Dwarf Galaxies: From the Deep Universe to the Present
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Star formation at low rates: impact of lacking massive stars on the evolution of dwarf galaxies

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Abstract. In recent years dedicated observations have uncovered star formation at extremely low rates in dwarf galaxies, tidal tails, ram-pressure stripped gas clouds, and the outskirts of galactic disks. At the same time, numerical simulations of galaxy evolution have advanced to higher spatial and mass resolutions, but have yet to account for the underfilling of the uppermost mass bins of stellar initial mass function (IMF) at low star-formation rates. In such situations, simulations may simply scale down the IMF, without realizing that this unrealistically results in fractions of massive stars, along with fractions of massive star feedback energy (e.g., radiation and SNII explosions). Not properly accounting for such parameters has consequences for the self-regulation of star formation, the energetics of galaxies, as well as for the evolution of chemical abundances. Here we present numerical simulations of dwarf galaxies with low star-formation rates allowing for two extreme cases of the IMF: a "filled" case with fractional massive stars vs. a truncated IMF, at which the IMF is built bottom-up until the gas reservoir allows the formation of a last single star at an uppermost mass. The aim of the study is to demonstrate the different effects on galaxy evolution with respect to self-regulation, feedback, and chemistry. The case of a stochastic sampled IMF is situated somewhere in between these extremes.

Keywords. hydrodynamics, galaxies: dwarf, galaxies: evolution, galaxies: star formation

1. Introduction

Dwarf galaxies (DGs) are the most numerous type of galaxies in the universe. They have low surface brightnesses, low gravitational potentials, and mostly relatively low star-formation rates (SFRs). Due to their low gravitation they react more vigorously to external and internal processes, such as feedback by massive stars, and are therefore ideal objects to study galaxy evolution. It is nowadays widely accepted that most stars are born in embedded clusters. Therefore, a mass distribution within each cluster has to be assumed, the so-called initial mass function (IMF), originally defined by Salpeter (1955). The IMF is the most important distribution function in astrophysics, because stars of different masses effect the galactic evolution manifoldly, whereby strengths and timescales of their action depend inversely on the mass. As part of the IMF, massive stars live most shortly and release most energy, mass and heavy elements per stellar mass to their environment. Vice versa, the long-living, less active low-mass stars accumulate the stellar mass budget. The IMF can be approximated with a single power-law function, e.g. Salpeter (1955), or by a multi-function power-law with a lower and even inclining slope at lowest stellar masses (Kroupa, 2001). The mass distribution of embedded clusters can as well be described by a single power-law, which results in more low-mass clusters. If the integral of the assumed IMFs over the the embedded star cluster mass function is taken, one gets the so-called integrated galactic IMF (IGIMF), which is steeper then the cluster IMF (Kroupa & Weidner, 2003). Various numerical simulations of DGs are performed in the last decade to investigate different internal/external processes, such as the interplay between mass and geometry and their effects on the distribution of heavy elements (Recchi & Hensler, 2013). Simulations nowadays include radiative gas cooling and stellar heating, star formation (SF) and chemical, energy and mass feedback, respectively, by type Ia and type II SNe. Recchi *et al.* (2009) investigate with semi-analytical models the chemical evolution of galaxies with the IGIMF theory. Since the energetic feedback from SNeII and stellar winds by massive stars play a crucial role in DG evolution, because in DGs it can more easily drive a galactic winds due to their shallower potential wells, the large mass range of stars is a sensitive ingredient for galactic energetics and chemistry.

2. The Simulations

To study the effect of different IMF descriptions on numerical models of DGs, we apply the hydrodynamical adaptive mesh refinement code FLASH 3.3 (Fryxell *et al.*, 2000). The simulations include a recipe for self regulation of star formation (Koeppen *et al.*, 1995), stellar feedback by massive stars, stellar radiation and winds, gas cooling and chemical enrichment (Ploeckinger *et al.*, 2014). The models start with a purely gaseous disk, embedded within a DM halo. For the initial conditions an equilibrium configuration of a rotating gas disk is calculated (Vorobyov *et al.*, 2012). Our model DG consists of a DM halo with a mass of $M_{DM} = 10^{10}\,M_{\odot}$ and a spin parameter of $\alpha = 0.9$, which results in a gas mass of $M_g = 1.4 \times 10^8\,M_{\odot}$ with a maximum of the rotation velocity at $30\,km\,s^{-1}$. The radius of $R = 9.5\,kpc$ of the DG is defined to be the distance, where the gas density reaches $\rho = 10^{-27}\,g\,cm^{-3}$. The circumgalactic gas has a density of $\rho = 10^{-30}\,g\,cm^{-3}$ and a temperature of $T = 10^6\,K$, to be in pressure equilibrium with the galaxy.

