Feedback processes in the early Universe

Gergö Popping

August 19, 2009

Abstract

This paper deals on feedback processes, governing them into three main groups: mechanical, chemical and radiative feedback. For each of these classes the origin of several mechanisms is discussed, their influence on the surrounding medium and the collapse of matter.

1 Introduction

After the formation of the first objects, their mass deposition, energy injection and emitted radiation can affect galaxy formation and the formation of stars, as well as the intergalactic medium (IGM). These processes, called feedback, invoke a back reaction on itself or on the causes that have produced it and the idea of feedback is linked to the possibility that a system can become self-regulated (Ciardi and Ferrara (2005)). Feedback can either reduce (negative) or increase (positive) the star formation (SF) process.
Although feedback processes can be disruptive, the most important ones (and the ones discussed in this paper) drive the system to a steady state.
Feedback processes are divided in three broad classes: mechanical, chemical and radiative feedback. Mechanical feedback describes processes driven by the energy injection of massive stars in forms of winds and super nova (SN) explosions. Chemical feedback deals with the cosmic transition form very massive to normal stars set by a critical metallicity. Radiative feedback describes those effects associated with ionization/dissociation of hydrogen atoms/molecules.
To get a better feeling of the effect of the different feedback classes, table 1 gives an overview of the feedback classes and their negative and/or positive star formation influence.
In the first three sections I will discuss the three different classes of feedback. Then I will treat other types of feedback, all of them dealing with so called shock heated gas. I will end with a short summary.

2 Mechanical feedback

Mechanical feedback can be described by mechanical energy injection from winds and/or SN explosions (Ciardi (2008)). SN explosions and galactic outflows have extensively been studied at low redshift. Metal-free or extremely metal poor stars are not expected to produce strong winds and therefore most of the work at high redshifts is concentrated on the effects from SN explosions. The energy fed to the halo by the SN can heat up the gas, inhibiting the formation of stars. There are more mechanical effects on the gas in galaxies though. I will discuss 'blowout and blowaway' and 'impinging shocks'.

2.1 Blowout and blowaway

SN explosions can expel the gas out of the host halo and by that reduce the reservoir of gas for subsequent star formation. Depending on the mass and dark matter content of the galaxy, a SN or multiple SN event can partially (blowout) or totally (blowaway) remove the gas from a host halo, regulating the SF. Mac Low and Ferrara (1999) showed that objects with a mass lower than $10^6 M_\odot$ can experience a total blowaway and larger objects can experience a blowout induced by a central SN. In the same paper also statements on the metal ejection were made. It was shown that stars up to $10^8 M_\odot$ are able to eject their metals into the surrounding medium depending on the SN explosion energy.
Bromm, Yoshida & Hernquist (2003) have done a similar study on Pair Instability SN (PISN) and run a cosmological stellar population history

	NEGATIVE	
Mechanical	Chemical	Radiative
1. Blowout/blowaway	1. Fragmentation	1. Photoionization/evaporation
2. Impinging shocks		2. H_2 Photodissociation
3. Preheating		3.Photoheating filtering
	POSITIVE	
Mechanical	Chemical	Radiative
1. Behind shocks		1. In front of HII regions
2. Shell fragmentation		2. Inside relic HII regions
		3. X-ray background

Table 1: Classification of different feedback effects (Ciardi and Ferrara (2005))

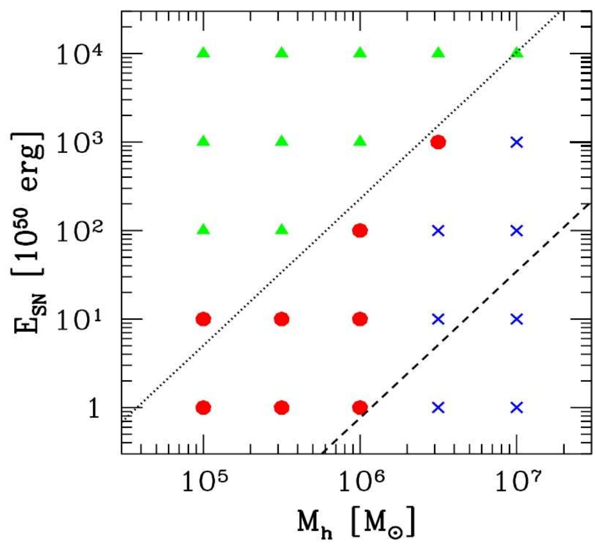

Figure 1: Fate of a halo at z = 20 with mass M_h and SN explosion energy E_{SN}. Triangels: more than 90 of mass is expelled without pre-existing HII regions. Circles: more than 90 of mass is expelled without pre-existing HII regions. Crosses: no substantial gas outflow. Dahsed line indicates the halo binding energy (Kitayama and Yoshida (2005)).

