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WIMPS AND STELLAR STRUCTURE

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ABSTRACT : We present the results of an analytic approximation to compute the effects of WIMPs on stellar structures in a self-consistent way. We examine in particular the case of the Sun and of horizontal branch stars.

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1- Dark matter and the solar neutrino problem

It was suggested [1-10] that dark matter could solve the long standing neutrino problem. The idea goes as follows : particles constituing the dark matter present [11] in the halo of our Galaxy may be trapped when they cross the Sun, and accumulate in the course of time. Their number remains quite small, less than one per 10^{10} nuclei, nevertheless they can carry enough energy out of the core to cool it. If the central temperature decreases by a few percent, the flux of neutrinos coming from the decay of ^8B may go down by a factor 3 and agree with the experimental results of Davis [12] and Kamioka [13]. To play this role, dark matter particles must have a mass m_x larger than 4 GeV (otherwise they will quickly evaporate [8] from the Sun), and a large mean free path, of the size of the radius of the Sun, to be able to carry energy away from the core. Such a large mean free path means that the particles interact weakly (hence the acronym WIMP which stands for Weakly Interacting Massive Particle), with a cross-section σ_i on nuclei (i = H, He,...) of the order of a few picobarns (10^{-36} cm^2). Moreover, they must not annihilate by pairs, otherwise their density would be far too small [5], and this rules out many candidates for dark matter, such as the photino or a heavy neutrino (unless there is a cosmic asymmetry preventing an equal number of particles and antiparticles [14]). Such requirements are difficult to fulfil, and many authors constructed particle physics models for these WIMPs [15-17]. Once inside the Sun, WIMPs settle in the center, and their distribution is roughly barometric, that is :

$$n_x(r) = n_x(0) \exp\{-r^2/r_0^2\} \qquad (1)$$

with a scale height r_0 :

$$r_0 = \left(\frac{3\,k\,T_x}{2\,\pi\,G\,\rho_c\,m_x}\right)^{\frac{1}{2}} \approx 0.04\,R_{sun}\left(\frac{10\,m_p}{m_x}\right)^{\frac{1}{2}} \qquad (2)$$

The energy that they carry away is :

$$\varepsilon_x(r) \approx 6\ \mathrm{erg/g/s}\left(\frac{10\,m_p}{m_x}\right)^{1.5}\left(\frac{\sigma_H}{1\,\mathrm{pb}}\right)^{2}\left(\frac{3}{2}-\frac{r^2}{r_0^2}\right)e^{-r^2/r_0^2} \qquad (3)$$

which is comparable to the nuclear energy produced in the core ($\varepsilon_{nuclear} \approx 10$ erg/g/s).

2- Effect on stellar structure

Since the energy carried out by WIMPs is nearly equal to the nuclear energy, the star must readjust its structure to take into account this energy drain. The best way to compute the effect of WIMPs on the stellar structure is to run a numerical code [7]. This easily takes into account the complexities of the structure and of the time evolution of the star. However, it takes a very long time on a big computer, and the physics is often not easily understood. An analytic approximation [18] allows a fast study of many different stars, and a quick scan of the WIMP parameter domain (mass and cross-sections). However, only simple stellar structures can be studied, and there is no possibility to follow the time evolution.

Our analytic approximation makes use of the exponential decrease of the density of WIMPs (Equ. 1) : only the central part of the star is affected. We start from a stellar structure [19] without WIMPs, with given density profile $\rho_0(r)$ and temperature profile $T_0(r)$, solutions of the equations of hydrostatic equilibrium :

$$\frac{dP}{dr} = -\frac{G\,M(r)\,\rho(r)}{r^2} \tag{4}$$

and radiative equilibrium :

$$L_{nuclear} = L_\gamma \tag{5}$$

where

$$L_{nuclear} = \int 4\pi\, r^2\, \rho(r)\, \varepsilon_{nuclear}\, dr \tag{6}$$

$$L_\gamma = -\frac{64\,\pi\,\sigma_{Stefan}}{3\,\kappa}\,\frac{T^3\, r^2}{\rho}\,\frac{dT}{dr} \tag{7}$$

We add WIMPs as a small correction :

$$\rho_1(r) = \rho_0(r) + \delta\rho(r) \qquad\qquad T_1(r) = T_0(r) + \delta T(r) \tag{8}$$

$$\delta\rho(r) = \delta\rho_c \,.\, (\text{smooth function of r}) \,.\, \exp\{-r^2/r_0^2\} \tag{9}$$

$$\delta T(r) = \delta T_c \,.\, (\text{smooth function of r}) \,.\, \exp\{-r^2/r_0^2\} \tag{10}$$

