

A Panchromatic Search for Light Bosons in Astrophysical Environments

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Doron Chelouche (CITA, University of Toronto, Canada)

Eduardo I. Guendelman (Ben-Gurion University, Israel)

David V. Bowen (Princeton University, USA)

Marco Roncadelli (Istituto Nazionale di Fisica Nucleare –INFN, Italy)

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Relevant missions: H.E.S.S. , Fermi, IXO, LSST, JWST, ALMA, Herschel, LOFAR,
and SKA

Abstract: *The existence of light bosons may help to explain the strong-CP¹ problem of quantum chromodynamics (QCD), the dark matter problem of cosmology and may be related to quintessence. Here we argue that low to medium resolution spectroscopy of magnetars, pulsars, and quasars, and the study of the radio light curves of magnetized pulsars can be used to search for photon-particle mixing features. In particular, these observations can be used as independent tests for the existence of light bosons, such as the axion, which are 3-5 orders more sensitive than current laboratory experiments over a broad particle mass range. Currently planned missions will make the astrophysical detection of light bosons observationally feasible.*

1. Introduction

The strong-CP problem of QCD gave birth to the axion as its solution [1]: a pseudo-scalar particle whose properties such as mass and coupling constant to the electromagnetic field are not predicted by theory. It was later realized that, for a range of particle mass, axions are promising dark matter candidates alongside, e.g., WIMPs² and CHAMPs³ [2]. In addition, scalar and pseudo-scalar fields can be found in many version of string theory [3] and, as with any quantum field, imply the existence of associated particles such as axion-like particles (ALPs). These may be connected to quintessence and the notion of dark energy [4]. Therefore, the detection of light bosons will shed light on several of the most fundamental physical problems in contemporary physics, which relate to nature's symmetries, the dark matter and dark energy in cosmology, as well as string theory.

For the aforementioned reasons, there is a considerable interest in detecting light bosons (among which are the axions) and many experiments have been especially devised for that purpose [5]. Most experiments make use of the Primakoff effect [5] whereby two photons and an axion interact. In particular, such an interaction may convert a real photon to an axion (and vice-versa) in the presence of an external magnetic field. This process is of a resonance nature and occurs when the effective photon mass (as it travels through a refractive medium) equals the particle mass. At resonance, the conversion probability from photons to axions is $P \propto g^2 B^2 L^2$, where g is the coupling constant of the axions to the electromagnetic field, B is the magnetic field, and L is the size of the system [6]. Many terrestrial experiments use a photon \Rightarrow axion/ALP \Rightarrow photon conversion process so that the probability, $P \propto g^4 B^4 L^4$ (other experiments are more efficient; e.g., for CAST⁴, $P \propto g^4 B^2 L^2$). Therefore, whether or not the effect is detectable depends crucially on our ability to produce strong magnetic fields over considerable length scales at resonance. As many astrophysical systems are known to have much stronger magnetic fields than laboratory produced ones, and those can extend over larger scales than typical experimental sizes, the potential to probe photon-boson oscillations occurring in celestial objects is remarkable [7]. Furthermore, astrophysical systems are characterized by stratified magnetospheres, and a photon created at the photosphere is likely to resonate with particles at some location in the magnetosphere as it travels towards us, thereby leading to a detectable conversion [8].

2. The Science

The search for light bosons links the smallest (QCD) and the largest (cosmological) mysteries of contemporary physics. Here we outline just a few such connections and demonstrate that

¹ Charge conjugation-Parity symmetry

² Weakly Interacting Massive Particles

³ Charged Massive Particles

⁴ Cern Axion Solar Telescope

observational astronomy stands a good chance of tackling these problems in the coming decade.

