PROCEEDINGS OF SCIENCE

PoS(idm2008)075

WIMP annihilation effects on primordial star formation

E. Ripamonti,[*] F. Iocco,[†] A. Bressan,[‡] R. Schneider,[§] A. Ferrara,[¶] P. Marigo[‖]

We study the effects of WIMP dark matter (DM) annihilations on the thermal and chemical evolution of the gaseous clouds where the first generation of stars in the Universe is formed.
We follow the collapse of the gas inside a typical halo virializing at very high redshift, from well before virialization until a stage where the heating from DM annihilations exceeds the gas cooling rate. The DM energy input is estimated by inserting the energy released by DM annihilations (as predicted by an adiabatic contraction of the original DM profile) in a spherically symmetric radiative transfer scheme. In addition to the heating effects of the energy absorbed, we include its feedback upon the chemical properties of the gas, which is critical to determine the cooling rate in the halo, and hence the fragmentation scale and Jeans mass of the first stars.
We find that DM annihilation *does* alter the free electron and especially the H_2 fraction when the gas density is $n \gtrsim 10^4 \#/\mathrm{cm}^3$, for our fiducial parameter values. However, even if the change in the H_2 abundance and the cooling efficiency of the gas is large (sometimes exceeding a factor 100), the effects on the temperature of the collapsing gas are far smaller (a reduction by a factor $\lesssim 1.5$), since the gas cooling rate depends very strongly on temperature: then, the fragmentation mass scale is reduced only slightly, hinting towards no dramatic change in the initial mass function of the first stars.

Identification of dark matter 2008
August 18-22, 2008
Stockholm, Sweden

---

[*] Università degli Studi dell'Insubria, Dipartimento di Fisica e Matematica, Como, Italy
[†] INAF/Osservatorio Astrofisico di Arcetri, Firenze, Italy
[‡] INAF/Osservatorio Astronomico di Padova, Padova, Italy; INAOE, Puebla, Mexico; SISSA, Trieste, Italy
[§] INAF/Osservatorio Astrofisico di Arcetri, Firenze, Italy
[¶] SISSA, Trieste, Italy
[‖] INAF/Osservatorio Astronomico di Padova, Padova, Italy

1. Introduction

In the currently favoured ΛCDM cosmological model (see e.g. Komatsu et al. 2008), the bulk of the matter component is believed to consist of unknown particles, commonly called Dark Matter (DM). Weakly Interacting Massive Particles (WIMPs) are among the favorite candidates complying with constraints from cosmology and particle physics (see e.g. Bertone et al. 2005). As the lightest supersymmetric partners of the standard model in theories with R–parity conservation, WIMPs are stable Majorana fermions *weakly* coupled to baryons, and are their own antiparticles.

DM drives the process of structure formation, dominating the large-scale gravitational potential of galaxies; but DM density is too small for the energy released by annihilations to affect the evolution of the Inter Galactic Medium, or stellar formation and evolution in the present-day Universe (the central parsecs of the Milky Way are a possible exception; see Scott et al. 2008).

The formation of the first generation of stars in the Universe is believed to be very different from all subsequent star formation episodes: the unique conditions of the gas in the star-forming halos at redshift $z \gtrsim 20$ (above all, the absence of metals, which implies that gas cooling depends on H_2 molecules) seem to indicate that typically only one massive star forms at the very center of each halo (see e.g. the proceedings of the "First Stars III" conference). However, Spolyar, Freese and Gondolo (2008, hereafter SFG) suggested that these unique conditions may enhance the effects of DM annihilations, altering primordial star formation.

SFG showed that the formation of a protostellar cloud at the center of an halo (predicted by the standard scenario) would largely increase the central DM density through the adiabatic contraction mechanism (AC; Blumenthal et al. 1986). This would boost the DM annihilation rate, and the energy deposited in the surrounding gas would equal the one radiated away by H_2 cooling by the time gas density exceeds $n \equiv \rho/m_p \gtrsim 10^6 - 10^{10}\,\mathrm{cm}^{-3}$ (depending on parameters). They dubbed a *dark* star the object resulting from an equilbrium between DM annihilation and gas cooling. Natarajan et al. (2008) confirmed these results by using DM and gas profiles from three-dimensional cosmological simulations of first star formation, relying on extrapolations of the inner DM profile. Freese et al. (2008ab; see also the contributions of Spolyar and Gondolo in these proceedings) and Iocco et al. (2008) studied the evolution of an hydrostatic object powered by DM annihilation, starting from an initial central density $n \sim 10^{16}\,\mathrm{cm}^{-3}$. Their initial conditions and techniques differ, and we address the reader to the original papers for further details.

