PROCEEDINGS OF SCIENCE

The Growth and Evolution of Axion Clouds around Pulsars

Dion Noordhuis,[a] **Anirudh Prabhu,**[b] **Christoph Weniger**[a] **and Samuel J. Witte**[c,*]

[a] *GRAPPA Institute, Institute for Theoretical Physics Amsterdam and Delta Institute for Theoretical Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands*

[b] *Princeton Center for Theoretical Science, Princeton University, Princeton, NJ 08544, USA*

[c] *Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Parks Road, Oxford OX1 3PU, UK*

E-mail: samuel.witte@physics.ox.ac.uk

Axions can be efficiently produced from the dynamical evolution of the electromagnetic fields in the polar caps of neutron stars. If the axion mass lies roughly in the range 10^{-10} eV $\lesssim m_a \lesssim 10^{-4}$ eV, a sizable fraction of the sourced axions will be gravitionally bound to the neutron star, accumulating on astrophysical timescales and producing high density clouds of axions. The characteristic density of these clouds near the neutron star surface can reach and exceed the local dark matter density by more than 20 orders of magnitude, producing environments in which the feeble nature of the axion coupling can be compensated for by large axion field values. We comment on a number of striking observational features that can arise in these systems, and demonstrate that existing radio telescopes can dramatically improve sensitivity to the axion-photon coupling.

1st General Meeting and 1st Training School of the COST Action COSMIC WSIPers
September 5, 2023
Bari, Italy

*Speaker

PoS(COSMICWISPers)022

1. Introduction

Axions are incredibly promising candidates for new fundamental physics, as they provide a leading solution to major outstanding questions in both high-energy theory and astrophysics (namely, the questions of why QCD seems conserve charge-parity symmetry, and what is the true underlying nature of dark matter), and appear abundantly in a variety of well-motivated extensions of the Standard Model. Recent years have seen an immense rise in the number of techniques proposed to detect axions, with both laboratory and indirect astrophysical observations offering a promising outlook in the search for these elusive particles (see *e.g.* [1–3]). One of the particularly compelling ideas that is emerged in recent years is to use radio telescopes to look for axion-photon interactions in the magnetospheres of neutron stars; here, the large magnetic fields and ambient plasma can play a crucial role in resonantly amplifying the interaction with the Standard Model, thereby overcoming the feeble nature of axion-photon coupling and giving rise to a variety of distinctive signatures (see *e.g.* [4–16]).

Rather than amplifying the axion-photon interaction, an alternative approach to offset the feeble nature of the axion coupling is to identify environments which naturally host abnormally large axion occupation numbers. Ref. [15] recently proposed a relatively simple mechanism capable of generating large axion field values near the surfaces of all pulsars. The general idea is that small-scale oscillations of the electromagnetic fields in the neutron star magnetosphere (which are intrinsically linked to acceleration, pair production, and electromagnetic emission in the magnetosphere) will unavoidably source a local population of axions, with typical axion energies roughly spanning the MHz-GHz range; if the axion mass lies near, or even slightly below, this regime, a sizable fraction of the sourced axions will become gravitaionally bound to the neutron star. Since axion interactions are weak, these gravitationally bound axions will continue to grow around the neutron star, accumulating on astrophysical timescales. This process leads to the formation of 'axion clouds', which can produce densities in excess of the local dark matter density by more than 20 orders of magnitude [15].

The appearance of axion clouds around pulsars are relatively generic, relying only on two very modest assumptions, namely: (1) that there exists an axion which couples to electromagnetism through the conventional dimension-five operator, $\mathcal{L} \supset -g_{a\gamma} a \, F_{\mu\nu}\tilde{F}^{\mu\nu}$ (importantly, one need not make any assumption that the axion-photon coupling be large – these objects form even when $g_{a\gamma} \sim M_{\rm Planck}^{-1}$), and (2) the axion mass is such that bound axions can be efficiently produced in the magnetosphere (this roughly translates into the condition that 10^{-10} eV $\lesssim m_a \lesssim 10^{-4}$ eV). The clouds tend to have a rather cuspy energy density profile, peaking near the neutron star surface and falling off at larger radii as $\rho \propto r^{-4}$ [15]. The characteristic densities found in the cloud are expected to evolve over the course of the neutron star lifetime, changing in response the evolving properties of the neutron star and dissipating energy via interactions with the ambient plasma. In the following sections, we briefly outline the formation mechanism, evolution history, and observable consequences that arise from these systems, showing that radio telescope observations of these systems could provide a powerful new probe of light axions.

