Probing Axions Through Astrophysical Phenomena

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July 30, 2020

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Axions 101

Motivating Axions

The Strong CP Problem - Classical Motivation

- **CP symmetry** - physical invariance under "mirroring" the system (parity, "P symmetry") while swapping particles and antiparticles (charge conjugation, "C symmetry")
- CP symmetry assumed to hold universally, until experiments revealed that the weak interaction violations
- Eventual theoretical explanations also pointed to strong CP violation, which hasn't been observed and is severely constrained by the neutron electric dipole moment
- **Strong CP Problem** (SCPP) - why does the strong force preserve CP symmetry, when it doesn't have to?
- What is now called the **QCD axion** originally arose as part of a natural theoretical resolution of the strong CP problem

String Theory - Modern Motivation

- **Axion-like particles** - any particle which shares fundamental properties with the original QCD axion but don't necessarily resolve SCPP
- **String axiverse** - A class of ALPs predicted to exist string theory
- QCD axions must have very specific properties, but the string axiverse containa wider variety of particles, motivating current axion research to consider a broader parameter space

Axion Properties: What We Know and What We Don't

Requirements

ALPs have certain defining characteristics, some of which are presented below (other Standard Model particles included for comparison)

	ALP a	Higgs Boson h	Photon γ	Electron e
Charge	0	0	0	-1
Spin	0	0	1	1/2
Statistics	Boson	Boson	Boson	Fermion
Parity	-1	1	-1	1

In almost all cases, ALPs are **dark matter** candidates.

Undetermined Quantites

- **No expected value** for either ALP masses or their coupling strengths to other particles
- The study of ALPs considers a broad **parameter space** of mass-coupling combinations
- Much axion research goes into **constraining** the mass-coupling parameter space
- The mass and couplings are correlated for the QCD axion, but not ALPs

Axion Properties: What We Know and What We Don't

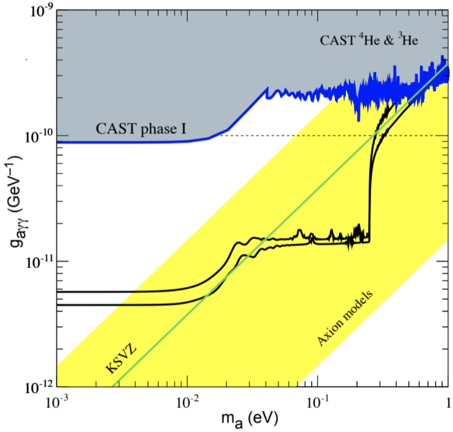


Figure: Visualization of how the QCD axion region lies within the ALP mass-coupling parameter space

Introduction to Astrophysical Axion Research

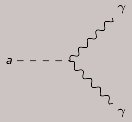
A General Approach: Axion-Photon Mixing

The Axion-Photon Interaction

Typical axionic Lagrangians include the following term.

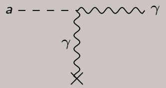
$$\frac{1}{\Lambda} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

This defines an interaction between axions a and photons $F_{\mu\nu}\tilde{F}^{\mu\nu}$ (with strength proportional to $1/\Lambda$), realized as the following Feynman diagram vertex.



Special Case: Strong Electromagnetic Fields

Photons being the quanta of electromagnetic fields, axion-photon interactions in such fields can appear as follows.



Thus, in strong electromagnetic fields we have **axion-photon mixing**, enabling the study of "invisible" axions through photons.

Finding Axions: CAST vs. Magnetars

CERN Axion Solar Telescope (CAST)

- Large-scale (110 participant) experiment conducted since 2002
- Axion source: **solar axions** should theoretically be produced from photon-photon interactions in the Sun
- Strong EM field: a 9.5 T magnetic field is maintained for roughly 10 m

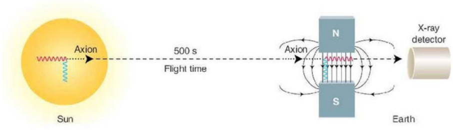


Figure: Illustration of CAST experiment.