The strong-CP problem of QCD: it was realized in the 1950's that the weak interactions do not preserve the charge conjugation (C) and parity (P) symmetries, individually, and Landau speculated that a more fundamental symmetry of nature is the CP symmetry. It was later realized by Cronin & Fitch (who were awarded the Nobel prize in 1980 for their experiment) that the CP symmetry is not a good symmetry of nature (it is violated by weak interactions). In contrast, the strong interaction does seem to preserve CP to a very good precision despite having CP violating terms in its Lagrangian. This property of QCD posed a serious problem to particle physics, and an elegant way out was proposed by Peccei & Quinn (1972) who hypothesized a new kind of particle, the axion [1] whose existence dynamically suppresses the CP violating terms in QCD Lagrangian making it CP-conserving. Although more than 30 years have passed since the solution was proposed, the axion has not been detected, and the Peccei-Quinn mechanism has not been shown to work. This problem is at the heart of our physical understanding of QCD and nature's symmetries and many experiments are being carried out to validate the solution [5].

The dark matter problem: the dark matter problem has been with us since 1933 when Zwicky pointed out a discrepancy between the velocity dispersion of galaxies in rich clusters and their inferred luminous mass. Today, our understanding of dark matter phenomenology has advanced considerably thanks to large coverage and high precision imaging. Upcoming surveys, such as LSST⁵, will continue to map dark matter across the sky and over cosmic times shedding further light on its properties. However, despite the huge progress in the field, the physical nature of dark matter still remains obscure and it is not known what dark matter is made of. Interestingly, for a certain mass range (around 0.01meV), the axion is a promising dark matter candidate. Unlike other potential dark matter particles (e.g., WIMPs), dark matter axions are not thermally produced and are created during the QCD phase transition in the very early universe. Therefore, if axions constitute some or all of dark matter, then a new window opens up for investigating the earliest stages of our Universe. This science nicely complements current and upcoming dark matter searches for WIMPs in the laboratory and in space, as well as the LHC science in the coming decade.

Scalar fields and dark energy: besides QCD axions, other (pseudo-)scalar fields (axion-like fields) may exist in nature. In fact, many versions of string theory predict a very large number of scalar fields each with its own associated particle. Such fields may be related to quintessence which gives rise to the revived acceleration of the expansion rate of the universe in recent cosmological epochs. Axion-like fields and their associated particles (ALPs) were considered recently as a possible explanation to the unexpected low opacity of the Universe to TeV γ -rays from high redshifts. This provides a more elegant solution to the problem than e.g., Lorentz symmetry violation [9] which implies severe shortcomings of all current physical theories. To date, however, no (pseudo-)scalar fields have been found. The detection of such fields would also be a major triumph for string theory. This science nicely fits with JDEM⁶ guidelines and is timely given the expected advent in γ -ray astronomy and LHC science.

The inner engines of compact objects: in the event that axions or ALPs are discovered either by astrophysical means or laboratory means, their existence can also be used to probe the innermost regions of compact astrophysical objects. This results from the fact that photon-particle oscillations

⁵ Large Synoptic survey Telescope: <http://lsst.org>

⁶ Joint Dark Energy Mission: <http://jdem.gsfc.nasa.gov>

have a particular dependence on the properties of the magnetosphere. More specifically, the presence or absence of oscillation features can be used to shed light on the magnetic field intensity and geometry as well as plasma physics at the core of compact objects. Such constraints cannot be obtained by other means. Furthermore, as photon-boson oscillations are polarization dependent [5-8], the emission mechanisms in quasars, pulsars, and magnetars may be constrained. This science complements traditional methods of investigation.

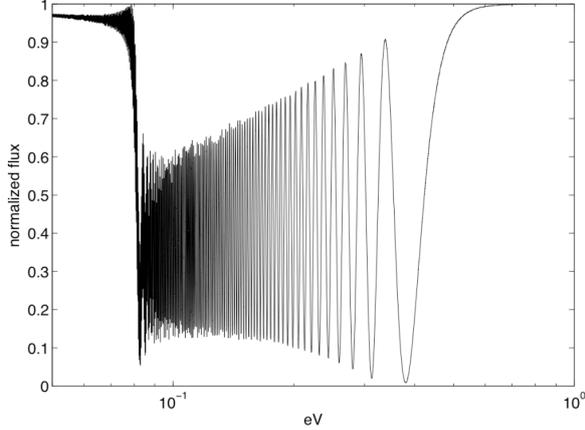


Fig.1: Spectral oscillation feature which would be observed for a pulsar given the current upper limit on the value of the coupling constant, $g \sim 10^{-10} \text{GeV}^{-1}$. Clearly, such a feature would be easily detectable and has a signature distinguishing it from atomic features. We emphasize that, physically, this is not an absorption feature and that no energy is dissipated in the process.

