Snowmass2021 - Letter of Interest

Search for Axion-Like Particles with X-rays and Soft Gamma Rays from Magnetars

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Topical Groups: (check all that apply □/■)
■ (TF9) Astro-particle physics & cosmology
■ (TF08) BSM model building
■ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes

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Abstract: Axion-like-particles (ALPs) emitted from the core of magnetars can convert to photons in their magnetospheres. We propose to study such emissions in the hard X-ray and soft-gamma-ray range. For the hard X-ray range, we will use published data from *NuSTAR*, *XMM-Newton*, *Swift-XRT*, *Suzaku*, and *INTEGRAL*. We will also investigate possible polarization effects. For the soft-gamma-ray range, we will use published quiescent soft-gamma-ray flux upper limits and data obtained with *CGRO* COMPTEL, *INTEGRAL* SPI/IBIS/ISGRI and the *Fermi* Gamma Ray Burst Monitor (GBM) to put limits on the product of the ALP-photon and ALP-neutron couplings obtained from ALP emission from the core followed by conversion in the magnetosphere. We will undertake a detailed study of the dependence of our results on the core temperature and modeling of the neutron star.

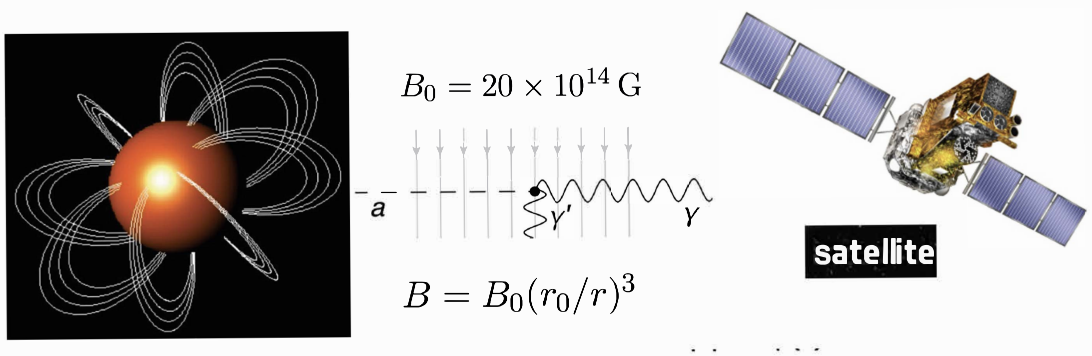

Figure 1: A schematic depiction of the search strategy under consideration.

The axion arises as a solution to the strong CP problem of QCD and is a plausible cold dark matter candidate. The search for axions, and more generally axion-like-particles (ALPs), now spans a vast ecosystem including helioscopes, haloscopes, interferometers, beam dumps, fixed target experiments, and colliders. The conversion of relativistic ALPs in the magnetosphere of neutron stars is a promising method to constrain these particles, leveraging the data-rich fields of X-ray and gamma-ray astronomy and magnetars on the one hand, and fundamental physics on the other. Like terrestrial experiments, such indirect detection techniques also utilize the coupling of dark sector particles to electromagnetism, but with the advantage that the relevant magnetic fields exceed the strongest fields achievable in laboratory experiments by orders of magnitude.

The mechanism of ALP-photon conversion is as follows: relativistic ALPs (a) emitted from the core by nucleon (N) bremsstrahlung (from the Lagrangian term $\mathcal{L} \supset G_n(\partial_\mu a)\bar{N}\gamma^\mu\gamma_5 N$) escape into the magnetosphere, where they convert to photons (from the Lagrangian term $\mathcal{L} \supset -\frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}$) in the presence of the neutron star magnetic field B. The product of ALP-nucleon and ALP-photon couplings can be constrained by requiring that the photon flux coming from ALP conversion cannot exceed the observed luminosity of the magnetar. The ALP emission rate strongly depends on T_c^6 while the conversion rate increases with stronger B, making magnetars, with their high T_c of $\sim 10^9$ K and strong $B \sim 10^{14}$ G, a natural target for these studies. A schematic picture of the search strategy is depicted in Fig. 1.

X-ray Luminosity: Imaging, spectroscopy, timing, and polarimetry of X-ray emission from neutron stars is a major target of several future experiments, making this a particularly opportune moment to add fundamental physics as a component of these missions. In [1, 2], we have studied X-ray emission from the magnetar SGR 1806-20 and shown that the ALP-photon coupling $g_{a\gamma\gamma}$ can be constrained at a level that is competitive with the CAST experiment, assuming a core temperature $T_c = 10^9$ K and that the ALP-nucleon coupling G_n is at a value that is just allowed by cooling.

