Search for Axion Dark Matter with MeerKAT UHF Sideband in 1051-1088MHz postprint

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Date: 2025-09-28T12:14:27+00:00

Abstract

Axions, as a leading dark matter (DM) candidate particle, can be converted into photons in the magnetosphere of neutron stars (NS) via the Primakoff effect, producing narrow-band radio emission that can be detected by high-sensitivity radio telescopes. Previous studies using MeerKAT Ultra-High Frequency (UHF) band (544-1088 MHz) observations searched for axion dark matter-induced signals from the isolated neutron star J0806.4-4123, but excluded the 1051-1088 MHz sub-band to avoid potential sideband contamination. To explore this unexplored parameter space, we reprocessed the 1000-1088 MHz sub-band data employing optimized radio frequency interference (RFI) flagging and refined sideband calibration. The flux stability of calibrator sources and their consistency with the MeerKAT system equivalent flux density confirmed the reliability of data within the 1000-1080 MHz range, while the 1080-1088 MHz sub-band was rejected due to flux anomalies. No signals exceeding 5σ significance were detected within the axion mass range of 4.136-4.467 eV (1000-1080 MHz), including the previously unexplored range of 4.347-4.467 eV (1051-1080 MHz). Our null detection results set new stringent constraints using MeerKAT neutron star data, excluding axion-photon coupling $|g\_a\gamma\gamma|$ 8.2×10^{-12} GeV^{-1} for dark matter masses between 4.347 and 4.467 eV at 95% confidence level.

Full Text

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Received 2025 March 3; revised 2025 April 24; accepted 2025 May 1; published 2025 June 16

Abstract

The axion, a leading dark matter (DM) candidate, can convert to photons in neutron star (NS) magnetospheres via the Primakoff effect, producing narrow-band radio emission that may be detected with high-sensitivity radio telescopes. Previous studies searched for axion DM-induced signals from the isolated NS J0806.4-4123 using observations of the MeerKAT UHF band (544-1088 MHz), but excluded the 1051-1088 MHz subband to mitigate potential sideband contamination. To probe this unexplored parameter space, we reprocessed the 1000-1088 MHz subband data using optimized radio frequency interference (RFI) flagging and meticulous sideband calibration. The flux stability of the calibrators and the consistency with MeerKAT' s system equivalent flux density confirmed the reliability of the data within the 1000-1080 MHz range, while the 1080-1088 MHz subband was omitted due to flux anomalies. No significant signals exceeding 5σ significance were detected within the axion mass range of 4.136-4.467 eV (1000-1080 MHz), including the previously unprobed range 4.347-4.467 eV (1051-1080 MHz). Our null detection sets new stringent constraints with MeerKAT NS data, excluding axion-photon couplings |g_{a$\gamma\gamma$}| 8.2×10^{-12} GeV^{-1} at the 95% confidence level for DM masses between 4.347 and 4.467 eV.

Key words: (cosmology:) dark matter -methods: observational -stars: neutron -radio lines: general

1. Introduction

It has been firmly established that the majority of the matter content in the Universe consists of dark matter (DM) [**?**, **?**], a substance that interacts extremely weakly with visible matter. Despite its ubiquity, the nature of this elusive component remains largely unknown (see [**?**, **?**] for comprehensive reviews). The quantum chromodynamics (QCD) axion, originally proposed to solve the strong CP problem in QCD [**?**, **?**, **?**], also serves as a compelling DM candidate [**?**, **?**, **?**, **?**]. The interaction between axion DM and photons forms the basis for axion DM searches, as described by the Lagrangian equation $\mathcal{L} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$, where $\mathbf{E}$ and $\mathbf{B}$ denote the electric and magnetic fields respectively, a represents the axion DM field, and $g_{a\gamma\gamma}$ is the axion-photon coupling parameter [**?**]. Both ground-based experiments [**?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**] and astrophysical observations have explored a wide range of the axion-photon coupling parameter space.

