.9 \times 10^9\,{\rm M}_\odot$ and each cloud is randomly assigned a time of inactivity $T_{\rm ia}$ between 0 and 200 Myr. Finally, a slowly rotating homogenous gas halo with a total mass of $M_{\rm hot,tot} = 2 \times 10^8\,{\rm M}_\odot$ is added. We do not follow the chemical evolution of the galaxy, so where a metallicity is needed we use solar abundances. In order to treat the feedback of 'old' star particles each star particle is assigned an age. For the bulge stars the age is 10 Gyr and for disk stars 0–10 Gyr.

Starting from this setup the galaxy model is evolved for 3 Gyr with all processes switched on. During an initial phase (0 to ~1 Gyr) the gas halo collapses and expands again to reach an equilibrium defined by the interplay

Table 1. Properties of the initial disk galaxy model

Component	Mass[1]	No. of particles
Disk	0.343	20 000
Stars	0.274	16 000
Clouds	0.069	4000
Bulge	0.167	10 000
DM halo	1.94	–
Hot gas	0.002	10 000
Total	0.002	40 000

[1] Units of $10^{11}\,{\rm M}_\odot$.

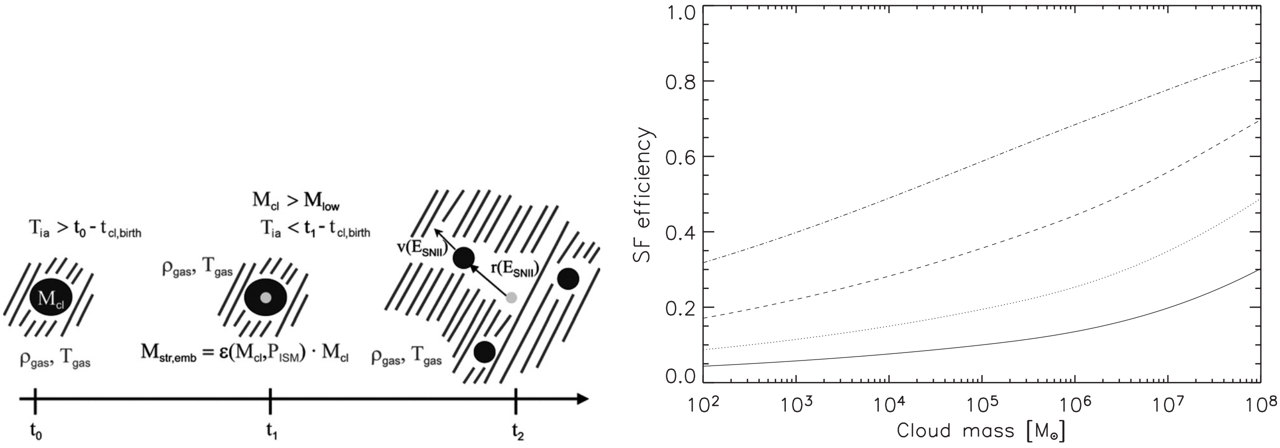

Figure 1 Left: The SF scheme. At t_0 the cloud is inactive (no SF); at t_1 an embedded star cluster has been formed with a local SF efficiency; at t_2 the cloud is fragmented by SNe energy input. Right: The local SF efficiency, depending on the mass of the star forming cloud and the local pressure, is shown. It is based on a model proposed by Elmegreen & Efremov (1997).

of the gravitational potential, radiative cooling, heating by SNe and condensation/evaporation. For the following 2 Gyr the galaxy shows a stable evolution with an average SF rate of $\sim 1\,\mathrm{M_\odot\,yr^{-1}}$ (Figure 2). The SF rate is slowly decreasing with time due to the consumption of the clouds while the average SF efficiency is roughly constant at 5–10%. In the end, the number of particles has increased by a factor of about 2.5. The final number of stars and clouds are 63 748 and 27 038, respectively.