In work in progress, we are analyzing magnetars shown in Table 1. We propose to further develop this

Name	B($10^{14}G$)	T_{BB}(ev)	d(kpc)	F_X(20-150kev) ($10^{-11} erg \cdot s^{-1} cm^{-2}$)
4U 0142+61	1.3	410	3.6	9.09×10^{-11}
SGR 0501+4516	1.9	500	2	$< 3.5 \times 10^{-11}$
1E 1547.0-5408	3.2	430	4.5	$< 1.5 \times 10^{-11}$
1RXS J170849.0-400910	4.7	456	3.8	5.2×10^{-11}
SGR 1806-20	20	550	8.7	3.83×10^{-11}
1E 1841-045	7	450	8.5	4.59×10^{-11}
SGR 1900+14	7	470	12.5	1.42×10^{-11}
1E 2259+586	0.59	370	3.2	$< 2 \times 10^{-11}$

Table 1: The magnetars that will be studied in the X-ray portion of this proposal.

program and obtain limits on $G_n \times g_{a\gamma\gamma}$ using data from *NuSTAR*, *XMM-Newton*, *Swift-XRT*, *Suzaku*, and *INTEGRAL*.

X-ray Polarization: The possibility of obtaining ALP signals via studying polarization of the emitted photons was put forward in [2,3]. Since ALPs only mix with the parallel mode of the photon, the polarization of the soft and hard X-ray spectra is predicted to have an O-mode component, in addition to the mainly X-mode component given by most astrophysical models. The relative strength of the O-mode component depends on the intensity of ALPs produced in the core and the probability of conversion. The O-mode polarization was studied in several benchmark points in [2, 3] and can be investigated in future missions dedicated to X-ray polarimetry.

Soft-Gamma-Ray Studies: In [4], we used published quiescent soft-gamma-ray flux upper limits (ULs) in the 5 magnetars 1E 2259+586, 4U 0142+61, 1RXS J170849.0-40091, 1E 1841-045, 1E 1048.1-5937, as obtained with *CGRO* COMPTEL and *INTEGRAL* SPI/IBIS/ISGRI to put 95%CL upper limits on the product of the ALP-nucleon and ALP-photon couplings (see Fig. 2). Here, we plot $G_n \times g_{a\gamma\gamma}$ for the five magnetars in our study, obtained for emissions in the energy range 300 keV−1 MeV, assuming core temperature $T_c = 10^9 K$. To compare with other experiments probing the same regions of ALP parameter space that are only sensitive to $g_{a\gamma\gamma}$, we show our results in Fig. 3 for the same core temperature and assuming that the ALP-nucleon coupling G_n is just at the limit coming from cooling.

These results are obtained from a resolved binned analysis by comparing the power in energy bins to the corresponding experimental limits. The best limit obtained from magnetar 4U 0142+61 is competitive with the CAST experiment, under the assumption of a core temperature of 10^9K and ALP-nucleon coupling at a value that is just constrained by cooling limits. Since the obtained constraints are strongly dependent on the core temperature, this analysis will be further refined by a more detailed modelling of the neutron star and thus a more detailed consideration of the ALP production in the core.

We also propose to further pursue this direction of research with the *Fermi* Gamma Ray Burst Monitor (GBM). While the flux limits we used for our initial study were the most stringent published to date, the GBM detector has now been operating for over 12 years, and as such, more stringent flux upper limits are possible. The GBM is a non-imaging instrument with a wide field of view. However, it is possible to assign detected events to individual pulsars using the Earth Occultation Technique (EOT) or pulsar timing models. EOT uses a catalogue of sources which exhibit step like changes in photon count rate as seen by the GBM, when the sources are eclipsed by or rise above the Earth limb. In 3 years, EOT has detected 9 of 209 sources between 100−300 keV. The GBM is thus a very useful instrument to determine the UL soft-gamma-ray fluxes of the 23 confirmed magnetars in the McGill Magnetar Catalog, most of which have no ULs defined in the 300 keV−1 MeV band of interest.

