# Axion Searches from Chandra Observation of Magnetic White Dwarf


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## Abstract


White dwarfs (WD) may emit axions produced in their dense cores through electron bremmstrahlung. These axions may convert to x-rays under the presence of strong magnetic fields surrounding the star. We use 40 ks observation from the Chandra X-ray Observatory of the magnetic white dwarf (MWD) ZTF J1901+1458 to potentially set the strongest constraints to date on the combination of the axion-electron coupling times the axion-photon coupling to $|g_{aee} g_{a\gamma\gamma}| \lesssim 3\times10^{-26}$ GeV$^{-1}$. Our results severely constrain axions arising from string theory models as well as astronomical anomalies such as anomalous stellar cooling.


## Introduction

The composition of dark matter has posed an important issue in cosmology. One strong dark matter candidate, the axion, was first proposed to resolve the strong CP problem of QCD. It is well known that axions may convert to photons in the presence of strong magnetic fields. In this project, we seek to unveil the first evidence for axions or place new limits in unexplored axion parameter space by observing X=ray emissions from the white dwarf ZTF J1901+1458.

## Axion-Photon System

We consider the following axion-photon system [1]

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_A^2 A_\mu - A_\mu j^\mu - \frac{1}{4}g_{a\gamma\gamma} a F_{\mu\nu}\widetilde{F^{\mu\nu}} + \frac{\alpha_{em}^2}{90 m_e^4}\left[\left(F_{\mu\nu}F^{\mu\nu}\right)^2 + \frac{7}{4}\left(F_{\mu\nu}\widetilde{F^{\mu\nu}}\right)^2\right]$$

where $F_{\mu\nu}$ is the field strength tensor, and $a$ is an axion field with corresponding axion mass $m_a$.

- Under some background magnetic field, there is some mixing between the axion and the photon field thus we can write a wave equation from the action for the combined axion-photon system.
- The photon-conversion probability is found from the solutions of the wave equation. The conversion probability approximately takes the form $P_{a\to\gamma} \approx g_{a\gamma\gamma}^2 B_T^{2/5} \frac{L^2}{4}$.

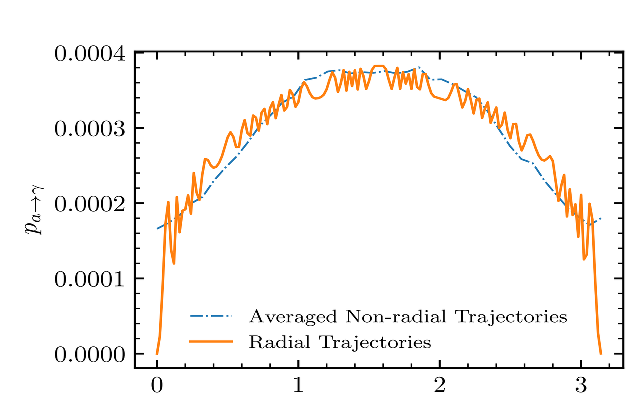


Figure 1: The axion-photon conversion probability, $p_{a\to\gamma}$ assuming a magnetic dipole field with strength $B_0 = 900\ MG$. The solid curve represents the axion trajectories that propagate radially outward from the star's center while the dashed curve shows the average over trajectories that originate throughout the star's interior.

## Astrophysical Modeling

- All parameters needed to predict the axion luminosity are directly measurable except for the core temperature, radius, and the mass.
- We combine photometric observations of the MWD with simulations and modeling of the MWD interior structure in order to constrain the relevant MWD parameters [3].

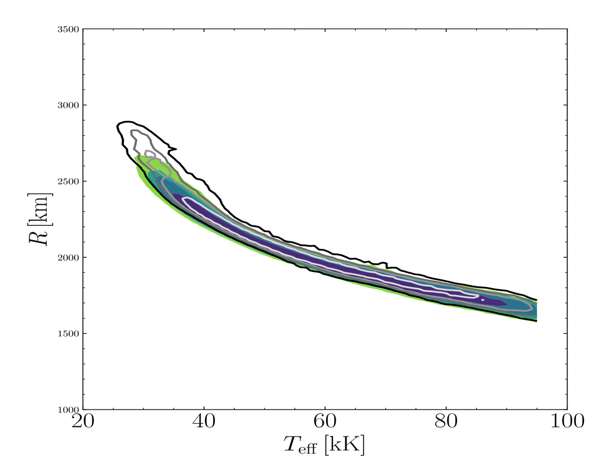

Fig 2: The joint posteriors on the $T_{\text{eff}}$ for WD ZTF J1901+1458.