A novel axion DM detection method has attracted significant attention recently. When axion DM traverses a neutron star (NS) magnetosphere, resonant conversion could occur if the plasma frequency matches the axion DM mass ($\omega_p \approx m_a$) via the Primakoff effect [**?**], making eV-scale axion DM convert into monochromatic radio photons [**?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**]. The photon flux primarily depends on the local axion DM density (ρ_{DM}), the axion DM mass (m_a), and the axion-photon coupling parameter ($g_{a\gamma\gamma}$), as well as NS parameters such as its radius (r_{NS}), mass (M_{NS}), surface magnetic field strength (B_0), rotation period (P), and distance to Earth (D) [**?**]. Subsequent theoretical work has refined these flux calculations by incorporating various effects, such as photon refraction, reflection, plasma broadening effects, anisotropic medium responses, and general relativistic corrections [**?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**].

Recent studies using high-sensitivity radio telescopes have searched for narrowband signals from the magnetospheres of individual NSs or NS populations [**?**, **?**, **?**, **?**]. In a notable study, [**?**] (hereafter Zhou22) analyzed UHF-band radio observations of the isolated NS J0806.4-4123 using the MeerKAT telescope [**?**]. Their analysis excluded a parameter region corresponding to $g_{a\gamma\gamma} \gtrsim 9.3 \times 10^{-12}$ GeV^{-1} at the 95% confidence level for DM masses between 3.18 and 4.35 eV. Despite this progress, limitations remain in the approach adopted by Zhou22. Specifically, Zhou22 utilized the MeerKAT Science Data Processor (SDP) pipeline products, which cover the UHF band (544–1088 MHz), but exclude the highest frequency 37 MHz subband (1051–1088 MHz) to mitigate potential sideband contamination. However, this extended frequency range provides critical complementarity to cavity-based haloscope experiments for the eV axion DM mass range, such as the Axion Dark Matter Experiment (ADMX; [**?**]) and the Center for Axion and Precision Physics Research (CAPP; [**?**]), through an independent astrophysical approach. We reprocessed the raw data from the 1000–1088 MHz subband using an enhanced pipeline with optimized radio frequency interference (RFI) flagging algorithms and meticulous sideband calibration, thereby enabling an axion DM search across the UHF sideband.

The rest of this paper is organized as follows. In Section 2, we describe the observation and data reduction process. Section 3 presents our results and sets constraints on the axion DM parameter space. Finally, Section 4 provides a summary and discussion of this research.

2. Observations and Data Reduction

We used the observational data obtained by Zhou22 in the MeerKAT UHF band (544–1088 MHz), targeting the isolated NS J0806.4-4123 (R.A. = 08h06m23.3471s, decl. = -41°22’ 30.179” , J2000). The observations were carried out from 2020 March to May, with a total integration time of 10 hr and a time resolution of 8 s, divided into six sessions. During each session, 8 minutes were allocated at both the start and the end to observe a bandpass calibrator (J0408-6545 or J1939-6342 depending on the Local Sidereal Time range). In addition, observations included a 2 minute viewing of a gain calibrator, J0828-3731, prior to each target observation. All observations were conducted using the MeerKAT “Spectral Line” observing mode, which provides 32768 frequency channels across the UHF band, reaching a frequency resolution of about 16.602 kHz.

Data reduction of MeerKAT spectral line observations was performed using the Containerized Automated Radio Astronomy Calibration (CARACal) pipeline [?]. First, data in the 1000–1088 MHz frequency range of 4818 channels were split out for processing. Second, we flagged 3σ outliers on calibrators using the automated RFI flagging CASA task “tfcrop” [?]. Then, the flux and gain calibrators mentioned above were utilized to derive solutions for flux scale, delay, bandpass, and complex gains (amplitude and phase). These solutions were first applied to the calibration sources for diagnosis, which identified poor data quality in the 1080–1088 MHz range. After flagging 1080–1088 MHz, the solutions were applied to the target field to correct for flux scale, time delay, frequency response, and time-variable gain fluctuations.