2. The Formation and Evolution of Axion Clouds

It was realized very early in the studies of neutron star magnetospheres that the parallel component of the induced electric field near the surface of the neutron star, $E_{\parallel} \equiv (\vec{E} \cdot \vec{B})/|\vec{B}|$, is strong enough to overcome the force of gravity, allowing charges to be directly extracted from the upper layers of a neutron star's surface [17]. The charges generated from this process in turn screen $E_{\parallel}$, driving the system toward a stable equilibrium with $E_{\parallel} = 0$; in order for an equilibrium to be maintained, however, the charges must co-rotate with the neutron star – a requirement which cannot be maintained at large radial distances near the light cylinder (LC), $R_{\rm LC} = 1/\Omega$ (where Ω is the rotational frequency of the neutron star), where the co-rotation velocity exceeds the speed of light. The breakdown of screening near the light cylinder induces a current along the open field lines of pulsars, and leads to the appearence of what are known as 'vacuum gaps' – small localized regions in the magnetosphere where $E_{\parallel} \neq 0$ [18].

The most well-studied of these vacuum gaps is located at the polar cap of the star – a small region situated just above the magnetic poles, and with a spatial scale on the order of $\mathcal{O}(100)$ meters [18, 19]. In the polar caps, an initially un-screened $E_{\parallel}$ extracts a current and accelerates these charges to ultra-relativistic speeds. The electrons emit high-energy curvature radiation, which travels a finite distance before pair producing in the strong magnetic fields. The newly produced pairs radiate sychro-curvature radiation, in turn producing a subsequent generation of charges in the gap; this process continues until the plasma is sufficiently dense to efficiently drive $E_{\parallel} \to 0$. At this point, the plasma responsible for the screening process is still relativistic, and thus will free-stream away from (or toward) the neutron star, eventually leading to the re-appearance of the un-screened electric field. This process is inherently quasi-periodic with a characteristic timescale on the order of $\mathcal{O}(1 - 10)$ times the light-crossing time of the gap (see *e.g.* [20, 21] for recent simulations of this dynamical screening process).

The coupling of axions to electromagnetism leads to a source term in the axion equation of motion of the form

$$\left(\Box + m_a^2\right) a(x) = g_{a\gamma\gamma} \, (\vec{E} \cdot \vec{B})(x) \, . \tag{1}$$

As a result, the space-time oscillations in $\vec{E} \cdot \vec{B}$ lead to the production of on-shell axions, with the differential rate of axion production given by [12, 13]

$$\frac{d\dot{N}_a}{d^3k} = \frac{\left|\tilde{S}(\vec{k})\right|^2}{2(2\pi)^3 \omega_a(\vec{k}) T} \, , \tag{2}$$

where $\omega_a(\vec{k})$ is the energy of mode $\vec{k}$, T is the characteristic period of the gap discharge process, and $\tilde{S}(\vec{k})$ is the Fourier transform (FT) of the source term, *i.e.*

$$\tilde{S}(\vec{k}) = g_{a\gamma\gamma} \int d^4x \, e^{ik\cdot x} (\vec{E} \cdot \vec{B})(x) \, . \tag{3}$$

The large electromagnetic fields near the surface of the neutron star imply that this dynamical screening process can generate as many as 10^{50} axions per second [13].