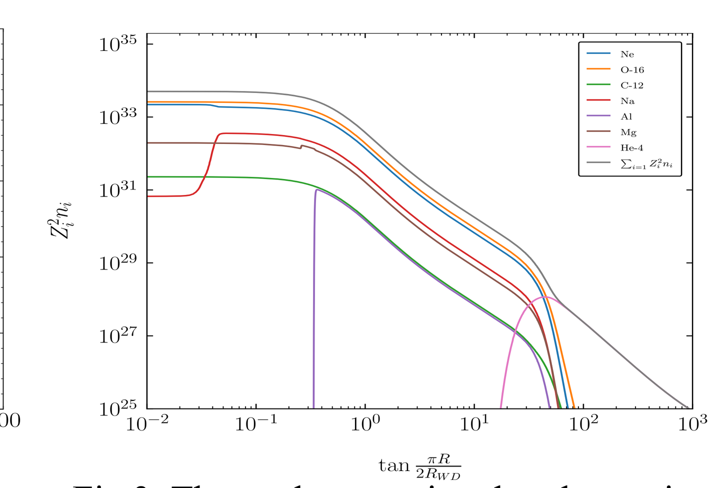

Fig 3: The nuclear species abundances in the MESA simulation for the best fit model of ZTF J1901+1458.

**Best Fit Parameters**

- $M \sim 1.34 M_\odot$
- O/Ne Core
- $T_C \sim 3.06$ keV
- $d \sim 41.40$pc
- $B \sim 900\ MG$

## Predicted Photon Flux

- The axion emissivity, shown below, is found through a matrix element calculation [2].

$$\frac{d\varepsilon}{d\omega} = \frac{\alpha_{EM}^2 g_{aee}^2}{4\pi^3 m_e^2} \frac{\omega^3}{e^{\omega/T} - 1} \sum_s \frac{Z_s^2 \rho_s F_s}{A_s u}$$

- The total X-ray flux is determined by convolving the axion luminosity with the conversion probability.

$$\frac{dF_\gamma}{d\omega} = \frac{dL_a}{d\omega} \times p_{a\to\gamma} \times \frac{1}{4\pi d_{WD}^2}$$

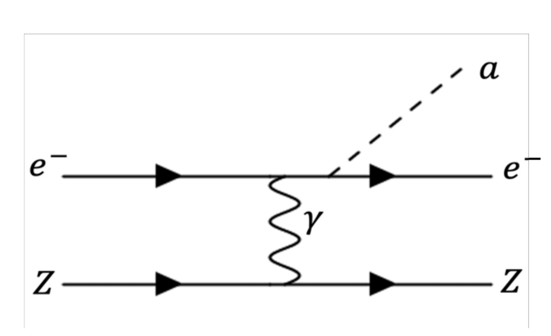

Figure 4: The Feynman graph for axion production through the electron-nucleus bremmstrahlung process.

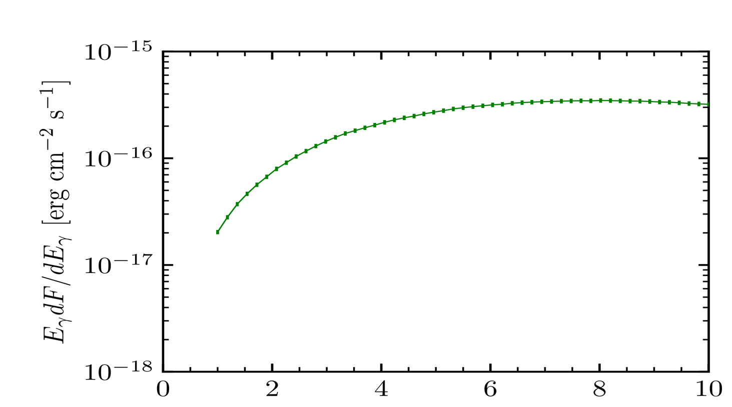

Figure 5: The predicted energy spectrum of MWD ZTF J1901+1458 for the set of parameters $g_{aee} = 1\times10^{-14}$ GeV$^{-1}$, $g_{a\gamma\gamma} = 1\times10^{-11}$ GeV$^{-1}$, and $m_a \ll 10^{-5}$ eV

- Our modeling predicts a peak X-ray flux of 3.48 erg cm$^{-2}$ s$^{-1}$ for $m_a \ll 10^{-5}$ eV and $g_{aee} g_{a\gamma\gamma} = 10^{-25}$ GeV. The X-ray spectrum peaks at roughly ~ 7 keV.

