Feedback In The Early Universe

Jithin Varghese George

May 13, 2008

Introduction

In the past 15 years or so the field of Cosmology has really taken off. Having currently at its disposal the might of technology has help answered a lot of the lingering questions about the past of the universe as a whole. This has brought about an unprecedented interest in early stars and galaxies, especially their formation. It has been found that once the first sources of luminosity were formed, their mass deposition, energy injection and emitted radiation has extremely important effects on the future evolution of the intergalactic medium. This directly translates to strong regulations of future galaxy formation and the reionization process. These processes are referred to in general as feedback effects or feedback processes.

In The Beginning...

In order to understand the concept of feedback it is necessary to first understand the environment of the universe when the first objects were formed and also what these first objects were. Under the currently accepted Cold Dark Matter (CDM) cosmology, "small-halo" galaxies are the first luminous objects in the universe [10]. These are nothing more than small mass protogalaxies which a virial temperature of less than $10^4 K$ and mostly rely on H_2 cooling to form stars. Hydrogen Lyα excitation is essentially quenched because of the temperature and mass range. This may seem counter-intuitive as the primordial H_2 is very small as very trace amounts are created during the recombination phase due to the presence of H^- ions which act as a catalyst for their creation. However, a large amount of H_2 is naturally reformed within the collapsing shells. Thus, the virialized structure's future depends crucially on its ability to increase by itself the H_2 content.

The first generation of stars created within these "small-halo" galaxies are essentially metal devoid. This is because of the current standing theory that elements that are heavier than Lithium must be produced during supernova explosions due to the intense heat or within the cores of much heavier stars. However the formation of these stars create feedback effects. These strongly affect the future galaxy formation, reionization and metal enrichment of the universe.

Feedback can be classified in two different ways. The broadest one is based on the effect it has on the star formation rate. The feedback that tends to increase the star formation efficiency is called positive feedback and thus the one that tends to decrease the star formation efficiency is called negative feedback. This classification, although it helps in identifying the end effect, does not help in identifying the true source, as such effects can be created by multiple sources [2]. For this purpose, feedback is divided into three separate classes: radiative, mechanical and chemical.

Radiative Feedback

Radiative Feedback relates to the ionization/dissocation of atoms/molecules and heating of the gas [1]. Of the three broad types mentioned above, this is the one that is the most studied and probably well understood.

The importance of this kind of feedback relates back to the importance of molecular H_2 in the collapse of "small-halo" objects. When radiative feedback comes into play the collapse and the amount of the cold gas available for star formation is almost directly related to the strength of this feedback. There are both negative and positive feedback effects that can arise from this situation and these are described below.

Negative Feedback

The first possible way that negative feedback could manifest itself is if these objects are outside the disassociated spheres of gas from pre-existing objects. Once the first stars are created within the "small-halo" objects, the further formation of stars within the object is greatly affected. This is because the UV radiation being emitted from these stars disassociate the molecular H_2 in the nearby star forming clouds. This also known as *local, internal feedback*.

However, through simulations it has been found that this idea of disassociated spheres are actually a very small portion of what is really happening. The much larger part of this negative feedback is the one which is caused by the sort of background radiation one would expect within these small-halo galaxies. The UV released from all of the stars within this galaxy creates enough of a background UV flux which is enough to essentially disassociate the entire H_2 cloud present. This is a much stronger effect and as a result plays a much larger role in the negative feedback.

According to [7], just one massive star can produce enough UV radiation to irradiate the entire object. There are exceptions to this case, where the star forming cloud is sufficiently far away from the star that emits the UV radiation and also if it is sufficiently dense. To put this idea in perspective, according to [11], a star of mass $120M_\odot$ will see its effect for about 30 pc. Beyond this limit, the clouds are able to form stars without too much of a feedback effect.