We simulate two DGs with identical initial conditions, but different descriptions of the IMF. One with a Kroupa IMF, where all mass bins are filled up to an upper mass of $120\,M_{\odot}$, allowing to form fractions of massive stars at low SFRs. The other IMF is filled bottom-up and truncated at an upper mass above which cannot form an integer number of stars.

3. ISFR and Type II SNe Feedback

The SFR, the rate at which gas mass gets converted to stars per unit time, is the most important property for the evolution of galaxies. The truncated IMF will experience a larger initial starburst, because it takes longer to accumulate mass to form massive stars, which will then regulate the SF. The filled IMF allows for fraction of massive stars, which start an early regulation of the SF by stellar radiation, because the lifetime of massive stars is inversely proportional to their mass. Therefore, the filled IMF has a lower initial burst in the SFR. For the filled IMF, the SNII feedback starts earlier due to the fraction of massive stars, that go supernova after a few Myr. For the truncated IMF, it takes longer to form massive clusters that are populated with integer number of massive stars to go supernova. Since the filled IMF is populated with fractions of massive stars, the resulting SNII energy are also fractions. This leads to energies below the 5% threshold down to $10^{48}\,erg$, and therefore the average SNII energy per Myr is much lower, because of the large range of energies. For the truncated IMF, on the contrary, the average SNII energy per Myr is larger, because of the lower range of energies due to the truncation.

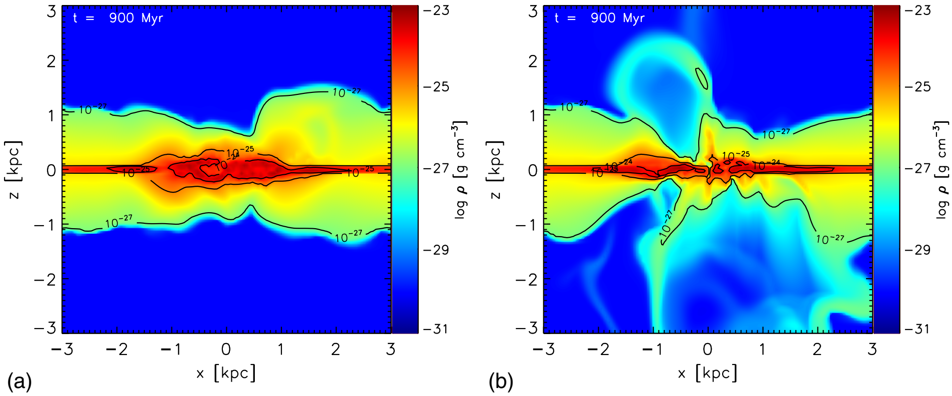

Figure 1. Slice through the xz-plane at a simulation time of $t = 900\,Myr$ for the filled (left) and truncated (right) IMF. The colour bars are given in volume densities.

4. Evolution

Fig. 1 shows a snapshot of the evolution at $t = 900\,Myr$ for the filled IMF model (left panel) and the truncated IMF model (right panel) of the gas density, cut through the xz-plane at $y = 0$. The highest spatial resolution is in both cases 50 pc in each dimension. Due to the fraction of massive stars, the filled IMF will produce fractions of type II SN energies. This will produce less SNeII energy compared to a few single explosions of the truncated IMF, with an 5% efficiency of $10^{51}\,erg$. This results in a bipolar outflow in the case of the truncated IMF model. At velocities up to 600 $km\,s^{-1}$ the ejected material will probably not fall back onto the galaxy. The filled IMF model does not show an outflow. The difference in the evolution is more prominent when looking at the distribution of the element abundances. The truncated IMF model produces higher element abundances that will break out of the plane in these superbubbles, compared to the filled IMF model.

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Discussion

Q1: Comparing the filled and truncated IMF, where would you expect a stochastic IMF to be?

A1: The stochastic IMF would be in between the filled and truncated IMF. I would expect it to be more closer to a truncated IMF than to the filled one.

Q2: Why is the feedback of the truncated IMF case stronger than for the filled IMF case?

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A2: Early feedback for filled IMF by UV radiation e.g. is much stronger and quenches star formation leading to a reduced total feedback.

Q3: Since the truncated IMF produces a larger bipolar outflow, wouldn't you expect that metals escape the galaxy and a lower Fe content?

A3: We have not studied the chemical content in detail.