Can the dark matter halo be a collisionless ensemble of axion stars?

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If dark matter is mainly composed of axions, the density distribution can be nonuniformly distributed, being clumpy instead. By solving the Einstein-Klein-Gordon system of a scalar field with the potential energy density of an axionlike particle, we obtain the maximum mass of the self-gravitating system made of axions, called axion stars. The collision of axion stars with neutron stars may release the energy of axions due to the conversion of axions into photons in the presence of the neutron star’s magnetic field. We estimate the energy release and show that it should be much less than previous estimates [1, 2]. Future data from femtolensing should strongly constrain this scenario.

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I. INTRODUCTION

Nowadays one of the most interesting problems in physics is to reveal the nature of dark matter (DM). The existence of DM is supported by large amount of astrophysical observations, on both galactic and cosmological scales [2, 3]. Since those effects are purely gravitational, the standard candidate is a massive particle with null or very weak interaction with the rest of the particles of the standard model of particles. Two of the leading candidates for dark matter are axions and weakly-interacting massive particles such as neutralinos [5].

The axion is the pseudo Nambu-Goldstone boson generated in the spontaneous breaking of the U(1) Peccei-Quinn (PQ) global symmetry [6, 7]. PQ symmetry was introduced to explain the smallness of the strong CP violation in QCD. Initially, this new field was assumed to be "invisible" as very weakly interacting but in 1983, it has been shown that axion couples to two photons through Primakoff effects [8] and could be detected through its conversion into a photon in presence of a strong magnetic field [10].

Most of the direct detection methods for the axion are based on the conversion of axions into photons [11, 12]. But it is also possible to constrain the axion mass and coupling through astrophysics observation. As stars usually have strong magnetic fields, the Sun or any other astrophysical object as dwarf star, supernova, etc. could produced axions in its core during cooling processes and transform them into photons through Primakoff effects. The search for photons produced in stars through axion conversion can be used to put an upper limit on axion mass $m_a$ and coupling $f_a$, where $f_a$ defines the scale of $U(1)_{PQ}$ symmetry breaking: $m_a \lesssim 10^{-3}\text{eV}$ and $f_a \geq 10^9\text{GeV}$ [14, 22]. Cosmological observations impose constraints on $m_a$ to be bigger than $10^{-6}\text{eV}$ and $f_a \lesssim 10^{-12}\text{GeV}$ [24, 27]. Therefore, cosmological and astrophysical observations constrain the range of $m_a$ to be

$$10^{-6}\text{eV} < m_a < 10^{-3}\text{eV}.$$  (1)

So, an axion mass within this range could be a nice candidate for cold dark matter [28, 29] as it could form Bose-Einstein condensate [30].

The rate of detection needs a prescription on the dark matter distribution in the galactic halo, and in particular, the local dark matter density. There are arguments in favor of a nonuniform distribution of dark matter in the galaxy [31, 32]. For instance, early fluctuations in the dark matter may go nonlinear long before photon decoupling, producing density-enhanced dark matter clumps. The evolution of the axion field at the QCD transition epoch may produce gravitationally bound miniclusters of axions [37, 38]. Such minicluster, due to collisional $2a \rightarrow 2a$ processes, may relax to a selfgravitating system [39, 41]. These self-gravitating systems made of axions are simply called axion stars (AS). Previously, some authors explored the possibility that such axion stars may have some observable consequences. For instance, the collisions between axions stars and neutron stars may induce gamma ray burst [42], ultra-high energy cosmic rays [43], or emission of x rays by neutron stars [1]. All of these observables have in common the possibility that the axion may oscillate into a photon.

In this paper, we study the self-gravitating system made of axions with a realistic potential for the scalar field as in [44] contrary to [1, 42, 43]. In section II, we obtain the typical Mass-density curve varying the central density. This curve exhibits a maximum mass which depends on the value of the axion mass and the central density. Section III is dedicated to update signatures of the AS in the Galactic Halo due to AS collisions with neutron stars (NS). The huge magnetic field in NS, $B \sim 10^8$ Gauss, may convert to photons all axions involved in the collisions. In this section, an estimate of the total radiated energy is computed. Finally, we present our results and compared to previous estimates in Section IV.
II. AXION STARS