3. Detecting photon-particle oscillations from space

Current laboratory experiments to detect light bosons span only a small region of the particle parameter space spanned by the particle mass, m_a , and its coupling to the electromagnetic field through the coupling constant, g . As noted above, this limitation is mainly due to a double conversion effect used by most laboratory experiments and the fact that the produced magnetic fields and length scales are small. Interestingly, the best constraints to-date on the axion/ALP properties come from astrophysical observations pertaining to the cooling time of stars rather from laboratory experiments and, as we show below, much better sensitivities to axion/ALP detection may be obtained by considering photon-particle oscillations in highly magnetized celestial systems.

Many compact astrophysical sources are luminous over a broad range of photon energies [10]. It is therefore likely that at some energy band, photon-particle mixing will occur as photons propagate through the magnetosphere [e.g., 7 and references therein]. The resonance energy depends primarily on the value of the magnetic field and the plasma density, both of which determine the effective photon mass. Looking for a photon deficit in the spectra of bright sources, will therefore “detect” photons which converted into axions with a probability which is proportional to $B^2 L^2$ and therefore much more efficient than terrestrial experiments. The conversion probability is also considerably increased by noting that the conversion $B^2 R^2$ factors for celestial objects are many (>20 in some cases) orders of magnitude larger than those in the laboratory. That said, unlike terrestrial experiments whose operating parameters are well known, astronomical objects cannot be controlled and great care must be taken to positively identify photon-particle oscillations. Fortunately, recent theoretical progress in the field [7] has resulted in better characterization of oscillation features which can help in their identification (see Fig. 1). Furthermore, results from different objects, at different wavelengths, and using different effects (spectral and light-curve features; see below) may be used for corroboration of the results and it seems that field has now reached maturity. The theoretical progress goes hand in hand with recent advances in low to medium resolution spectroscopy which goes fainter than ever and is able to probe an increasingly larger fraction of the sky and of the photon energy

spectrum. Below we discuss the specific effects that should be looked for in particular objects and identify the relevant wavelengths for this study.

Spectral oscillation features due to photon-boson mixing

Pulsars and magnetars: these highly magnetic rotating objects [11] are expected to show photon-boson oscillations features from sub-mm energies to the near-IR [7]. In particular, very prominent broad features may be easily detectable by broad band photometry for values of the coupling constant, g , at current upper limits (of the CAST experiment of $g \sim 10^{-10} \text{GeV}^{-1}$, [5]). Provided a higher spectral resolution power ($R \sim 100$) is available, spectral oscillation features may be detected down to g values ~ 3 orders of magnitude smaller than current upper limits. Template fitting of the predicted oscillation signal to the time-dependent spectra (as a function of orbital phase of the star) may further enhance the detection capability as unique variability patterns (such as energy shifts) are expected to occur [7]. The expected signal for the case of magnetars is shown in figure 2a.