The spectrum of sourced axions is broadband, with characteristic energies spanning the MHz-GHz range. For sufficiently light axion masses, a majority of these axions will be relativistic, and

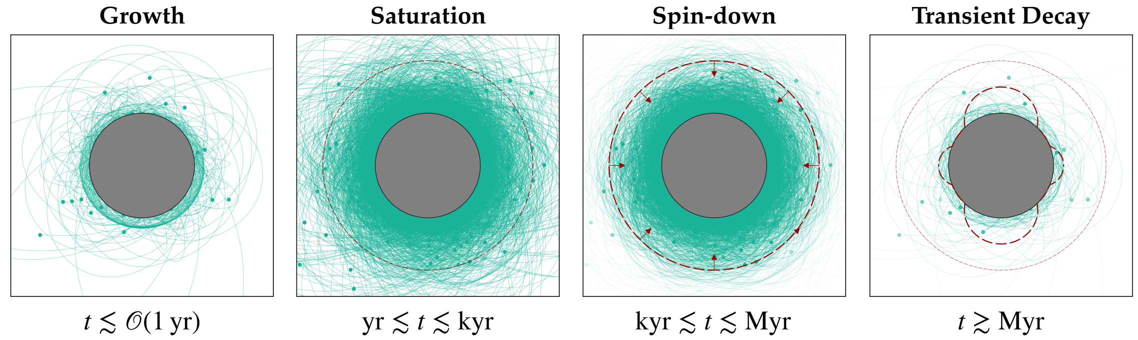

Figure 1: Overview of the evolution of axion clouds. **Growth** (left): axion production is efficient early in the neutron star lifetime, and axion interactions are not relevant, implying the cloud grows unimpeded. **Saturation** (center-left): at large radial distances, resonant axion-photon conversion causes the density profile to saturate. The inner part of the density profile remains unaltered by resonant-photon mixing, but for sufficiently large axion-photon couplings the growth of the cloud can be quenched via radiative processes in the polar cap [16]. **Spin-down** (center-right): magneto-rotational spin-down decreases the efficiency of axion production, and reduces the characteristic charge densities, implying resonant transitions begin occurring at smaller radii. **Transient Decay** (right): late in the lifetime of the star the dynamical screening process ceases, terminating axion production. The magnetosphere relaxes to a fully charge-separated state, opening resonant transitions for all remaining axions – all remaining energy is radiated in the form or radio emission.

will free-stream away from the neutron star. During the transit of the magnetosphere, some of these axions can resonantly mix with the Standard Model photon (a process which occurs when the four-momentum of the axion and photon are approximately equal, *i.e.* $k_\mu^a \simeq k_\mu^\gamma$), generating a large broadband radio flux. A recent analysis searching for excess radio emission from 27 nearby neutron stars has lead to leading limits on the axion-photon coupling across a broad range of axion masses, demonstrating the power of using the pulsar's local electromagnetic fields to source axions [13].

If the axion mass lies in the MHz-GHz range, or even slightly below, then a non-negligible fraction of the produced axions will necessarily be gravitationally bound to the neutron star. The inherently feeble nature of axion couplings implies that these particles do not easily scatter off the ambient medium, and as such will accumulate around the neutron star on long astrophysical timescales, forming what are referred to as 'axion clouds' [15].

To understand the evolution of axion clouds, one must self-consistently follow the production and evolution of axions in these systems – determining how, and when, these particles dissipate their energy. This can be accomplished by simulating a mock population of neutron stars from birth to death, carefully tracing the the magneto-rotational spin-down of the star, the change in the production rates of bound axions, and the evolutionary trajectories of axions through the magnetosphere [15]. In the absence of interactions, the axions are found to produce a energy density profile $\rho \propto r^{-4}$ for $r \gtrsim r_{\rm NS}$, with the profile growing linearly in time over the early stages of its lifetime until spin-down decreases the efficiency of axion production can causes the profile to saturate. Axions, however, are not non-interacting particles, and this naive time evolution merely reflects the behavior in the limit that the axion decay constant f_a is large (*i.e.* the limit where all couplings are negligibly small). In reality there are a number processes which can inhibit or modify the evolution of the axion cloud, including most notably the resonant mixing of axions with radio photons, and the

