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The axion-photon interaction and gamma ray signals of dark matter

J Barranco[1], A Carrillo Monteverde[2] and D Delepine[3]

División de Ciencias e Ingenierías, Universidad de Guanajuato, Campus León, C.P. 37150, León, Guanajuato, México.

E-mail:
[1]`jbarranc@fisica.ugto.mx`,[2]`alcarrillo@fisica.ugto.mx`,[3]`delepine@fisica.ugto.mx`

Abstract. We explore two scenarios where the axion-photon interaction could induce additional astrophysical gamma ray signals for the dark matter. In the first scenario, dark compact objects made of axions, named axion stars, could collide with neutron stars. The whole energy of the axion star can be dissipated in the magnetized conducting medium of the neutron star generating gamma rays. The second scenario is an indirect method for observing self-annihilating dark matter trapped in stars: Gamma rays produced by the self-annihilation of neutralinos in the interior of the Sun can be transformed into axions due to photon-axion conversion. Then, the axion will travel freely in the Sun and be converted into photons again. This process is often referred as 'shine light through walls', in this case, the wall will be the solar interior. Hence, GeV gamma rays might pass through the Sun. We may conclude that observation of GeV photons by gamma-ray observatories like HAWC, coming from the Sun, may be a signal of annihilation of neutralinos in the interior of the Sun.

1. Introduction

Last decade had witnessed the confirmation of the double dark universe: a universe where 23% of its total energy density is made of some collisionless, gravitationally attractive matter of unknown nature, named dark matter [1], plus another 74% made of a gravitationally 'repulsive' dark energy [2]. This double dark universe is complemented with a 3% of the total energy density made of the 'standard' matter that is well described by the Standard Model of Elementary Particles (SM). Now, one of the most interesting question turns out to be: what is the nature of dark matter? Although it is possible that a modification of the theory that describe the gravitation (i.e. General Relativity) could be the explanation to the dark matter problem, a more plausible explanation for the dark matter comes from the particle point of view: a weakly interactive massive particle (WIMP) arises as the most natural candidate for dark matter. Nevertheless, to say a WIMP is as generic as to say a dark matter particle. From the point of view of a particle's physicist, the WIMP could be any hypothetical particle that has a small or negligible interaction with the rest of the particles of the SM. In other words, a WIMP is a particle that is rather a cold, mostly stable and neutral particle that matches the appropriated relic density [3]. The beauty of many of the theories beyond the SM is that they naturally provide such type of WIMP candidates. Let us take as examples the axion or the lightest supersymmetric particle. The axion arises as a solution to the strong CP problem in QCD. It is the pseudo Nambu-Goldstone boson that results form the spontaneous breaking of the $U(1)$ Peccei-Quinn symmetry. The Peccei-Quinn symmetry was introduced to explain the apparent smallness of the strong CP violation [4]. Axion properties have been constrained from astrophysical and cosmological considerations. In particular, its mass is given in terms of the axion decay constant f_a as

$$m_a \simeq 6\mu\text{eV}\left(\frac{10^{12}\text{GeV}}{f_a}\right) . \tag{1}$$

This constant f_a is related with the magnitude of the vacuum expectation value that breaks the Peccei-Quinn symmetry. Current bounds on the axion decay constant are $10^{10}\text{GeV} < f_a < 10^{12}\text{GeV}$ [5] All remaining axion couplings are inversely proportional to f_a. In particular, an axion-photon coupling is possible and it will be described by the following Lagrangian:

$$\mathcal{L} = \frac{1}{2}(\partial^\mu a \partial_\mu a - m^2 a^2) - \frac{1}{4}\frac{ca}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} , \tag{2}$$

where c is a coupling constant of order unity. Concerning the lightest supersymmetric particle, in the Minimal Supersymmetric Standard Model (MSSM), the superpartners of the photon, the Z-boson and the neutral Higgs bosons are called binos ($\tilde{B}$), winos ($\tilde{W}_3$) and higgsinos ($\tilde{H}_1^0$ and $\tilde{H}_2^0$). These states mix into fermionic, majorana mass eigen-states called *neutralinos*. Those are typically labeled as $\tilde{\chi}_i^0$, $i = 1..4$, ordered with respect to their mass. The lightest of the four will be refereed as *the neutralino* and denoted simply by χ.