Production in the neutron star core: For both X-ray and gamma-ray studies, we will undertake a detailed study of the production of ALPs from the neutron star core. Magnetar cores are likely below the

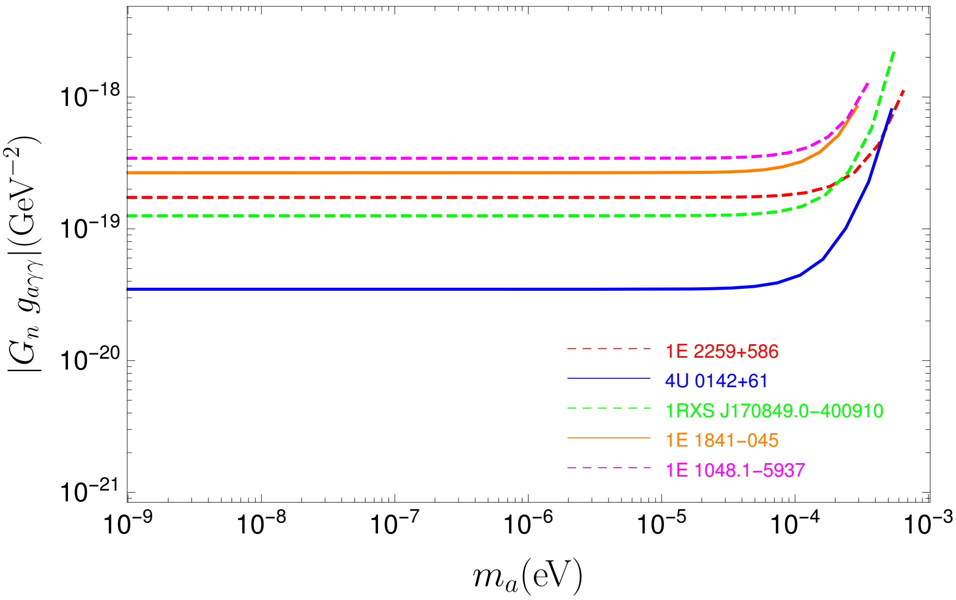

Figure 2: Figure taken from [4] (*work in progress*). The 95% CL upper limits on the product of ALP-nucleon and ALP-photon couplings $G_n \times g_{a\gamma\gamma}$ for the five magnetars in our sample, obtained for emissions in the energy range 300 keV−1 MeV, assuming core temperature $T_c = 10^9 K$.

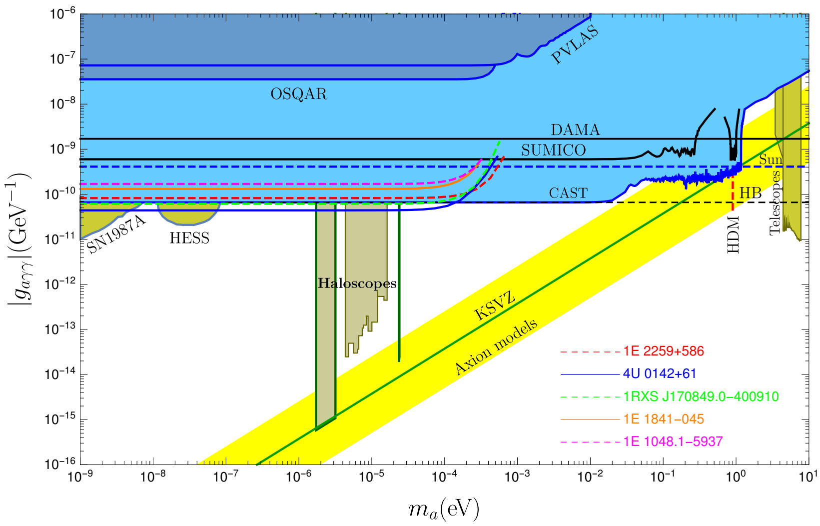

Figure 3: The 95% CL upper limits on the ALP-photon coupling $g_{a\gamma\gamma}$ for the five magnetars as labelled in the figure, obtained for emissions in the energy range 300 keV−1 MeV, assuming $T_c = 10^9$K. In contrast to the previous figure, the ALP-nucleon coupling G_N here is assumed to be just at the limit coming from cooling. All other constraints are taken from Fig. 6 of Ref. [5].

critical temperature for the onset of neutron superfluidity [6]. Superfluid pairing of a nucleon species creates a gap in its energy spectrum, which strongly suppresses the rate of axion production in the magnetar core. In addition, the nucleon Cooper pairs continuously break and re-form, each time producing an axion [7]. We will calculate axion luminosity from a magnetar due to both nucleon bremsstrahlung and Cooper pair breaking/formation, using a realistic nuclear equation of state derived from a relativistic mean field theory [8] and a model of nucleon superfluidity, which determines the superfluid gap and critical temperature throughout the magnetar.

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