ABSTRACT. Using a two-dimensional hydrodynamics code with axial symmetry we explore the chemical, thermal, and dynamical evolution of a shell formed by a high-energy supernova explosion \(10^{53}\) erg) in dwarf protogalaxies with a total (dark matter plus baryonic) mass \(10^7\) M\(_\odot\) at a redshift \(z = 12\). We consider two initial configurations for the baryonic matter, one without rotation and the other having the ratio of rotational to gravitational energy \(\beta = 0.17\). The (non-rotating) dark matter halo is described by a quasi-isothermal sphere. We find that the dynamics of the shell is different in protogalaxies with and those without rotation. For instance, the Rayleigh-Taylor instability in the shell develops faster in protogalaxies without rotation. The fraction of a blown-away baryonic mass is approximately twice as high in models with rotation than in models without rotation. We argue that these differences are caused by different initial gas density profiles in non-rotating and rotating protogalaxies. On the other hand, the chemical evolution of gas in protogalaxies with and without rotation is found to be similar. The relative number densities of molecular hydrogen and HD molecules in the cold gas \((T \leq 10^4\) K) saturate at typical values of \(10^{-3}\) and \(10^{-7}\), respectively. The clumps formed in the fragmented shell move with velocities that are at least twice as high as the escape velocity. The mass of the clumps is \(\sim 0.1 - 10\) M\(_\odot\), which is lower than the Jeans mass.

Key words: cosmology, galaxies, ISM, molecules, stars, shock waves.

1. Introduction

The detection of extremely metal-poor stars in our Galaxy with an iron abundance equal to or less than \(10^{-3}\) of the solar value (Beers et al., 1992, Christlieb et al., 2002) has motivated scientists to put forward possible scenarios for the formation of such stars. According to Tsujimoto et al. (1999), extremely metal-poor (EMP) stars form in a dense shell produced by Type II supernova explosions of the first stars and accrete metals from the surrounding medium during the subsequent evolution. The formation of EMP stars is made possible by fragmentation of the primordial gas in a supernova shell due to efficient cooling by molecular hydrogen and HD molecules (see review by Nishi & Susa (1999), Salvaterra et al., (2004), Greif et al., (2007)). It now becomes evident that the formation of EMP stars due to fragmentation of supernova driven shells is a complicated phenomenon that depends on a variety of physical conditions in a host protogalaxy, which may vary from allowing star formation to shutting it off completely. In such circumstances, the construction of increasingly more sophisticated numerical models is justified. Here we perform axially symmetric numerical hydrodynamics simulations of high-energy supernova explosions \(10^{53}\) erg) in a model dwarf protogalaxy with total mass \(10^7\) M\(_\odot\). We seek to determine the effect of galactic rotation on the dynamical and chemical evolution of a supernova-driven shell.

2. Model protogalaxy

Our model protogalaxy consists of a baryonic component surrounded by a spherical dark matter halo. We assume that the dark matter halo profile is spherically symmetric and is determined by a modified isothermal sphere. The dark halo mass \((M_h)\) in our numerical simulations is set to \(10^7\) M\(_\odot\), which, at a redshift of \(z = 12\), corresponds to \(3\sigma\) perturbations in the \(\Lambda\)CDM model for the parameters determined from the third
The virial radius of our model protogalaxy is \( r_v = 520 \) pc (Ciardi & Ferrara 2004).

The initial distribution of the total gas density \((\rho_g)\) is found by solving numerically the steady-state momentum equations in cylindrical coordinates \((z, r, \phi)\) using a finite-difference operator-split code (Stone & Norman 1992). The computational domain has a size of 750 pc in both the vertical \((z)\) and horizontal \((r)\) directions. The numerical resolution is \(780 \times 780\) grid zones.

Once the equilibrium gas density distribution is constructed, we let our model galaxies evolve out of equilibrium. We stop this process when the temperature in the centre drops below 500 K. The resulted distributions are shown in Fig. 1. After we release \(10^{53}\) erg of thermal energy in the central sphere with radius 5 pc. Such energetic supernovae are expected to result from the explosion of massive metal-free stars (Heger & Woosley 2002).

The gas component of our model protogalaxy consists of a standard set of species: H, He, \(H^+\), \(H^-\), \(H_2\), \(\text{D, D}^+\), HD. The cooling rates are computed separately for temperatures below and above \(2 \times 10^4\) K. In the low-temperature regime, the cooling rate includes cooling due to recombination and collisional excitation of atomic hydrogen (Cen 1992), \(H_2\) (Galli & Palla 1998) and HD molecules (Lipovka et al., 2005). In the high-temperature regime, the cooling rates for zero metallicity are taken from (Sutherland & Dopita 1993). The list of chemical reactions and other details of solving chemical kinetics can be found in (Vasiliev et al 2008).

The dynamics of the gaseous component is followed by numerically solving a usual set of hydrodynamic equations in cylindrical coordinates \((z, r, \phi)\) using a finite-difference operator-split code (Stone & Norman 1992). The computational domain has a size of 750 pc in both the vertical \((z)\) and horizontal \((r)\) directions. The numerical resolution is \(780 \times 780\) grid zones.