simulation. They chose there conditions such, that the first stars form in a halo of mass $\sim 10^6 M_\odot$ at $z \sim 20$. They assumed that the first stars have a mass of 150 $M_\odot$ (which equals an explosion energy of $E_{SN} \sim 10^{51}$ ergs) or 250 $M_\odot$ (which equals an explosion energy of $E_{SN} \sim 10^{53}$ ergs). In the former case they found that the halo remains intact, while in the latter case the halo gets disrupted completely. Similar results with a total disruption at stellar mass 200 $M_\odot$ (equaling an explosion energy of $E_{SN} \sim 10^{52}$ ergs) have been reached by Greif et al. (2007). A parametric overview of blowaway efficiency for a given explosion energy and halo mass is shown in figure 1 (Kitayama and Yoshida (2005)). This figure is in agreement with the above studies, showing a total blowaway for a halo with mass $M \sim 10^6 M_\odot$ and an explosion energy of $E_{SN} \sim 10^{51}$ ergs.

If the system consists of multiple SN in stead of only one, it becomes much more complicated. Such a system has been simulated for a halo with $M = 10^8 M_\odot$ at $z = 9$ and is a good example of what can be expected at higher redshifts (Mori et al. (2002)). Off center SNae can take place and drive inward propagating shocks, pushing the gas to the center where an episode of SF can take place. In this case the feedback is positive, in stead of negative. This effect is shown in figure 2. The sweeping of the gas by a SN explosion can also create a dense shell immediately behind the shock front, which could fragment and form stars (Salvaterra et al. (2004)).

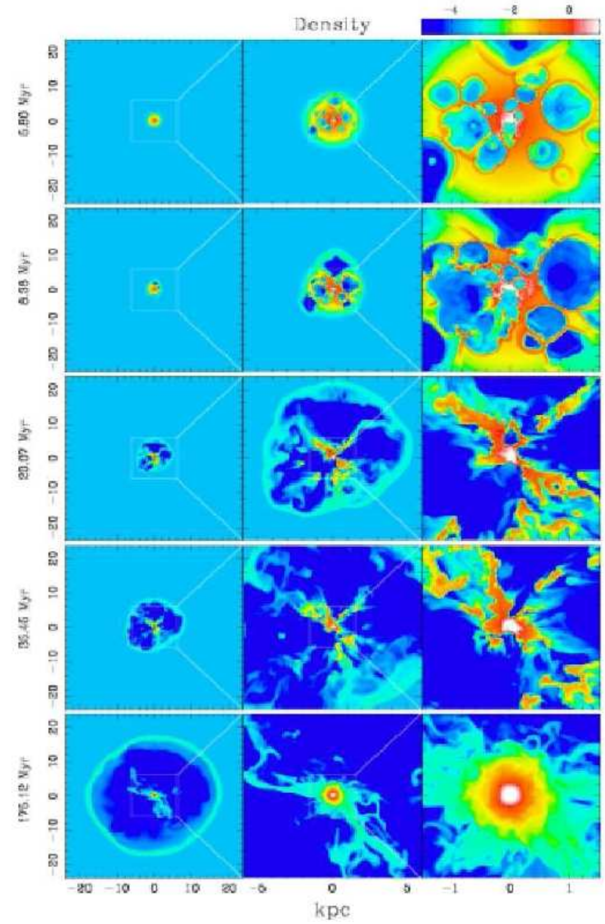

Figure 2: Snapshots of the logarithmic number density of the gas in a halo with $M = 10^8 M_\odot$ at $z = 9$ at different timesteps after multiple SN explosions. The three panels show the halo at different scales. (Mori et al. (2002)).

2.2 Impinging shocks

Beside processes from within the galaxy, the SF in a galaxy can also be inhibited by neighboring objects. Due the the collapsing perturbation by a shock from a neighboring source, the gas may be stripped. The momentum of the shock can be high enough to empty the halo of its baryons and prevent the formation of the galaxy, as the gas is carried away by the shock. If the galaxy is virialized this effect in neglegible. However, up to 70 % of its gas content can be stripped away when the galaxy is at the turnaround stage (Sigward et al. (2005)).

