Study of evolution of Sun-like stars in Dark Matter halos

On physics of Dark Matter capture

Daniel Gonçalves de Faria Eugénio

Under supervision of Ilídio Lopes

Dep. Physics, IST, Lisbon, Portugal

October 19, 2010

Abstract

The formation and evolution of low-mass stars within dense halos of dark matter (DM) leads to evolution scenarios quite different from the classical stellar evolution. We describe these new scenarios and analyze in detail the equation of capture of dark matter, applying the case of simulation of the evolution of low-mass stars and study how the capture differs for the elements of the pp chain and CNO cycle.

Keywords: Astrophysics, Dark matter, Stars: - evolution, Stars: - interior, Stars: capturing dark matter, Hertzsprung-Russell diagram.

1 Introduction

Studying the rate at which stars capture dark matter (DM) particles or Weak Interactive Massive Particles (WIMP) is of vital importance to extract valuable information from solar neutrino experiments and to understand in which situations other stars are able to capture enough DM to influence their evolution.

In the thesis the aim was to understand how the capture differs for the elements of the pp chain and CNO cycle, inside the star, both in terms of its radial profile and with respect to its total value. We began with a brief review of the theme of dark matter at the level of particle physics and astrophysics. In the field of stellar evolution we discussed, from a classical perspective, the changes made internally, through the structure of the star which is reflected externally, in the path on the Hertzsprung-Russell. Subsequently, by introducing the dark matter in stellar evolution, we showed the main physical changes experienced by many low-mass stars, each within a different DM halo.

We started by presenting the main arguments for the existence of dark matter and its nature. We presented the candidates, starting from the theoretical models which are currently most considered by the scientific community, and discussed the profiles of distribution of dark matter in the galaxy and its importance to the experiences of the indirect detection of these particles. We also argued why the stars are good probes with respect to capture, annihilation and even detection (indirectly) of the dark matter and discussed the internal structure and evolution of a star, using as reference stars without DM (classical evolution).

2 Stellar evolution code

Our group has modified a standard stellar evolution code to take into account the impact of dark matter particles in the evolution of low-mass stars.

Taking into account the process that allows the evolution of stars in DM halos, this is regulated by the capture of DM particles in the stellar interior.

To compute the number of particles that are captured inside the star per second, we adapted part of the publicly available DarkSUSY code, which allows us to calculate the capture rate C_χ.

3 Dark Matter on stars

Here we discuss the procedures for capturing dark matter from the halo, the additional transport of energy that these particles can make inside the star, the additional energy produced by the process of its self annihilation and yet some more specific physical parameters like the equation of capture and the cross sections of interaction between the WIMPs and the baryons inside the star.

We are interested into understanding the physics that is behind the interaction of particles of dark matter in particular with some (metallic) elements (^{3}He, ^{4}He, ^{12}C, ^{14}N, ^{16}O) from the pp-chain and the CNO cycle. In this work so we will be focus on the spin independent scattering cross section, rather than spin dependent scattering cross section.

4 Evolution of sun-like stars in DM halos

If WIMP-baryon interaction is sufficient for the WIMP to lose energy until its velocity is lower than the escape velocity, then it is trapped in the gravitational field of the star and will accumulate in the star's interior, as the DM particles annihilate it will produce energy, providing a new additional energy source for the star.

Figure 1 shows the contribution of the different energy sources to the total energy generation rate, ϵ_{tot} , of a Sun-like star. We found that stars can experiment quite different evolution paths, which we classified in three distinct cases: Weak, Intermediate and Strong scenarios.

Figure 1 (**a**) refers to the Weak scenario; approximate to the classical, since the production of energy from the annihilation of dark matter particles is not significant, during the evolution of the star. (**b**) concerns to the Intermediate case scenario; The star has a new source of energy that can help offset the gravitational collapse and triggering the onset of a convective core in the star. (**c**) presents the case of a star in the scenario of evolution with the highest density of dark matter in the halo. The capture and annihilation of these particles of dark matter is such that the star is completely convective and the temperature inside the star never gets to be enough for the thermonuclear reactions to be triggered.