There is also another way that negative feedback can take place. This is when the radiation emitted by the stars affect the IGM and nearby objects evolution. A good measure of this kind of feedback is the escape fraction f_{esc}, which is the fraction of the radiation that can escape into the IGM. For massive stars, the f_{esc} is larger that 70% and it follows a direct relationship with the mass. On the other hand, "small-halo" objects at high redshift finds that $\langle f_{esc} \rangle$ should be very small ($10^{-2} - 10^{-5}$) and decreasing with increasing halo mass. [10]

There have been lots of research in this topic, much of it by way of simulations. Each one yet is different from the other because of the different approaches they take to the same problem. One of the earliest methods used was to the study the ability of a halo to self-shield against an external UV radiation field and to collapse. The various radiative transfer equation are calculated for different redshifts. [3] Another approach to the same problem was undertaken in [4] and this was to study the collapse of one particular halo in an UV background. They were able to show that if the UV flux was less was than 10^{-22} all the object cool and collapse. They were also able to find that the same was true even if the mass of the object was greater than $10^{8} M_{\odot}$ independent of the value of the UV flux. If neither condition was met, their evolution depended heavily on the mass, the flux and the spectral shape. Similar results were also obtained in [6] by studying the collapse of an object from different initial conditions and analyzing the halos formed, and also in [8] which uses high resolution cosmological simulations on Population III star formation to study systematic effects.

On a larger scale, the radiation emitted by the stars can completely photoevaporate small mass halos. However, these form an almost negligible amount in the universe. This is attributed to the fact that the time scale associated with this phenomenon is longer than the average lifetime of a Population III star.

Positive Feedback

This refers to a second group of stars that form within the disassociated sphere of gas of an already collapsed object. In such areas, radiation actually favor structure formation by helping the molecules to efficiently reform. This is indeed what is called positive feedback. [9]

Here too, the negative feedback mentioned above does indeed happen. The radiation that is emitted by the star at this point is usually around the range of 11.6 - 13.6 eV. This is not sufficient to actually ionize the gas. So what happen is that the dissociated molecular H_2 is initially depleted and forms neutral H. However, closer to the star the radiation energy is sufficient to actually create ionization and thus there is a region close to the star where there exists more of a electron - proton mix. At the barrier between the two regions, the formation of H^- ions because favorable and the presence of this ion acts as a catalyst for the creation of H_2 molecules. So after a while, it is able to reform H_2 efficiently and thus aiding in star formation. There is also the possibility of an enhanced star formation because of the formation of HD. The scenario mentioned above for the efficient formation of H_2 is applicable to HD as well. This further cools the gas temperature which improves the star formation rate. This is more important in scaled of much higher density.

Mechanical Feedback

This kind of feedback as the name suggests refers to the mechanical energy injection from winds and/or supernova explosions [1] . In the early universe, winds are almost non-existent due to metal poor stars, supernova explosions then become an ever more important object.

One of the obvious consequences of supernova explosions is expulsion of gas outside the "small-halo" object. This reduces the amount of raw material available for star formation and thereby causing a form of negative feedback. Simulations on this phenomenon have shown that the scenario is a lot more complicated than one would expect. Even if the supernova energy is larger than the halo binding energy, the gas can still be retained [5] . This places a great deal of importance then on the initial conditions viz. the existence and extent of the pre-existing HII region. The scenario is even more complicated when there are multiple supernova explosions. Under certain situations, this could cause all the gas to move to the center and bring about a case of positive rather than negative feedback. Positive feedback can also arise from the propagation of shocks from the supernova. The sweeping of the gas, creates dense shells of gas, which could then fragment and form stars.

The best part however, is the efficient formation of HD molecules. In the shocked gas formed above, HD formation is very efficient. This as mentioned previously aids in further cooling the temperatures of the gas and thus acts as another mode of positive feedback. This process is the most efficient process of HD formation, so much so that it cools the primordial gas down to the CMB temperature within the Hubble time.

Chemical Feedback

This particular mode of feedback is associated with the existence of a critical metallicity of the gas, Z_{crit}, that induces a transition from massive to a more standard star formation mode. This is by far the least studied of the three kinds although it has come under a revival of sorts very recently. Even then very little literature is available on the subject.

Of the simulations done on the topic, they all seem to hinge on one particular aspect: the presence of dust. With the presence of dust, clumps of even very low metallicity is able to clump while this is not the case when there is no dust involved. Dust also plays an important role in the formation of H_2. Type II supernova are able to create molecular H_2 on grainy surfaces much more easier and this creates a positive feedback on star formation. It is now apparent then than dust plays a crucial role in the evolution of the early universe.

Chemical feedback is also a lot harder to quantify in such early redshifts as only those stars in the mass range of supernova can have significant metallicity. It then becomes necessary to calculate the Initial Mass functions of the first stars and also the efficiency with which they are able to enrich the IGM with metals. As mentioned earlier, winds are almost non-existent and the distribution is far from homogeneous.