3 Chemical feedback

Chemical feedback is associated with the existence of a critical metallicity of the gas, Z_{crit}, that induces a transition from a massive to a more standard star formation mode (Ciardi (2008)). The existence of the Pop III stars and the transition into a Pop II/I star formation epoch depends on the efficiency of metal enrichment from first stellar explosions. These metals can cool the gas and induce the formation of lower mass stars.
Models in the past have included more and more metals and also dust. The largest difference in results between past investigations is the presence of dust. Studies that include dust (Clark et al. (2008)) found that clouds with $Z \leq 10^{-6} M_{\odot}$ typically fragment into clumps of 100 $M_{\odot}$, while for $Z \geq 10^{-4} Z_{\odot}$ clouds are created out of which more typical stars form. A higher metallicity induces the cooling of clouds, wich decreases the Jeans Mass of these clouds. This enhances the formation of more typical stars. In the intermediate range the fragmentation size depends on the amount of metals depleted onto dust grains. When dust is not included though, the formation of high mass stars takes place up to at least $Z \sim 10^{-4} Z_{\odot}$ (Smith and Sigurdsson (2007)). Therefore it is crucial to get a better idea of the role of dust in the early universe.
To get a better understanding of the chemical feedback it is also crucial to have knowledge of the initial mass function and the efficiency of metal enrichment. It turns out metal enrichment is far from being homogeneous and only stars in the mass range of SN and PISN explosions contribute to the IGM. This makes the mechanical feedback and the transition from Pop III to Pop II/I stars a local process.

4 Radiative feedback

Radiative feedback is the ionization/dissociation of atoms/molecules and heating of the gas by massive stars or quasars (Ciardi (2008)). The radiation can have a local effect (on the same galaxy as that produced it) but also on neighboring objects. The fraction of radiation escaping the host galaxy f_{esc} is larger than 70 % and even increasing with the mass of the star (Alvarez et al. (2006)). Although the scenarios are different, the physical processes within the host galaxy and on neighbouring objects are similar. In this section I will treat photoionization/evaporation and H_2 photodissociation.

4.1 Photoionization/evaporation

The presence of a UV radiation field nearby can inhibit the collapse and formation of a primordial object. Because of the decreased fraction of neutral hydrogen the cooling can be suppressed and gas can be photoevaporated out of the halo. It was found that objects as small as $v_c \sim 15$ km s^{-1} are able to collapse at weak UV intensities ($J < 10^{-23}\mathrm{erg s^{-1} cm^{-2} sr^{-1} Hz^{-1}}$). This is because of the self-shielding of the gas and H_2 cooling. Objects as large as $v_c \sim 40$ km s^{-1} can be photoevaporated and prohibited from collapsing and forming at stronger UV intensities (Susa and Kitayama (2000); Kitayama et al. (2000)). Ciardi et al. (2000) studied the ability of a halo to self shield against soft-UV radiation as a function of mass and intensity. This is shown in figure 3. It shows the minimum mass necessary for self-shielding to increase with redshift.

For the photoevaporation process the number of ionized photons needed depends on the ionizing spectrum, how deep it penetrates into a halo and the absorption of photons it induces. So, though the ability of self-shielding decreases with decreasing redshift and therefore the completion of the process of photoevaporation is reached easier at lower redshifts, it turns out that overall Pop III stellar sources (older higher redshift sources) are most efficient in completing the photoevaporation process. It is worthwhile to note that the lifetime of massive Pop III sources is shorter than the timescale of photoevaporation, and therefore minihalos generally survive evaporation (Alvarez et al. (2006)).

4.2 H_2 Photodissociation

The first generation of formed stars can affect subsequent SF, by dissociating H_2 in the nearby SF cloud. For this local internal feedback, one massive star can produce enough radiation to dissociate an entire host halo (Nishi and Tashiro (2000)). However, SF can proceed gradually if the SF clouds are dense and far enough from the radiation of the emitting star (Glover and