A. On the formation of axion stars

The formation of axion miniclusters was studied in \cite{37,39,40}. They did a numerical study of the evolution of a spherically symmetric axion fluctuation in an expanding universe at the QCD epoch, where the mass of the axion effectively switches on. The axion potential considered was

\[ V(\phi) = m_a^2 f_a^2 \left[ 1 - \cos \left( \frac{\phi}{f_a} \right) \right] , \tag{2} \]

where \( \phi \) is the axion field, \( f_a \) the energy scale of decoupling, and \( m_a \) the axion mass. The study was done for a wide range of initial conditions and a common feature of the final density distribution is that it developed a sharp peak in the center, i.e. due to the attractive self-interaction, some non-linear effects induce axion perturbations that lead to very dense axion miniclusters. If such density peaks are high enough, gravitational collapse and subsequent virialization can occur. This relaxation is due to \( 2a \to 2a \) scattering and the associated relaxation time is smaller than the age of the universe if the energy density of the minicluster is \( \rho > 10^{10} \text{eV}^4 \) \cite{38}. As we will see later, the axion star fulfills the conditions needed, such as relaxation, and annihilation processes prevent a gravothermal catastrophe for the axion minicluster \cite{41}.

An improved numerical resolution of the axion miniclusters revealed that around \( \sim 10\% \) of the axion density will be in miniclusters with densities that can virialize to coherent axion fields on a self-gravitational well, i.e. axions stars \cite{42}.

Other mechanisms that may lead the formation of axion miniclusters and dark matter miniclusters were proposed in \cite{43}. There, at the time where the phase transition from a quark-gluon plasma to a hadron gas take place, the spectrum of density perturbations develops peaks and dips produced by the growth of hadronic bubbles. Afterwards, kinematically decoupled cold dark matter falls into the gravitational potential wells provided from those peaks, leading the formation of dark matter clumps with masses \( < 10^{-10} M_\odot \).

B. Properties of the axion stars

The previous picture of the formation of axion stars did not study the final self-gravitating system made of coherent axion fields. In order to do so, we have solved the Einstein-Klein-Gordon equation in the semiclassical limit:

\[ G_{\mu\nu} = 8\pi G \langle \mathcal{T}_{\mu\nu} \rangle , \tag{3} \]

\[ \left( \Box - \frac{dV(\Phi)}{d\phi^2} \right) \Phi = 0 , \tag{4} \]

where the source of Einstein equations, the energy momentum tensor \( \langle \mathcal{T}_{\mu\nu} \rangle \), is the average over the ground state of a real, quantized scalar field \( \Phi(r,t) \) with potential given by the energy potential in Eq. (2). We work in a spherically symmetric metric \( ds^2 = B(r)dt^2 - A(r)dr^2 - r^2(\sin^2 \theta d\phi^2 + d\theta) \), and to assume a harmonic dependence of the field \( \Phi(r,t) = e^{i\omega t} \phi(r) \). The EKG system reduces to the following system of equations:

\[ a' + \frac{(1-a)a}{x} + (1-a)^2 x \]

\[ \times \left[ \left( \frac{1}{B} + 1 \right) m_a^2 \sigma^2 - \frac{m_a \sigma^4}{12} + \frac{\alpha \sigma^2 x}{a - 360} \right] = 0 \]

\[ \sigma'' + \frac{2B}{x} + \frac{2a}{x} - \frac{a'}{2(1-a)} \sigma' + \frac{1-a}{\alpha} \left[ \left( \frac{1}{B} - 1 \right) m_a^2 \sigma^2 + \frac{m_a \sigma^3}{6} - \frac{\sigma^5}{120} \right] = 0 \tag{5} \]

where we have defined \( \phi = \frac{m_a}{f_a} \sigma, \hat{B} = \frac{m_a^2 B}{\omega^2}, r = \frac{m_a}{\sqrt{4\pi}} x, a = 1 - A \) and \( \alpha = \frac{4\pi}{m_a \omega^2} \) as was done in \cite{44}. In the present work, we extend the results of \cite{44} by solving the same system but for a wider range of masses of the axion field and many initial values of the axion field at the center \( \sigma(x = 0) \). Since the axion mass is restricted to be \( 10^{-6} \text{eV} < m_a < 10^{-3} \text{eV} \), we show in Fig. 1 the resulting masses of the AS as a function of the value of the central density \( \rho(0) = m_a^2 \sigma(0)^2/2 \). The mass-density plot shows that there exists a maximum mass for a particular value of the central density. The density profile of those maximum mass configurations are shown in Fig. 2 and the numerical values are reported.
FIG. 2: Density profile. Top Panel: $m_a = 10^{-5}$ eV. Bottom Panel: $m_a = 10^{-3}$ eV.