In these proceedings we study the yet unexplored phases between virialization and the formation of an hydrostatic object, investigating whether the energy released by DM annihilation has an effect on the cooling of the gas, and on the Jeans mass and final mass range of primordial stars.

2. Method and results

We follow the gas evolution introducing a feedback between gas contraction, DM annihilation, energy absorption and gas chemistry; we do so by means of a lagrangian 1D spherically symmetric code including the treatment of gravitation, hydrodynamics, chemistry and cooling (see Ripamonti et al. 2007). We have modified it by introducing an AC algorithm (from Gnedin et al. 2004) accounting for the modification of the DM profile due to the extra pull from baryons, as they collapse to the center of the halo. The energy per unit time per unit volume released by the DM

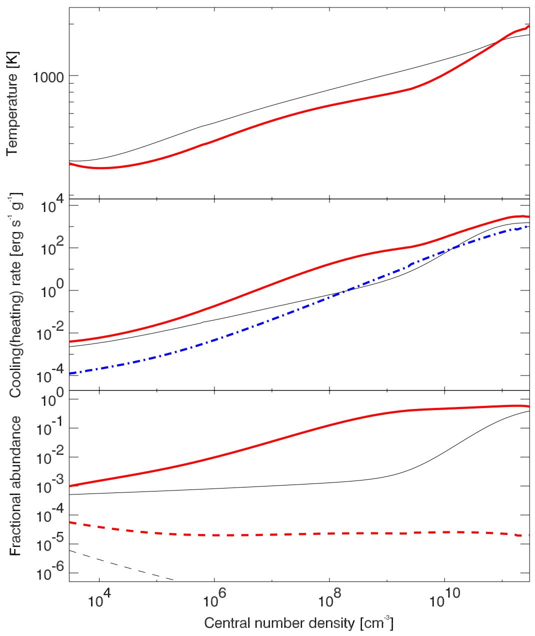

Figure 1: Evolution of the central shell of the simulated object, as a function of its density. Top panel: temperature (solid); middle panel: gas cooling rate (solid) and heating rate from DM annihilations (dot-dashed); bottom panel: abundances of H_2 (solid) and e^- (dashed). Thick (red) lines refer to the case with DM annihilation, thin (black) ones to the "standard" case with no DM annihilations.

annihilation reads:

$$l_{dm}(r) = fc^2 \frac{\langle \sigma v \rangle}{m_{DM}} \rho_{DM}^2(r), \tag{2.1}$$

where ρ_{DM} is the local DM density, and we adopr m_{DM}=100GeV/c^2, $\langle \sigma v \rangle$=3$\times$10^{-26}cm^3/s for the neutralino mass and its self-annihilation rate. The factor f=2/3 accounts for the fraction of energy carried away by neutrinos (typically 1/3) at the end of the shower induced by annihilation primaries (see Bertone et al. 2005). However, this energy is in the form of photons and stable charged particles (electrons or positrons) with hard spectra and cutoff at the neutralino mass. We estimate the energy actually absorbed by the baryons through the code radiative transfer algorithm, assuming an effective frequency integrated opacity κ=0.01 cm^2/g. This value (which might be treated as a parameter) does not come from a rigorous treatment; however, it is in rough agreement with the treatment from SFG, thus allowing for result comparison.

We consider a typical halo with mass 10^{6}M$_\odot$, with a gas fraction 0.175, virializing at $z_{vir} = 20$. We start integrating at $z = 1000$, from flat DM and gas profiles; the code follows the gas evolution, whereas the DM evolution is taken from a smooth recipe (based on analytical theories of structure formation) which slowly transforms a flat DM profile into an appropriate ($R_{200} \simeq R_{\rm vir} \simeq 5 \times 10^{20}$ cm, $c = 10$) NFW profile (Navarro et al. 1996) at $z = z_{vir}$; after virialization, the DM profile remains fixed, with the exception of the central regions, where its shape is modified by AC.