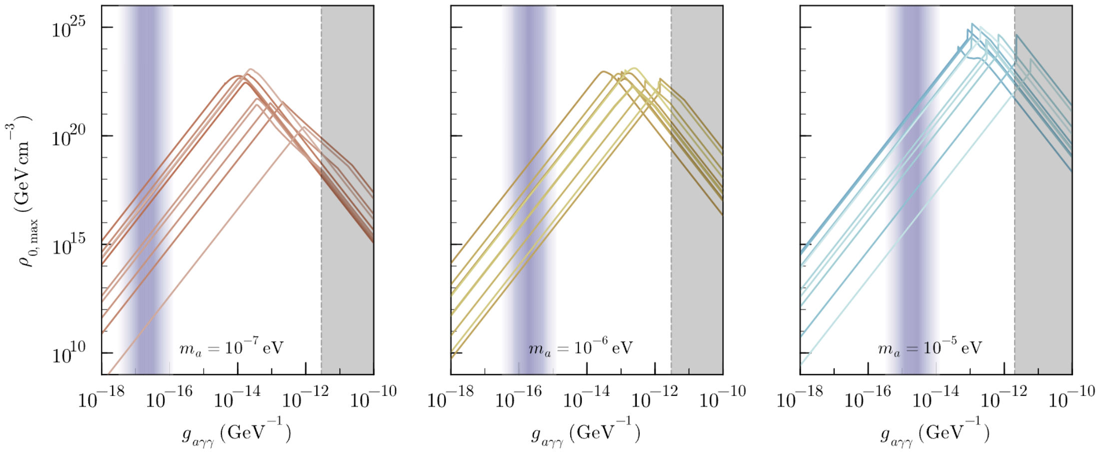

Figure 2: Maximal density of the axion cloud for each neutron star in our sample as a function of axion-photon coupling and axion mass. The QCD axion parameter space is shown in purple, and current excluded parameter space is shown in grey [13].

dissipation of energy in the polar cap via the axion-induced electric field [15, 16]. The former process has the effect of reducing the density profile at large radii, but tends to leave the near-field regime unaltered (this is because tightly bound axions never traverse regions where on-shell photon production is kinematically accessible). The latter process instead has the potential to quench axion production, establishing an equilibriated density profile – for large axion-photon couplings, this equilibrium can be achieved before spin-down has had time to alter the axion production rate. As the neutron star spins down, the characteristic charge density in the magnetosphere falls, causing resonant production to occur at smaller radii and in turn dissipating more of the axion cloud. On timescales $t \gtrsim$Myr, pair production in the magnetosphere stops (halting axion production) and the magnetosphere charge-separates, opening resonant photon production for all remaining axions – this process dissipates the remainder of the axion cloud in the form a transient decay. The general evolution of the axion cloud is illustrated in Fig. 1, and described in more detail in Ref. [15].

In order to illustrate the immense densities that can be achieved, we plot in Fig. 2 the maximum energy density in the axion cloud achieved over the course of the lifetime for each simulated neutron star as a function of the axion photon coupling and axion mass. Here, one can see that even for couplings on the order of the inverse Planck scale, the characteristic densities can extend as high as $\sim 10^{15}$ GeV/cm^3.

Axion clouds can give rise to a variety of observational signatures, including narrow spectral features at radio frequencies and a short-time periodic suppression of the intrinsic radio spectrum of the pulsar. Here, we comment on the former (as discussed in Ref. [15]), and refer the reader to [16] for a discussion of vacuum radio emission and pulsar nulling.

The resonant axion-photon transitions which deplete the axion cloud at large radii naturally lead to the production of radio emission. Photons sourced form this process are kinematically confined to energies $m_a \leq \omega \lesssim m_a\sqrt{1+v_{\rm esc}^2}$ (where $v_{\rm esc}$ is the escape velocity evaluated at the resonant radius) – this implies the signal will appear as a spectral line, with a width on the order of a few percent, sitting just above the axion mass. By synthesizing galactic neutron star populations,