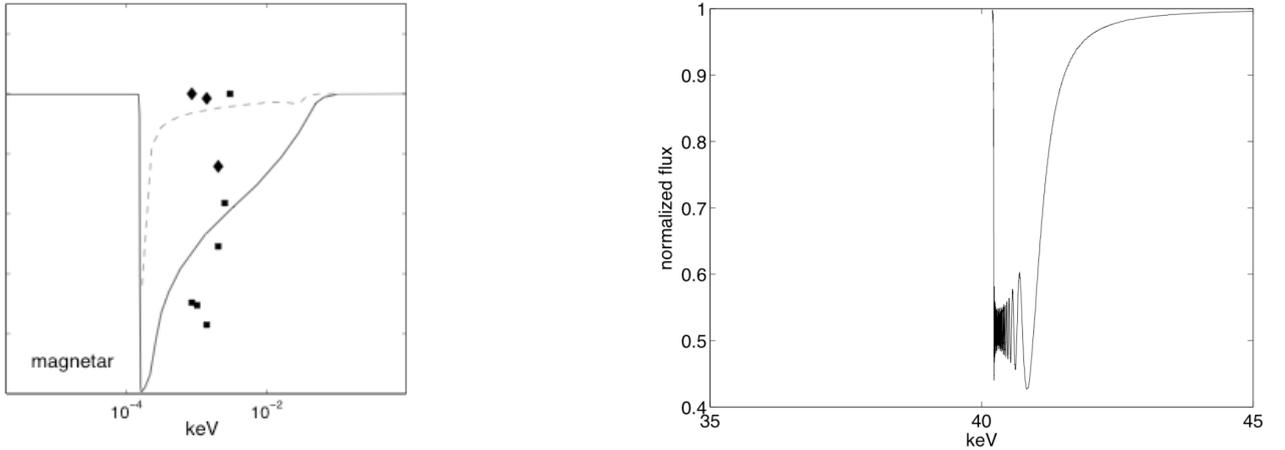


Fig. 2: (a) The photon-axion oscillation feature in magnetars assuming a coupling constant $g \sim 10^{-10} \text{GeV}^{-1}$ (solid line) which is at the current upper limit from the CAST, and assuming $g \sim 10^{-11} \text{GeV}^{-1}$ (dashed line). The feature is clearly visible from sub-mm/IR to UV energies and does not resemble atomic features. For lower values of g , the feature narrows with a prominent signature at IR energies but may still be detected with a spectral resolution power, $R \sim 100$, down to $g \sim 10^{-13} \text{GeV}^{-1}$ [7]. (b) The spectral oscillation feature observed toward a quasar assuming $g \sim 10^{-12} \text{GeV}^{-1}$ and parameters typical of quasar magnetospheres (taken from [7]). The feature is expected to show up as a photon deficit at hard X-rays to γ -ray energies, depending on whether oscillation occurs in the quasar magnetosphere [7,12] or the IGM [13], and would be clearly detected down to coupling constant of order $g \sim 10^{-14} \text{GeV}^{-1}$.

Quasars: these objects have much weaker magnetic fields but the weakness is compensated for by the large size of the system resulting in a large $B^2 L^2$ values compared to laboratory experiments. This allows us to probe for light bosons ($m_a < 0.01 \text{meV}$) down to values of the coupling constant 3-4 orders of magnitude smaller than the CAST limits [7,12]. The photon-boson spectral oscillation feature is expected to fall in the hard X-ray to γ -ray energies (of order 0.01-1 MeV). Depending on the plasma temperature and the stratification of the magnetosphere, the features may be very broad (photometrically detectable with $R \sim 1$, [7,12]) or narrow (requiring $R \sim 10$ -100; see Fig. 2b).

In addition to oscillation features that originate from the quasar itself, photons can convert to ALPs as they pass through the inter-galactic medium (IGM). This is due to the latter being threaded by a magnetic field. Such oscillation signatures have recently been proposed to explain the apparent transparency of the high redshift universe to γ -ray radiation [13]. As before, the oscillation signal is expected to be broad and clearly detectable with broadband photometry at $\sim \text{TeV}$ energies [13]. Such oscillations, if confirmed, imply the existence very low mass axions (ALPs)

Beam splitting due to photon-boson mixing

Apart from the photon-boson spectral features described above, there are other observational signatures for photon-boson mixing. In particular, in the presence of magnetic fields, quasi-particles consisting of linear combination of photons and bosons propagate at different speeds through the medium [14]. When the medium is stratified such that magnetic field gradients exist, the two quasi-particle beams follow different paths according to Fermat's principle and diverge. Objects that emit beamed radiation (such as pulsars) may therefore show split pulses rather than a single peaked one. This was shown to enable light-boson (ALP) detection down to values of g , which are >4 orders of magnitude lower than the CAST upper limit. The splitting is proportional to the photon wavelength and can therefore be easily identified even in relatively noisy lightcurves. Furthermore, unlike spectral oscillation features, the effect is proportional to BL rather than the square of it, allowing it to be detected to potentially lower values of g . The recently discovered magnetized pulsars (or radio loud magnetars) provide ideal settings to study splitting effects at long radio wavelengths (see Fig. 3).