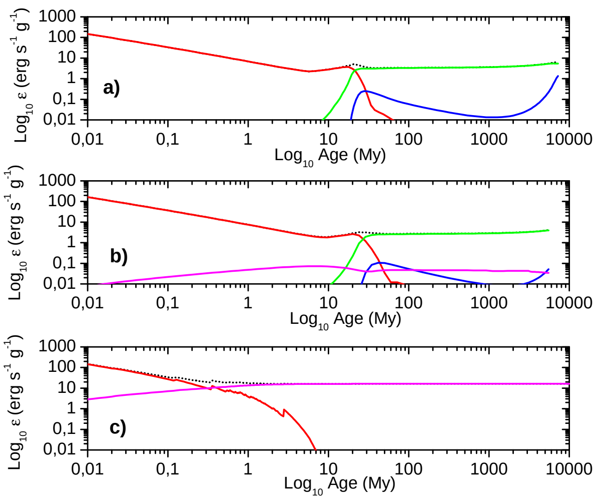

Figure 1: Variation of rates of energy production during the evolution of a star of one solar mass. Total energy ϵ_{tot} is the dashed black line, the gravitational energy ϵ_{grav} - continuous red line, energy from the pp chain ϵ_{pp} - continuous green line, the energy of the CNO cycle ϵ_{CNO} - the continuous blue line and the energy from the annihilation of dark matter particles captured ϵ_{χ} - continuous line in pink. These tests were performed to a star within halos with densities of 0, 10^{11} and 10^{15} GeVc^{-2}cm^{-3}, respectively.

The accretion of more WIMPs in the star's core increases the central luminosity of the star causing that, in the center of the star, a convective core appears and grows in order to evacuate the central energy produced in the annihilation of dark matter particles.

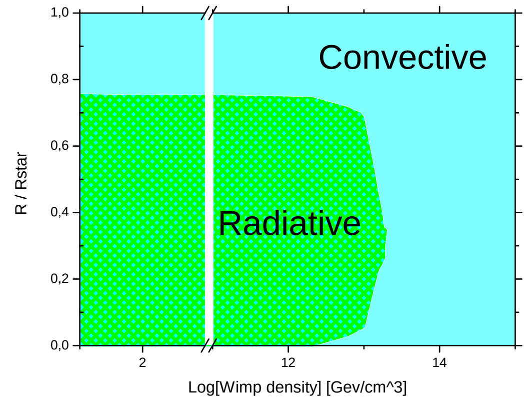

Figure 2: How the star behaves in terms of internal transport of energy, within different dark matter halos. The values for this figure were taken to an age of 4591 Myr. This is a star of one solar mass with Z = 0.0134, Y_0 = 0.27. In this case the values of cross sections for the capture of WIMPs are $\sigma_{\chi,SD} = 10^{-45}$ and $\sigma_{\chi,SI} = 10^{-44}$ cm^2. (From our dark matter code)

In Figure 2, we show that for low densities the star begins with a radiative center going up to about 75% of its radius. From there until the surface energy transport is convective. As the density increases it begins to form a convective center, which is a response to the evacuation of extra energy that is produced by the annihilation of the wimps in the center. For larger densities of dark matter, this convective core grows until it becomes the only mechanism of energy within the star. This happens from density of around 8×10^{13} GeVc^{-2}cm^{-3}.

When we consider the evolution of stars in the Strong scenario, we notice that since the initial gravitational contraction of the cloud, the energy produced by dark matter at the center of the star gets to be enough to stop the gravitational collapse (when compared with the classical evolution). The star stabilizes somewhere in the pre main sequence and because it never comes to producing nuclear reactions (not even the PP chain or the CNO cycle) the star will never enter the main sequence.

The star's gravitational collapse stops before reaching a central temperature high enough to begin nuclear fusion, as in the intermediate case. This equilibrium is reached quite early in the formation of these stars, depending upon the value of ρ_χ, as illustrated in Figure 3.