TABLE I: Masses and typical radio $R_{09}$ for the maximum mass configurations shown in Fig. 1 where $R_{09}$ is the radius of the AS where 90% of the mass is contained.

| Axion mass (eV) | $\rho(0)$ (Kg/m$^3$) | Mass ($M_\odot$) | $R_{09}$ (meters) |
|----------------|-----------------|----------------|-----------------|
| $m_a = 10^{-5}$ | $2.1 \times 10^{10}$ | $5.0 \times 10^{-15}$ | 119.40 |
| $m_a = 10^{-3}$ | $6.8 \times 10^{10}$ | $7.4 \times 10^{-21}$ | 0.89 |

in Table II Those configurations are our benchmark in order to study possible astrophysical signatures. Once we have computed the maximum masses of AS for different choices of $m_a$, we can come back to the question of their plausibility. In [41], it was found that AS formation is possible if the mass in the core region $M$, the escape velocity $v_e$ and the axion self-coupling $f_a$ satisfy the relation $M < 10^8 e^{-5/2}(f_a/10^{10} \text{GeV})^{-1/4}$. By using the lower value of $f_a = 10^9$ GeV [14,23], and the maximum mass we have obtained for an AS for $m_a = 10^{-5}$ eV, and $v_e = \sqrt{2GM}/r$, we can check that such condition is fulfilled, and then, that the relaxation time is lower than the age of the universe. For the annihilation processes, one may be worried for the stimulate decays into photons. It occurs when the condition $\Gamma_\gamma m_a^2 v_e f_a / (R m_a^2 f_a) > 1$ is fulfilled [44,47], but such a condition implies densities $\rho > 10^{15}$ Kg/m$^3$ for $m_a = 10^{-5}$ eV. As we can see from Fig. 2 the AS’s density is always below $\rho(0) < 2.1 \times 10^{10}$ (Kg/m$^3$). Hence, no stimulated decays of axions is produced.

III. POSSIBLE AXION STAR SIGNATURES IN THE GALACTIC HALO

The dark matter halo of galaxies can be considered as a collisionless ensemble of mini-MACHOs, as far as this hypothesis is not in contradiction with the limits imposed by microlensing or gravothermal instability. In particular, scalar field mini-MACHOS has been considered as a possible realization if their masses are below $10^{-7} M_\odot$ [48].

TABLE II: Energy radiated for an AS with the maximum mass configurations shown in Fig. 2 for a NS magnetic field $B = 10^8$ G and an electric conductivity $\sigma = 10^{26}$ s$^{-1}$. [57].

| Axion mass (eV) | $f_a$ (GeV) | Mass ($M_\odot$) | $W$ (erg/s) |
|----------------|-------------|----------------|------------|
| $m_a = 10^{-5}$ | $6 \times 10^9$ | $5.0 \times 10^{-15}$ | $5.3 \times 10^{13}$ |
| $m_a = 10^{-3}$ | $6 \times 10^{11}$ | $7.4 \times 10^{-21}$ | $7.9 \times 10^{17}$ |

to evade the microlensing limits. Recently, it was shown that mini-MACHOS with masses below $10^{-10} M_\odot$ have not measurable dynamical consequences in internal Solar System dynamics (planets, Earth-Moon) [49]. In turns out from our analysis on the maximum mass for an axion star, for $m_a = 10^{-5}$ eV, axions stars may play the role of such mini-MACHOs. In addition to microlensing, femtolensing could be a useful tool in order to look for axion stars [43]. Recently, new limits from femtolensing of gamma ray burst provides new evidence that primordial black holes in the mass range $10^{-16} - 10^{-13} M_\odot$ do not constitute a major fraction of the dark matter [50] and once again, the maximum mass of the axion star are consistent with those limits. In the case for an axion mass of $m_a = 10^{-3}$ eV, the maximum AS mass is far to be excluded from these current limits from femtolensing of GRBs since $M_{\max} \sim 10^{-21} M_\odot$, but it is encouraging that in the future, femtolensing measurement may confirm or deny the possibility that the dark matter halo may be made of an ensemble of axion stars. In addition to AS, other types of dark matter clumps may play the role of mini-MACHOS. In particular if dark matter is a non self-annihilating fermion, for some values of its mass it may fulfill the requirements to be a mini-MACHO [51]. For a self-annihilating fermion as the neutralino, neutralino stars [52,53], have been proposed. Actually, the maximum mass for a neutralino star is $\sim 10^{-7} M_\odot$ making them suitable dark matter mini-MACHOS candidates, although their stability is questionable [54].

