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Axion-Polariton in dense quark matter: a solution to the missing pulsar problem

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We propose a mechanism to solve the missing pulsar problem, a puzzle created by the failed expectation to observe a large number of pulsars within the distance of 10 pc of the galactic center. Pulse observations of the magnetar SGR J1745-2900 indicate that magnetar formation should be efficient in the center of the galaxy, so the low abundance observed in the region underlines that some suppression effect must be operating that leads to short-lived magnetars. The proposed mechanism is based on the idea that if magnetars created in the galaxy center are hybrid stars with a core of quark matter in the so-called magnetic dual chiral density wave phase, their exposure to $\gamma$-ray burst radiation produce hybridized modes of photons and axions, known as axion-polaritons, which contribute to the magnetar mass and induce its collapse into a black hole.

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Introduction. Neutron stars (NS) are the most suitable laboratories, and so far the only ones, to probe the physics of very dense QCD. If densities of a few times the saturation density are reached at the star core, quarks can be freed from hadrons and restructure themselves into new quark phases. Besides being some of the densest objects in nature, NS typically exhibit very strong magnetic fields. The largest surface magnetic fields have been observed in magnetars where they reach $10^{12}$-$10^{15}$G. Inner fields depend on the core composition and their maximum values have been roughly estimated to be $10^{17}$-$10^{18}$G for nuclear matter \cite{1}, and $10^{19}$-$10^{20}$G for quark matter \cite{2}.

In recent years, intense efforts have been dedicated to use the newly found richness of observables in the multi-messenger era of astronomy to constraint the inner composition of NS \cite{3}. These studies are complemented by others aimed to connect star composition with possible explanations of existing astrophysical puzzles. The goal of this paper is aligned with the latter line of studies.

In this paper, we propose a mechanism to solve the missing pulsar problem in the galactic center (GC) based on the properties of matter-light interaction in the cores of the NS that form in the region. The missing pulsar problem is an open problem in astrophysics that refers to the contradiction between observations and the widely shared expectation that the central parsec should host a large NS population. For instance, Ref. \cite{4} predicted that $\sim 100 - 1000$ pulsars should have a semi-major axis $\lesssim 0.02$ pc from the GC black hole Sgr A*. Nevertheless, after several deep radio surveys, no ordinary pulsars have been detected to date \cite{5}.

Our proposed solution is based on having NS cores with quark matter in the spatially inhomogeneous phase known as magnetic dual chiral density wave (MDCDW) \cite{6-8}. Spatially inhomogeneous quark-matter phases have long been argued to be favored over the chirally restored phase at intermediate densities, i.e. densities large enough for the system to be on the quark phase, but small enough to support nonperturbative interactions. Inhomogeneous chiral phases have been found in the large-N limit of QCD \cite{9,10}, NJL models \cite{11-14}, and quarkyonic matter \cite{15}. The MDCDW phase is of particular interest for various reasons. First, it is formed by particle-hole pairs and as such, it is not subject to the Fermi surface stress that affect color superconductivity at intermediate densities \cite{16}. Second, it lacks the Landau-Peiers instability \cite{17} that usually destroys long-range correlation in single-modulated phases in 3-dimensional systems. And third, it is compatible with the observed $2M_{\odot}$ in NS \cite{18}.

As it will become clear below, the essence of the proposed mechanism is based on having magnetars with cores of quark matter in the MDCDW phase and the abundance of gamma ray bursts (GRB) in the GC \cite{19-20}. These two conditions favor the production of hybridized modes in the core of the star eventually inducing its collapse into a black hole.

Axion Polariton in Dense Quark Matter. The MDCDW phase of dense quark matter occurs at intermediate baryon densities in the presence of a magnetic field $B_0$ and is characterized by a particle-hole condensate $-2G[(\bar{\psi}\psi) + i(\bar{\psi}\gamma^5\tau_i\psi)] = m\exp(iqz)$, with modulation $q$ parallel to $B_0$ \cite{4}. This phase exhibits several topological effects. They include a lowest-Landau-level anomalous contribution to the free energy that significantly enhances the window of inhomogeneity \cite{4}, and a chiral-anomaly contribution $\frac{e^2}{24\pi^2}F_{\mu\nu}F^{\mu\nu}$ that leads to anomalous electric transport \cite{8}.