Both the axion and the neutralino are excellent WIMP candidates and there are current experiments looking for their direct and indirect detection signals. In the present work we sketch two scenarios where the axion-photon interaction shown in Lagrangian (2) could provide a new source of gamma rays due to the conversion of axions into photons. Hence, offering new indirect ways for dark matter detection. In the first scenario, dark compact objects made of axions, named axion stars (AS) [6], could collide with neutron stars. The whole energy of the axion star can be dissipated in the magnetized conducting medium of the neutron star generating gamma rays. A similar idea was originally proposed by Iwazaki [7] as a mechanism to generate gamma-ray-burst. Now we incorporate this idea as an indirect method for detection of axion as a dark matter candidate. The second scenario is an indirect method for observing self-annihilating dark matter trapped in stars. The usual mechanism incorporates the idea that a self-annihilating dark matters, as the case of the neutralinos, can be accumulated in the interior of the stars. The increase of the dark matter density increases the probability that two neutralinos annihilate each other into another SM particles. In particular, neutrinos or photons are possible final states of this annihilation. Since νs have a very small cross section, they can scape from the star's interior while the photons are trapped due to the strong interaction of the photons with the star's matter. The non-observation of high energy neutrinos coming from the Sun has been used to set constraints on the neutralino-nucleon cross section by the Super-Kamiokande collaboration [8]. Gamma rays produced by the self-annihilation of neutralinos in the interior of the Sun are not usually considered since photons will be trapped. But Lagrangian (2) imply the possibility that a photon can be transformed into an axion when an external magnetic field is present. Since the axion has a negligible interaction with the other SM particles, axions will travel freely in the Sun and in some cases they can be converted into photons again. This process is often referred as 'shine light through walls', in this case, the wall will be the solar interior. Hence, GeV gamma rays might pass through the Sun. We may conclude that observation of GeV gamma rays from the Sun may be a signal of annihilation of neutralinos in the interior of the Sun. In [9] it was shown that for certain range of axion parameters, the Sun is transparent to high energy photons coming form distance sources, hence, the previous mechanism for detecting neutralino annihilation into photons could be possible.

In the following sections we will complement the previous ideas with some numerical

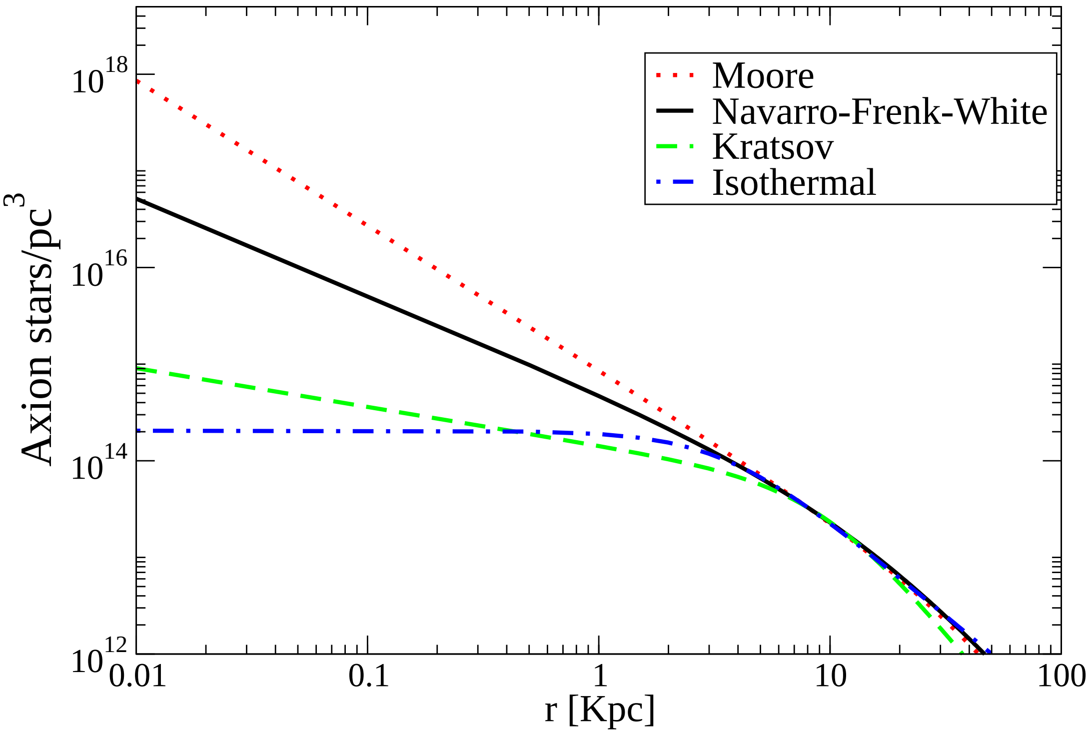

Figure 1. Number of axion stars for different dark matter profiles.

calculations in order to have an estimation on the strength of the effects. A more detailed analysis is under way and will be published elsewhere.