In Fig. 1 we compare the evolution of the central properties of models with (thick lines) and without (thin lines) DM annihilation effects, as a function of the gas central density. In most of the range we show, the DM energy input induce a *reduction* of the gas temperature (top panel). This is a consequence of the enhanced cooling rate (central panel, solid), induced by the increase in the H_2 abundance (bottom panel, solid), which in turn is due to the catalyzing effects of the increased free electrons abundance (bottom panel, dashed) on the the H_2 formation chain ($H + e^- \rightarrow H^- + \gamma$; $H^- + H \rightarrow H_2 + e^-$). However, the temperature drops only by a factor $\lesssim 1.5$, much smaller than the increase in the H_2 abundance: in fact, given the strong dependence of H_2 cooling from temperature, a modest temperature reduction can balance a much larger increase in the H_2 abundance.

In the model with annhilations, when $n \gtrsim 10^9 \mathrm{cm}^{-3}$ most of H is already molecular, and H_2 cannot increase any more: the cooling rates of the two models slowly converge, as H is converted into H_2 also in the standard case. Furthermore, as the central gas and DM densities increase, direct heating from annihilations (central panel, dot-dashed) becomes significant, and finally takes central temperature over that of the standard case ($n \gtrsim 10^{11} \mathrm{cm}^{-3}$).

3. Conclusions

We present results from the first calculation of the primordial star formation process which self-consistently includes gas hydrodynamics, chemistry, and DM annihilation. We show that the feedback between DM annihilations and chemistry *does* change the gas thermodynamics. However, this appear to have limited effects on the fragmentation scale of primordial clouds, which should be reduced by a factor $\lesssim 2$ (if the fragment mass is $\propto M_{Jeans} \propto T^{3/2}$). Although further study is definitely necessary (see the forthcoming Ripamonti et al. 2008), our results strongly hint that DM annihilation effects do not alter dramatically the fragmentation during the first star formation episode in the Universe.

A. B. and P. M. acknowledge contract ASI I/016/07/0.

References

[Bertone et al. 2005] Bertone G., Hooper D., Silk J., 2005, Phys. Rep. 405, 279

[Blumenthal et al. 1986] Blumenthal G. R., Faber S. M., Flores R., Primack, J. R., 1986, ApJ, 301, 27

[FS3 Proceedings] "First Stars III", 2008, AIP Conf. Proc., 990, T. Abel, A. Heger, and B. W. ‘O. Shea eds

[Freese et al. 2008a] Freese K., Gondolo P., Sellwood J. A., Spolyar D., arXiv:0805.3540 [astro-ph]

[Freese et al. 2008b] Freese, K., Bodenheimer, P., Spolyar, D., & Gondolo, P., arxiV:0806.0617 [astro-ph]

[Gnedin et al. 2004] Gnedin O. Y., Kravtsov A. V., Klypin A. A., Nagai D., 2004, ApJ, 616, 16

[Komatsu et al. 2008] Komatsu E. et al., 2008, arXiv:0803.0547

[Iocco et al. 2008] Iocco, F., Bressan, A., Ripamonti, E., Schneider, R., Ferrara, A., & Marigo, P., 2008, MNRAS, in press

[Navarro et al. 2008] Navarro J.F., Frenk C.S., White S.D.M., 1996, ApJ, 462,563

[Natarajan et al. ‘08] Natarajan A., Tan . C. and O’Shea B. W., arXiv:0807.3769 [astro-ph].

[Ripamonti et al. 2008] Ripamonti E., Iocco F., Bressan A., Schneider R., Ferrara A., Marigo P., in prep.

[Ripamonti et al. 2007] Ripamonti E., Mapelli M., Ferrara A., 2007, MNRAS, 375, 1399

[Scott et al. 2008] Scott P., Fairbairn M., Edsjö J., arXiv0809.1871 [astro-ph].

[Spolyar et al. 2008] Spolyar D., Freese K., Gondolo P., 2008, Phys. Rev. Lett., 100, 051101