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3. Results

Fig. 2 presents snapshots of the gas density distribution at four consecutive times after the supernova explosion. When the characteristic cooling time becomes shorter than the dynamical time (the age of a supernova remnant), an expanding shell becomes unstable to the Rayleigh-Taylor (RT) instability (Gull 1973). As a result, small ripples that distort a spherical shape of the shell appear in model 1 at \(t = 1\) Myr. The subsequent evolution of the shell is governed by the RT instability, which acts mostly in the compressed gas of the shell outside the interface between hot supernova ejecta and the shell of compressed material. The characteristic time for the development of the RT instability is shorter for steeper initial gas density profiles and vice versa. Fig. 1 indicates that both the gas density distribution in model 1 and the vertical gas density distribution in model 2 have profiles similar to \(r^{-3}\), where \(r_s = (r^2 + z^2)^{1/2}\) is the distance from the galactic centre. On the other hand, the radial gas density distribution in model 2 is noticeably shallower and follows an \(r_s^{-1.7}\) profile. Hence, we expect the RT instability to grow faster in the non-rotating model 1.
This is indeed seen in the top row of Fig. 2 – the shell has lost its spherical shape by $t = 4$ Myr and prominent spurs (or fingers) start to grow into the unperturbed medium. Model 2 shows little spurs at the same evolutionary time, though the shell has already started to show first signs of instability.

Figure 3: Fraction of the baryonic mass blown away by a supernova energy release of $10^{53}$ ergs in model 1 (solid) and in model 2 (dash).

Figure 4: Logarithmic distribution of temperature (left), H$_2$ (middle) and HD (right) abundances at time $t = 12$ Myr after the explosion of SN with energy $E_{SN} = 10^{53}$ erg in halo with mass $M = 10^7 M_\odot$ and the parameter $\beta = 0$ (upper) and $\beta = 0.17$ (lower).

Figure 2 shows that at $t = 12$ Myr some spurs are found outside the virial radius (520 pc) in both models. This implies that a fraction of the baryonic mass is blown away by the supernova explosion (Fig. 3). We find that the spurs are characterized by mean mass-weighted velocities of the order of 26 km s$^{-1}$ in model 1 and 22 km s$^{-1}$ in model 2, whereas the escape velocity at the virial radius in both models is $v_e \approx 13$ km s$^{-1}$.

Fig. 4 shows the distribution of gas temperature, relative number densities of molecular hydrogen and HD molecules at $t = 12$ Myr. It is evident that low gas temperatures (below $10^3$ K) are found in the shell and the spurs, where cooling takes place due to H$_2$ and HD molecules. In particular, the lowest temperatures found in the spur cores are of the order of 500 K and the relative number densities of H$_2$ and HD are approximately $10^{-3}$ and $10^{-7}$, respectively.

Figs. 5 present the temporal evolution of different molecular hydrogen tracers in model 1 and model 2. The comparison of those figures shows that the H$_2$ traces saturate during the evolution. The saturation is explained by the fact that we consider the gas evolution behind strong shock waves. The saturation times in model 2 are systematically longer than in model 1. This can be attributed to longer cooling times in model 2 due to a shallower initial gas density profile.

4. Evolution of fragments

One can see from Figs. 2 that the typical radial length of the most cold and dense regions is several parsecs. The clumps form due to desintegration of the shock wave under Rayleigh-Taylor instability which develops when gas behind the shock front starts cooling rapidly and the front decelerates. A typical size of fragments is expected to be close to the thickness of the compresses gas behind the front at the moment, when it becomes unstable.

Among possible mechanisms of cloud destruction stripping of the external layers of clouds seems the most efficient under the conditions of interest. This process operates mostly by Kelvin-Helmholtz instability. The stripping time for typical conditions in the case considered here equals $\sim 3$ Myr. This is short compared to the dynamical time, and from this point of view dense clumps should be destroyed quickly. However, the radiative cooling time is of the same order $t_c \sim 1 - 3$ Myr, which means that the density increase always connected with the radiative cooling can inhibit the destruction through stripping, so that the clumps can survive on longer dynamical time. The clumps however asymptotically are destroyed, which is seen from the fact that the mass contained in
relatively dense \((n > 0.56 \text{ cm}^{-3})\) and cold \((T < 5 \times 10^3 \text{ K})\) fragments decreases at \(t > 3 \text{ Myr}\) as shown in Fig. 5 by dashed lines. Moreover, a typical mass of the most dense \((n > 1.8 \text{ cm}^{-3})\) clumps \(M \sim 0.1 - 10 \, M_\odot\) (see Fig. 6) is much smaller than the Jeans mass for the corresponding conditions \((n \leq 1.8 \text{ cm}^{-3} \text{ and } T \sim 0.5 - 1 \times 10^3 \text{ K})\). All this means that protostellar clouds do not form in the shell unless the clumps merge.

Finally, we would like to note that the typical masses of most fragments are \(~0.1 - 10 \, M_\odot\). For the typical densities and temperatures in the fragments to be \(~0.5 - 1 \text{ cm}^{-3} \text{ and } (0.5 - 1) \times 10^3 \text{ K}\), respectively, these masses are strongly sub-Jeans and the fragments are expected to be pressure-supported. Their further evolution depends on both the efficiency of cooling and destruction due to the Kelvin-Helmholtz instability. We do not expect that the low-mass stars can be formed in such conditions as suggested by Salvaterra et al. 2004. In our opinion, a more feasible mechanism for low-mass, metal-poor star formation is related with the re-collapse of a supernova bubble in protogalaxies, whose total gravitational binding energy is much larger than supernova energy.

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