2. Galactic halo made of axion stars

The possibility that the galactic dark matter halo is a collisionless ensemble of scalar field mini-MACHOs is not in contradiction with the limits imposed by microlensing or gravothermal instability [10]. In fact, microlensing observations limits the dark matter mini-MACHOS have masses smaller that $10^{-7}M_{\odot}$, $M_{\odot}$ the Solar Mass. An interesting result comes from the fact that self-gravitating objects made of axions, that we will call axion-stars (AS), have the masses and radii needed to fulfill those requirements [6]. Actually, axion star masses are far from those limits. A typical AS will have a mass of $\sim 10^{-15}M_{\odot}$. We can estimate the number of AS in a galactic halo that follows a dark matter density profile. In Fig. 1 it is shown the expected number of axion star with a mass of $10^{-15}M_{\odot}$ for four different DM density profiles. The number of axion stars can be very high at the center of the galaxy. It is expected that a typical galaxy has around $\sim .1\%$ of its total stars to be neutron stars. A galaxy like the Milky-Way, there should be $\sim 10^9$ neutron stars. Both, the high number of axion stars and neutron stars, implies a high probability that AS will collide with a neutron star and dissipate their energy under the effect of the strong magnetic field of the NS. As a result, the gravitational energy of the AS is radiated away in form of low energy photons. In order to estimate the amount of energy radiated, we start with the Lagrangian (2) and express in terms of the electric and magnetic fields $\vec{E}, \vec{B}$.

$$\mathcal{L}_{a\gamma\gamma} = \frac{c\alpha}{f_a} a\vec{E}\cdot\vec{B}\,. \tag{3}$$

Then, it is possible to derive a “modified” Gauss law:

$$\partial \vec{E} = \frac{-c\alpha}{f_a} \vec{\partial} \cdot (a\vec{B})\,. \tag{4}$$

Then, the axion field a induce a electric field $\vec{E}_a = -c\alpha a\vec{B}/f_a$, which induces an electric current $J_m = \sigma E_a$ in a magnetized conducting media with electric conductivity σ. The dissipation in the magnetized conducting media, with average σ electric conductivity can be evaluated using the Ohm's law:

$$W = \int_{AS} \sigma E_a^2 d^3x = 4\pi \frac{c^2\alpha^2 B^2 \sigma}{f_a^2} \int_0^R a(r)^2 r^2 dr\,. \tag{5}$$

Let us for the moment assume that the AS is given as in [7], and just update the values of the mass of the AS and the radius as was recently obtained in [6]. The axion star profile can be approximated as

$$a = f_a a_0 exp(-r/R_a)\,, \quad \text{with} \quad a_0 = 1.73 \times 10^6 \left(\frac{10cm}{R_a}\right)^2 \left(\frac{10^{-5}\text{eV}}{m_a}\right)\,. \tag{6}$$

According to [6], for $m_a = 10^{-5}$ eV, $R_a = 8.54$ meters and its mass is $M = 10^{-16} M_\odot$. Inserting this values in eq. 5, we obtain that such axion star will dissipate its whole energy

$$W \sim 10^{42} \left(\frac{\sigma}{10^{26}/s}\right) \left(\frac{M}{10^{-16} M_\odot}\right) \left(\frac{B}{10^8 \text{Gauss}}\right)^2 \text{ergs/sec}\,. \tag{7}$$

That is, the energy dissipated is around $W \sim 10^9 L_\odot$, with $L_\odot$ the solar luminosity. In case there is such type of collisions, the luminous could equal the total galaxy luminosity.

3. Photon-axion conversion inside the Sun

Indirect methods for the detection of dark matter mostly consist in observing the radiation produced in dark matter annihilation. The intensity of such radiation is proportional to the annihilation rate, which depends on the dark matter density. Hence, the best places to look are the regions where dark matter density accumulates. An excellent region for such accumulation is the center of the Sun. It is commonly believed that only neutrinos can escape these dense objects. Nevertheless, here we will shown that neutralino annihilation into photons can be detected trough the photon-axion conversion in the Sun's interior. The channel we are proposing is $\chi + \chi \rightarrow \gamma$'s → 'oscillation' → *axions* → 'oscillation' → γ's.