## Results

We observed the MWD ZTF J1901+1458 on 12/9/2022 and 12/10/2022 with the ACIS-I instrument with no grating for a total of 40ks (PI Safdi, observation ID 27597).

- 10 counts are observed in the 1-3 keV range. The data is analyzed using a Poisson likelihood function
- The observed spectrum is inconsistent with the predicted spectrum.
- The best fit coupling combination is $|g_{aee} g_{a\gamma\gamma}| \sim 3.1\times10^{-25}$GeV$^{-1}$

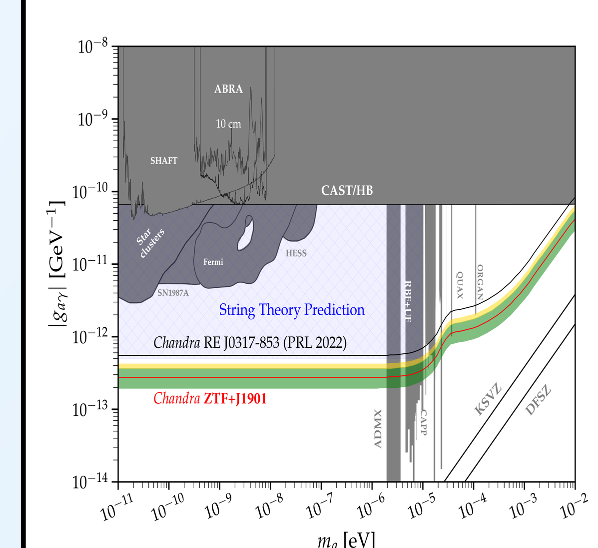

Figure 6: The constraint $|g_{aee} g_{a\gamma\gamma}| \lesssim 3\times10^{-26}$GeV$^{-1}$ at 95% confidence for low $m_a$ from the non-observation of X-rays from the MWD ZTF J1901+1458.

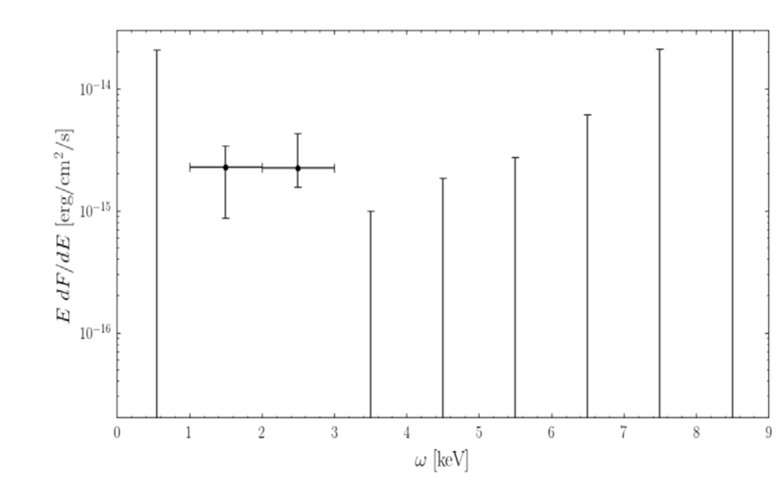

Figure 7: The energy spectrum found from our analysis of the *Chandra* data from the MWD ZTF J1901+1458.

- Currently, there are no known astrophysical X-ray sources to explain the observed low energy counts.
- If astrophysical events or objects such as accretion or thermal dust emissions are able to explain the excess counts, the resulting new 95% confidence upper coupling combination surpasses the limit obtained from all past observations and experiments $|g_{aee} g_{a\gamma\gamma}| \lesssim 3\times10^{-26}$GeV$^{-1}$

## References


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[2] A. S. Jermyn, J. Schwab, E. Bauer, F. X. Timmes, and A. Y. Potekhin, The Astrophys-ical Journal 913, 72 (2021