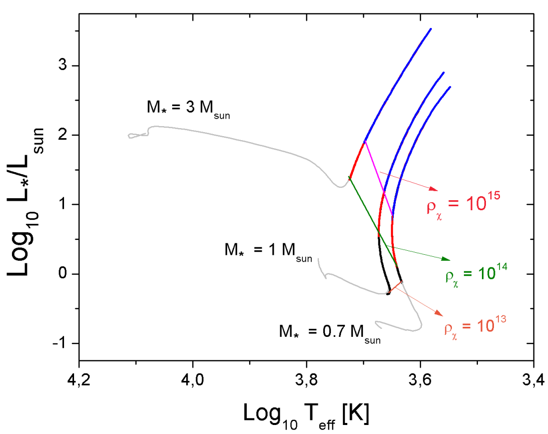

Figure 3: Stationary states reached by stars with masses from 0.7 to 3 M_{sun} (= $M_\star$) when the energy from DM annihilation compensates the gravitational energy during the collapse. As the number of WIMP trapped inside the star increases, the rate of energy production due to the annihilation of DM begins to be sufficient to balance the gravitational collapse of the star. This means that the star will slow and stop the gravitational collapse, even before the start of production of energy through nuclear fusion. These equilibrium positions, where stars will remain for an indefinite time, are plotted for different dark matter halo densities, indicated in units of GeV$c^{-2}cm^{-3}$ at the side of each line. The grey lines represent the classical evolutionary paths, which these stars follow before stopping. (From DMP code)

5 Inside the star

We examine in detail the physical processes that occur inside a star that is immersed in a halo of dark matter and study in detail the physics that lies behind the processes of interaction. The capture equation has direct and indirect dependencies on several variables and the aim is to study the dependence on these variables.

It is interesting to see how the profiles of capture vary, for each chemical element under study, when considering various simulations of stars with different masses. Here, we consider the case of stars with masses of $0.7M_\odot$, $1M_\odot$ and $2M_\odot$.

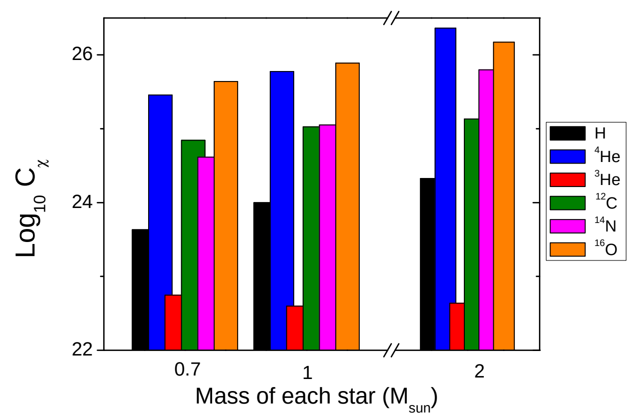

Figure 4: Values of the total captures for each chemical element $C_{\chi,i}$, considering the evolution (in the same initial conditions) to three stars with different initial masses, whose evolution stops when their final age is 4 000 Myr old We infer that the more massive the star, the greater amount of dark matter particles catch, of course, since their gravitational potential is larger, has greater radius and has a larger amount of nuclei with which WIMPs can interact.

As expected, for stars with larger masses, the capture of DM is higher than those of lower mass. This result is no surprise since we know the biggest stars have larger radius, with more mass with which the dark matter particles can interact and moreover their gravitational potential is stronger.

Another global parameter of the star is the metallicity Z. We analyze the simulation of the evolution of the same three stars with one solar mass, until a final age of 4000 Myr, with metallicity as the only parameter that distinguishes the cases, Z = 0.005, Z = 0.0134 and Z = 0.03.