The clumping of dark matter may change the expected number of events for direct dark matter searches, since the local density may be largely affected at the vicinity of the Earth. Nevertheless, the clumpy dark matter may offer new ways for indirect detection. In the case of the axion, early studies of luminous axion clusters where done in the 1980s [56]. In this work we reconsider the proposal of Iwazaki [42] where axion stars interact with the strong magnetic field of a neutron star producing photons, now we consider the mass and radius of the AS obtained as general relativity indicates by solving Eq. [5]. First, we shall estimate the number of AS in a galactic halo using dark matter density profiles. The AS number density is modified by the tidal destruction of axion miniclusters which occurs within a hierarchical model of clump structure. The tidal destruction arise by the gravitational interaction of two clumps passing near each other or when the minicluster falls into the gravitational field of the host. The clump survival probability, as a function of the mass and radius of the clump, for
non dissipative DM particles, was computed in [35, 36]. It was found that only $0.1 - 0.5\%$ of the small clumps survive the stage of tidal destruction. In Fig. 3 it is shown in the left $y$ axis (right $y$ axis) the number of axion star with a mass of $10^{-15}M_\odot \ (10^{-21}M_\odot)$ for five different DM density profiles: the Navarro-Frenk-White profile [58], the Moore profile [59], the Kravtsov profile [60], the modified isothermal profile [61] and the Salucci et al. profile [62, 63]. The values reported in Fig. 3 included a factor $10^{-3}$ to account the tidal destruction of clumps and a factor $10^{-1}$ due to the fact that around $\sim 10\%$ of the axion density will be in miniclusters with densities that can virialize to coherent axion fields [45]. Notice the high number of axion stars at the center of the galaxy. Furthermore, it is expected that $\sim 1\%$ of a galaxy’s total stars will finish their life as neutron stars. The Milky-Way, for instance, could have around $\sim 10^9$ neutron stars. The high number of axion stars (see Fig. 3) and the expected number of neutron stars implies a non-zero probability that AS collide with a neutron star and dissipate their energy under the effect of the neutron stars’ magnetic field. In order to estimate the amount of energy radiated by this process, we closely follow Ref. [12]. Starting with the Lagrangian

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

(6)

here $c$ is a coupling constant of order unity, $a$ is the axion field and $F^{\mu\nu}$ is the electromagnetic stress tensor and $\tilde{F}^{\mu\nu}$ its dual [11, 64]. And expressing this Lagrangian \(^{(6)}\) in terms of the electric and magnetic fields $\vec{E}, \vec{B}$.

$$\mathcal{L}_{a\gamma\gamma} = \frac{ca}{f_a} a \vec{E} \cdot \vec{B}$$

(7)

we can now derive a “modified” Gauss law, namely:

$$\partial \vec{E} = -\frac{ca}{f_a} \vec{B} \cdot (a \vec{B}).$$

(8)

Thus, the axion field $a$ may induce an electric field $\vec{E}_a = -ca \vec{B}/f_a$. If the neutron star has an electric conductivity $\sigma$, an electric current $J_m = \sigma \vec{E}_a$ is produced. The dissipation in the magnetized conducting media, with average $\sigma$ electric conductivity, is evaluated using Ohm’s law $W = \int_{aS} \sigma E_a^2 d^3 x$, which, with help of the modified Gauss Law, can be directly related with the axion field and the neutron star magnetic field:

$$W = 4\pi c^2 a^2 B^2 \sigma \int_0^R a(r)^2 r^2 dr.$$

(9)