The mass exchange by C/E reaches a quasi-equilibrium after a few 100 Myr (Figure 3, left). Before, evaporation is the dominant process due to the initial collapse and heating of the diffuse gas. In the later evolution, the condensation rate is in the range of 0.1–$1\,\mathrm{M_\odot\,yr^{-1}}$ while the evaporation rate occasionally drops by few orders of magnitude. These drops can be correlated with a lower SF rate, i.e. a lower heating by SNe.

The initially strong evaporation can also be seen in the comparison of the total mass in the gas phases (Figure 3, right). The diffuse gas mass increases strongly in the beginning but is roughly constant after that. The total cloud mass is slowly decreasing, showing the depletion by SF. A detailed look at the diffuse gas shows also that only a small fraction (5%) is in the halo, while most of the gas (65%) is located in the disk ($R < 20$ kpc and $z < 1$ kpc). Some gas (30%) has even left (at least temporarily) the galaxy ($R > 50$ kpc). The average densities in halo and disk are $3 \times 10^{-4}\,\mathrm{cm^{-3}}$ and $1 \times 10^{-1}\,\mathrm{cm^{-3}}$, respectively. The gas in the halo is hot ($>10^6$ K) while the gas in the disk is cooler ($\sim 10^4$ K) and could be described as a warm phase. In fact, it could form clouds from thermal instabilities, so that this process should also be taken into account in future calculations. In the Milky Way the total amount of warm and cold gas observed in the disk is $\sim 6 \times 10^9\,\mathrm{M_\odot}$ which is about a factor of two more than what we see at the end of our simulation. In order to get a better agreement we could increase the initial gas mass fraction (i.e. select more clouds) or add an extended gas disk as a reservoir for a continuous gas infall.

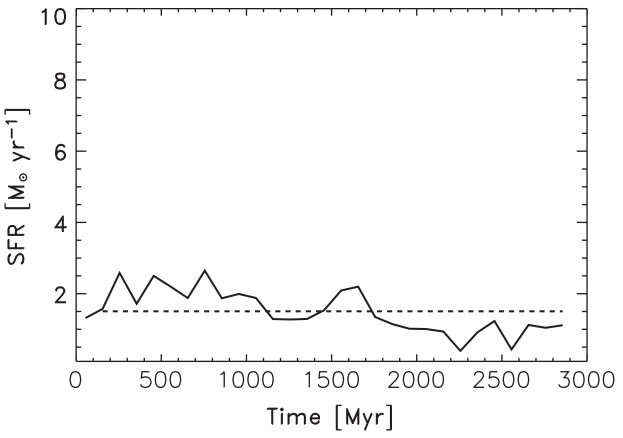

Figure 2 Temporal evolution (solid line) and average (dashed line) of the SF rate for a model Milky Way type galaxy.

The disk is stable over the full 3 Gyr of evolution. This can be seen in Figure 4, where a comparison of the stellar surface density for the full model (i.e. including SF and all other processes) with a pure N-body model is shown (left panel). In the full model the surface density in the centre ($R < 2$ kpc) has increased significantly. The explanation for this is that due to dissipation clouds have fallen towards the centre before forming stars. The surface density profiles of the clouds confirm this idea. The velocity dispersion profiles (Figure 4, right) show that the disk is heating up a little. A comparison with the pure N-body model shows that some of the heating is due to two-body relaxation but a significant amount is also due to the kinetic feedback of SF. Simulations with higher initial partical numbers should be performed to minimise effects of two-body relaxation in order to determine the heating rate due to feedback.

4 Summary and Future Prospects

We presented a particle code to model the evolution of galaxies with a multi-phase description of the ISM including a new approach to SF. A model of a Milky Way type galaxy shows a reasonable behaviour in terms of SF rate and stability of the disk.