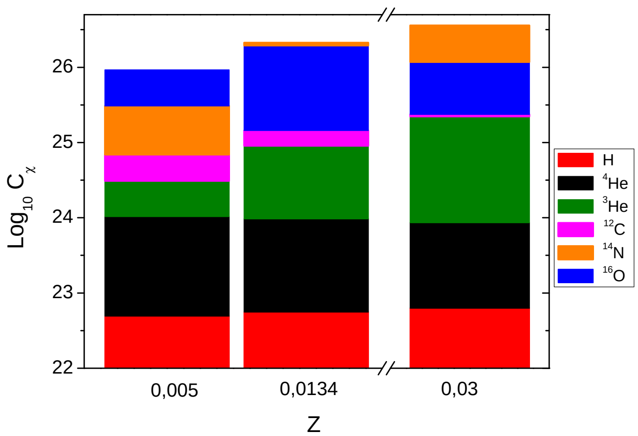

Figure 5: Values of the total captures for each chemical element $C_{\chi,i}$, considering the evolution (in the same initial conditions) of three stars with different metalicities, but whose evolution stops when the stars reach the stage where they have inside only about 30% of central hydrogen, Xc = 0.3.

In Figure 5 we can prove the strong dependence on metallicity for the value of the total capture per element, C_χ. As the metallicity of a star is higher compared to another equal star, the total value of the capture of dark matter from halo (the sum of all contributions of every element) grows significantly. Comparing the two extreme cases studied, the values of total capture are 1.8×10^{26} and 5×10^{26} particles, respectively. This means an increase in the total number of dark matter particles captured in the order of 65%.

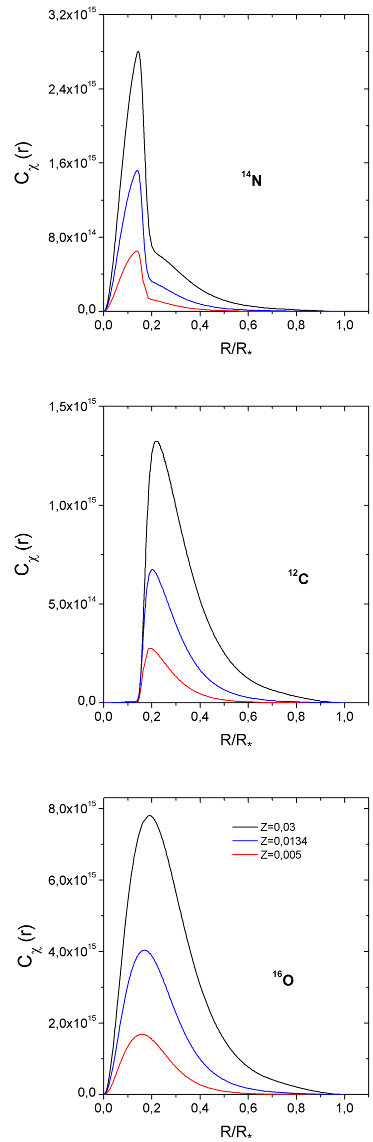

Figure 6: Radial capture function, $C_\chi(r)$, for the main elements of the CNO cycle in the case of three simulations with different metallicities. The black line represents the case of a metallic star with Z=0.03, blue line Z=0.0134 and red line Z=0.005. This figure presents the radial profiles of capture $C_\chi(r)$ for the elements ^{12}C, ^{14}N and ^{16}O and allows us to be sensitive about the value of total captures of each element. We also realize that, for increasing values of Z, the capture profiles are more concentrated toward the center of the star.

In Figure 6 we can see the change that occurs to the capture, regarding to the main elements of the CNO cycle. We infer about the value of the capture for stars of different metallicities and confirm that a higher metallicity implies a greater capture of dark matter from the halo.

Furthermore we infer, in Figure 6, that the capture profiles are more concentrated toward the center of the star, as the metallicity increases. In the thesis we approach influences of other parameters, whether general (such as age of the star) but also several parameters of the dark matter particles which form the halo.

6 Conclusion

We conclude that the stars are astrophysical objects privileged with respect to the possible detection of dark matter due to their strong gravitational field and because if WIMPs interact with the baryons in the star, these may be trapped inside and then self-annihilate in decay products that may be detectable. Furthermore, we understand that the main stages of evolution of a low mass star and how it can be affected when subjected to evolution in a halo of dark matter.