The equation of radiative equilibrium now takes into account the WIMPs luminosity L_x :

$$L_{nuclear} = L_\gamma + L_x \tag{11}$$

$$L_x = \int 4\pi\, r^2\, \rho(r)\, \varepsilon_x(r)\, dr \tag{12}$$

and we look for the new equilibrium state of the star. The key parameter is actually the ratio $X \equiv L_x(0) / L_\gamma(0)$. Our results were first obtained for small X (i.e. X<1), but have been generalised since the Moriond meeting to any value of X [18]. When X increases, the X appearing in Eq.15 and 16 is replaced by an effective value $X_{eff} < X$, which remains small. For the core of the Sun :

$$X \approx 14 \left(\frac{10\, m_p}{m_x}\right)^{1.5} \left(\frac{\sigma_H}{1\ \text{pb}}\right)^2 \tag{13}$$

We can expand the solutions around the center :

$$\rho(r) = \rho_c \left(1 - A \frac{r^2}{R^2} + \dots \right)$$
$$T(r) = T_c \left(1 - B \frac{r^2}{R^2} + \dots \right) \tag{14}$$

We find that the temperature gradient is indeed lowered due to WIMP energy transport :

$$B \Rightarrow B\,(1 - X) \tag{15}$$

The central density increases, and the central temperature decreases :

$$\frac{\delta\rho_c}{\rho_c} \approx B \frac{r_0^2}{R^2} X \qquad\qquad \frac{\delta T_c}{T_c} \approx - \frac{\delta\rho_c}{\rho_c} \tag{16}$$

Notice that it is not a homologous contraction of the stellar core. For the core of the Sun, these formulas lead to :

$$\frac{\delta T_c}{T_c} \approx - \left(\frac{10\, m_p}{m_x}\right)^{2.5} \left(\frac{\sigma_H}{1\ \text{pb}}\right)^2 \tag{17}$$

This leads to a change in the total luminosity :

$$\frac{\delta L}{L} \approx -0.05 \left(\frac{10\, m_p}{m_x}\right)^{4} \left(\frac{\sigma_H}{1\ \text{pb}}\right)^2 \tag{18}$$

The total luminosity of the Sun is well known, and if we require that it decreases by less than 1%, we get a lower bound on the WIMP mass :

$$m_x > 15\, m_p \sqrt{\sigma_H / 1\ \text{pb}} \qquad (18)$$

But then the decrease of the solar neutrino flux is too small : due to the larger temperature dependence of the ppIII chain, this decrease is larger than the decrease of the total luminosity, but (within our approximations) it is about 20 times larger only. This ratio depends weakly on the WIMP properties, and *if* we take this result seriously, it means that we cannot solve the solar neutrino problem and decrease the neutrino flux by 70% without decreasing too much the total luminosity.

3- Horizontal branch stars

Stars in the horizontal branch of the Hertzsprung-Russell diagram burn helium in their core, and hydrogen in a shell. In the helium core, the photon luminosity L_γ is less than 10% of the nuclear luminosity $L_{nuclear}$, and the core is convective. Renzini [20] suggested that WIMPs could carry enough energy to stop convection. The amount of usable nuclear fuel is then lowered, because convection no longer brings fresh fuel to the center of the star, and the lifetime of the star on the horizontal branch is drastically reduced. Later, Spergel and Faulkner [21] argued that the WIMP luminosity L_X could never be larger than 10% of the nuclear luminosity. However, we showed [22] that this affirmation rests on assumptions about the cross-sections on hydrogen and helium which are not necessarily true for many candidates (e.g. for the magnino [16]), and on hypotheses on the halo density and velocity dispersion which are not necessarily true at different places of the Galaxy (e.g. at the center, the halo density is probably much larger than in the solar neighbourhood, and the WIMP accretion rate and their subsequent density in the core of stars is larger). It is therefore **possible** that WIMPs which are tailored to solve the solar neutrino problem also stop convection in HB stars. On the other hand, WIMPs may, here also, lead to a slight decrease of the central temperature of the HB star , which reduces the nuclear luminosity, and therefore the rate of fuel consumption : the lifetime may actually increase due to WIMPs !

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