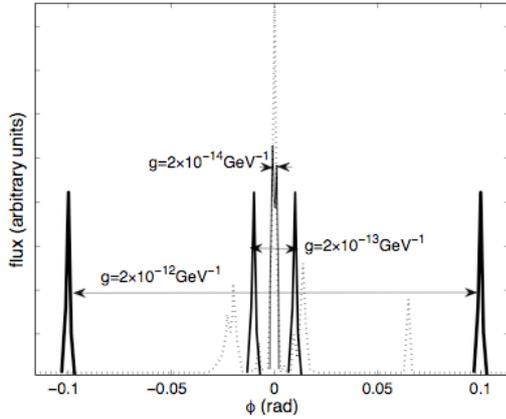


Fig.3: Beam splitting of pulses (thick lines) in the radio light curve of a magnetar for various values of the coupling constant, g , and assuming radio observations at 1m photon wavelengths. The original, unsplit pulse at zero phase is shown in dotted line. Flux is conserved in the splitting process. The splitting effect may be resolved down to $g \sim 10^{14} \text{GeV}^{-1}$; i.e., ~ 4 orders of magnitude below the CAST upper limit. (from [14]).

4. Future directions

Recent progress in the field of astronomical detection of light bosons has shown that one may expect to see signatures of photon-particle oscillations in many compact astrophysical systems. Nevertheless, a better understanding of those systems is required to be able to securely detect such features and/or place limits on the particle properties should such features not be observed. The latter task is particularly difficult given the uncertainties in the physical properties of compact objects as well in their spectroscopic manifestation. Below we outline a few directions that we believe are important for making astrophysical objects better laboratories for particle physics.

Theory

Magnetospheres of compact objects: Photon-particle conversion is sensitive to the properties of the magnetic field and plasma along the photon path. In particular, the shape and depth of the spectral feature, as well as the effect of splitting are sensitive to gradients in the magnetic field and plasma density. To a lesser degree, the plasma temperature may also affect the shape and location of the spectral oscillation features. A better understanding of the emission mechanisms of the photons in or just below the magnetosphere is also important since photon-boson mixing is polarization-dependent. For example, if radio photons from magnetized pulsars are emitted closer to the light cylinder than to the stellar surface, magnetic fields would be much lower and the splitting effect less noticeable. Particular emphasis should be made of the magnetospheric properties of the recently detected radio

loud magnetars as those are promising laboratories as far as light boson detection is concerned. Understanding the emission of TeV photons from quasars as a function of quasar luminosity and cosmic time is essential for correctly identifying the ALP signal [13]. Better calculations of the dielectric tensor for (sub-)relativistic plasma should also be promoted if we wish to identify the spectral energies where resonance occurs. Lastly, we emphasize that searching for axions in the spectra of multiple classes of systems is important for reducing theoretical and observational uncertainties related to any particular class of objects and for corroborating the results.

Atomic and molecular physics in magnetized environments: It is well known that strong magnetic fields alter the level configurations of atoms [15]. This is especially true for magnetized pulsars where, for example, the Ly α line can be shifted to X-ray energies. The observed spectra of magnetized objects require us to understand not only the continuum emission mechanisms but also to identify and model the relevant emission and absorption lines and edges. This is especially critical if one wishes to distinguish photon-particle spectral oscillations features from other spectral signatures.

Axion physics: Recent years have shown that it is possible to devise many experiments to observe “invisible” light bosons and we expect that further observational tests are likely to emerge. An example for such a test is the de-stabilizing effect of axions on cosmic strings [16] with the latter being, in principle, observable with future, high resolution deep sky surveys [17].