In general, we classified the possible scenarios of evolution into three categories:

1) The weak scenario that resembles the classical case. The star stays virtually undisturbed by the evolution of particle dark matter halo. Not significantly alter the production or the transport of energy inside. This scenario is observed when the star evolves within a halo of dark matter with densities between 0 and approximately 10^9 GeVc^{-2}cm^{-3}.

2) At a higher level, the intermediate case arises to classify stars that evolve in a halo with densities between 10^9 and 10^{12} GeVc^{-2}cm^{-3}. In this scenario the capture of dark matter particles is significantly higher and this reflected in the evolution of the star. The accumulation of the captured WIMPs in the center of the star allows them to self-annihilate, creating a new energy source that requires the formation of a convective core in order to evacuate the energy from the new source. This may slow down the entrance of the star in the main sequence, but will allow it to produce nuclear fusion.

3) Finally, the most extreme case (the strong scenario) occurs when the star evolves into a halo of very high density, up to about 10^{13} GeVc^{-2}cm^{-3}, or more. The capture of WIMPs is so high that even during the gravitational contraction phase (in the pre main sequence) it starts the annihilation of dark matter captured. This new source of energy is enough to prevent the gravitational collapse and causes the star to ”freeze” its development, once it has reached a state of equilibrium between the energy produced by WIMPs and the gravitational forces of contraction. We name these ”dark stars”. These stars are fully convective and when compared with stars in the weak scenario, they show a decrease in the effective temperature of around 27%. The core temperature drops about 35% and the central density is diminished by roughly 12%.

We also conducted a study extended to several variable parameters of the equation of capture. We conclude that the values of the radius of the star where there was a maximum of capture for each element (of the pp chain and the CNO cycle) is between about 0.1 and 0.3 $R_\star$. The biggest factor that has relevance to these results is the abundance profile of each element, which also has a crucial influence on the value of total captures of each element.

However, for these elements, there are two competing factors: the form-factor suppression and the dependence on m_N^4 of the value of cross section, at zero momentum transfer. The first - form-factor suppression - implies that the larger the nucleus the most significantly suppressed will be the capture, while the second - the dependence on m_N^4 - implies that the larger the nucleus, the greater the number of dark matter particles captured due to interaction with this element. It was found that the form-factor suppression is quite significant for the heavier elements and thus justifies that the oxygen (^{16}O) was responsible for greater capture of WIMPs in the various stars.

Finally we found that when considering similar stars with different metallicities, the values of the total dark matter capture is strongly altered. It was observed that these values can vary by about 60%, depending on the metallicity considered. This implies that it is necessary to observe fairly consistent values of stellar metallicities, in case if one wants to observe a star as a probe for the detection of dark matter. A publication of our work about this subject is under preparation.

References

[1] Asplund, M. et al., Astronomy and Astrophysics, v.359, p.729-742 (2000)

[2] Bertone, G., Hooper, D., Silk, J., 2005, Physics Reports, Volume 405, Issue 5-6, p. 279-390

[3] Bouquet, A. & Salati, P. 1989, ApJ, 346, 284,

[4] Casanellas, J. & Lopes, I. , Astrophysical Journal 705 (2009) 135-143,

[5] Freese, K. et al., 2008, The Astrophysical Journal, Volume 685, Issue 2, pp. L101-L104

[6] Gould, A. ApJ 321, 571-585 (1987)

[7] Gould, A. Astrophysical Journal, Part 1 (ISSN 0004-637X), vol. 388, April 1, 1992, p. 338-344

[8] Jungman, G. , Kamionkowski, M. , Griest, K. , Phys.Rept. 267 (1996) 195-373,

[9] Lopes, I., Bertone, G., Silk, J., 2002, Monthly Notice of the Royal Astronomical Society, Volume 337, Issue 4, pp. 1179-1184,

[10] Morel, P., A & A Supplement series, Vol. 124, September 1997, 597-614

[11] Press, W. H. and Spergel, D. N. 1985, Astrophys. J. 296, 679

[12] Salati, P. & Silk, J. 1989, ApJ, 338, 24,

[13] Turck-Chieze, S., Lopes, I., 1993, Astrophysical Journal, Part 1 (ISSN 0004-637X), vol. 408, no. 1, p. 347-367,