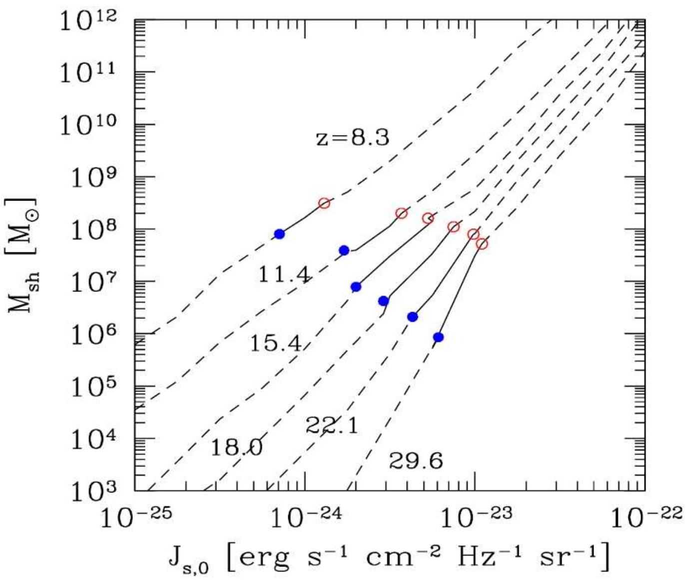

Figure 3: Minimum mass for self-shielding from an external radiating soft-UV intensity at the Lyman-limit at different redshifts. The solid lines indicate the area affected by the feedback. The filled circles indicate the minimum mass for collapse in absence of feedback, the open circles indicate the minimum mass for objects to cool via H line cooling (Ciardi et al. (2000)).

Brand (2001)).

Next to the negative feedback there is also positive feedback from H_2 reformation. This occurs in front of HII regions and inside HII regions. Once SF is suppressed in a halo, the ionized gas starts to recombine to H_2 (Ricotti et al. (2001)). This also occurs in the cooling gas behind shocks produced during the ejection of gas from these objects (Ferrara (1998)). Ricotti et al. (2002) showed that this positive feedback usually counterbalances the negative feedback and therefore the formation of small mass galaxies is not inhibited.

Beside H_2, also HD can be formed inside relic HII regions, which will reduce the gas temperature further (Nagakura and Omukai (2005)). This effect will lower the typical Jeans Mass and therefore the stars formed inside relic HII regions might have masses smaller than the stars that emitted the radiation. The reformation of H_2 and HD can be increased by collisions of cold atomic gasclouds and X-ray background Cen (2005). This can also enhance the SF process.

4.3 Photoheating filtering

Cosmic re-ionization can have a strong impact on galaxy formation, in special for low mass objects. The heating associated with photoionization will enhance the temperature of the IGM gas and inhibit the formation of galaxies with masses below the Jeans mass. Gnedin (2000) showed that the effect of re-ionization depends on the re-ionization history and is not universal at a given redshift. To take this into account one should introduce a filtering scale k_F, that describes the smoothing of the baryonic mass compared to the dark matter. This gives the relation $\delta_b = \delta_{dm} e^{-k^2/k_f^2}$. This can be transformed in a filtering mass related to the Jeans mass:

$$M_F^{2/3} = \frac{3}{a} \int_0^a da' M_J^{2/3} a' \left[1 - \left(\frac{a'}{a} \right)^{1/2} \right]$$

The filtering mass depends on the full thermal history of the gas, and not only the instantaneous state. It increases from $\sim 10^7 M_\odot$ at z≈10 to $10^9 M_\odot$ at z≈ 6 suppressing the formation of objects below this mass.
A similar effect is found inside HII regions around the first luminous stars. The HII regions compton cools when the ionizing source 'turns of' and recombines. However, the remaining HII regions fossil does not allow gas accretion and cooling, prohibiting stellar formation (Oh and Haiman (2003)). There is an entropy floor in the relic HII regions present, suppressing SF. This was confirmed when it was showed there exists a critical intensity for the UV flux. Beneath this flux H_2 formation is enhanced, while above this flux SF is reduced (Mesinger et al. (2006)).

5 Some other feedback processes

Beside the more thoroughly described feedback processes, also some other feedback mechanisms are present. In this section I will treat three of them. First AGN feedback, then the two-phase medium and finally the dynamical-friction feedback. All three of the feedback processes deal with shock heated gas. Gas is shock heated when the dark matter halo relaxes to virial equilibrium and the gas falls in to a virial temperature near the halo virial radius. Multiple shocks can occur when the halo keeps on accreting matter and has to find virial equilibrium again.

5.1 AGN feedback

The power emitted by AGNs by for example their jets seems to be more than necessary for keeping the gas hot if the energy is released during long and quiet phases of self-regulated AGN activity. AGN feedback is most effective when the gas is shock heated into a dilute medium. At this point the gas becomes vulnerable to heating and pushing by the central energy source and is therefor a good trigger for effective AGN feedback (Dekel and Birnboim (2006)). The effectivety of AGN feedback depends on the amount of hot shock heated gas, rather than on the AGN energy release. When AGN feedback becomes effective, the dilute clouds are pushed away and the dense clouds are hardly affected (Slyz et al. (2005)). Because of the removal of gas and the heating of the gas the SF shuts down.