The photon-axion oscillation probability is obtained by starting with the Lagrangian (2). Let us expand the photon field $A(t, x)$ in components of fixed frequency $A(x)e^{-i\omega t}$. We may assume that the variations of the magnetic field in space occurs on larger scales than the photon/axion wave-lengths. Therefore, for particles propagating in the z-axis, the operator in the equation of motion $\omega^2 + \partial_z^2$ can be expanded as $\omega^2 + \partial_z^2 \rightarrow 2\omega(\omega - i\partial_z)$ and then, the Schrödinger equation will be

$$i\partial_z \Psi = -(\omega + \mathcal{M})\Psi\,; \quad \Psi = (A_x, A_y, a)\,, \tag{8}$$

where we have defined the matrix $\mathcal{M}$ as:

$$\mathcal{M} = \begin{pmatrix} \Delta_p & 0 & \Delta_{M_x} \\ 0 & \Delta_p & \Delta_{M_y} \\ \Delta_{M_x} & \Delta_{M_y} & \Delta_m \end{pmatrix}. \tag{9}$$

and we have introduced the quantities:

$$\begin{aligned}
\Delta_{M_i} &= \frac{B_i}{2f_a} = 1.755 \times 10^{-11} \left(\frac{B_i}{1\mathrm{G}}\right) \left(\frac{10^5\mathrm{GeV}}{f_a}\right) \mathrm{cm}^{-1}\,, \\
\Delta_m &= \frac{m^2}{2\omega} = 2.534 \times 10^{-11} \left(\frac{m}{10^{-3}\mathrm{eV}}\right) \left(\frac{1\mathrm{GeV}}{\omega}\right) \mathrm{cm}^{-1}\,, \\
\Delta_p &= \frac{\omega_p^2}{2\omega} = 3.494 \times 10^{-11} \left(\frac{n_e}{10^{15}\mathrm{cm}^{-3}}\right) \left(\frac{1\mathrm{GeV}}{\omega}\right) \mathrm{cm}^{-1}\,,
\end{aligned} \tag{10}$$

where ω_p^2 is the plasma frequency which is given in terms of the electron density n_e as $\omega_p^2 = 4\pi\alpha n_e/m_e$. B is the magnetic field, m_e is the electron mass and α is the fine structure constant and ω is the photon's energy. The Schrödinger equation (8) is solve numerically, although it can be solved for the case of constant magnetic field B and constant electron density n_e. In this case the probability is given by:

$$P = \frac{4B^2\omega^2}{f_a^2(\omega_p^2 - m_a^2)^2 + 4B^2\omega^2} \sin^2\left(\pi \frac{z}{l_{osc}}\right)\,, \tag{11}$$

where we have defined the oscillation length:

$$l_{osc} = \frac{4\pi\omega f_a}{\sqrt{f_a^2(\omega_p^2 - m^2)^2 + 4B^2\omega^2}}\,.$$

We can estimate from the probability eq. (11) the resonance condition for typical values of the electron density n_e and constant magnetic field B. In particular, we are interested in the photon energy values needed to fulfill the resonance condition for eq. (11). This can be completed if at least one oscillation length fulfill the condition $l_{osc} \simeq R_\odot$. This condition is fulfilled for photon energies given by:

$$\omega^2 < \frac{3.527^2\mathrm{GeV}^2 \left(1.38\left(\frac{n_e}{10^{15}\mathrm{cm}^3}\right) - \left(\frac{m_a}{10^{-3}\mathrm{eV}}\right)^2\right)^2}{64\pi^2 - 2.376 \times 10^{-9} \left(\frac{B}{\mathrm{Gauss}}\right)^2 \left(\frac{10^{10}\mathrm{GeV}}{f_a}\right)^2}\,. \tag{12}$$

The electron density at the center of the Sun is as high as $n_e \sim 10^{18}/\mathrm{cm}^3$, and condition eq. (12) gives as resonance energy of the photons to oscillate into axions to be $\omega \sim 340$ GeV, almost independent of the value of the magnetic field B. Hence, a high energy photon produced by the $\chi\chi \to \gamma\gamma$ annihilation reaction can fulfill condition (12), oscillate to axions and converted to photons again. Future Gamma-ray observatories, like HAWC [11], can be sensitive to those high energy photons, since HAWC is developed to perform a high-sensitivity synoptic survey of the sky at wavelengths between 100 GeV and 100 TeV.

4. Conclusions

We have entertained with the possibility that the axion-photon interaction given by Lagrangian (2) could be the source of new astrophysical photons. In the first scenario, collision of axion stars with neutron stars can liberate the axion star energy and to be radiated away. Such collision will liberate a luminosity as high as $10^9 L_\odot$. In the second scenario, photons produced by the neutralino-neutralino annihilation can escape the solar interior trough photon-axion conversion in a 'shine light through walls' mechanism, in this case, the wall will be the solar interior. We have estimated that the photon energy needed to fulfill the resonance condition for such oscillation to occur is around ~ 340 GeV, which for a neutralino that annihilate mono-energetically is possible for a neutralino mass of the same order, which is above the current limit for the neutralino mass.

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