The fluctuations of the MDCDW order parameter $M(z) = me^{iqz}$ are driven by a phonon field $u(x)$, $M(z) \rightarrow M(z + u(x))$. If one ignores light-matter interactions, the low-energy theory of these fluctuations can be described by

$$\mathcal{L}_1 = \frac{1}{2}[\partial_\mu \theta]^2 - v^2_\perp (\partial_\perp \theta)^2 - v^2_\parallel (\partial_\parallel \theta)^2],$$

with pseudoscalar field $\theta = qmu(x)$, and parallel ($v^2_\parallel$) and transverse ($v^2_\perp$) phonon group velocity squares being functions of $B_0$, the quark chemical potential $\mu$ and the temperature $T$ \cite{17}. 


Adding photons to the mix adds light-matter interaction contributions besides a Maxwell term
\[ L_2 = \frac{\kappa}{8} \theta_0(x) F_{\mu\nu} F^{\mu\nu} + \frac{\kappa}{8} \theta(x) F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + J^\mu A_\mu. \]
Here \( \kappa = \frac{2a}{m} \). The two first terms in (2) are axial anomalies with axion field \( \theta_0(x) = m q x \) and its phonon fluctuation \( \theta(x) \). The last term is the current term obtained after integrating out the fermions in the original MD-CDW effective action [8].

To explore light-matter interaction effects we now assume that a linearly polarized electromagnetic wave with electric field parallel to the background magnetic field \( B_0 \) propagates in the MDCDW medium. The combined Lagrangian \( L = L_1 + L_2 \) of the photon and phonon fields effectively describes the low-energy theory of an axion field \( \theta(x) \) nonlinearly interacting with the photon via the chiral anomaly. The field equations of this theory are:
\[
\nabla \cdot E = J^0 + \frac{\kappa}{2} \nabla \theta_0 \cdot B + \frac{\kappa}{2} \nabla \theta \cdot B, \quad (3)
\]
\[
\nabla \times B - \partial E/\partial t = J - \frac{\kappa}{2} \nabla \theta \times E, \quad (4)
\]
\[
\nabla \cdot B = 0, \quad \nabla \times E + \partial B/\partial t = 0 \quad (5)
\]
\[
\partial^2 \theta - v^2 \partial^2 \theta - \frac{v^2_1}{2} (\frac{\partial^2 q}{\partial z^2} + \frac{\partial^2 q}{\partial y^2}) + \frac{\kappa}{2} B_0 \cdot E = 0. \quad (6)
\]
For application to NS, we should consider a neutral medium, hence we assume that \( J^0 \) contains an electron background charge that ensures overall neutrality. In the presence of a static and uniform background magnetic field, the coupling between the axion and the photon is linear. Thus, the linearized field equations lead to
\[
\frac{\partial^2 E}{\partial t^2} = \nabla^2 E + \frac{\kappa}{2} \frac{\partial^2 q}{\partial x^2} B_0, \quad (7)
\]
\[
\frac{\partial^2 q}{\partial z \partial t} - v_1^2 \frac{\partial^2 q}{\partial x^2} - v_1^2 (\frac{\partial^2 q}{\partial z^2} + \frac{\partial^2 q}{\partial y^2}) + \frac{\kappa}{2} B_0 \cdot E = 0. \quad (8)
\]
Their solutions describe two hybrid modes known in the condensed-matter literature as axion polaritons (AP) [21]. Polaritons are hybridized propagating modes that emerge when a collective mode is linearly coupled to a photon. The dispersion relations of the hybrid modes are
\[
\omega_\gamma^2 = A - B, \quad \omega_{\text{AP}}^2 = A + B \quad (9)
\]
with
\[
A = \frac{1}{2} \left[ p^2 + q^2 + (\frac{\kappa}{2} B_0)^2 \right], \quad (10)
\]
\[
B = \frac{1}{2} \sqrt{\left[ p^2 + q^2 + (\frac{\kappa}{2} B_0)^2 \right]^2 - 4 p^2 q^2}, \quad (11)
\]
and \( q^2 = v_1^2 p_x^2 + v_1^2 p_y^2 \). We identify the massless mode \( \omega_\gamma \) as the rotated photon mode in the medium and reserve the term axion polariton from now on to describe the massive mode \( \omega_{\text{AP}} \) with field-dependent mass \( m_{\text{AP}} = \alpha B_0/\pi m \). Hence, when linearly polarized electromagnetic waves penetrate the star core, they propagate via these two modes. Similarly coupled modes of axion and photon have been found in topological magnetic insulators [21], underlining once again the striking similarities between MDCDW quark matter and topological materials in condensed matter.