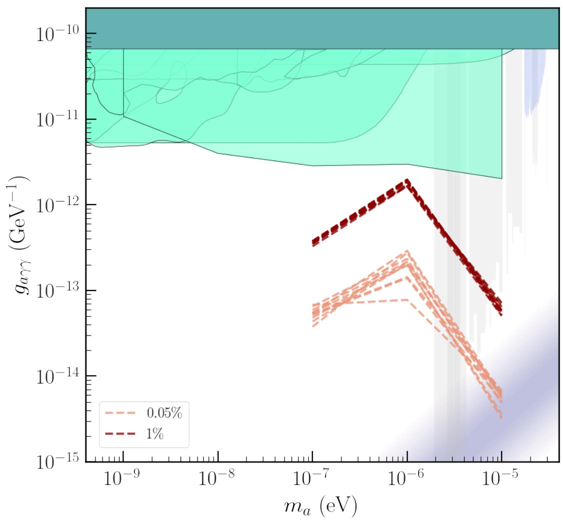

Figure 3: Estimated sensitivity of current radio telescopes to the spectral radio feature produced by resonant photon production from axion clouds. For reference we also show the parameter space for the QCD axion (purple), and current constraints from astrophysical searches (light green and light blue), axion haloscopes (grey), and heliscopes (dark green). See [15] for additional details.

one can estimate the sensitivity that radio telescopes should have to such a feature – this has been derived in [15], and reproduced in Fig. 3, by imposing a threshold which requires either 1% or 0.05% of the total neutron star population in the Milky Way produce a spectral line above the detection threshold of modern radio telescopes.

3. Conclusions

Here, we have discussed the formation and evolution of dense clouds of gravitationally bound axions which are produced from the dynamical screening of the electric field in the polar caps of neutron stars. We have shown that the existence of dense axion clouds are relatively generic – they merely require the existence of an axion with a mass 10^{-10} eV $\lesssim m_a \lesssim 10^{-4}$ eV, and a coupling to electromagnetism (with no strong constraint on the size of that coupling beyond the mild constraint that it is not $g_{a\gamma\gamma} \ll M_{\rm Planck}^{-1}$). The clouds evolve over the course of the neutron star lifetime, emitting a spectral line at radio frequencies. Using a synthesized population of neutron stars, we have demonstrated that current radio telescopes could dramatically improve sensitivity to axion-photon interactions in a broad range of parameter space. While we have focused on one observable that is expected to arise in these systems, the phenomenology of these objects is rich, and they may very well prove to be transformative in how we search for axions in astrophysics.

4. Acknowledgments

SJW acknowledges support from the Royal Society University Research Fellowship (URF-R1-231065). This article is based upon work from COST Action COSMIC WISPers CA21106, supported by COST (European Cooperation in Science and Technology).

References

[1] Igor G. Irastorza and Javier Redondo. "New experimental approaches in the search for axion-like particles". In: *Prog. Part. Nucl. Phys.* 102 (2018), pp. 89–159. DOI: 10.1016/j.ppnp.2018.05.003. arXiv: 1801.08127 [hep-ph].

[2] Kimberly K. Boddy et al. "Snowmass2021 theory frontier white paper: Astrophysical and cosmological probes of dark matter". In: *JHEAp* 35 (2022), pp. 112–138. DOI: 10.1016/j.jheap.2022.06.005. arXiv: 2203.06380 [hep-ph].

[3] C. B. Adams et al. "Axion Dark Matter". In: *Snowmass 2021*. Mar. 2022. arXiv: 2203.14923 [hep-ex].

[4] Fa Peng Huang et al. "Radio telescope search for the resonant conversion of cold dark matter axions from the magnetized astrophysical sources". In: *Phys. Rev. D* 97.12 (2018), p. 123001. DOI: 10.1103/PhysRevD.97.123001. arXiv: 1803.08230 [hep-ph].

[5] Anson Hook et al. "Radio Signals from Axion Dark Matter Conversion in Neutron Star Magnetospheres". In: *Phys. Rev. Lett.* 121.24 (2018), p. 241102. DOI: 10.1103/PhysRevLett.121.241102. arXiv: 1804.03145 [hep-ph].

[6] Mikaël Leroy et al. "Radio Signal of Axion-Photon Conversion in Neutron Stars: A Ray Tracing Analysis". In: *Phys. Rev. D* 101.12 (2020), p. 123003. DOI: 10.1103/PhysRevD.101.123003. arXiv: 1912.08815 [hep-ph].