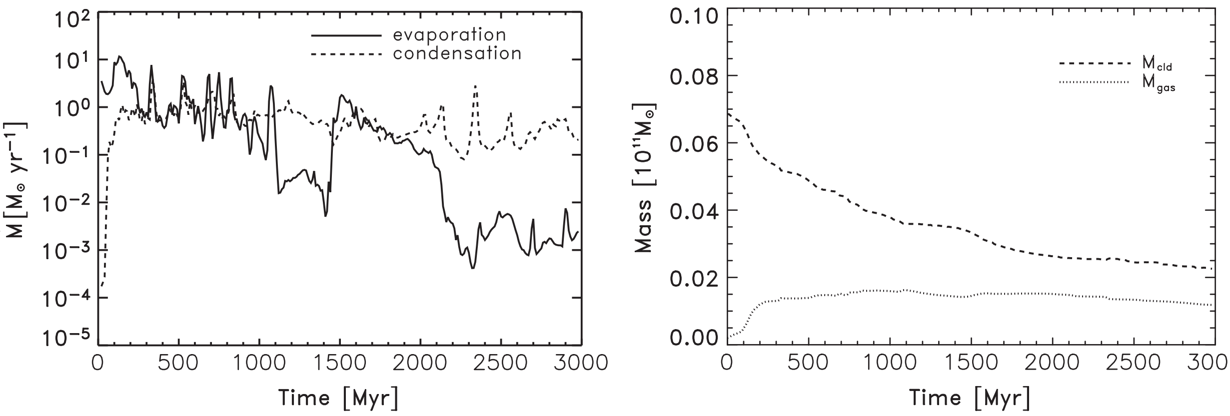

Figure 3 Left: The C/E rates versus time. After an initial phase (<300 Myr) both processes reach an equilibrium at roughly $1\,\mathrm{M_\odot\,yr^{-1}}$ (300–1000 Myr). The lower evaporation rate at ~1 Gyr and ~2 Gyr coincides with a lower SF rate. Right: The total mass in the cloudy and the diffuse ISM. The mass of the diffuse gas is almost constant after an early strong increase while the cloud mass is decreasing due to SF.

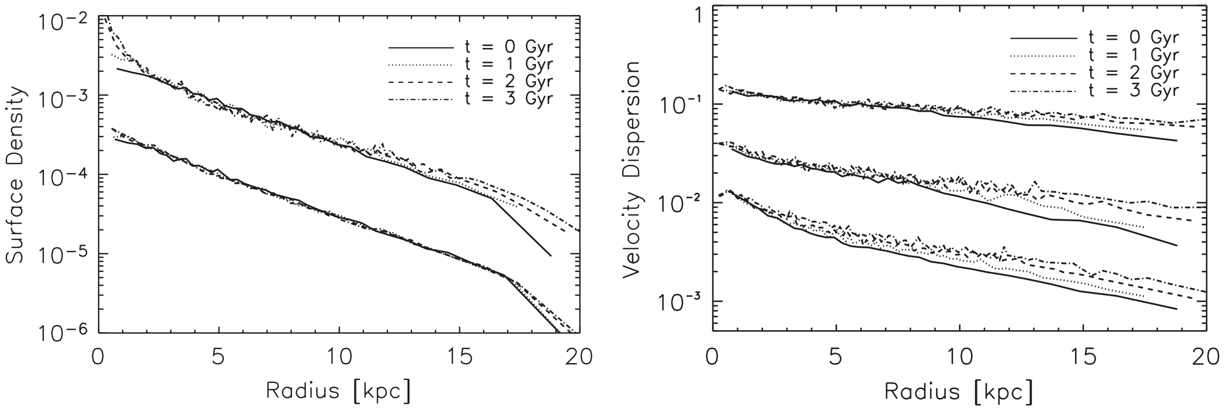

Figure 4 Left: The surface density of the stellar disk is plotted for different times of 3 Gyr of evolution. The upper group of curves is for the presented model including SF and all other processes. For a comparison the lower group of curves (scaled by a factor of 0.1 to avoid overplotting) is for the pure N-body evolution of the same galaxy model. The full model shows an increased surface density in the centre as well as in the outer parts. Right: From top to bottom, the velocity dispersions σ_R, σ_ϕ (scaled by 0.2), and σ_z (scaled by 0.1). A heating of the disk can be seen.

More simulations are needed to determine how the results depend on initial conditions (e.g. the initial set-up for the hot gas or initial particle numbers) and how other parameters in the model (e.g. the energy feedback by SNe) affect the evolution of the model galaxy. This should result in a reference model, that could be used in simulations of interacting galaxies, to shed, for example, more light on trigger mechanisms of star bursts.

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