**Missing Pulsar Problem.** The Milky Way GC is a very active astrophysical environment with numerous γ-ray emitting point sources [19]. Extragalactic sources of GRB show an isotropic distribution over the whole sky flashing with a rate of 1000/year. The energy output of these events is \( \sim 10^{56} \) MeV, with photon energies of order 0.1 – 1 MeV [21], meaning that each one of these events can produce at least \( 10^{56} \) photons. If we assume that only 10% of these photons reach the star core, which is a conservative estimate if the star is in the narrow cone of a GRB beam, about 10\(^{55}\) of those photons can reach the star.

Considering that the mass of the axion polariton \( m_{\text{AP}} \) can be estimated to be of order 0.8 MeV for parameters \( \mu = 350 \) MeV, \( B_0 = 5 \times 10^{18} \) G and \( m = 89 \) MeV taken from [3], one can gather that the most energetic of the \( 10^{55} \) photons reaching the core will propagate inside as polaritons. The conversion of a large number of γ-photons into axion polaritons in the NS core can be realized through the so-called Primakoff effect [22]. This effect states that thanks to the anomalous two-photon vertex, a photon in the presence of a background magnetic field can transform into an AP field. Such a transformation can in turn affect the total star mass and could eventually lead to the star collapsing into a black hole. To explore this possibility, we should consider the Chandrasekhar limit that determines the number of AP required to induce the collapse. For boson particles this limit is given by [23, 24]
\[
N_{\text{Ch}}^{\text{AP}} = \left( \frac{M_{\text{pl}}}{m_{\text{AP}}} \right)^2 = 1.5 \times 10^{46} \left( \frac{10 \text{ MeV}}{m_{\text{AP}}} \right)^3 \quad (12)
\]
where \( M_{\text{pl}} = 1.22 \times 10^{19} \) GeV is the Planck scale. Using \( m_{\text{AP}} = 0.8 \) MeV, we find \( N_{\text{Ch}}^{\text{AP}} = 2.9 \times 10^{49} \). This means that if just 10\(^{-4}\)% of the photons reaching the core has energy \( \geq 0.8 \) MeV, they will generate enough number of axion polaritons to produce the collapse.

Another important fact to consider is whether the axion-polaritons, created by γ-photons in the energy range of 0.8 – 1 MeV, can be gravitationally trapped. This can be gathered by comparing the escape velocity of the star with the velocity the axion-polariton can gain from photons
\[
v_{\text{AP}}/c = \sqrt{1 - \left( \frac{m_{\text{AP}} c^2}{E_\gamma} \right)^2}, \quad (13)
\]
which gets a maximum value for \( E_\gamma = 1 \) MeV. Using \( m_{\text{AP}} c^2 = 0.8 \) MeV we obtain \( v_{\text{AP}} = 0.6c \), which is below the escape velocity \( \sim 0.8c \) found from \( v_\gamma/c = \sqrt{2GM_{\text{star}}/c^2R_{\text{star}}} \) for a star with \( M_{\text{star}} = 2M_\odot \) and \( R_{\text{star}} = 10 \) km. Therefore, even the most energetic axion-polaritons cannot escape. Using \( M_{\text{star}} = 2M_\odot \) in this
calculation was motivated by recent indications \cite{25} that the heaviest neutron stars, with masses $\sim 2M_\odot$, should have deconfined quark-matter in their cores. Such a conclusion was reached through a combination of astrophysical observations and theoretical ab initio calculations in a model-independent way \cite{27}, and it was consistent with the most reliable up-to-date observations of heavy pulsars masses in the interval $1.9282M_\odot - 2.14M_\odot$ \cite{28}. The same study concluded that a hadron phase is compatible with more standard NS with $M_{\text{star}} \sim 1.4M_\odot$.