[7] Benjamin R. Safdi, Zhiquan Sun, and Alexander Y. Chen. "Detecting Axion Dark Matter with Radio Lines from Neutron Star Populations". In: *Phys. Rev. D* 99.12 (2019), p. 123021. DOI: 10.1103/PhysRevD.99.123021. arXiv: 1811.01020 [astro-ph.CO].

[8] Richard A. Battye et al. "Dark matter axion detection in the radio/mm-waveband". In: *Phys. Rev. D* 102.2 (2020), p. 023504. DOI: 10.1103/PhysRevD.102.023504. arXiv: 1910.11907 [astro-ph.CO].

[9] Samuel J. Witte et al. "Axion-photon conversion in neutron star magnetospheres: The role of the plasma in the Goldreich-Julian model". In: *Phys. Rev. D* 104.10 (2021), p. 103030. DOI: 10.1103/PhysRevD.104.103030. arXiv: 2104.07670 [hep-ph].

[10] Joshua W. Foster et al. "Extraterrestrial Axion Search with the Breakthrough Listen Galactic Center Survey". In: *Phys. Rev. Lett.* 129 (25 Dec. 2022), p. 251102. DOI: 10.1103/PhysRevLett.129.251102. URL: https://link.aps.org/doi/10.1103/PhysRevLett.129.251102.

[11] Samuel J. Witte et al. "Transient radio lines from axion miniclusters and axion stars". In: *Phys. Rev. D* 107.6 (2023), p. 063013. DOI: 10.1103/PhysRevD.107.063013. arXiv: 2212.08079 [hep-ph].

[12] Anirudh Prabhu. "Axion production in pulsar magnetosphere gaps". In: *Phys. Rev. D* 104.5 (2021), p. 055038. DOI: 10.1103/PhysRevD.104.055038. arXiv: 2104.14569 [hep-ph].

[13] Dion Noordhuis et al. "Novel Constraints on Axions Produced in Pulsar Polar-Cap Cascades". In: *Phys. Rev. Lett.* 131.11 (2023), p. 111004. DOI: 10.1103/PhysRevLett.131.111004. arXiv: 2209.09917 [hep-ph].

PoS(COSMICWISPers)022

[14] R. A. Battye et al. "Searching for time-dependent axion dark matter signals in pulsars". In: *Phys. Rev. D* 108 (6 Sept. 2023), p. 063001. DOI: 10.1103/PhysRevD.108.063001. URL: https://link.aps.org/doi/10.1103/PhysRevD.108.063001.

[15] Dion Noordhuis et al. "Axion Clouds around Neutron Stars". In: (July 2023). arXiv: 2307.11811 [hep-ph].

[16] Andrea Caputo et al. "Pulsar Nulling and Vacuum Radio Emission from Axion Clouds". In: (Nov. 2023). arXiv: 2311.14795 [hep-ph].

[17] Peter Goldreich and William H. Julian. "Pulsar Electrodynamics". In: ApJ 157 (Aug. 1969), p. 869. DOI: 10.1086/150119.

[18] M. A. Ruderman and P. G. Sutherland. "Theory of pulsars: polar gaps, sparks, and coherent microwave radiation." In: ApJ 196 (Feb. 1975), pp. 51–72. DOI: 10.1086/153393.

[19] A. N. Timokhin and J. Arons. "Current Flow and Pair Creation at Low Altitude in Rotation Powered Pulsars' Force-Free Magnetospheres: Space-Charge Limited Flow". In: *Mon. Not. Roy. Astron. Soc.* 429 (2013), p. 20. DOI: 10.1093/mnras/sts298. arXiv: 1206.5819 [astro-ph.HE].

[20] Alexander Philippov, Andrey Timokhin, and Anatoly Spitkovsky. "Origin of Pulsar Radio Emission". In: *Phys. Rev. Lett.* 124.24 (2020), p. 245101. DOI: 10.1103/PhysRevLett.124.245101. arXiv: 2001.02236 [astro-ph.HE].

[21] Fábio Cruz et al. "Coherent emission from QED cascades in pulsar polar caps". In: (Aug. 2021). DOI: 10.3847/2041-8213/ac2157. arXiv: 2108.11702 [astro-ph.HE].