5.2 Two-phase medium

Virialized shock heated gas at $\gtrsim 10^6 K$ develops into a two-phase medium with cold, dense clouds confined within the hot, dilute medium. This occurs because the cooling function peaks near $\gtrsim 10^4 K$ (Fall and Rees (1985)). Some of the hot gas can be locked into the cold clouds, reducing the density of the hot gas and inhibiting the cooling and the infall of the hot gas preventing the formation of stars. Gas may be kept hot for even longer periods by repeated shock heatings due to the accretion of matter to the halo (Dekel and Birnboim (2006)).

5.3 Dynamical-friction feedback

Gas can be heated by the dynamical friction acting on galaxies in a halo core. The gas response to dynamical friction has a sharp peak when it is heated to near the virial temperature in a halo with $M > M_{shock}$ with M_{shock} the mass at which shock heating occurs (Dekel and Birnboim (2006)).

6 Summary

In this report I discussed several classes of feeback processes, what triggers them and how they influence the SF. I will briefly summarize them here:

- Feedback can be positive or negative and comes in three different broad classes: mechanical, chemical and radiative.
- It depends strongly on the local conditions, e.g. ionization structure of the radiation, metallicity of the gas, density of the gas.
- Mechanical feedback can blow gas away out of the halo inhibiting star formation and enhancing the metallicity of a halo. Multiple SN can drive the gas to the center of the galaxy and enhance the formation of stars.
- Metallicity will define the transition between massive Pop III stars and Pop II/I stars. Taking into account that metals attach to dust particles, this critical metallicity of transition varies widely
- Radiative feedback is able to completely heat and ionize or evaporate gas. The evaporation process is particularly interesting for Pop III objects. Depending on the mass of the halo and the UV radiation intensity, halos may be able to self-shield and still form into stars. Beside this, radiation is able to dissociate or reform H_2 atoms, inhibiting or respectively enhancing the formation of stars
- For radiative feedback the full thermal history has to be taken into account, in stead of the instantaneous values. This leads to a filtering mass, that describes the mass necessary for a gas cloud to form into an object.
- There are also feedback processes that occur in hot dilute gas, created by shock heating of the halo. These processes are AGN feedback, two-phase medium and dynamical-friction feedback.

Although much is known, several questions still have to be answered to get a better understanding on feedback, e.g. What is the role of dust in the early universe? Which IMF do the first stars have?

References

M. A. Alvarez, V. Bromm, and P. R. Shapiro. The H II Region of the First Star. *ApJ*, 639:621–632, March 2006. doi: 10.1086/499578.

V. Bromm, N. Yoshida, and L. Hernquist. The First Supernova Explosions in the Universe. *ApJ*, 596:L135–L138, October 2003. doi: 10.1086/379359.

R. Cen. Formation of First Stars Triggered by Collisions and Shock Waves: Prospect for High Star Formation Efficiency and High Ionizing Photon Escape Fraction. *ApJ*, 624:485–490, May 2005. doi: 10.1086/429359.

B. Ciardi. Feedback From the First Stars and Galaxies and its Influence on Structure Formation. In B. W. O'Shea and A. Heger, editors, *First Stars III*, volume 990 of *American Institute of Physics Conference Series*, pages 353–363, March 2008. doi: 10.1063/1.2905580.

B. Ciardi and A. Ferrara. The First Cosmic Structures and Their Effects. *Space Science Reviews*, 116:625–705, February 2005. doi: 10.1007/s11214-005-3592-0.

B. Ciardi, A. Ferrara, F. Governato, and A. Jenkins. Inhomogeneous reionization of the intergalactic medium regulated by radiative and stellar feedbacks. *MNRAS*, 314:611–629, May 2000. doi: 10.1046/j.1365-8711.2000.03365.x.

P. C. Clark, S. C. O. Glover, and R. S. Klessen. The First Stellar Cluster. In B. W. O'Shea and A. Heger, editors, *First Stars III*, volume 990 of *American Institute of Physics Conference Series*, pages 79–81, March 2008. doi: 10.1063/1.2905678.