Subsequently, we conducted two rounds of phase self-calibration to correct for residual phase errors caused by atmospheric fluctuations. To remove the contribution of the continuum emission and derive spectral line features, we fitted and subtracted a linear continuum model from the data in the uv plane (Fourier space) in the 1000–1080 MHz frequency range. Then, the spectral line cubes were created with the package “WSClean” [?, ?]. We adopted natural weighting during the imaging process to maximize imaging sensitivity, thereby enhancing the ability to detect weak signals. They were cleaned to five times the theoretical noise level to suppress the sidelobes of the point-spread function (PSF) and enhance the signal-to-noise ratio (SNR).

Due to the point source properties of NSs, we extracted its spectrum over a single pixel at the NS position (also the phase center of the image), correcting for beam size variations across channels to accurately capture the total point-source flux density.

[Figure 1: see original paper]. The derived fluxes of calibrators after applying calibration solutions across 1040–1088 MHz.

[Figure 2: see original paper]. A channel map at 1077 MHz of the final spectral line cube for illustration. The target NS J0806.4-4123 is located at the image center, marked by a square cyan dot. A source-free annulus surrounding the target is drawn to measure the noise spectrum. The lower left ellipse next to the axes shows the synthesized beam size, which is about 42 × 36 .

3. Results

3.1. Cube Reliability Analysis

The fluxes of calibrators across 1040-1088 MHz were derived for calibration checking. Figure 1 shows that both the bandpass and phase calibrators exhibit stable fluxes from 1040-1080 MHz, but display significant deviations above 1080 MHz. The flux of the bandpass calibrator decreases more rapidly with frequency in the 1082-1085 MHz range, contrasting with the nearly flat spectrum in 1040-1080 MHz. This suggests that the calibration is reliable at 1040-1080 MHz but poor at 1082-1088 MHz. We conservatively excluded the 1080-1088 MHz subband to avoid possible systematic biases.

Under the assumption of thermal noise dominance, the noise in the NS spectral cube is expected to scale with the MeerKAT system equivalent flux density (SEFD), providing a benchmark to validate the data quality. The noise for each channel was estimated by measuring the rms (σ_i) from a source-free annulus surrounding the target in each channel map, as illustrated in Figure 2. The 1040-1042 MHz subband was excluded due to severe RFI contamination. In particular, the rms noise curve at 1060-1080 MHz exhibits a characteristic rise-and-fall fluctuation. This pattern closely matches the frequency-dependent trend of MeerKAT' s SEFD (see bottom panel of Figure 3). The rms-SEFD alignment indicates that the observed fluctuations are due to MeerKAT' s intrinsic noise properties, validating the robustness of our data reduction pipeline.

We also compared the noise levels with Zhou22 as shown in the top panel of Figure 3. First, our noise level of 0.20 ± 0.01 mJy beam^{-1} in 1000-1051 MHz is 1.45× lower than Zhou22' s 0.29 ± 0.05 mJy beam^{-1}. This improvement aligns with the expected sensitivity gain of MeerKAT when switching from Robust-0 to natural weighting. Second, while Zhou22 showed multiple sharp spectral features, our results demonstrate improvements in RFI removal. Through comprehensive validation of MeerKAT UHF band (1000-1080 MHz) data quality —including calibrator flux stability, noise-SEFD consistency, and comparison with Zhou22—we confirm the reliability of the reprocessed spectral cubes for axion DM searches.

[Figure 3: see original paper]. Top panel: The rms noise level of this work (black), compared with Zhou22 (blue). Our analysis used natural weighting while Zhou22 used a robust parameter of 0, which leads to an improvement in sensitivity by roughly 1.45×. Bottom panel: The measured MeerKAT UHF-Band SEFD in Jy, provided by the South African Radio Astronomy Observatory (SARAO) via personal communication. The alignment between rms and SEFD suggests that fluctuations in the noise spectrum likely originate from the telescope' s instrumental performance.