Observations

The spectral properties of magnetized objects: At present, many of the spectral characteristics of highly magnetized compact objects are poorly constrained. For example, the spectral energy distribution from magnetars is only now beginning to emerge and the results are poorly understood. Similar uncertainties apply to the TeV spectrum of high redshift quasars. Better statistics and time-series photometry and spectroscopy are required to understand the source of the emission and whether it can be attributed to the compact object itself. Upcoming sky surveys with large coverage such as LSST as well as object selection in γ -ray bands (with Fermi) will undoubtedly reveal more extreme objects that can serve as ideal laboratories for particle physics. Specific bands are of particular importance for detecting photon-boson oscillations at low values of the coupling constant:

- *Medium resolution ($R \sim 100$) spectroscopy in the sub-mm to infrared energies of magnetars.* Good throughput or time tagging of events would be of great advantage due to the expected variability of those features with rotation phase of the object. ALMA and Herschel will play a central role in studying these objects.
- *Low-medium resolution ($R \sim 10-100$) X-ray to γ -ray spectroscopy of quasars and low resolution ($R \sim 1$) TeV spectroscopy of high-z quasars.* IXO and Fermi will play a major role in studying these objects. TeV telescopes (such as H.E.S.S. and VERITAS) are crucial for constraining the spectra of high-z quasars and studying ALPs.

Extragalactic Background light (EBL): It is important to estimate the EBL since its flux determines the opacity of the universe to \sim TeV γ rays and determines the observed spectral shape of high redshift sources. Combined with a better determination of the intrinsic TeV emission from quasars, it may be possible to shed light on the viability of photon-particle oscillations in explaining the apparent transparency of the Universe to γ -ray energies. The launch of JWST will provide new insights into the cosmic star formation rate and background light.

Time series observations at long radio wavelengths: Probing magnetic pulsars/radio-loud

magnetars at the longest wavelength can increase the sensitivity to low values of photon-boson mixing. In particular, radio observations at $\sim 30\text{m}$ wavelengths would potentially probe down to coupling constant values of $g \sim 10^{-15} \text{GeV}^{-1}$; i.e., ~ 5 orders of magnitude lower than current best upper limits! As such, LOFAR, SKA and the recently discussed lunar based observatories for $>30\text{m}$ wavelength observations seem promising in this respect.

5. Summary

The existence of light bosons may help to explain the strong-CP problem of QCD, the dark matter problem of cosmology and may be related to quintessence. Astrophysical environments can be used to search for such particles with typical sensitivities several orders of magnitude higher than laboratory experiments and other indirect astrophysical considerations. Specifically, low to medium resolution spectroscopy of magnetars, pulsars, and quasars are ~ 2 orders of magnitude more sensitive to axion detection than the best upper limits on axions and ALPs given by CAST. Radio light curves of magnetized pulsars can be used to probe light bosons (ALPs) down to a coupling constant, $g \sim 10^{-15} \text{GeV}^{-1}$; i.e., 4-5 orders of magnitude lower than reached by CAST and indirect astrophysical constraints on the lifetime of HB stars (see Fig. 4).

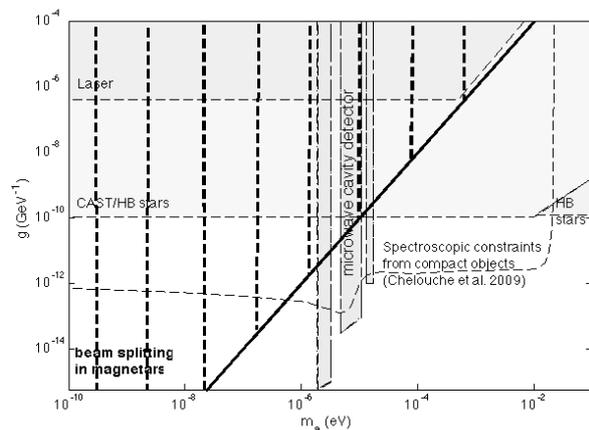


Fig. 4: The axion/ALP parameter space, which is currently explored by various terrestrial experiments and is indirectly inferred from astrophysical considerations (grey surfaces). The thick-dash and dash-dotted lines show the ALP parameter space that can be explored by spectroscopy of compact astrophysical objects (like magnetars and quasars) and by the effect of beam splitting on the radio light-curves of magnetars (thick line and hatched surface).

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