All this shows that Chemical Feedback is almost impractical in a universal scale. It is a very a local phenomenon and it is dependent on a lot of the local variables. Thus this is another form of local feedback.

Conclusions

In conclusion, the feedback effects can be summarized as follows:

- Feedback refers to the effects that the first sources have on the subsequent galaxy and star formation
- It depends very strongly on the local conditions like density, metallicity etc.
- There are broadly three different kinds: Radiative, Mechanical and Chemical
- Radiative Feedback refers to the kind of feedback brought about by ionization/dissociation of atoms because of the radiation emitted by the new star.
  - the UV radiation from the star disassociates the molecular H_2 which inhibits star formation and thus causing a negative feedback.
  - The usual negative feedback brought about by this can be countered by having a high mass or being sufficiently far away from the star, a few tens of pc.
  - If the cloud is within relics of older stars, it will create a positive feedback as it causes efficient formation of H_2 and HD which helps in cooling the temperature.

- Mechanical Feedback refers to the kind of feedback brought about by the mechanical energy injection from winds/SN explosions
  - Supernova explosions expel gas out which reduce the star formation rate.
  - Multiple supernova explosions can actually push the gas towards the center, giving a positive feedback. Also the shocks created can create dense shells that can trigger star formation.
  - The shock shells are the most efficient method of HD formation.
- Chemical Feedback refers to the kind of feedback brought about by the existence of metallicity.
  - Dust plays a critical role in determining transition point.
  - It is not easy to quantify effect without knowledge of the IMF function or efficiency of metal enrichment.

It is thus obvious, that the various mechanisms still have a lot of unanswered questions, like does metal free stars, if there is indeed such a thing cause winds? What are the possible IMFs of the first stars? All these are crucial questions which need to be answered to get a better understanding of the early universe.

References

[1] B. Ciardi. Feedback From the First Stars and Galaxies and its Influence on Structure Formation. In *American Institute of Physics Conference Series*, volume 990 of *American Institute of Physics Conference Series*, pages 353–363, March 2008.

[2] B. Ciardi and A. Ferrara. The First Cosmic Structures and Their Effects. *Space Science Reviews*, 116:625–705, February 2005.

[3] B. Ciardi, A. Ferrara, F. Governato, and A. Jenkins. Inhomogeneous reionization of the intergalactic medium regulated by radiative and stellar feedbacks. *Monthly Notices of the Royal Astronomical Society*, 314:611–629, May 2000.

[4] T. Kitayama, H. Susa, M. Umemura, and S. Ikeuchi. Criteria for the formation of Population III objects in the ultraviolet background radiation. *Monthly Notices of the Royal Astronomical Society*, 326:1353–1366, October 2001.

[5] T. Kitayama and N. Yoshida. Supernova Explosions in the Early Universe: Evolution of Radiative Remnants and the Halo Destruction Efficiency. *The Astrophysical Journal*, 630:675–688, September 2005.

[6] M. E. Machacek, G. L. Bryan, and T. Abel. Simulations of Pregalactic Structure Formation with Radiative Feedback. *The Astrophysical Journal*, 548:509–521, February 2001.

[7] R. Nishi and M. Tashiro. Self-Regulation of Star Formation in Low-Metallicity Clouds. *The Astrophysical Journal*, 537:50–54, July 2000.

[8] B. W. O'Shea and M. L. Norman. Population III Star Formation in a ΛCDM Universe. I. The Effect of Formation Redshift and Environment on Protostellar Accretion Rate. *The Astrophysical Journal*, 654:66–92, January 2007.

[9] M. Ricotti, N. Y. Gnedin, and J. M. Shull. The Fate of the First Galaxies. I. Self-consistent Cosmological Simulations with Radiative Transfer. *The Astrophysical Journal*, 575:33–48, August 2002.

[10] M. Ricotti, N. Y. Gnedin, and J. M. Shull. The Fate of the First Galaxies. II. Effects of Radiative Feedback. *The Astrophysical Journal*, 575:49–67, August 2002.

[11] H. Susa and M. Umemura. Secondary Star Formation in a Population III Object. *The Astrophysical Journal*, 645:L93–L96, July 2006.