Magnetars

- **Magnetars** - neutron stars producing very strong magnetic fields
- The unique properties of magnetars enable them to both produce axions (similar to the sun) and convert them to photons in their surrounding magnetic field (up to 10^{11} T)

The Magnetar Approach

Probing the Axion Parameter Space with Magnetars I

$$\mathcal{L}_{a\to\gamma} = \int_{\omega_i}^{\omega_f} \mathcal{L}_a \cdot p_{a\to\gamma} \, d\omega$$

Axion Luminosity $\mathcal{L}_a$

- Energy of axions produced in magnetar (per second)
- Two approaches:
  - Assume neutrino luminosity $\mathcal{L}_\nu$ dominates: $\mathcal{L}_a \leq \mathcal{L}_\nu$
  - Derive an analytic expression for $\mathcal{L}_a$

Conversion Probability $P_{a\to\gamma}$

- Probability of axion-to-photon conversion
- Asymptotic limit of function $P_{a\to\gamma}(x)$ varying with distance from magnetar, emerging as solution to coupled system of ODEs

Produced Photon Luminosity $\mathcal{L}_{a\to\gamma}$

- Energy of photons produced from axions (per second)
- Requires selection of a frequency band (FB), $\omega \in [\omega_i, \omega_f]$
- Total photon luminosity $\mathcal{L}_\gamma$ in given FB can be measured, thus **axion mass, coupling can be constrained** by requiring $\mathcal{L}_\gamma \leq \mathcal{L}_{a\to\gamma}$

Probing the Axion Parameter Space with Magnetars II

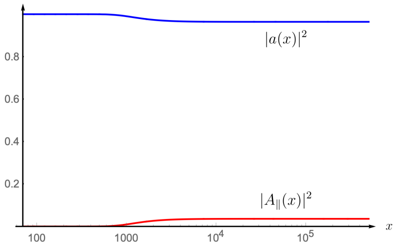


Figure: Reproduced amplitudes of axion field a and photon field $A_{||}$ as a function of $x = r/r_0$ for radial distance from magnetar r and magnetar radius r_0. Benchmark input parameters selected. Normalized such that probabilities sum to unity.

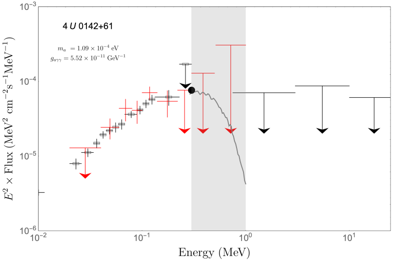
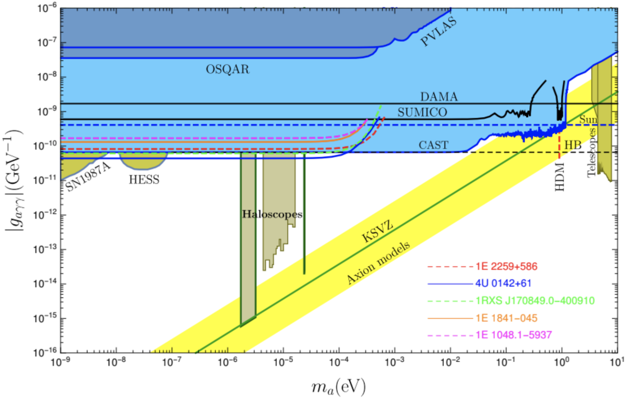


Figure: Reproduced visualization of how photons produced from axions (gray curve) compare with experimental data points for total observed photons for a given magnetar (black and red points/lines). Photons production computed using maximal coupling $g_{a\gamma\gamma}$ permitted by experimental data for a given axion mass m_a (demonstrated by intersection at black dot).

Comparing Methodologies

So how do CAST and magnetar-based findings compare?



A computational approach using limited data sets can rival an expensive, long-lasting experiment!

Conclusion

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Takeaways

- Axions are a well-motivated, promising area of beyond-the-Standard-Model high energy physics research
- Magnetars enable a uniquely accessible yet powerful methodology for studying axions
- The success already found with magnetar-based axion research points to an even brighter future as our understanding of magnetars continues to develop

Acknowledgements

- I'd like to thanks Dr. Strauss and Dr. Abbott for overseeing such a successful remote REU program.
- I'd also like to thank Dr. Sinha for advising me for the duration of this research
- And I'd like to thank you all for listening!

Questions?