3.2. Axion DM-induced Signal Search

Using this validated spectral line cube, we conducted a blind search for narrowband radio signals throughout the axion mass range 4.136–4.467 eV, with particular focus on the previously unexplored 4.347–4.467 eV subrange (1051–1080 MHz). Following the analysis in Zhou22, the spectral width of the NS radio signal is approximately equal to the MeerKAT 32k mode channel bandwidth (16 kHz). To quantify the significance of spectral features in each channel, we derived the SNR for each channel, calculated as:

$$\mathrm{SNR}_i = \frac{d_i - \mu_i}{\sigma_i}$$

where d_i is the target flux, σ_i is the uncertainty of the target flux, and μ_i is the background value. Due to the point-source properties of NSs, we extracted the target flux for each channel (d_i) over a single pixel at the NS position, correcting for beam size variations across channels to accurately capture the total point-source flux density. The background value and flux uncertainty for each channel (μ_i and σ_i) were estimated by measuring the mean and rms of a source-free annulus surrounding the target in each channel map, as illustrated in Section 3.1 and Figure 2.

The top panel in Figure 4 shows the observed flux density, background value, and flux uncertainty of NS J0806.4-4123, while the bottom panel displays the SNR of the target region. No emission features above the 5σ threshold were detected within the frequency range of 1000–1080 MHz.

[Figure 4: see original paper]. The top panel shows the measured flux density of the isolated NS J0806.4-4123 (blue), with flux uncertainty (1σ, black) and background value (yellow). The bottom panel is the SNR of the target region across the 1000–1080 MHz search range. No significant emission (SNR $> 5\sigma$) features were detected.

3.3. Constraints on Axion Coupling Parameter

In the case of null detection, we placed upper limits on the axion-photon coupling constant $g_{a\gamma\gamma}$ using a Bayesian grid-based parameter estimation framework [**?**]. The likelihood function was constructed as:

$$\mathcal{L}(m_a, g_{a\gamma\gamma}, \theta, \theta_m) = \prod_{i=1}^{N_{\mathrm{ch}}} \frac{1}{\sqrt{2\pi}\sigma_i} \exp\left[-\frac{(d_i - \mu_i - S_i(m_a, g_{a\gamma\gamma}, \theta, \theta_m))^2}{2\sigma_i^2}\right]$$

where ν_i labels the frequency channel, with a total of N_{ch} channels. d_i is the target flux, while μ_i is the background value and σ_i is the uncertainty of the target flux, measured in the i-th frequency channel of the observed data cube (see Section 3.2 for details). μ_i and σ_i characterize the Gaussian-distributed noise in the i-th channel. $S_i(m_a, g_{a\gamma\gamma}, \theta, \theta_m)$ is the expected signal flux density from axion DM conversion in the i-th channel, where m_a is the axion DM mass, $g_{a\gamma\gamma}$ is the axion-photon coupling parameter, θ is the angle between the NS rotation axis and our line of sight, and θ_m is the angle between the NS rotation axis and its magnetic dipole axis. For comparison and compatibility with previous results, we follow the approach presented in Equation (2) of Zhou22 for computing $\bar{S}(m_a, g_{a\gamma\gamma}, \theta, \theta_m)$.

To obtain the posterior distribution of $g_{a\gamma\gamma}$, we adopted a grid sampling method. The procedure was as follows:

1. We assumed a flat prior distribution for $g_{a\gamma\gamma}$, θ, and θ_m and performed grid sampling on these parameters. For $g_{a\gamma\gamma}$, we uniformly sampled in the range $[-13, -10]$, corresponding to physical values of $g_{a\gamma\gamma}$ in the interval $[10^{-13}, 10^{-10}]$ GeV^{-1}. For θ and θ_m, we performed uniform sampling in the intervals $[0, \pi]$ and $[0, \pi/2]$, respectively.
2. For each sampled triplet $(g_{a\gamma\gamma}, \theta, \theta_m)$, we evaluated the likelihood function $P(D_a|g_{a\gamma\gamma}, \theta, \theta_m)$, which quantified the probability of observing the data D_a given the specific parameter values.
3. To eliminate dependence on the nuisance parameters θ and θ_m, we marginalized them. This marginalization resulted in a likelihood function $P(D_a|g_{a\gamma\gamma})$ that depended solely on $g_{a\gamma\gamma}$.
4. Finally, we applied Bayes' theorem to obtain the posterior distribution of $g_{a\gamma\gamma}$ using the marginalized likelihood function: $P(g_{a\gamma\gamma}|D_a) \propto P(D_a|g_{a\gamma\gamma})P(g_{a\gamma\gamma})$, where $P(g_{a\gamma\gamma})$ was the prior distribution.