Taking the two profiles for the axion field shown in Fig. 2 we perform the integration of Eq. (9) numerically. The radiated energy is shown in Table II. Finally, we estimate the rate of collisions, such as we estimate the luminosity radiated every second. The number of collisions per $pc^3$ per second will be

$$R_c = n_{AS}(r) \times \rho_{NS}(r) \times S \times v,$$

(10)

where $n_{AS}$ is the number of AS per $pc^3$ as a function of the distance to the galactic center (Fig. I). $\rho_{NS}$ is the probability to find a Neutron Star at that point, and we will assume this distribution to be [65]

$$\rho_{NS}(r) = A r^{\alpha-1}/\lambda^\alpha e^{-r/\lambda},$$

(11)

where $\alpha \simeq 1.7$ and $\lambda(kpc) = 5.21$, as given in Ref. [63]. For simplicity, the $z$--dependence is neglected. This assumption implies that NS distribution is assumed to be spherically symmetric. $A$ is the normalization constant defined such that

$$10^{12} = \int R_{NS}(r)^2 sin^2 \theta d\theta d\phi d\phi.$$

(12)
The velocity $v$ of AS is assumed to be around $v = 2 \times 10^7 \text{cm/s}$. Finally, $S$ is the cross section which can be computed either as the effective area of the AS, i.e. $S_{99} = \pi R_{99}^2$, or we can define a distance $L_c$ such that the kinetic energy of the axion star is equal to the potential energy between the AS and the neutron star, $GM_{AS}M_{NS}/L_c$. When such condition happens, we can say the collision occurs. Thus $S_{L_c} = \pi L_c^2$. The number of collision per year $R_c$ is shown in Fig. 4 for two cases: The left y-axis illustrate the case for the maximum mass of the axion star $M_{AS} = 10^{-15} M_\odot$ and $S = S_{99}$ while the left y-axis shows the case where $M_{AS} = 7.4 \times 10^{-21} M_\odot$ and effective cross section $S = S_{L_c}$. $R_c$ is very small in the first case, while the second case is more optimistic, $\sim$ one per century per galaxy. Nevertheless, even in this ideal case, the effects will be hard to detect. The release of energy due to the collision is shown for both maximum cases in Table III. We can estimate the change in temperature if all energy is transferred to the NS. By assuming that the thermal energy in the NS is $U = 6 \times 10^{47} \text{erg} (M_{NS}/M) (\rho/\rho_n)^{-2/3} \left( T/10^9 \text{K} \right)^2$ with $\rho_n = 2.8 \times 10^{14} \text{cm}^{-3} \text{g}$ the nucleon density and $\rho$ the average density of the NS, that for $W = U = 7.9 \times 10^{37} \text{erg/s}$ implies a change in the NS’s temperature of $\Delta T \sim 10^9 \text{K}$, hence it is very hard to detect such changes of temperature in NS cooling observations. For the maximum AS mass $M_{AS} = 10^{-15} M_\odot$, the change in temperature will be $\Delta T \sim 10^9 \text{K}$, but the rate of collisions per year is very small.

It may happen that the energy is not completely absorbed by the NS, but instead the axion-photon conversion occurs out the NS’s crust; perhaps on the NS’s magnetosphere. If this scenario happens, some photons may escape liberating the whole energy. But in this case, a particle physics treatment for the oscillation may be required to compute the photon spectrum.

IV. CONCLUSIONS

As we can see from Table III the energy dissipated by one collision of an AS with a NS is many orders of magnitude bigger than the solar luminosity. But our results for the total dissipated energy per second in NS-AS collisions are around 10 orders of magnitude less than previous estimates [1, 2]. As it can be seen from Fig. 4 this difference comes from our computation of the maximal AS mass obtained through resolution of EKG equations. The obtained maximal AS mass is much smaller than the corresponding parameter used in ref. [1, 2]. It is important to notice that the maximal AS mass used in these references are now excluded by last observational results from Femtolensing of Gamma Ray Bursts [57].

Furthermore, improvement in femtolensing will help us to constrain the axion mass by constraining the maximum mass of AS. Observation of a sudden release of energy in Neutron stars may indicate the interaction of an AS with its strong magnetic field. If some of those signatures are observed, they can be considered as indications that the dark matter halo is made of an ensemble of axion stars. In our estimations, we have considered the largest mass of the AS and a hypothetical electric conductivity $\sigma$ [57], nevertheless, we hope our results will encourage further studies in the possibility of detecting the axion by its possible clustering.

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