A. Dekel and Y. Birnboim. Galaxy bimodality due to cold flows and shock heating. *MNRAS*, 368:2–20, May 2006. doi: 10.1111/j.1365-2966.2006.10145.x.

S. M. Fall and M. J. Rees. A theory for the origin of globular clusters. *ApJ*, 298:18–26, November 1985. doi: 10.1086/163585.

A. Ferrara. The Positive Feedback of Population III Objects on Galaxy Formation. *ApJ*, 499:L17+, May 1998. doi: 10.1086/311344.

S. C. O. Glover and P. W. J. L. Brand. On the photodissociation of H2 by the first stars. *MNRAS*, 321:385–397, March 2001. doi: 10.1046/j.1365-8711.2001.03993.x.

N. Y. Gnedin. Effect of Reionization on Structure Formation in the Universe. *ApJ*, 542:535–541, October 2000. doi: 10.1086/317042.

T. H. Greif, J. L. Johnson, V. Bromm, and R. S. Klessen. The First Supernova Explosions: Energetics, Feedback, and Chemical Enrichment. *ApJ*, 670:1–14, November 2007. doi: 10.1086/522028.

T. Kitayama and N. Yoshida. Supernova Explosions in the Early Universe: Evolution of Radiative Remnants and the Halo Destruction Efficiency. *ApJ*, 630:675–688, September 2005. doi: 10.1086/432114.

T. Kitayama, Y. Tajiri, M. Umemura, H. Susa, and S. Ikeuchi. Radiation-hydrodynamical collapse of pre-galactic clouds in the ultraviolet background. *MNRAS*, 315:L1–L7, June 2000. doi: 10.1046/j.1365-8711.2000.03589.x.

M.-M. Mac Low and A. Ferrara. Starburst-driven Mass Loss from Dwarf Galaxies: Efficiency and Metal Ejection. *ApJ*, 513:142–155, March 1999. doi: 10.1086/306832.

A. Mesinger, G. L. Bryan, and Z. Haiman. Ultraviolet Radiative Feedback on High-Redshift Protogalaxies. *ApJ*, 648:835–851, September 2006. doi: 10.1086/506173.

M. Mori, A. Ferrara, and P. Madau. Early Metal Enrichment by Pregalactic Outflows. II. Three-dimensional Simulations of Blow-Away. *ApJ*, 571:40–55, May 2002. doi: 10.1086/339913.

T. Nagakura and K. Omukai. Formation of Population III stars in fossil HII regions: significance of HD. *MNRAS*, 364:1378–1386, December 2005. doi: 10.1111/j.1365-2966.2005.09685.x.

R. Nishi and M. Tashiro. Self-Regulation of Star Formation in Low-Metallicity Clouds. *ApJ*, 537:50–54, July 2000. doi: 10.1086/309037.

S. P. Oh and Z. Haiman. Fossil H II regions: self-limiting star formation at high redshift. *MNRAS*, 346:456–472, December 2003. doi: 10.1046/j.1365-2966.2003.07103.x.

M. Ricotti, N. Y. Gnedin, and J. M. Shull. Feedback from Galaxy Formation: Production and Photodissociation of Primordial H2. *ApJ*, 560:580–591, October 2001. doi: 10.1086/323051.

M. Ricotti, N. Y. Gnedin, and J. M. Shull. The Fate of the First Galaxies. II. Effects of Radiative Feedback. *APJ*, 575:49–67, August 2002. doi: 10.1086/341256.

R. Salvaterra, A. Ferrara, and R. Schneider. Induced formation of primordial low-mass stars. *New Astronomy*, 10:113–120, December 2004. doi: 10.1016/j.newast.2004.06.003.

F. Sigward, A. Ferrara, and E. Scannapieco. Suppression of dwarf galaxy formation by cosmic shocks. *MNRAS*, 358:755–764, April 2005. doi: 10.1111/j.1365-2966.2005.08576.x.

A. D. Slyz, J. E. G. Devriendt, G. Bryan, and J. Silk. Towards simulating star formation in the interstellar medium. *MNRAS*, 356:737–752, January 2005. doi: 10.1111/j.1365-2966.2004.08494.x.

B. D. Smith and S. Sigurdsson. The Transition from the First Stars to the Second Stars in the Early Universe. *ApJ*, 661:L5–L8, May 2007. doi: 10.1086/518692.

H. Susa and T. Kitayama. Collapse of low-mass clouds in the presence of a UV radiation field. *MNRAS*, 317:175–178, September 2000. doi: 10.1046/j.1365-8711.2000.03616.x.