Our results provide a plausible explanation for the missing pulsar problem in the galaxy center. As mentioned above, the mixing pulsar problem refers to the failed expectation to observe a large number of pulsars within the distance of 10 pc of the galaxy center. Theoretical predictions have indicated that there should be more than $10^3$ active radio pulsars in that region \cite{27}, but these numbers have not been observed. This paradox has been magnified by pulse observations of the magnetar SGR J1745-2900 detected by the NuSTAR and Swift satellites \cite{28,29}. These observations revealed that the failures to detect ordinary pulsars at low frequencies cannot be simply due to strong interstellar scattering, but to an intrinsic deficit produced by other causes. Furthermore, as pointed out in \cite{30}, the detection of the young ($T \sim 10^4$ yr) magnetar SGR J1745-2900 implies high efficiency for magnetars formation from massive stars in the GC, because it will be barely probable to see a magnetar unless magnetar formation is efficient there. It was then argued that the efficiency in magnetar formation can be elicited by an unusual progenitor population in the galaxy center, and that the missing pulsar problem can be explained as a consequence of a tendency to create short-lived magnetars rather than long-lived ordinary pulsars.

The AP mechanism proposed in this paper can be the basis for a plausible short life-time magnetar scenario, since the existence of an inner magnetic field in this compact objects is crucial for several reasons: first of all, because a background magnetic field is essential to make the MDCDW phase stable against thermal fluctuations \cite{17}, second, because in the creation of the APs through the Primakoff effect the magnetic field also plays a fundamental role, and third, because the AP mass is proportional to it. All these facts, together with the intense $\gamma$-ray activity in the galaxy center, guarantee the conditions needed for the collapse of those short-lived magnetars.

**Concluding Remarks.** In conclusion, we have shown that if magnetars are created in the GC as hybrid stars with a core of quark matter in the MDCDW phase, the bombardment of these stars with $0.1$-1-MeV photons from $\gamma$-ray bursts, generate enough AP to eventually produce a star collapse. This scenario can serve to explain the missing pulsar problem in the galaxy center.

It should be mentioned an alternate scenario that has been suggested to explain the missing pulsar problem \cite{30}. According to it, the capture of enough ambient dark matter (DM) by the pulsar, can produce its collapse into a black hole. The idea is that once the DM inside the star is thermalized at the NS temperature, it starts to sink into the star center. When the agglomeration exceeds certain critical mass, a mini black hole can be formed at a small central radius. Once the mini black hole is formed, it can promptly consume the whole star, leaving behind a black hole.

We underline that for this DM-collapse scenario to work, the DM density profile should satisfy a very restrictive constraint as pointed out in \cite{31}. Since the DM capture rate is proportional to the ambient DM density, to collapse a pulsar at a galacto-centric radius of $r = 1$ pc within $10^6$ yr, while living intact to survive for more than $10^{10}$ yr the NS in the solar system neighborhood (i.e. at $r \sim 10^5$ pc), an increase of the DM density in a factor of at least of $10^3$ in that radial range is needed.

As highlighted in \cite{31} and also noticed in \cite{32}, the DM-induced collapse scenario is intrinsically unlikely because it will constrain DM to a very stringent parameter space. On the other hand, the AP scenario proposed in this paper only relies on the existence of massive magnetars at intermediate densities with MDCDW quark cores, and on a high $\gamma$-burst activity in the GC, which is a well established observational fact \cite{33}. We recall that after the discovery of the young magnetar SGR 1745-2900 with a projected offset of only 0.12 pc from the GC, it was argued that the detection of such a magnetar should not have been expected unless magnetar formation is efficient in the GC with an order unity efficiency \cite{3}. Moreover, there is evidence that several magnetars are associated with massive stellar progenitors ($M > 40M_\odot$ \cite{34}, which support the idea that magnetars formed in the GC are very massive compact objects that can sustain quark matter cores. All these elements combined favor the AP mechanism proposed in this paper.

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