From the posterior distribution, we derived the 95% upper limits on $g_{a\gamma\gamma}$. Our constraints on $g_{a\gamma\gamma}$, along with other observational and experimental limits, are shown in Figure 5, showcasing the complementarity of our findings to earlier works and highlighting the potential of radio astronomical observations in searching for axion DM.

[Figure 5: see original paper]. The 95% confidence level upper limits on the axion-photon coupling constant $g_{a\gamma\gamma}$, derived from 10 hr of MeerKAT observations of the NS J0806.4-4123 (highlighted in yellow). These limits are compared with results from laboratory experiments and previous astrophysical constraints reported by [**?**].

4. Conclusions and Discussion

Axion DM, as one of the well-motivated candidates for cold DM, has attracted widespread attention in recent years. The coupling between axion DM and photons allows for photon production through axion DM conversion in an external magnetic field via the Primakoff effect, providing a solid basis for searching for axion DM.

In this study, our objective was to supplement previous axion DM detection experiments by searching for potential radio signals from axion DM conversion in the NS magnetosphere. To achieve this, we reprocessed the MeerKAT UHF-band (1000–1088 MHz subband) observations targeting isolated NS J0806.4-4123. We used a customized CARACal pipeline that incorporates two key advancements: (1) refined RFI flagging and sideband calibration, and (2) natural weighting during imaging to maximize sensitivity. These optimizations extended the detectable frequency range from 1051 to 1080 MHz, while achieving a noise level 1.45× lower than Zhou22. We confirmed the reliability of the reprocessed spectral cubes through a series of validations of the MeerKAT UHF sideband (1000–1080 MHz) data quality, including calibrator flux stability, noise-SEFD consistency, and comparison with Zhou22.

Despite our efforts, no signals exceeding 5σ were detected within the mass range of 4.136–4.467 eV (1000–1080 MHz), with particular emphasis on the previously unexplored 4.347–4.467 eV subrange (1051–1080 MHz). Consequently, we set new stringent constraints on the axion-photon coupling by excluding a region of parameter space corresponding to $|g_{a\gamma\gamma}| \gtrsim 8.2 \times 10^{-12}$ GeV^{-1} at the 95% confidence level in this mass range. Notably, we followed the computational approach of Zhou22 for calculating the axion-induced signal flux density, and these results could be further improved via more sophisticated theoretical modeling. In particular, recent works more fully take plasma effects into consideration, which could simultaneously influence the conversion probability and broaden the signal spectral width [**?**, **?**, **?**]. These broadening effects, as well as the exact photon trajectories (which can be altered due to refraction and reflection in the plasma), can be incorporated via a fuller ray-tracing approach. We leave this analysis for future work.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (NSFC, grant No. 12220101003), the Leading Innovation and Entrepreneurship Team of Zhejiang Province of China (grant No. 2023R01008), and the National Key R&D Program of China No. 2023YFE0110500. H.C. thanks the Center for Astronomical Mega-Science, Chinese Academy of Sciences, for the FAST distinguished young researcher fellowship (19-FAST-02). Y.C. acknowledges support from the National Natural Science Foundation of China (NSFC, grant No. 12050410259) and the Ministry of Science and Technology (MOST) of China grant No. QNJ2021061003L. N.H. is supported by the National Natural Science Foundation of China (NSFC, grant No. 12150410317) and the Beijing Natural Science Foundation (IS23025). The data published here have been reduced using the CARACal pipeline, partially supported by ERC Starting grant No. 679627 "FORNAX," MAECI grant No. ZA18GR02, DST-NRF grant No. 113121 as part of the ISARP Joint Research Scheme, and BMBF project 05A17PC2 for D-MeerKAT. Information about CARACal can be obtained online at https://caracal.readthedocs.io. We also acknowledge the cosmology simulation database (CSD) in the National Basic Science Data Center (NBSDC) and its funding under NBSDC-DB-10. The assistance of the South African Radio Astronomy Observatory (SARAO) toward this research is hereby acknowledged (www.sarao.ac.za).

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